AN ADAPTIVE CONTROL SYSTEM FOR PRECISION CYLINDRICAL GRINDING

Thesis submitted in accordance with the requirements of the
University of Liverpool for the degree of Doctor in Philosophy by

David Andrew Thomas

October 1996

AN ADAPTIVE CONTROL SYSTEM FOR PRECISION CYLINDRICAL GRINDING

BY D.A THOMAS

ABSTRACT

The cylindrical grinding process is used extensively in the automotive, aerospace and general engineering industry because of the fine tolerances that can be achieved. With CNC grinding, the same part program is used every time a particular workpiece type is machined. However, the optimum machining conditions are difficult to predict and do not remain constant. This is because the grinding forces depend upon grinding wheel sharpness which changes with wear and dressing of the wheel. Any optimisation must take into account the process variability, and in practice conservative values of machining parameters are used in order to maintain the quality of the finished workpieces. Consequently, cycle times are much longer than necessary.

The aim of this research was to improve accuracy, quality, and productivity in cylindrical grinding through the application of adaptive techniques within the control system. The specific objectives were to identify the control problems when grinding between centres, formulate strategies to overcome these problems, and to design, implement, and evaluate an adaptive control system.

The performance of a non-adaptive CNC grinding machine was evaluated under a variety of operating conditions and with a number of different workpiece types. This identified the controlling parameters of the process and highlighted the areas where the performance of the CNC machine could be improved by the introduction of adaptive features.

A new method was developed for the in-process identification of the time constant of the machining system from the grinding power characteristics. Knowing the value of the time constant the deflection of the machining system was calculated. This technique was integrated into the control system and infeed cycles were implemented which modified the target infeed position and the dwell period according to the magnitude of the deflection. A new gauging cycle was developed which simplified the set-up procedure, reduced the dependence on manual intervention and also allowed more accurate measurement of errors in the infeed axis position.

Initial values of grinding parameters were calculated using a process model together with a data base of grinding wheel and workpiece material properties. The infeed rate was subsequently updated to maintain a desired grinding power level.

An adaptive control system was designed and built, initially based on a personal computer interfaced with a CNC grinding machine. The performance of the grinding machine with adaptive control was evaluated and compared to that of the non-adaptive CNC machine. The adaptive system was found to improve workpiece quality, reduce cycle times, simplify set-up procedures and reduce the need for supervision and manual intervention. Advantages were shown for systems both with and without diameter gauging.

ACKNOWLEDGEMENTS

I would like to express my gratitude to Prof. Brian Rowe and Prof. Jim Moruzzi for their invaluable guidance with conducting the research, and to Dr. D.W. Shimmin for his greatly appreciated encouragement and guidance with preparing the thesis.

Thanks are due to Jones & Shipman plc, Allen Bradley, Liverpool John Moores University, and the University of Liverpool for initiating and supporting the project. Particular thanks are due to Dr. John Liverton, Roger Palmer and Engineers of Jones & Shipman for their advise concerning the practical application of the adaptive strategies, and to Derrick Morgan of Allen Bradley for his advice with developing the control system.

I would also like to thank my colleagues at Liverpool John Moores University , particularly David Allanson, Paul Wright, Peter Moran and Xun Chen for their contributions to the project, and Mike Morgan and Nick Shepherd for assistance with preparing the thesis.

Thanks in particular are to my parents, my sisters Jackie and Sara, and especially to my wife Julie, for their patience, encouragement and support during the preparation of the thesis.

TABLE OF CONTENTS

LIST OF SYMBOLS

A_r	chip aspect ratio
d_e	equivalent diameter
d_s	grinding wheel diameter
d_w	workpiece diameter
k	gain of a first order system
k_p	constant of proportionality relating grinding power to infeed rate
l_c	chip length
l_d	dynamic grit spacing
OS	overshoot
P_t	target grinding power
P_{n-1}	maximum grinding power attained during the last grinding operation
P_{max}	maximum grinding power attained during a grinding cycle
t	time elapsed since the start of grinding
t_1	time over which the grinding power is integrated
t_2	time over which the grinding power is integrated
τ	time constant of the machine-wheel-work system
T_1	time at the end of the infeed period of a basic grinding cycle
T_2	time at the end of the dwell period
T_d	dwell period
T_d'	measured duration of the dwell period
U	input of a first order system
u	rate of radius reduction
v_f	infeed rate
v_{fn}	infeed rate for the current grinding cycle
v_{fn-1}	infeed rate for the last grinding cycle
v_{ff}	very fine feed rate
v_s	grinding surface wheel speed
v_w	workpiece surface speed
x	programmed infeed rate

x_i	deflection of the machine-wheel-work system
x_1	deflection of the machine-wheel-work system at time T1
X_e	infeed position error
X_i	actual infeed position
X_p	programmed infeed position
y	output of a first order system

LIST OF FIGURES

1 INTRODUCTION

1.1 A Brief Description of the Grinding Process

The grinding wheel consists of many abrasive particles held together by a bond material. The abrasive for grinding ferrous materials is usually aluminium oxide or silicon carbide with a vitreous or resinoid bond. Very hard abrasives such as cubic boron nitride (CBN) may also be used, either vitrified or in conjunction with an electroplated metal bond.

The grinding wheel is a porous structure, allowing coolant to be absorbed and assisting in the formation of grinding chips. As the grinding wheel is rotated and brought into contact with the workpiece, each grit acts as a miniature cutting edge, removing material from the workpiece. The coolant applied to the wheel and workpiece assists the abrasive process by acting as a lubricant, and also cools the workpiece, helping to prevent thermal damage

As grinding proceeds, wear of the grinding wheel occurs by attritious wear, bond failure and grit fracture. The wheel may become loaded as the pores of the wheel fill with grinding debris. The effects of wear and loading of the grinding wheel are overcome by dressing of the grinding wheel. This involves removing material from the grinding wheel in order to generate a fresh cutting surface. This is achieved by passing a dressing tool across the surface of the wheel. The dressing tool is normally a single point or multi-point diamond. By varying the dressing increment and lead, the severity of the dressing operation may be altered. Generally, coarse dressing produces an open, free cutting wheel, whereas fine dressing gives a closed wheel surface that will improve surface roughness.

For the external cylindrical grinding process the workpiece may be held in a chuck that is rotated by the workhead. Alternatively, the workpiece may be held between workhead and tailstock centres, and driven from the workhead via a carrier. Material is removed from the workpiece by plunging the wheel into the workpiece or by traversing the wheel across the workpiece. The front of the wheel is used for grinding diameters, and the side of the wheel for grinding faces. A basic plunge grinding cycle consisting of an infeed period and a dwell period is shown in figure 1.1. The actual infeed position lags behind the programmed infeed position because grinding forces cause the machine-wheel-workpiece system to deflect. During the dwell period the deflection relaxes, bringing the workpiece to size and also improving the roundness and surface roughness of the finished part. This is often referred to as the sparkout process.

1.2 The Need for Adaptive Control

This thesis addresses the adaptive control of plunge grinding operations for the external cylindrical grinding process. The cylindrical grinding process is used extensively in the aerospace, automotive and other manufacturing industries because of the fine tolerances that can be achieved. If components are scrapped however, the cost can be high due to the expense of the materials used and the number of hours of work that may have been incurred in the production of the components.

The grinding process is inherently variable because the grinding wheel sharpness depends upon wear and dressing of the grinding wheel. As a result, the optimum machining conditions do not remain constant. The selection of appropriate values of machining parameters is not a straight forward task and requires the skill of an experienced engineer. In practice, conservative values of machining parameters are often used in order to maintain the quality of the finished workpieces. Consequently, cycle times are much longer than required to attain the specified tolerances.

Most production cylindrical grinding machines are now supplied with Computer numerical control (CNC), which has been applied to the grinding process with considerable success. A part program comprising of a set of commands which specify the movements of the machine tool axes, is executed by the controller which moves the machine tool axes under servo control. Parts can be produced with reduced supervision, reduced scrap levels, reduced inspection requirements, and simplified machining procedures. These advantages over manual machining have led to improved throughput by reducing non-productive time, and costs have been reduced.

Until now, commercially available CNC grinding machines have lacked intelligence for the selection of grinding parameters or process optimisation. An adaptive control system which automatically selects grinding parameters, monitors the process, and alters the grinding parameters in order to attain optimum operating conditions, has the potential to significantly improve the performance that can be achieved. Adaptive control may also contribute towards the effective implementation of a computer integrated manufacturing (CIM) strategy. The automatic selection and adaption of machining parameter values will reduce the need for extensive pre-production trials and hence reduce lead times. In addition, reduced supervision requirements will allow an adaptively controlled machine to be operated automatically as part of a manufacturing cell.

The aim of this research is to improve accuracy, quality, and productivity in cylindrical grinding through the application of adaptive techniques. Specific objectives are to identify the control problems of grinding between centres, formulate strategies to overcome these problems, and to design, implement, and evaluate an adaptive control system.

In order to produce system that is appropriate for industrial application, the adaptive techniques are designed to be specifically for implementation in software within the controller of a CNC system. In addition, the sensors used should be easily installed on any grinding machine without the need for major machine modifications, and should not interfere with the operation of the machine.

1.3 Scope of the Investigation

Previous work on automation of the grinding process is described in chapter two. The principal developments in adaptive control are described with particular attention given to control strategies, control system design and instrumentation requirements. It is argued that an adaptive control system should be capable of single and multi-diameter grinding, with and without automatic size gauging.

Chapter three proposes adaptive strategies for the control of cylindrical grinding. Significant advances in this area include the development of strategies and algorithms that are suitable for practical implementation on a modern machine tool controller.

Chapter four gives an account of the modifications made to a machine tool controller in order to implement the adaptive strategies. Details of the additional instrumentation requirements are also provided. The initial development was based on a personal and computer interfaced with a CNC machine. However, the strategies are proposed as the basis for commercial system, integrating the system within a CNC system.

Chapter five describes grinding trials conducted using a conventional CNC grinding machine. The purpose of the investigation was to determine standards of performance that could be attained, and also to determine the controlling parameters for the cylindrical grinding process.

Chapter six concerns the design and evaluation of grinding cycles that incorporate the adaptive strategies proposed in chapter two. In chapter seven, the performance of the adaptive control system is compared with the performance of the conventional control system. The operation of both systems is summarised and the results of grinding cycles both with and without gauging are given.

Chapter eight summarises the new advances achieved, and chapter nine gives recommendations for further work in the areas of adaptive control strategies, adaptive control system design and instrumentation requirements.

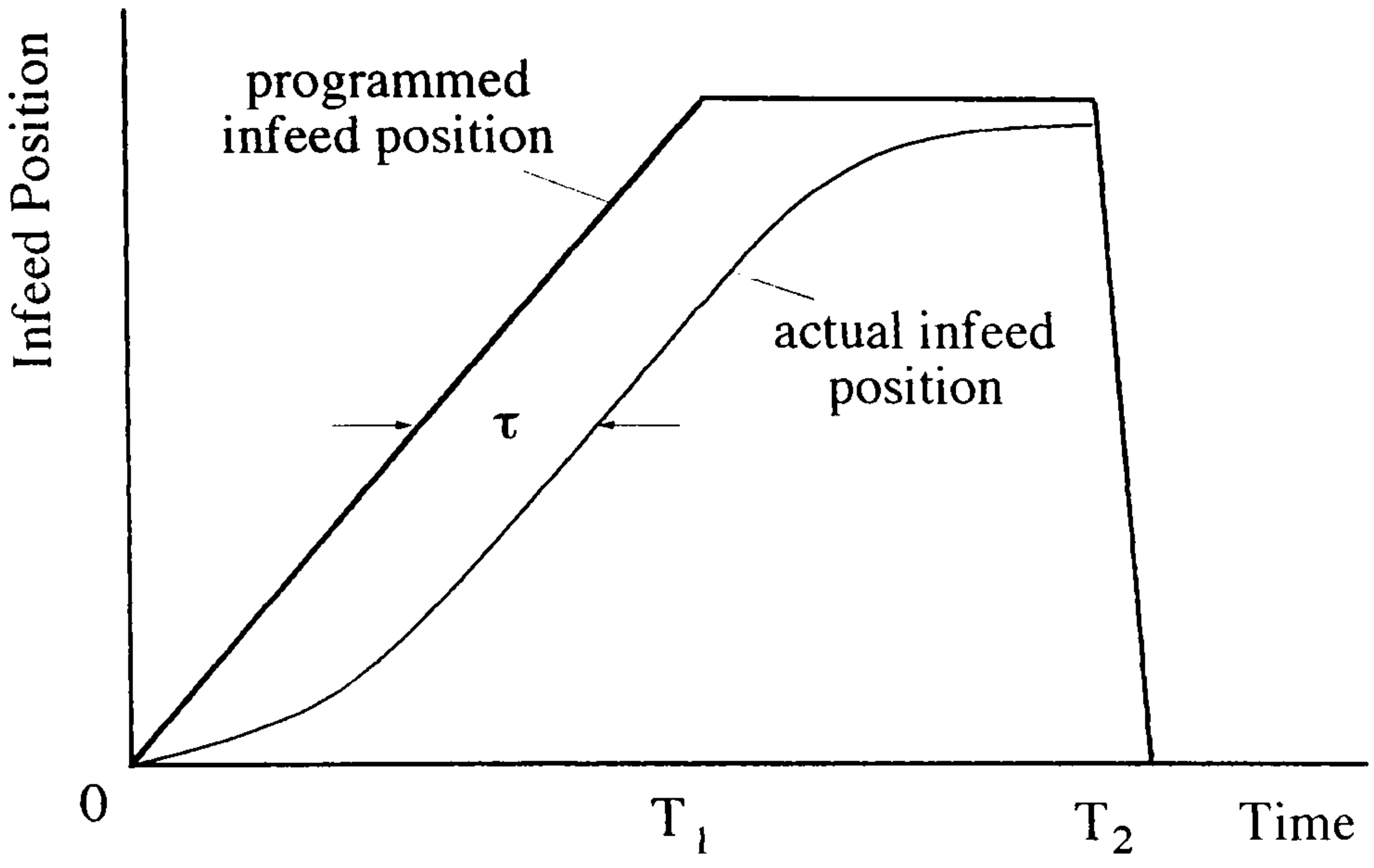


Figure 1.1 - A plunge grinding cycle consisting of an infeed period and a dwell.

2 PREVIOUS WORK

2.1 Computer Numerical Control

Groover and Zimmers (1984) described the development of machine tool control systems and described the progression from numerical control (NC), to direct numerical control (DNC), to computer numerical control (CNC). The first NC machines, with controllers that were hardwired for a particular machine tool, became available in the mid 1950s. Part programs were stored and run using paper tapes. In the late 1960s DNC was developed to provide a communications link between machine tool controllers and computer systems, primarily for storing and downloading part programs electronically. With the advent of CNC machines in the early 1970s computers were used to control machine tools. The interface with the machine tool was implemented in software and the controller was no longer hardwired for a particular machine. The use of a computer also facilitated the storage of part programs, and the increased processing power allowed the development of more sophisticated features such as tool wear compensation.

Through the application of this technology a variety of machining processes benefited from increased accuracy, simplified machining procedures, reduced scrap levels, and reduced inspection requirements.

2.2 Computer Numerical Control for Grinding

The application of CNC to grinding occurred considerably later than for other processes such as turning, milling and machining centres. Sprow (1991) attributed this to the large number of process variables to be controlled and to the high development and capital costs associated with CNC grinding machines. However, the widespread use of CNC grinding machines since the early 1980s has demonstrated the improvements in performance that can be achieved.

TenClay (1989), Liverton (1990), Terada (1990), Sprow (1991) and Koelsch (1992) described the benefits of CNC grinding. High resolution measurement of position allowed the machine tool axes to be accurately controlled, resulting in improved workpiece quality and reduced scrap levels. Simultaneous control of a number of axes allowed complex forms to be dressed onto the grinding wheel and also allowed the wheel to follow a contoured path. This greatly simplified the grinding of complex forms. Compensation for changes in wheel geometry with dressing were incorporated into the control software and the use of in-process gauging further improved the accuracies that could be achieved.

Another benefit of CNC grinding was the reduction in set-up time that resulted from the ability to perform a number of grinding operations in one setting. Cycle times were also reduced by the use of gap-elimination devices which decreased the time taken for the wheel to contact the workpiece.

To summarise, the main benefits of CNC grinding were increased accuracy, reduced inspection requirements, the ability to grind complex forms, shorter set-up times and shorter cycle times.

2.3 Adaptive Control

A characteristic of NC and CNC machines is that the values of machining parameters, such as workpiece speed and infeed rate, are specified based on the knowledge and experience of the user. However, because of tool wear, machining conditions are not constant, and the values of the machining parameters must be selected to account for the most severe conditions that may occur. In practice conservative values are chosen in order to ensure that the desired process output is always achieved. This often results in cycle times that are longer than necessary. Adaptive control systems counter this problem by monitoring the process and altering the machining parameters or the controller parameters in order to improve performance.

Ulsoy, Koren and Rasmussen (1983) and Ulsoy and Koren (1989) summarised the research in this area, giving examples for turning, milling and grinding. A control system for milling developed by Bendix under a U.S. air force contract in 1962-1964 was cited as the first application of adaptive control to machine tools. Ralston and Ward (1988) also reviewed the research on adaptive control of machine tools. Systems for grinding, EDM, turning, milling and drilling were described.

Adaptive control systems were often classified into three types, namely adaptive control constraint (ACC), geometric adaptive control (GAC) and adaptive control optimisation (ACO). With ACC, the effects of process variability are reduced by maintaining measured outputs such as force or power within predetermined limits. In contrast, the aim of GAC is to maintain part geometry within specified tolerances. With ACO, a performance index was optimised. The index indicates the overall performance of the system and may be defined in terms of production costs, productivity, or part quality. ACO systems are characterised by the ability to identify process parameters, decide how to optimise the process and then modify the machining parameters. Ralston and Ward (1988) acknowledged that some systems may combine the different approaches.

Wada and Kodama (1977) also cite the Bendix project as the first application of adaptive control to a machining process. An overview of adaptive control principals is given and the early work conducted into adaptive control of grinding is reviewed.

2.4 Adaptive Control for Grinding

2.4.1 Controlling the Normal Grinding Force

The normal grinding force is regarded as a useful measure as it is proportional to deflection of the machining system. A popular control strategy has been to vary the infeed rate in order to control the normal grinding force as shown in figure 2.1, thereby reducing the effect of variable deflections. A number of systems have been implemented. Hahn proposed controlled force grinding as a new technique for precision internal grinding in 1964, and has further investigated the process (Hahn 1965, 1984, 1986). Controlled force grinding reduced the time taken to reach steady state grinding. Also, because deflection is proportional to the normal force, size errors due to variations in deflection were reduced. Calculating the work removal parameter, or stock removal per unit force, allowed the wheel sharpness to be monitored. The wheel was dressed when this parameter fell below a predetermined limit and in this way thermal damage to the workpiece was avoided. Hahn (1986) also developed a control system that compensated for deflections by pivoting the workhead based on force measurements.

Toenshoff (1980) investigated the instrumentation requirements for monitoring internal grinding, with a view to controlling the process. Toenshoff, Zinngrebe and Kemmerling (1986) implemented a system for controlled force grinding that relied on an identification cycle during which the infeed rate was varied in a random fashion. From the response of the force signal during this period process parameters were calculated. Grinding cycles commenced by advancing the grinding wheel at a rapid infeed rate until contact with the workpiece was sensed by a rise in force. For the rest of the grinding cycle a constant force was maintained. Out of round workpieces were handled by inputting to the control algorithm the maximum force measured during a given workpiece revolution. Grinding power could also be used as the controlled variable.

Bell, Lambert, Matson and Vaillette (1988) developed a data acquisition system for monitoring force and power, with a view to developing adaptive control strategies for internal grinding.

A controlled force system for plunge grinding was implemented by Brinksmeier and Popp (1991). After the start of the cycle, wheel-workpiece contact was detected from the force signal. The amount and phase of workpiece eccentricity was then determined from the force signal. The grinding wheel was advanced and retracted in order to remove material from the high spots of the workpiece and not from the low spots. Once acceptable roundness was achieved, the remaining stock was removed using self tuning adaptive control. Model parameters were continuously estimated so as to account for disturbances such as changes in wheel sharpness. A high force was used for roughing. During finishing the force was decreased linearly with distance, causing an exponential reduction of workpiece size with time. This improved the quality of the finished workpiece.

The adaptive control system for external cylindrical grinding developed by He Xiu-Shou (1985) used controlled force grinding for the roughing stage. The force level was chosen to minimise the total time taken to remove a given volume of material, taking into account both the time spent grinding and the time spent dressing the wheel. A finishing stage consisting of a constant infeed rate was used to satisfy surface roughness constraints. During the dwell period a diameter gauge was applied to ensure that size and roundness requirements were met. The system was applicable to a range of workpieces, and improved productivity by 180 per cent for a particular aerospace component.

Adaptive Force Control was also applied to robotic disk grinding by Elbestawi et al (1991). The disk grinding process was used extensively for removing defects from steel castings and much attention was paid to automating the process. Models were developed both for the process and for disturbances. With the application of adaptive control algorithms the normal grinding force was regulated by varying the position of a robot arm.

2.4.2 Controlling the Grinding Power

The maximum grinding power that may be developed is limited by the rating of the wheel spindle motor. This limits the grinding parameters that may be safely employed by a control system. Rowe, Bell and Brough (1987) established limits for centreless grinding. By reducing the workpiece speed, higher infeed rates could be used without exceeding the available power, but burn occurred if the workpiece speed was too slow. Kelly et al (1989) and Rowe et al (1991) incorporated this into a strategy that monitored the power and then reduced the workpiece speed and increased the infeed rate for the next workpiece. This was repeated until the grinding power approached the critical power above which burn occurred, as shown in figure

2.2. The thermal model proposed by Rowe et al 1988 was used to calculate the critical power based on grinding power measurements, grinding parameter values, and the dimensions and thermal properties of the grinding wheel and workpiece. A kinematic model based on the work of Rowe, Bell and Brough (1987) was used to calculate the chip volume and chip aspect ratio from grinding parameter values, wheel and workpiece diameters and grinding wheel properties. By storing the kinematic parameters in a data base, the improvements made to the process were saved for future use with workpieces having different dimensions.

Amitay, Malkin and Koren (1981) developed a pilot adaptive control system for cylindrical grinding. The optimisation was based on a grinding model that predicted workpiece burn. The model also accounted for the effect of grinding parameters on surface roughness and the influence of dressing parameters on grinding performance. The strategy had previously been implemented off-line by Malkin and Koren (1980). The principle was to maximise infeed rate while maintaining grinding power at the critical value, above which workpiece burn would occur. An optimal locus defined the infeed rate and workpiece speed that satisfied this equality for various wear flat areas, as shown in figure 2.3. Within a grinding cycle the infeed rate and workpiece speed were modified along the optimal locus until the critical grinding power was attained. The optimisation was halted if the surface roughness constraint was reached before the power constraint. The optimisation was also constrained by the available power and the maximum and minimum programmable infeed rate and workpiece speed. If the surface roughness constraint was tight finer dressing was used, and if the power constraint was tight coarser dressing was used. Optimal dressing was achieved when the surface roughness and power constraints coincided on the optimal locus. Illustrative results were given that showed the system converging on the optimum conditions over a short number of grinding operations. When grinding was optimised but the dressing conditions were kept constant, results showed that the surface roughness requirement severely constrained performance. Higher removal rates were achieved when both grinding and dressing were optimised.

A later paper by Xiao, Malkin and Danai (1993) described a system for the intelligent control of cylindrical plunge grinding. The grinding cycle consisted of a coarse and a finishing infeed rate followed by a dwell period. From the grinding power the dullness of the wheel was estimated and the infeed rate and feed change points were adapted to minimise cycle time within the constraint of workpiece burn, but also considering surface roughness, roundness and size. Results showed that cycle times were significantly reduced while the grinding power and surface roughness constraints were maintained.

A control system was proposed by Kim and Shumsheruddin (1983) to minimise cycle time by adapting infeed rate, workpiece speed and wheel speed. The grinding cycle consisted of a coarse infeed and a fine infeed. For rough grinding the constraints were the machine limits, workpiece thermal damage and surface roughness. For the fine feed the constraints were roundness and surface roughness. If the power limit or burn power was encountered during the fine feed the need to dress was indicated. Similarly, if the infeed rate required to achieve the required surface roughness dropped below a lower limit the need to dress was indicated. At intervals during the grinding cycle, parameters indicating the wear of the grinding wheel were identified, the optimum values were calculated and the grinding parameters were adapted. In addition to power, the system required in-process measurement of force, size, and surface roughness.

An energy adaptive CNC system developed by Smith (1980) utilised the self-sharpening ability of the grinding wheel. With conventional grinding a low wheel wear rate was maintained to ensure size and surface roughness requirements were met. However, this resulted in a high value of specific energy (ratio of grinding power to removal rate). With the energy adaptive system a constant infeed rate was used throughout the grinding cycle. When an increase in specific energy was detected the wheel speed was decreased causing the grinding wheel to sharpen. Conversely, when a decrease in specific energy was detected the wheel speed was increased causing the wheel to dull. In this way the specific energy at which the wheel surface operated was maintained at a steady value. By operating at a low specific energy, workpiece burn was avoided and higher infeed rates could be used without exceeding the available grinding power. The high wear rate of the grinding wheel associated with low specific energy was compensated for by monitoring the workpiece size. The size signal was included in the control loop in order to maintain the material removal rate at the programmed value. The infeed was halted when the programmed size was attained.

Rao and Malkin (1990) implemented a process monitoring system to investigate the use of power and workpiece diameter feedback for the intelligent control of grinding. Inasaki (1991) investigated feasibility of monitoring the grinding power for optimisation of the internal grinding process.

2.4.3 Controlling the Dwell Period

A number of techniques have been proposed to achieve accurate size with minimum cycle time. Many adaptive systems accomplish this by the use of in-process gauging to control the dwell period. The energy adaptive system implemented by Smith (1980) resulted in high wheel wear rates, necessitating the monitoring of workpiece size and ending of the grinding cycle when size was achieved. The system presented by He Xiu-Shou (1985) measured the elastic deformation of the machining system and calculated the position at which to stop infeeding and commence the sparkout. During the dwell period workpiece roundness was monitored by measuring the size of the workpiece over an entire revolution. Once the required roundness was achieved the dwell was ended only if the required workpiece size had been attained. Otherwise, a micro-feed was applied by delivering single pulses to the stepper motor infeed drive until size was achieved. Trmal (1979) also proposed a strategy for in-process control of size using a diameter gauge.

Kaliszer (1980) implemented a basic infeed cycle consisting of a single infeed period followed by a dwell period. The spark-out stage of the cycle was terminated when both the desired size and roundness were achieved. Surface roughness measurements were used to set the infeed rate for subsequent grinding cycles and the dressing procedure was recalled when poor roundness or surface roughness results were experienced. The deflection in grinding cycles was also modelled, confirming that the machine-wheel-workpiece system behaves predominantly as a first order system, and that the deflection depends on the system time constant.

The meaning of the system time constant may be explained by considering the general response of a first order system to a step input, given by

$$\frac{y}{U} = k\left(1 - e^{-t/\tau}\right) \qquad (2.1)$$

where y is the output of the system,
U is the input of the system,
k is the gain of the system, and
τ is the time constant of the system.

For grinding, the gain of the system is one and the particular case is

$$\frac{\dot{u}}{\dot{x}} = 1 - e^{-t/\tau} \qquad (2.2)$$

where $\dot{u}$ is the rate of radius reduction,
$\dot{x}$ is the programmed infeed rate,
t is the time elapsed since the start of grinding, and
τ is the time constant of the system.

Steady state grinding is attained when the time elapsed since the start of grinding is greater than three times the system time constant. At this point the rate of radius reduction is ninety five per cent of the programmed infeed rate, and the radius reduction lags behind the infeed rate by the time constant as shown in figure 2.4. Kaliszer (1980) calculated the system time constant by measuring the steady state deflection with an in-process gauge, and dividing by the programmed infeed rate.

Identification of the system time constant allowed the use of more complex control strategies. Spiewak and Kaliszer (1983) proposed a grinding cycle to accelerate the spark-out process. Material was removed at the maximum permissible infeed rate, and the grinding wheel was then retracted to a predetermined position as shown in figure 2.5. The gradual decrease of the tension in the machining system improved the size, form and surface roughness of the finished part. An expression for the infeed time was given in terms of the system time constant, the infeed rate and the target workpiece size. The time constant was determined by dividing the deflection by the rate of diameter reduction. The time constant was also determined by applying least mean squares to an expression relating the deflection to the infeed rate, the time constant and the time elapsed.

Malkin (1981,1986) and Malkin and Koren (1984) proposed a similar control policy to minimise the cycle time. The retraction was commenced when a given stock allowance was indicated by a diameter gauge. After the retraction, a dwell for at least one revolution of the workpiece was provided to ensure satisfactory surface roughness over the entire workpiece circumference. The optimal cycle time was expressed in terms of the actual and programmed infeed rates, the system time constant and the stock allowance. It was proposed to estimate the time constant by dividing the steady state deflection by the programmed infeed rate.

Zhao Webster and Kaliszer (1988) also adopted the accelerated sparkout method, with a dwell period to improve the final roughness and roundness. The roundness was monitored during the dwell and the size tolerance band was used to achieve the required roundness. The time constant was identified from the size signal during the initial infeed stage, by dividing the deflection by the rate of diameter reduction. Webster and Zhao (1990) refined this method of determining the time constant, and showed that it could be accurately calculated during the initial stages of the infeed period, providing that the start of grinding was determined accurately.

A variation of the accelerated spark-out strategy was implemented for centreless grinding by Kelly et al (1989), Allanson et al (1989) and Rowe et al (1991). An overshoot was applied but without retracting the wheel back to the target position.

At the end of an intermediate dwell period the workpiece size was measured and from this value the time constant was calculated. The part was finished to size using a new overshoot value calculated from the time constant. This two stage 'pecking' cycle, shown in figure 2.6, was required because the highly compliant nature of the workpieces rendered in-process gauging inaccurate. The 'pecking' cycle allowed the workpiece size to be measured with the grinding wheel retracted from the workpiece.

Another strategy was the integrated size and roundness adaptive control system proposed by Gao, Jones and Webster (1992). The grinding cycle consisted of a single infeed followed by a dwell period. The dwell commenced when a given stock allowance remained as indicated by a diameter gauge, and was terminated when the workpiece size fell within a specified tolerance. By altering the stock allowance from one grinding operation to the next the dwell time was lengthened or shortened in order to maintain the desired workpiece roundness. The diameter gauge was used to measure both workpiece size and roundness. The system time constant was estimated at the end of each cycle.

The optimum size and roundness adaptive control method, proposed by Gao and Jones (1992) also required an estimate of the system time constant to be made at the end of each cycle. The control algorithm employed caused a high infeed rate to be used at the start of the infeed cycle. As deflection built up the infeed rate was reduced towards a constant value. In this way the effect of the transient stage at the start of grinding was reduced, shortening the cycle time. An accelerated sparkout strategy was also employed. Simulation was used to validate the control method.

The optimisation strategy adopted by Xiao (1993) also relied on the estimation of the system time constant, which was achieved by applying least square estimation to the signal from a diameter gauge during the infeed cycle. The infeed rate and feed change points were adapted to minimise cycle time within the constraint of surface roughness, roundness, size and workpiece burn.

2.4.4 Optimising Wheel Wear or Production Costs

Inoue et al (1974) conducted preparatory work towards the development of an adaptive control system for grinding. The aim was to achieve high removal rates with economical operation and yet maintain high quality finish. Productivity or cost were to be optimised during coarse grinding, and the required accuracy was to be achieved by a finishing feed and a dwell period. Experiments were conducted using a Toyoda NC cylindrical grinding machine. The wheel life, as indicated by the re-dressing period, was identified by detecting vibrations due to chatter. Wheel life was expressed as a power function in a similar way to Taylors tool life equation. The feasibility of adapting the infeed cycle to changes in the wheel surface topography and controlling the active cutting edges was also investigated.

Koenig and Werner (1974) discussed an adaptive control optimisation technique based on a process model and a modifiable optimisation algorithm. The parameters of the model were adjusted by comparing the output of the model with the output of the process. In this way the model was modified so that it gave a true representation of the process. The model parameters were in turn used by the optimisation, allowing adaptive operation of the system.

The application of this technique to grinding was also discussed. Wheel wear was proposed as the controlled process parameter, with grinding force and depth of the heat affected zone as limiting process parameters. The input parameters to be optimised were infeed rate, workpiece speed and wheel speed. Force, wheel wear and thermal models were formulated. The parameters of all three models could be readily determined from force measurements. It was noted that further work was required to empirically determine starting values for the model parameters, and to develop appropriate sensors.

Younis (1990) developed a grinding model based on a grinding coefficient. It was proposed to use the model as the basis for an adaptive control system. Wheel wear, surface roughness, or grinding forces were to optimised by varying the wheel speed, workpiece speed, and infeed rate.

Storm (1970) applied adaptive control to the cut-off grinding process used for parting large sections of hard material. The approach taken was to vary the downfeed rate from part to part in order to minimise the total cost, which comprised of machining costs per unit time and the cost of wheel wear. Wear was indicated by the change in downfeed position after grinding each part.

Stelson, Komanduri and Shaw (1979) developed a manual adaptive control system for axial feed centreless grinding. The operator dressed the grinding wheel depending on factors such as dimensional accuracy, surface roughness, force, power or temperature. The optimisation was based on attaining the lowest cost per part by adjusting the wheel speed. Machine, labour and overhead costs which decreased with material removal rate, were offset against wheel cost which increased with material removal rate. The operator entered into a programmable calculator values for the number of parts ground between dressing and and the total time elapsed. A least mean squares wheel wear curve was used to calculate the optimum number of parts per dress. The operator compared this value with the actual value and adjusted the wheel speed until the actual value approached the optimum. Grinding trials showed a substantial decrease (42 %) in cost per part.

2.5 Control Systems

A number of approaches to implementing adaptive control systems have been adopted. Storm (1970) developed a purely hardware solution. An analogue electronic circuit was used to compute the machining cost for cut off grinding. Another circuit calculated the downfeed rate required to optimise the total machining cost, and the downfeed rate was varied from part to part by means of a servo valve for a hydraulic piston.

He Xieu Shou (1985) adapted an NC cylindrical grinding machine to give controlled force grinding for plunge grinding operations. The normal grinding force was determined from the pressure difference across the wheel spindle hydrostatic bearings. The difference between the demanded and actual force was amplified and a gate circuit controlled the signal to a stepper motor drive for the infeed.

The majority of adaptive control systems utilised computer systems to analyse the data from sensors and determine suitable grinding parameters. A number of computer systems were interfaced directly to the machine tool by monitoring the output from sensors and controlling the axis drives. Amitay, Malkin and Koren (1981) developed a pilot adaptive control system which consisted of a Kellenburger 600R cylindrical grinder interfaced with a PDP-11/40 computer. A power transducer was used to monitor the grinding power. Surface roughness was measured by the operator and input manually to the system. Infeed rate and workpiece speed were adapted automatically. The dressing parameters were adapted manually by the operator who used the dressing parameters suggested by the computer.

The autonomous system by Xiao, Malkin and Danai (1993) consisted of a stepper motor infeed drive, a power monitor, a size gauge and a personal computer for data acquisition and control. The system was used to control a Bryant Model 1116 internal grinder. Manual post process measurements of roundness and surface finish were also made and input to the system.

Kaliszer (1980) interfaced a Nova mini-computer with a cylindrical grinding machine. A stepper motor drive advanced the wheelhead to a nominal infeed position. The dwell period was ended when the required size and roundness were achieved, as indicated by a diameter gauge. Surface roughness measurements were used to set the infeed rate for subsequent grinding cycles and to initiate dressing. A prototype sensor for the in-process measurement of surface roughness was developed for this purpose.

Spiewak and Kaliszer (1983) proposed a modular approach to control system development. Tasks of the computer system including measurement, control, identification, and optimisation, were to be carried out by separate modules. Each module was to be based on microprocessor. Modules were to communicate with each other via a bus, with a supervisory module to coordinate the actions of the system. Some progress was made towards implementing the system, with the development of a module for the measurement of size and form error and a module for wheel balancing. The broader aim was to develop an hierarchical system, with the lowest level controlling the wheelhead position, the medium level identifying process parameters and the highest level optimising a performance index.

Zhao, Webster and Kaliszer (1988) made further progress towards implementing a modular adaptive control system for cylindrical plunge grinding. A combined size and roundness sensor, and a surface roughness module based on work by Kaliszer (1979) Spiewak and Kaliszer (1983), were developed. Separate modules were provided for measuring and analysing the output of these sensors. A wheel balancing module was provided and a supervisory module coordinated the actions of the control system. Force and power levels were used as constraints. Monitoring of the acoustic emission indicated when the grinding wheel contacted the workpiece.

An industrial standard STE bus with a Z80A microprocessor was used for the integrated size and roundness adaptive control strategy for plunge grinding developed by Gao, Jones and Webster (1992). Size and roundness were measured using an in-process diameter gauge, and the system time constant was estimated at the end of the cycle from the size signal. This allowed the use of an inexpensive computer system as the strategy was not intensive in processing power. Gao and Jones (1992) also proposed to use this platform for both an integrated sensor system and an optimum size and roundness adaptive control.

An alternative to interfacing a computer system directly to the machine tool was to execute data acquisition and adaptive control functions on a computer, which then passed instructions for control of the grinding cycle to a CNC machine. The controlled force system by Brinksmeier and Popp (1991) was based on a Studer S50-42 machine with Brutsch CNC. Adaptive control optimisation was implemented on a VME based computer system with an MC68020 CPU board. A special board sampled the normal force and transmitted the infeed velocity command to the CNC. The normal grinding force was measured by piezo-electric force transducers mounted on the centres of the machine.

Toenshoff, Zinngrebe and Kemmerling (1986) applied a similar approach to controlling the internal grinding process. Software for controlled force grinding ran on a 68020 based micro-computer, and a position signal was output to a CNC grinding machine. The normal grinding force was measured using a piezo-electric dynamometer mounted underneath the wheel spindle.

Kim and Shumsherradin (1983) used a Newall cylindrical grinder controlled by an Allen Bradley 8200 system, with a Zilog PDS 800 micro-computer providing adaptive capability. Workpiece diameter was measured by in-process gauging. Two methods of force measurement were employed, a piezo-electric transducer mounted on the tailstock centre, and piezo-electric load washers located between the nut of the ballscrew and the wheelhead. A watt-meter indicated the grinding power, and an optical method of surface roughness measurement was employed.

Other systems implemented adaptive control within the CNC system. The energy adaptive system developed by Smith (1980) was implemented on a Norton 6" by 30" CTU cylindrical grinding machine with a prototype control system by Giddings and Lewis Electronics Company. Infeed position was under servo control, with feedback derived from an eddy current probe indicating workpiece size. Wheel speed was adjusted based on power feedback from the spindle drive.

Kelly et al (1989) and Rowe et al (1991) implemented an adaptive CNC system for centreless grinding using an AB 8600 controller and a modified Cincinatti Number 3 centreless grinding machine. Grinding parameters were adapted based on workpiece size and grinding power measurements. The software developed was based on the modular conceptual framework shown in figure 2.7. The framework consisted of an executor, a data logger, process models, adaptive and learning strategies, database, infeed cycles, input / output routines and a safety strategy. The aim of the modular conceptual framework was to allow a flexible approach to system development.

2.6 Discussion

The introduction of computer numerical control to grinding resulted in a number of benefits, including simplified machining procedures, increased accuracy, and reduced scrap levels and inspection requirements. Other benefits were shorter set-up times, shorter cycle times and the ability to grind complex forms. Despite increased automation of the grinding process, considerable variability is introduced by wear and dressing of the grinding wheel. Much research has been directed at improving performance by the application of adaptive control techniques. This involved monitoring the outputs of the process, and altering grinding parameter values in order to approach optimum operation. Control strategies were based on controlling the grinding force, the grinding power, or the dwell period. Other approaches aimed to optimise wheel wear or production costs.

Controlled force grinding consists of continually varying the infeed rate in order to maintain a given value of normal grinding force. The main advantage is that as the deflection is proportional to the normal force, errors due to changes in deflection are reduced. The wheel sharpness can be determined from the grinding force and material removal rate, allowing workpiece burn to be avoided. The rounding up process could also be controlled. The main limitation of controlled force grinding is the difficulty in conveniently measuring forces from the pressure difference across a hydrostatic spindle bearing, strain gauges mounted on workhead or tailstock centres, or a piezo-electric transducer incorporated into the infeed mechanism.

Controlling the grinding power is more suitable for the industrial application of adaptive control. The power developed by the grinding wheel drive can be easily measured by inexpensive and easily installed transducers. Although the grinding power depends on both the normal and tangential grinding forces, and lags behind the force signal because of the response of the drives and the motor, it presents a more practical solution than force measurement. The grinding power may be used in conjunction with a thermal model to predict workpiece burn, and the power rating of the wheelhead motor also represents a process limit.

A number of strategies have been proposed for controlling the dwell period in order to achieve accurate size and roundness results. The simplest strategy is to end the dwell period when in-process gauging indicated that the required workpiece diameter has been attained. A development of this strategy is to commence the dwell period when a given workpiece diameter is indicated by the gauge. In order to achieve complete sparkout this diameter must be set equal to the required size plus the system deflection as measured by the diameter gauge.

More complex strategies are made possible by identifying the system time constant from the workpiece diameter. It is generally accepted that identification should be in-process, because of the variation of the time constant with the changing condition of the grinding wheel. However, some systems used post-process identification because of control system or gauging limitation. One control strategy is to accelerate the sparkout process, by extending the infeed period and then retracting to a predetermined position prior to the dwell period. This shortens the dwell time required to relieve the deflection. Another strategy is to shorten or lengthen the dwell period in order to achieve the required roundness. This was accomplished by varying the workpiece diameter at which the dwell period was commenced.

These strategies relied on identification of the system time constant based on the signal from a diameter gauge. However, this presents difficulties for multi-diameter parts, where for reasons of cost, set-up times and accessibility of the part, gauging is usually applied to only one of the ground diameters. Furthermore, machines supplied without diameter gauging should not be excluded from improved control of the grinding cycle, better part quality and shorter cycle times. This leaves scope for further work, to develop a method of identifying the time constant in-process without the use of a diameter gauge. This would in turn contribute towards a practical, widely applicable adaptive control system incorporating real time dwell adjustment and accelerated sparkout strategies.

A number of approaches to adaptive control system design have been adopted. Some early systems used analogue electronics, but later systems were based on computers. A popular approach is to use a microprocessor or a computer system to perform all the control operations. The computer system samples the signals from sensors, calculates appropriate grinding parameters, and controls the motion of the machine tool axes accordingly. Another approach is to interface a computer system to a CNC machine. The computer logs data, calculates appropriate grinding parameters, and then outputs a position or size signal to the machine tool controller. Other systems incorporated adaptive control software into the controller of a CNC machine.

For the development and testing of adaptive control strategies, all of these approaches were acceptable. The principal requirements were for the control system to sample data from sensors, calculate suitable grinding parameters, and alter the grinding parameters according to an adaptive strategy. However, for an adaptive control system to be viable for industrial applications, wider issues must be addressed.

Interfacing a computer to a CNC machine is feasible, but requires an additional computer system and interface. This incurs further hardware costs and also raises concerns for reliability. Furthermore, should the adaptive control system require data to be input by the machine operator, an additional screen and keyboard is required, rendering the system cumbersome to use.

With the cost of computer systems reducing rapidly, and the wide variety of data acquisition and control boards available, the use of a microprocessor system to perform all the control operations represents a more attractive option. However such systems are relatively basic, and for more sophisticated features such as part programming, tool offsets, tool radius compensation, interpolation of a number of axes, and communications a proprietary CNC system is required.

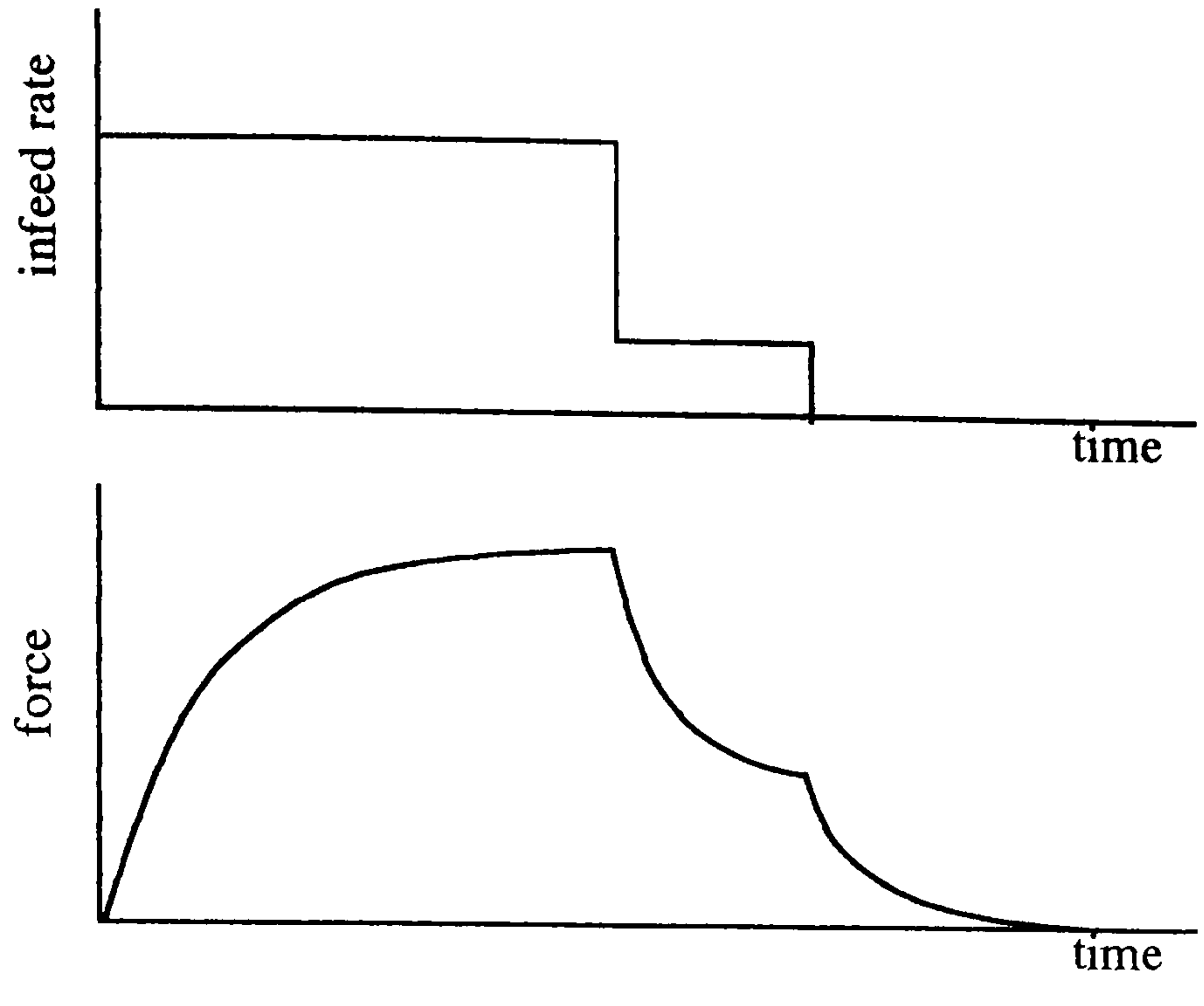
The most attractive option is to incorporate adaptive control software into the controller of a CNC machine. The potential for new advances in this area lies in combining the advanced features of a CNC machine with the benefits of adaptive control. Adaptive control may then be regarded as an additional feature of the CNC machine, giving improved workpiece quality and shorter cycle times. The facility to combine adaptive grinding cycles with conventional grinding cycles for the production of a particular part is also a requirement. For example an adaptive plunge grinding operation may be combined with non-adaptive traverse or face grinding operations. The facility should be provided to grind multiple diameters, using different initial grinding parameters depending on the part geometry. The adaption of the grinding cycle should be independent from one diameter to the next, to allow for differences in deflections and wear.

Adopting this approach also requires adaptive control software to be designed for implementation within the architecture of a specific controller, and written using languages suitable for the controller. There is a need for algorithms and strategies to be designed so that they do not interfere with the correct operation of the controller, or prevent non-adaptive cycles from running. For example, attention should be paid to the avoidance of timing problems for in-process identification of parameters, or when adapting grinding parameters in-process.

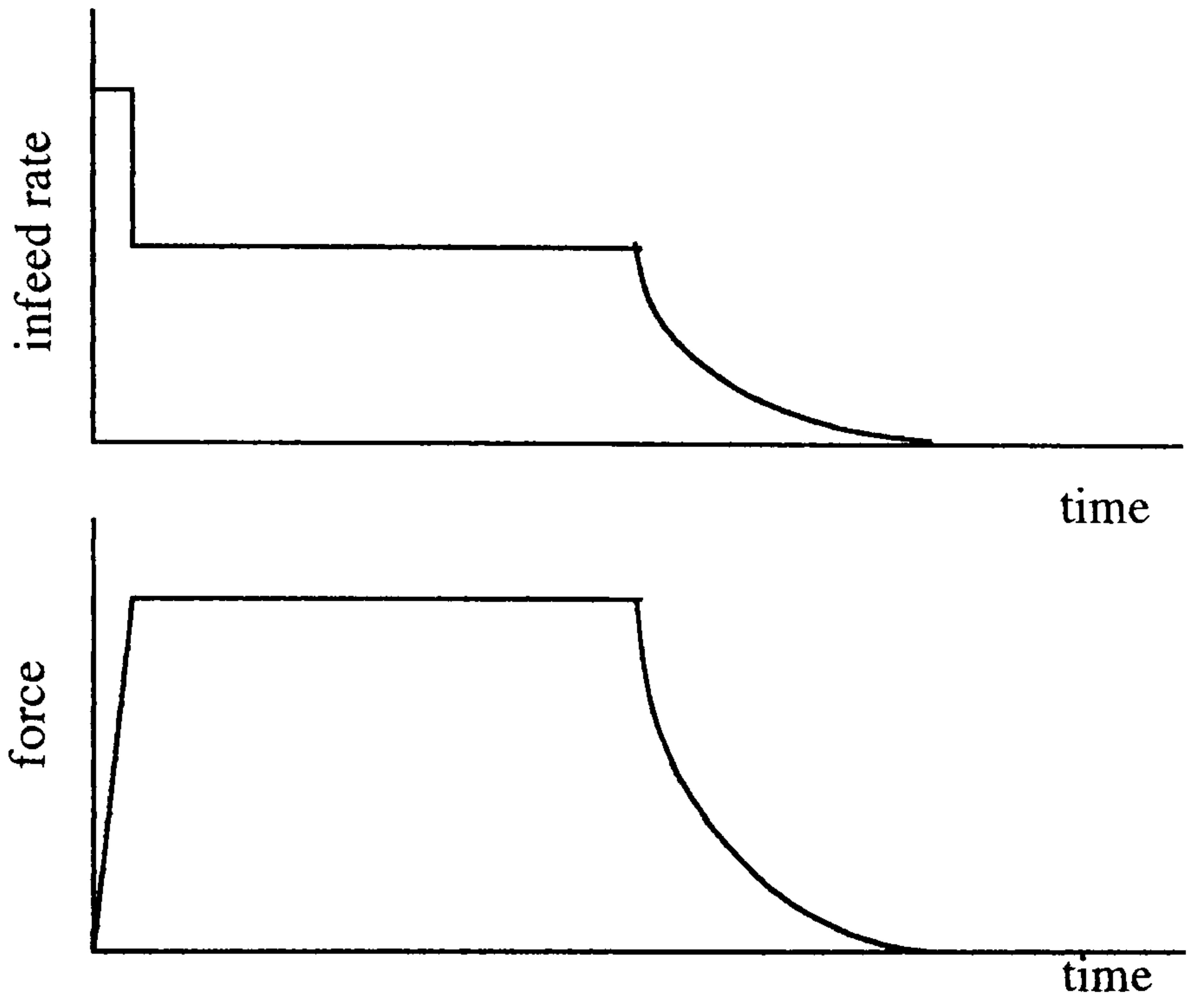
2.7 Conclusions

From the above discussion it may be concluded that there is a need for an adaptive control system that selects initial grinding parameters, and subsequently controls the grinding cycle based on grinding power measurements. Scope for new advance lies in developing a method of in-process identification of the system time constant which does not require diameter gauging. As a result, real-time adjustment of the sparkout period will be feasible both with and without a diameter gauge. This is particularly relevant as many machines are supplied without gauging, and for multi-diameter parts gauging is usually applied to one diameter only.

Adaptive control strategies should be implemented in software within the controller of a CNC system. Opportunities for new advances lie in the design of algorithms and strategies specifically for implementation within a machine tool controller, incorporating in-process identification of parameters and in-process adaption of the grinding cycle. Also, the system should handle multi-diameter parts by selecting initial grinding parameters independently for each diameter based on part geometry. Grinding parameters should be adapted independently for each diameter based on wheel condition. The system should make use of sensors that are appropriate for industrial application. Workpiece size and grinding power are particularly suitable as they are readily available, easy to install, reliable and do not require calibration for particular grinding operations.



Conventional grinding



Controlled force grinding

Figure 2.1 - Idealised normal grinding force and infeed rate for conventional and controlled force grinding

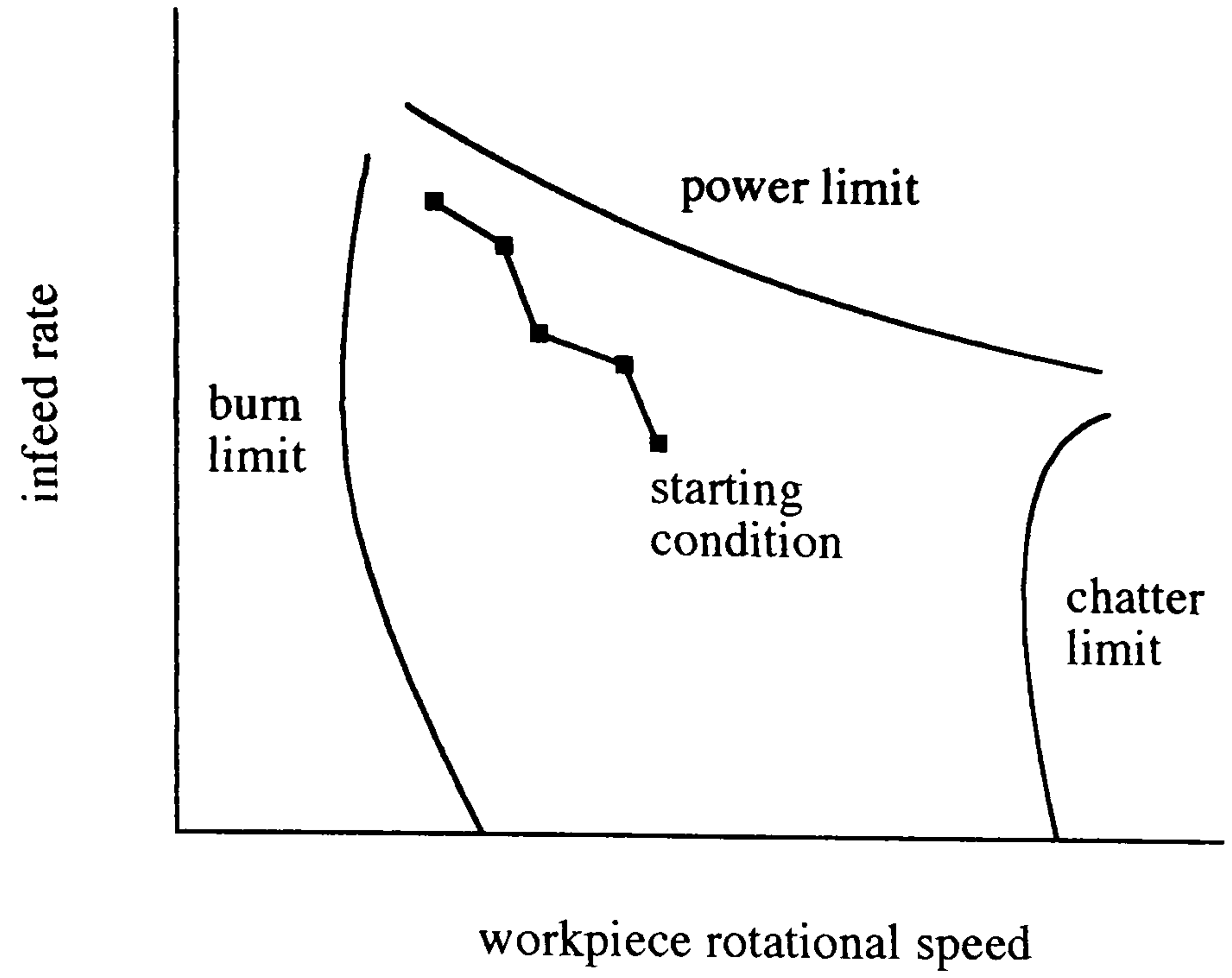


Figure 2.2 - Optimising grinding conditions within the process limits of available power and workpiece burn, as proposed by Kelly et al (1989)

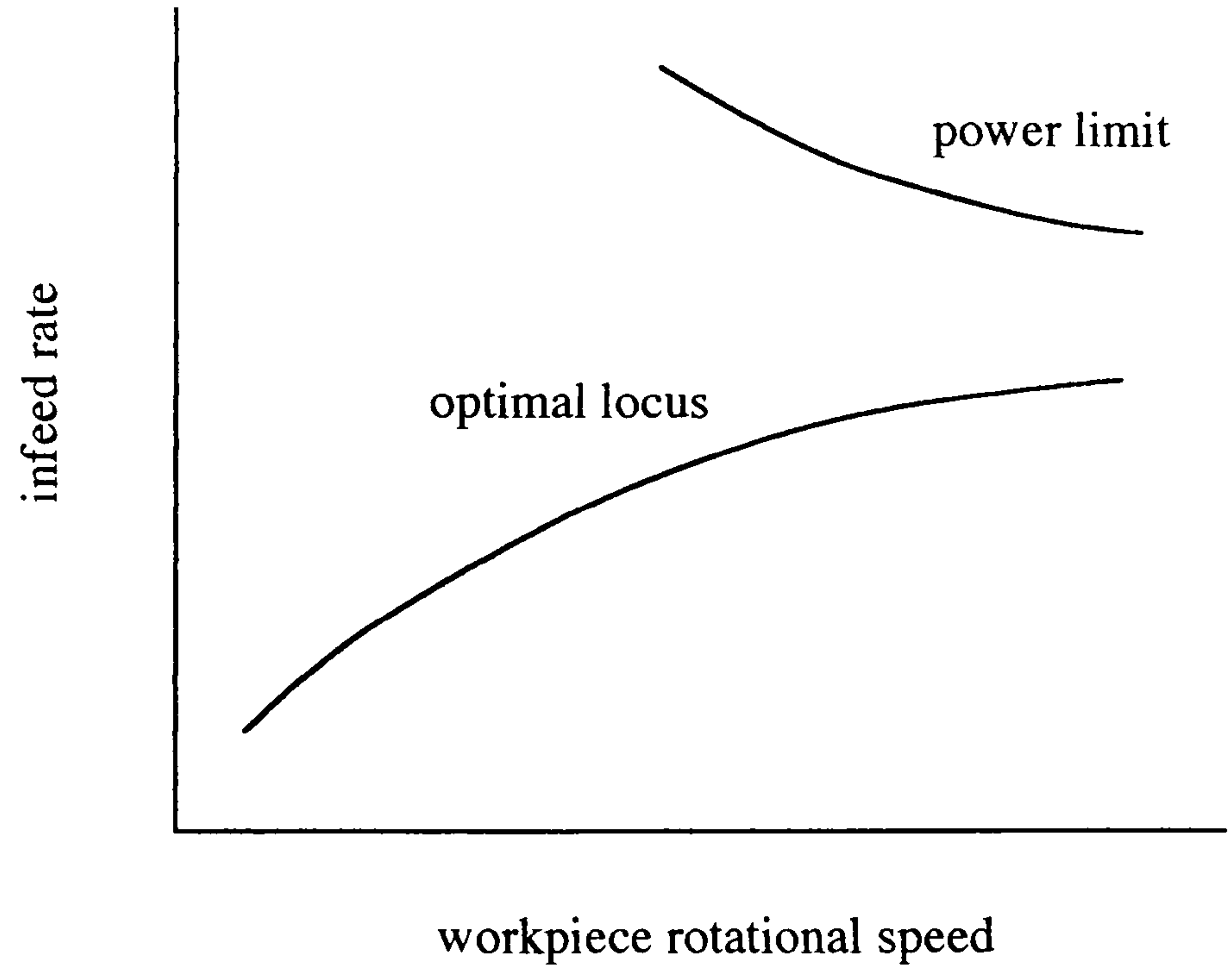


Figure 2.3 - An optimal locus defining the optimum infeed rate and workpiece speed for various wear flat areas, as proposed by Malkin and Koren (1980)

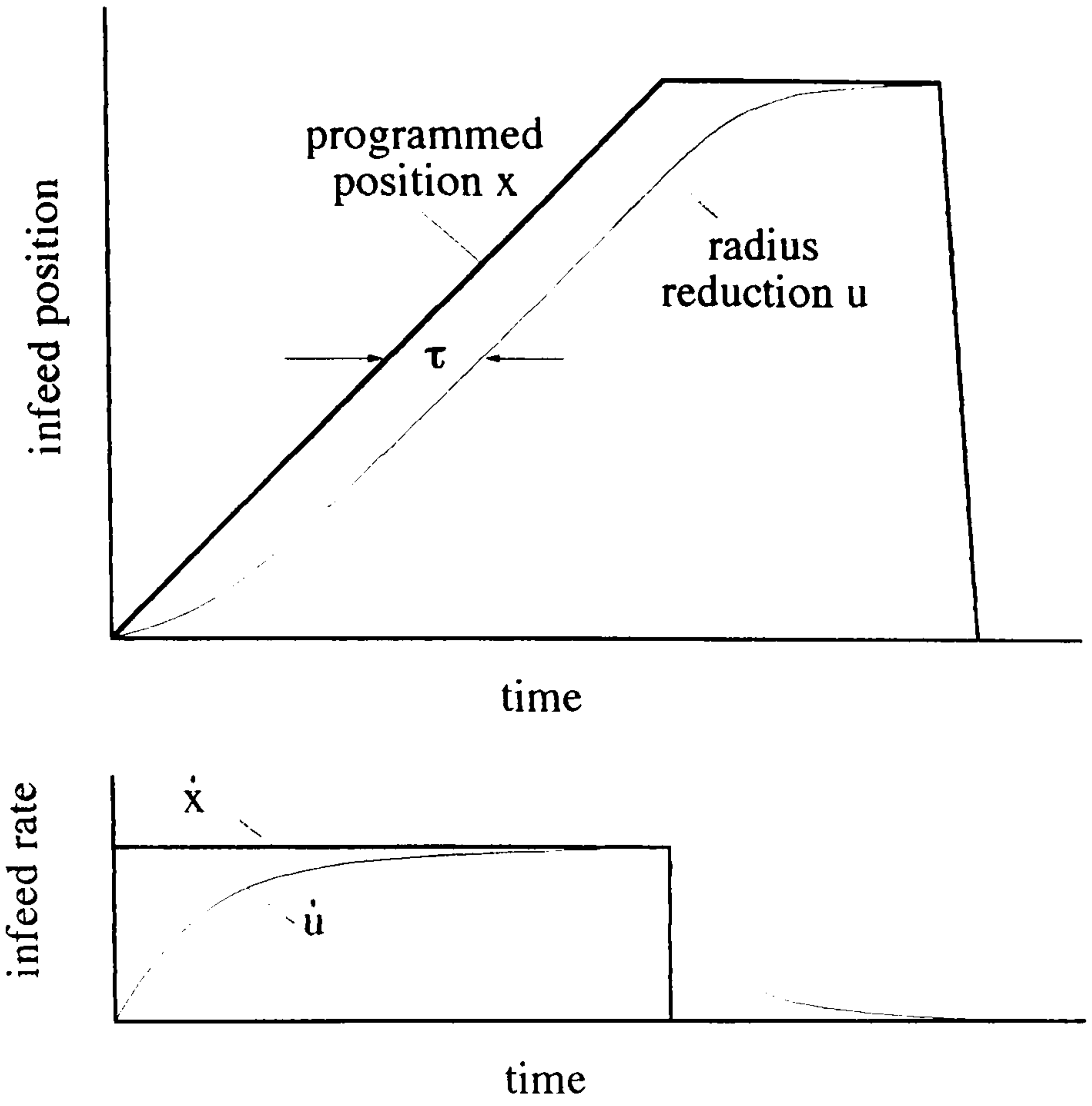


Figure 2.4 - A basic infeed cycle showing the first order response of the machine - wheel - workpiece system.

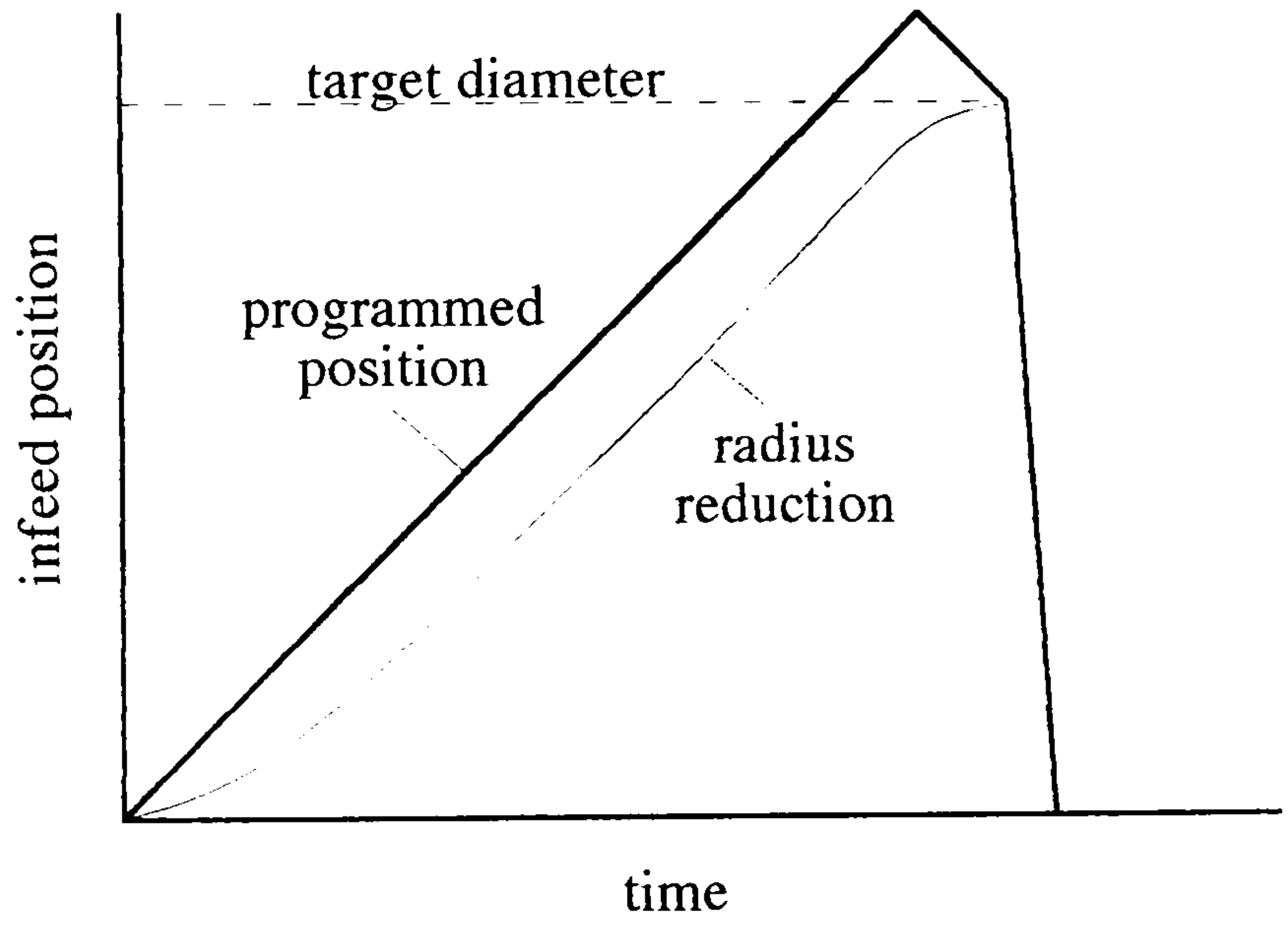


Figure 2.5 - Accelerating the sparkout process by extending the infeed period and retracting to a pre-determined position, as proposed by Spiewak and Kaliszer (1983) and Malkin and Koren (1984).

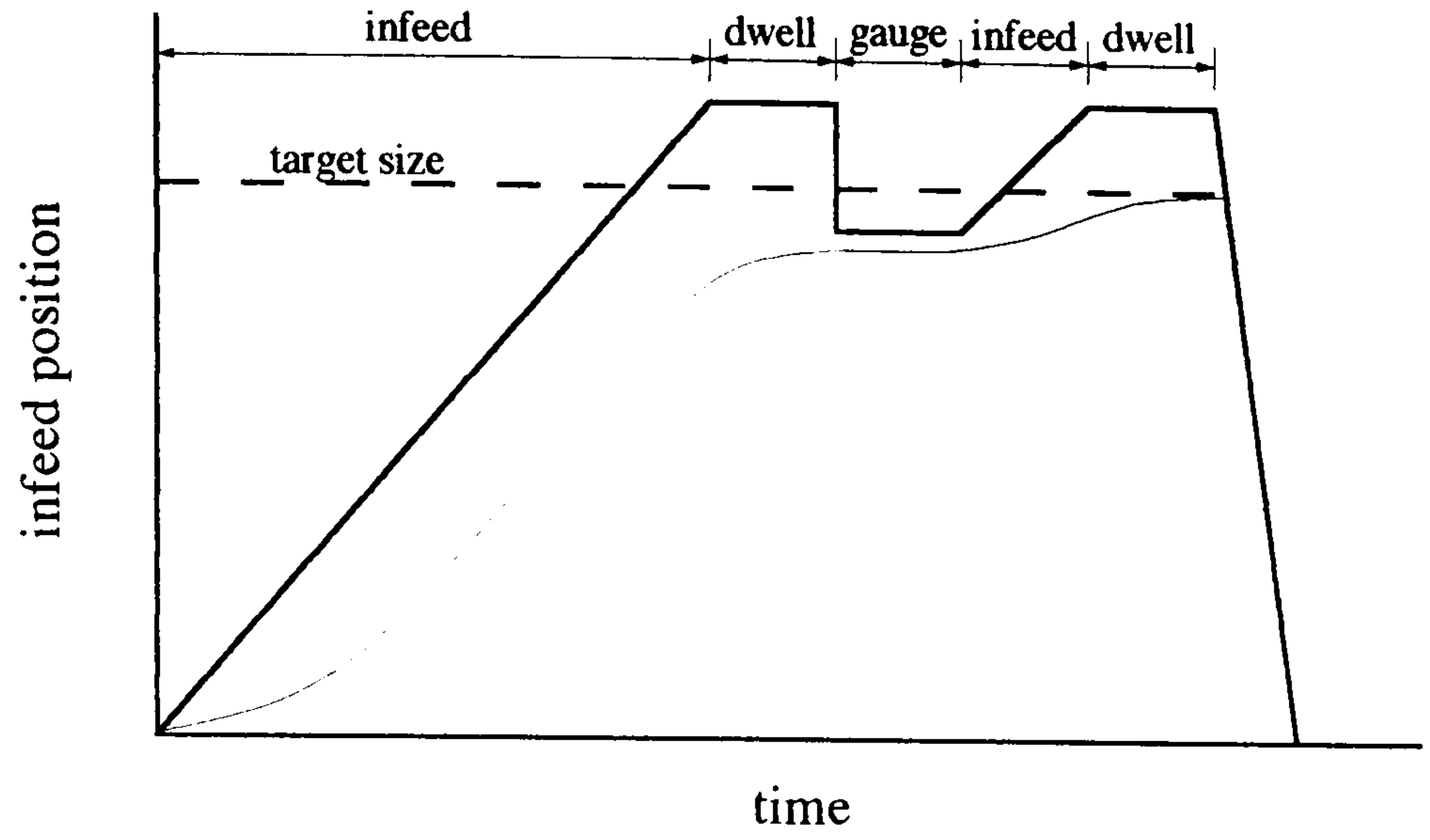


Figure 2.6 - The pecking cycle proposed by Allanson et al (1989) gauges and calculates the system time constant before finishing the part.

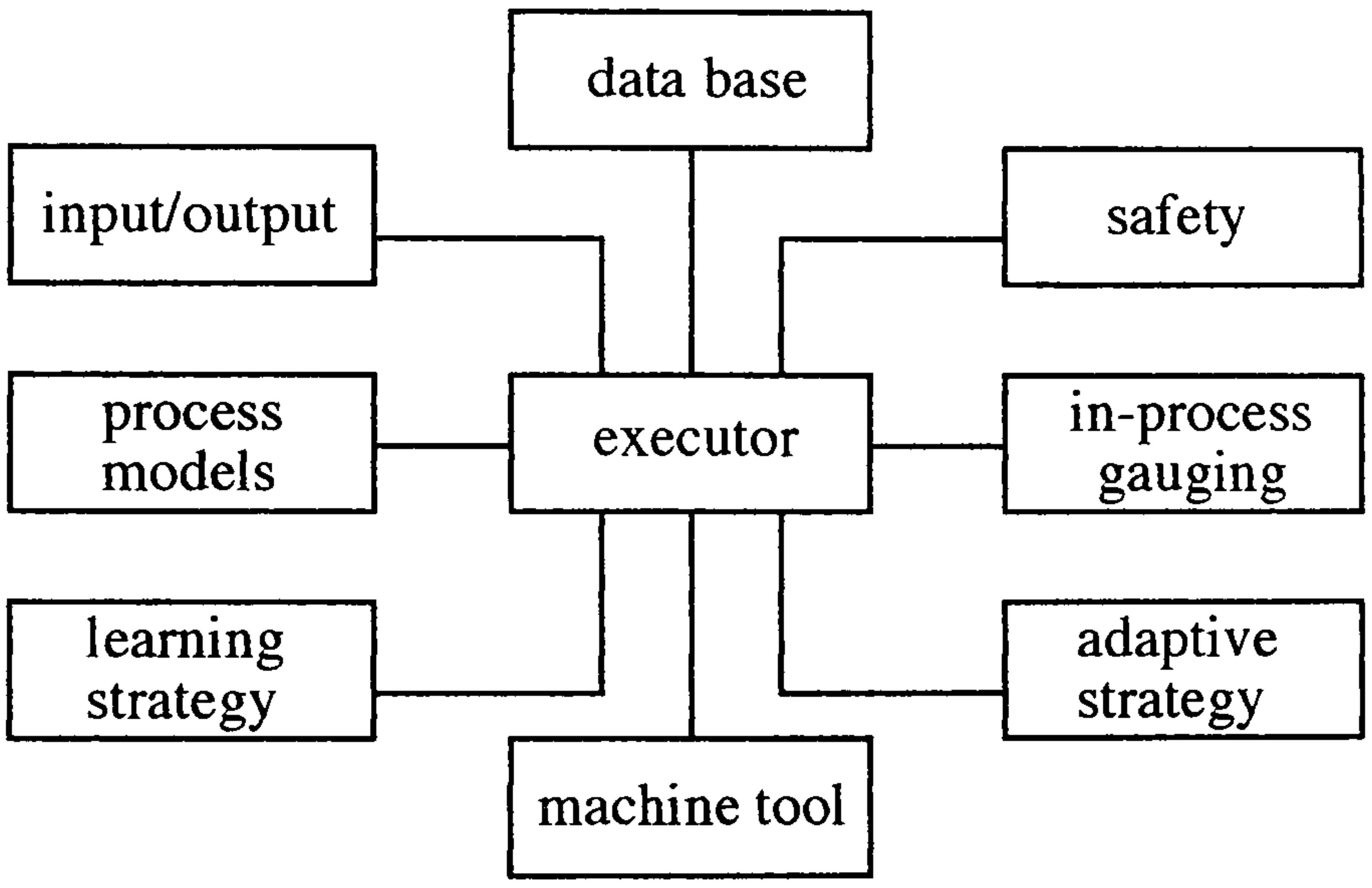


Figure 2.7 - The modular conceptual framework for adaptive control of machine tools proposed by Kelly et al (1989)

3 THE ADAPTIVE STRATEGIES

3.1 Introduction

In designing the adaptive control system, the aim was to develop a system which would automatically determine suitable grinding parameters, monitor the process, and alter the grinding parameters in order to achieve optimum operating conditions.

The grinding parameters that define a typical plunge grinding cycle are the wheel speed, workpiece speed, infeed rate, initial infeed position, final infeed position and the dwell period. For the adaptive control system, the grinding wheel runs at the maximum surface speed that can be maintained over the permitted range of grinding wheel diameters, in order to maintain the best possible cutting action of the grinding wheel. The initial infeed position is set to a fixed value according to the initial workpiece diameter and the stock to be removed. This leaves the workpiece speed, infeed rate, final infeed position and the dwell period to be determined automatically by the adaptive system.

The following sections describe the adaptive strategies in detail. Particular features discussed are the automatic selection of infeed rate and workpiece speed values from a data base, adapting the infeed rate to maintain constant grinding power, and adapting the final infeed position and the dwell period to control the sparkout process. A new method for in-process identification of the system time constant from the grinding power is presented, and a summary of the operations required to implement the adaptive strategy on a CNC system is given.

3.2 Automatic Selection of Infeed Rate and Workpiece Speed

As outlined in the previous chapter, the control system for centreless grinding developed by Kelly et al (1989) and Rowe et al (1991) used a kinematic model as the basis for selecting grinding parameters. Infeed rate and workpiece speed values were calculated from experimentally determined values of mean chip volume and chip aspect ratio stored in a data base. The underlying principal is that for a given combination of grinding wheel and workpiece material, similar grinding conditions are achieved provided that grinding chips of similar dimensions are produced.

This approach allows grinding parameters to be calculated for a wide range of grinding wheel and workpiece diameters, minimising the size of the data base and making effective use of the available data. For this reason it was decided to adopt a similar approach for cylindrical grinding. The new advance made with the strategy proposed in this section, lies in the practical application of these concepts to cylindrical grinding, including the development of a strategy for handling situations where there are a number of different diameters to be ground on a part. In addition, the structure of the proposed data base is designed to be suitable for implementation within the architecture of a modern CNC system.

Because the infeed rate and workpiece speed can be readily calculated from the chip aspect ratio and the chip length, these kinematic parameters are stored in the data base. The information is stored within the control system in order to provide the control system with the ability to update the data base as required with new information. This requires the control system to calculate the chip aspect ratio and chip length from data readily available in the control system. The following expressions given by Rowe et al (1987) are suitable for this purpose.

The chip aspect ratio A_r is given by

$$A_r = \frac{d_e \, v_s}{l_d \, v_w} \qquad (3.1)$$

where d_e is the equivalent diameter,

v_s is the grinding wheel surface speed,

l_d is the dynamic grit spacing, that is the average distance between active grits,

v_w is the workpiece surface speed.

The chip length l_c is given by

$$l_c = \sqrt{\frac{v_f}{v_w} d_w d_e \pi} \qquad (3.2)$$

where v_f is the infeed rate,

v_w is the workpiece surface speed,

d_w is the workpiece diameter, and

d_e is the equivalent diameter.

The equivalent diameter d_e is given by

$$d_e = \frac{d_s d_w}{d_s + d_w} \qquad (3.3)$$

where d_s is the grinding wheel diameter and

d_w is the workpiece diameter.

From the above equations it can be seen that the terms required for calculating the kinematic parameters are the wheel diameter, workpiece diameter, wheel speed, infeed rate, and workpiece speed. These parameters are all readily available in the control system data. The dynamic grit spacing is assumed to be constant for a given type of grinding wheel and can be omitted from the calculations without undermining the effectiveness of the strategy.

It is proposed that the control system calculate the chip aspect ratio and the chip length and store them in a data base, together with the grinding wheel type and the workpiece material type. Information relating to the type of dressing tool, the dressing parameters and the coolant type is also to be stored. The dressing tool and the dressing parameters influence the topography of the wheel, and therefore effect the dimensions of the grinding chips. The type of coolant effects the grinding forces and the grinding power developed. The proposed data base structure is shown in figure 3.1. The data base consists of a number of records containing the chip aspect ratio and chip length produced for a particular combination of grinding wheel, workpiece material, dressing tool, dressing parameters and coolant type. The use of control system data to calculate kinematic parameter values, which are then stored in the data base is illustrated in figure 3.2.

To automatically select infeed rate and workpiece speed values, the control system searches the data base for a record that corresponds to a given combination of grinding wheel, workpiece material, dressing tool, dressing parameters and coolant type. Optionally, the search may only include grinding wheel and workpiece material types. On finding the relevant record, the chip length and chip aspect ratio are retrieved. Given the current values of wheel speed, wheel diameter and workpiece diameter, the infeed rate and workpiece speed required to generate the same grinding chip dimensions are calculated. Re-arranging equation 3.1 gives the following expression for calculating the workpiece speed v_w

$$v_w = \frac{d_e\, v_s}{l_d\, A_r} \qquad (3.4)$$

Similarly, re-arranging equation 3.2 gives the following expression for calculating the infeed rate v_f

$$v_f = \frac{l_c^2\, v_w}{d_w\, d_e\, \pi} \qquad (3.5)$$

The retrieval of kinematic parameters from the data base for the calculation of infeed rate and workpiece speed, which are then copied to the control system data, is shown in figure 3.3.

For parts where a number of different diameters are to be ground, different infeed rate and workpiece speed values are required to produce the same grinding chip dimensions. Therefore it is necessary to calculate the infeed rate and workpiece speed values independently for each diameter. It is also possible for different diameters to be of different materials, for example with the use of sleeves, inserts or plating. In addition, for universal grinding with a swivelling wheelhead, different grinding wheels may be used to grind diameters on the same part. Therefore, the facility to specify different grinding wheel and workpiece types for each diameter are provided. The types specified for the first diameter are used as defaults.

The selection of infeed rate and workpiece speed values is a pre-process operation prior to grinding the first workpiece of a batch. Data concerning the grinding wheel, workpiece material, dressing tool, dressing parameters and coolant type are input by the user. The current values of wheel speed, wheel diameter and workpiece diameter are read from the control system data, and the chip length and chip aspect ratio retrieved from the data base. This is collected for each diameter, prior to calculating the infeed rate and workpiece speed values. Figure 3.4 shows the data required to access the data base and calculate infeed rate and workpiece speed values for each diameter. The data is organised as a series of records containing the information required for each diameter.

3.3 Updating Infeed rate to Maintain Constant Grinding Power

The facility is provided to adapt the infeed rate in order to maintain a given grinding power level. The principal aim of this feature is to allow the infeed rate to be maximised within the constraint of the available grinding power. However, it is also anticipated that the variation in normal force will be reduced, lessening the effects of process variability and offering advantages at both high and low power levels.

Implementing the strategy on a CNC system presents some difficulties. Motions are conventionally programmed from point to point at a given feed rate, presenting difficulties for continuously varying the infeed rate. The additional processing time required to implement control algorithms is also a concern. However, because the infeed rate is not critical for maintaining accuracy, it is not necessary to continuously vary the infeed rate. It is anticipated that updating the infeed rate on a post-process basis will give significant benefits. Thus it was decided to adapt the infeed rate on a post process basis.

The adaptive system measures the peak grinding power during the infeed cycle, and updates the infeed rate from one cycle to the next in order to maintain a target power level. The grinding power is assumed to be proportional to the infeed rate. The infeed rate v_{fn} to be used for the current grinding cycle is calculated using the following equation

$$v_{fn} = \frac{P_t}{P_{n-1}} v_{fn-1} \quad . \qquad (3.6)$$

where v_{fn-1} is the infeed rate used for the last grinding cycle,

P_t is the target grinding power, and

P_{n-1} is the peak grinding power measured during the last grinding cycle.

3.4 Setting the Dwell Period to Relax System Deflection

The grinding forces developed during the infeed period cause deflection of the machine-wheel-workpiece system. This deflection relaxes during the dwell period, bringing the workpiece to size and improving the roundness and surface texture.

Because of changes in grinding wheel sharpness that occur with wear and dressing, the magnitude of the deflection is difficult to predict. It is possible to determine the correct dwell period by measuring the deflection with in-process diameter gauging and calculating the system time constant. However, the use of gauging is sometimes restricted by cost, long set-up times, and the physical size of the gauges. To overcome these problems, the adaptive system uses the signal from a power transducer to determine the correct dwell period.

Figure 3.5 shows the programmed and actual positions X_p and X_i of the grinding wheel-workpiece interface during the infeed cycle. The programmed and actual positions are described by the following equations during the infeed period (Allanson et al 1989).

$$X_p = v_f\, t \qquad 0 < t < T_1 \qquad (3.7)$$

$$X_i = v_f\,(t - \tau + \tau\, e^{-t/\tau}) \qquad 0 < t < T_1 \qquad (3.8)$$

where v_f is the infeed rate,

t is the time elapsed since the start of grinding,

T1 is the time at the end of the infeed period, and

τ is the system time constant.

The deflection of the system x_i is given by the difference between the programmed and actual infeed position

$$x_i = v_f \tau\, (1 - e^{-t/\tau}) \qquad 0 < t < T_1 \qquad (3.9)$$

During the dwell period the programmed and actual positions X_p and X_i are given by

$$X_p = v_f T_1 \qquad T_1 < t < T_2 \qquad (3.10)$$

$$X_i = v_f T_1 - x_1\, e^{-(t - T1)/\tau} \qquad T_1 < t < T_2 \qquad (3.11)$$

where x_1 is the deflection at time T_1.

The deflection of the system x_i is given by the difference between the programmed and actual infeed position

$$x_i = x_1\, e^{-(t - T1)/\tau} \qquad T_1 < t < T_2 \qquad (3.12)$$

The grinding power signal follows the form shown in figure 3.6, rising to a peak value during the infeed period and decreasing towards zero during the dwell period. The grinding power is given by equation 3.13 during the infeed period and by equation 3.14 during the dwell period.

$$P = P_{max} (1 - e^{-t/\tau}) \qquad 0 < t < T_1 \qquad (3.13)$$

$$P = P_{max} \, e^{-(t - T_1)/\tau} \qquad T_1 < t < T_2 \qquad (3.14)$$

By comparing equations 3.13 and 3.14 to equations 3.9 and 3.12 it is evident that the expressions for both the grinding power and the deflection follow the same form, that is

$$y = k (1 - e^{-t/\tau}) \qquad 0 < t < T_1 \qquad (3.15)$$

$$y = k \, e^{-(t - T1)/\tau} \qquad T_1 < t < T_2 \qquad (3.16)$$

where k is a constant.

The exponential rise and decay of the power signal corresponds to a similar exponential rise and decay of the system deflection. The adaptive control system makes use of the relationship between the grinding power and the deflection, by identifying the system time constant from the power signal during the infeed period. This value is then used to predict the magnitude of the deflection during the infeed cycle.

Ninety five per cent of the deflection is relieved by applying a dwell period of three time constants. This ensures that the target diameter is achieved without using an excessively long dwell time. Obtaining a measure of the system time constant gives the control system the ability to determine the dwell time required for a grinding operation. In this way the variation in deflection that occurs with conditioning of the grinding wheel is accounted for.

3.5 Using Overshoot to Decrease the Dwell Period

An alternative strategy is also offered, to shorten the dwell time so that a significant proportion of the system deflection remains at the end of the infeed cycle. To compensate for this deflection the infeed position is advanced past the target position as shown in figure 3.7. The overshoot OS required to compensate for the deflection remaining at the end of the dwell period is calculated using the following expression

$$OS = x_1 \, e^{-T_d/\tau} \qquad (3.17)$$

where x1 is the deflection at the end of the infeed period,

T_d is the dwell time, and

τ is the system time constant.

With the overshoot strategy, a dwell period of two time constants is applied, leaving thirty seven per cent of the deflection in the system at the end of the cycle.

3.6 In-Process Identification of the System Time Constant

In process identification of the time constant is required to allow the control system to adapt the dwell period according to the deflection. A new method is proposed for identifying the system time constant from the grinding power characteristic during the infeed section of the grinding cycle. The mathematical relationships for the new method are as follows.

The grinding power is assumed to be proportional to the infeed rate for constant workpiece speed and grinding wheel speed. This assumption works very well for the purposes of characterising the system performance.

$$P \alpha \frac{dX_i}{dt} \qquad (3.18)$$

Differentiating equation 3.8 and combining with equation 3.18 gives the following expression for the grinding power

$$P = k_p\, v_f\, (1 - e^{-t/\tau}) \qquad 0 < t < T_1 \qquad (3.19)$$

where k_p is a constant of proportionality linking the infeed rate to the grinding power.

Equation 3.19 takes account of the transient section as the infeed rate of the grinding wheel / workpiece interface approaches the programmed value and steady state grinding is achieved. From the typical data log of the power signal shown in Figure 3.8 it is evident that the transient section of the grinding power follows the exponential model well.

It was decided to use the integral of the grinding power for the time constant identification in order to reduce the effect of noise on the power signal. Integrating equation 3.19 gives

$$\int_0^t P\, dt = k_p\, v_f \left(t - \tau + \tau e^{-t/\tau}\right) \qquad 0 < t < T_1 \qquad (3.20)$$

Steady state state grinding conditions are established when the the value of $e^{-t/\tau}$ approaches zero. This is achieved after an infeed period of three time constants as $e^{-t/\tau}$ is equal to 0.02 at this point.

$$\int_0^t P\,dt \approx k_p\, v_f\,(t - \tau) \qquad 3\tau < t < T_1. \qquad (3.21)$$

Hence at steady state conditions the grinding power is given by equation 3.21. The value of the system time constant is given by the intercept of the tangent to the integral of the grinding power with the time axis as shown in figure 3.9.

To implement this identification method on a control system, the integral of the grinding power is calculated from

$$\int_0^n P\,dt = \int_0^{n-1} P\,dt + P_n\,T_s \qquad 3\tau < t < T_1. \qquad (3.22)$$

where P_n is the grinding power at the nth sample and T_s is the sampling period. A sampling frequency of 20 Hz was found to be suitable for the range of time constants of one to ten seconds typical for grinding, and sampling at this frequency is unlikely to place undue demands on processing time.

Integrated power values approximately one second apart are used to calculate the intercept of the tangent of the integrated power with the time axis. This interval was determined empirically by running calculations on data logged from a number of grinding operations to ascertain a suitable value. The following equation obtained from similar triangles is used to calculate the time constant, from the intercept of the tangent to integrated power with the time axis.

$$\tau = \frac{t_2\int_0^{t1} P\,dt - t_1\int_0^{t2} P\,dt}{\int_0^{t1} P\,dt - \int_0^{t2} P\,dt} \qquad 0<t<T_1. \qquad (3.23)$$

The time constant calculation is deemed to be complete when the time elapsed from the start of grinding is greater than three times the measured time constant, that is when steady state grinding has been established.

To obtain the value of the time constant using this method requires the start of grinding to be known accurately. A method is proposed for detecting the start of grinding from the variance of the grinding power. At the start of the infeed cycle, the first six samples are used to characterise the no-load power. The mean of the samples is calculated and this value subtracted from subsequent samples to give the grinding power. The variance of the no-load power is also calculated and used as a reference for detecting the start of grinding. After the first twelve samples, detection of the start of grinding commences. Every time the power signal is sampled the variance of the last six samples is calculated and compared to the variance of the first six samples. This continues until the variance exceeds a threshold level which is taken to be the start of grinding. The threshold level and number of samples used for calculating the mean and variance were determined empirically by running calculations on data logged from a number of grinding operations to ascertain suitable values.

As each new power sample is logged the variance of the last n samples is calculated. Figure 3.10 shows that two large increases in the variance occur. The first is due to the contact of the grinding wheel with the coolant and the second is due to the contact of the grinding wheel with the workpiece. The second increase in the variance is taken as the start of grinding. Using this method it is possible to accurately detect the start of grinding.

3.7 A Summary of the Operations Required to Implement the Adaptive Strategy

The operations required to implement the adaptive strategy are summarised in the form of flow charts in figures 3.11 and 3.12. It can be seen that a number of 'pre-process' operations are carried out before grinding a workpiece or a batch of workpieces. The user enters the target power level for the grinding operation and also enters the grinding wheel and workpiece material type. If the data base contains information relative to the grinding operation the kinematic parameters are retrieved and the machining parameter values calculated. Otherwise the machine user is prompted for infeed rate and workpiece speed values to use. The infeed rate and workpiece speed are then passed to the infeed cycle for grinding the first workpiece.

A number of 'in-process' operations are carried out during the execution of each grinding cycle. The purpose of these operations is to determine the system time constant and to use the measured value to adjust the infeed cycle, to compensate for deflection of the machining system. The maximum grinding power value is also recorded as it is required for updating the infeed rate to maintain a target power level.

Figure 3.12 shows the operations carried out in-process. A number of power samples are used to calculate the mean and variance of the no load power. The mean is subtracted from subsequent power samples to give the grinding power. The variance serves as a reference for detecting the start of grinding. Once the start of grinding is detected the sampled data are used for calculating the time constant. For infeed cycles without diameter gauging the overshoot and dwell time values are calculated and passed to the infeed cycle. For infeed cycles with diameter gauging the desired dwell time is calculated and the actual dwell time is measured. The desired and actual dwell times are required by the post process operation of compensating for infeed position error.

A number of 'post-process' operations are carried out at the end of each grinding cycle. If the cycle uses diameter gauging the difference between the desired dwell time and the actual dwell time is used to calculate the error in the infeed position and an offset is applied to compensate. The grinding results are written to file and the infeed rate for the next grinding operation is calculated. The next workpiece is ground and the in-process operations are performed again. The procedure is repeated until all the workpieces of the batch have been ground. At this point the kinematic parameters for the last grinding operation are calculated and saved to the data base.

3.8 Discussion and Conclusions

The grinding parameters that define a typical plunge grinding cycle are wheel speed,workpiece speed, infeed rate, initial infeed position, final infeed position and the dwell period. For the adaptive system, the workpiece speed, infeed rate, final infeed position and the dwell period are selected and adjusted automatically by the adaptive system.

The kinematic model by Rowe et al (1986) is used as a basis for selecting infeed rate and workpiece speed values. A data base of suitable chip dimensions for different combinations of grinding wheel type and workpiece material is used by the control system to determine appropriate values of infeed rate and workpiece speed. This approach allows grinding parameters to be calculated for a wide range of wheel and workpiece diameters, minimising the size of the data base and making effective use of the available data. Although this approach has been used previously for controlling centreless grinding, the application of these concepts to cylindrical grinding represents a new advance. In particular, the new system is designed to handle multi-diameter parts by selecting appropriate grinding parameters inependently for each diameter. Additionally, the data base structure is designed for practical implementation within the architecture of a modern CNC system.

The facility to adapt the infeed rate in order to maintain a given grinding power level is also provided. The purpose of this feature is to allow the infeed rate to be maximised within the constraint of the available grinding power. Another aim is to improve performance at lower power levels by reducing the effects of process variability. Because of the difficulties in continuously varying the infeed rate on a machine tool controller, the infeed rate is updated on a post-process basis. However, it is anticipated that this will give significant benefits. Thus, in developing this strategy, the aim is to attain significant benefits while also considering the practical implications for an industrially applicable system.

The strategy for selecting values of the final infeed position and the dwell time, takes into account that these parameters are critical for attaining the required accuracy of the finished parts. Because deflections vary according to the condition of the grinding wheel, real time control of the sparkout process is required. This is achieved by adapting the final infeed position and the dwell time, based on in-process identification of the system time constant. A new method of identifying the system time constant from the grinding power is proposed, together with a new method of detecting the start of grinding from the variance of the grinding power. This represents a significant advance that allows improved control of grinding cycles both with and without diameter gauging. To allow practical implementation within a CNC system, the identification algorithms are designed so that they can be readily implemented on a machine tool controller.

To summarise, the adaptive control strategies include the automatic selection of infeed rate and workpiece speed, the updating of infeed rate to maintain a constant grinding power, and the adaption of the final infeed position and the dwell time to control the sparkout process. The strategies and algorithms are designed to be readily implemented on a machine tool controller, and it is anticipated that the performance of the new control system will be improved in terms of ease of use, set-up time, cycle time and accuracy of the finished parts.

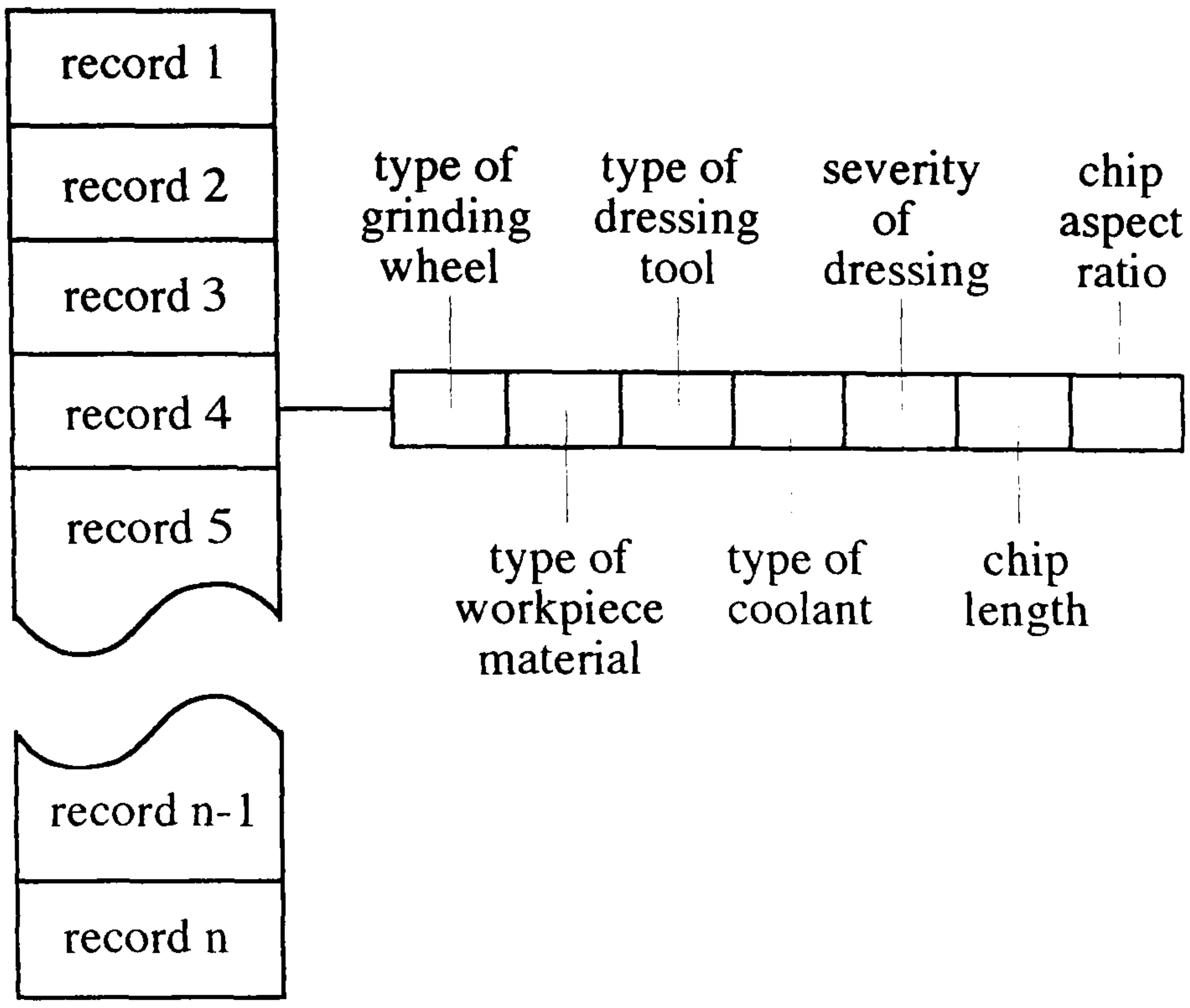


Figure 3.1 - The structure of the data base

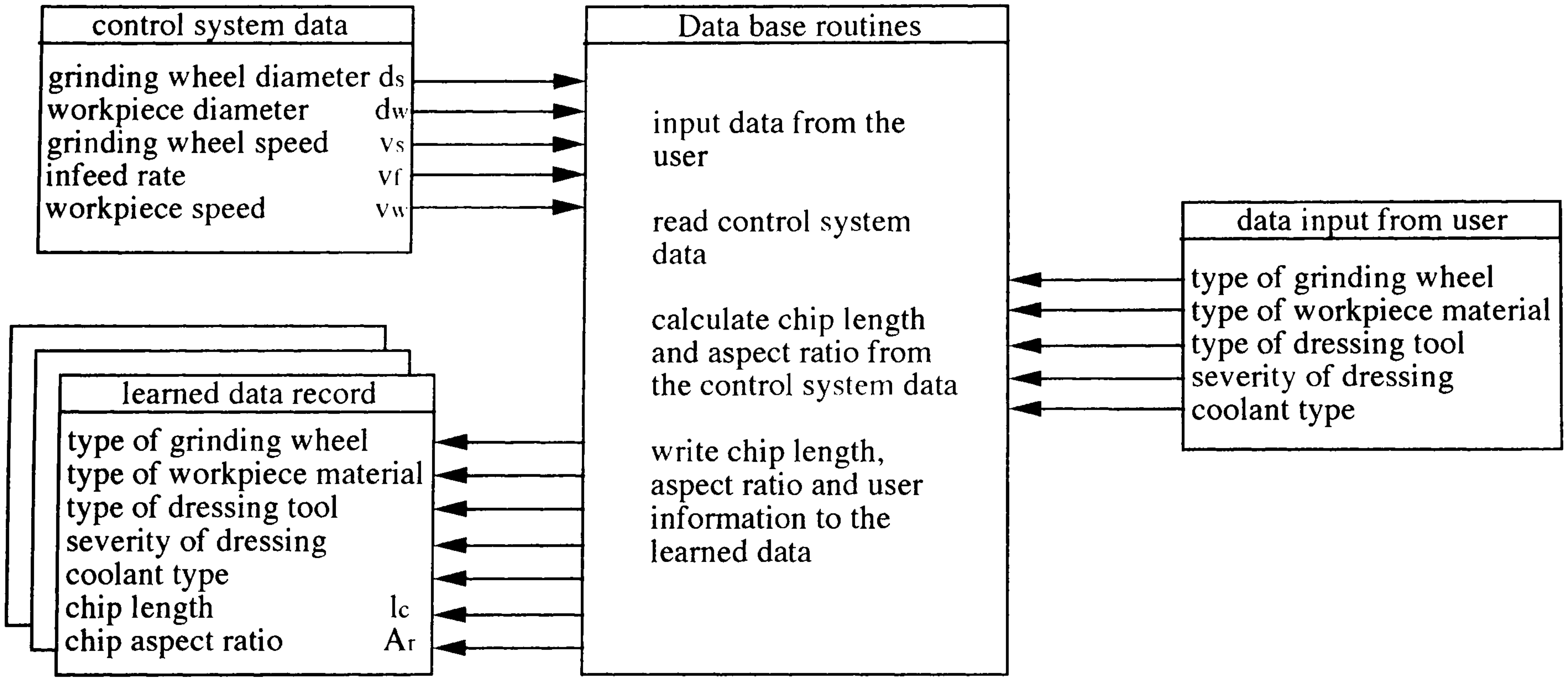


Figure 3.2. Saving new data to the data base

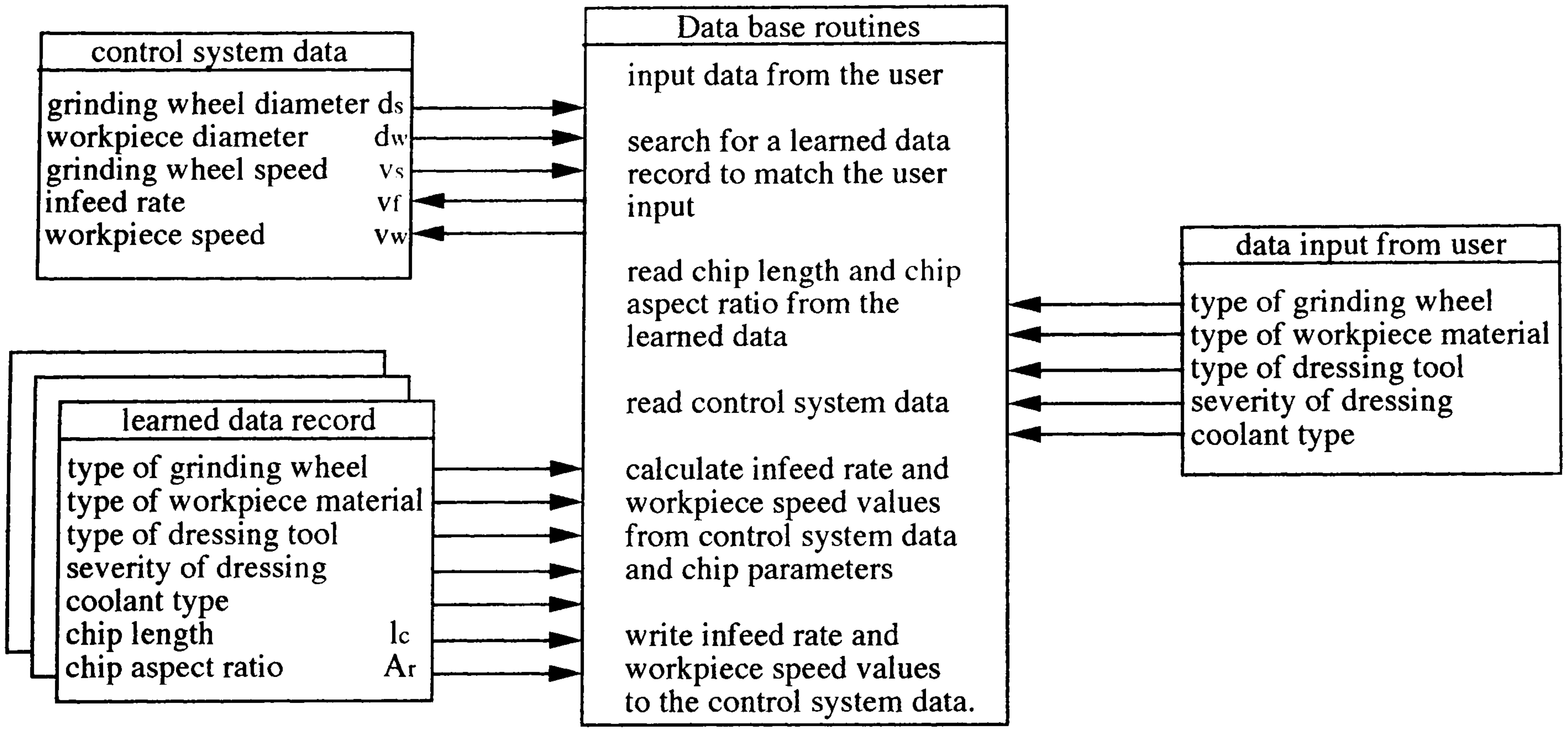


Figure 3.3. The automatic selection of infeed rate and workpiece speed from the data base

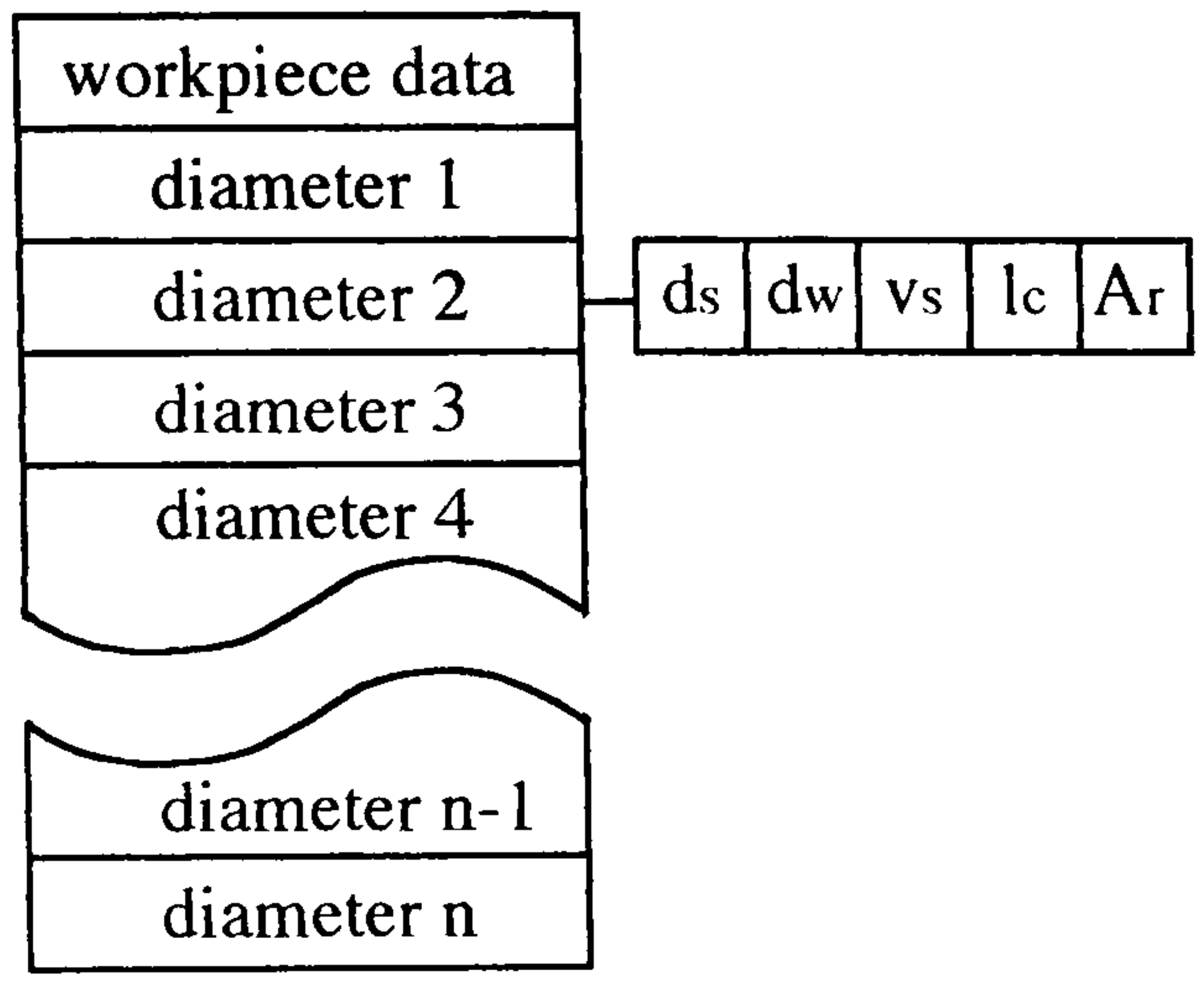


Figure 3.4 - The data required to calculate infeed rate and workpiece speed values for each diameter.

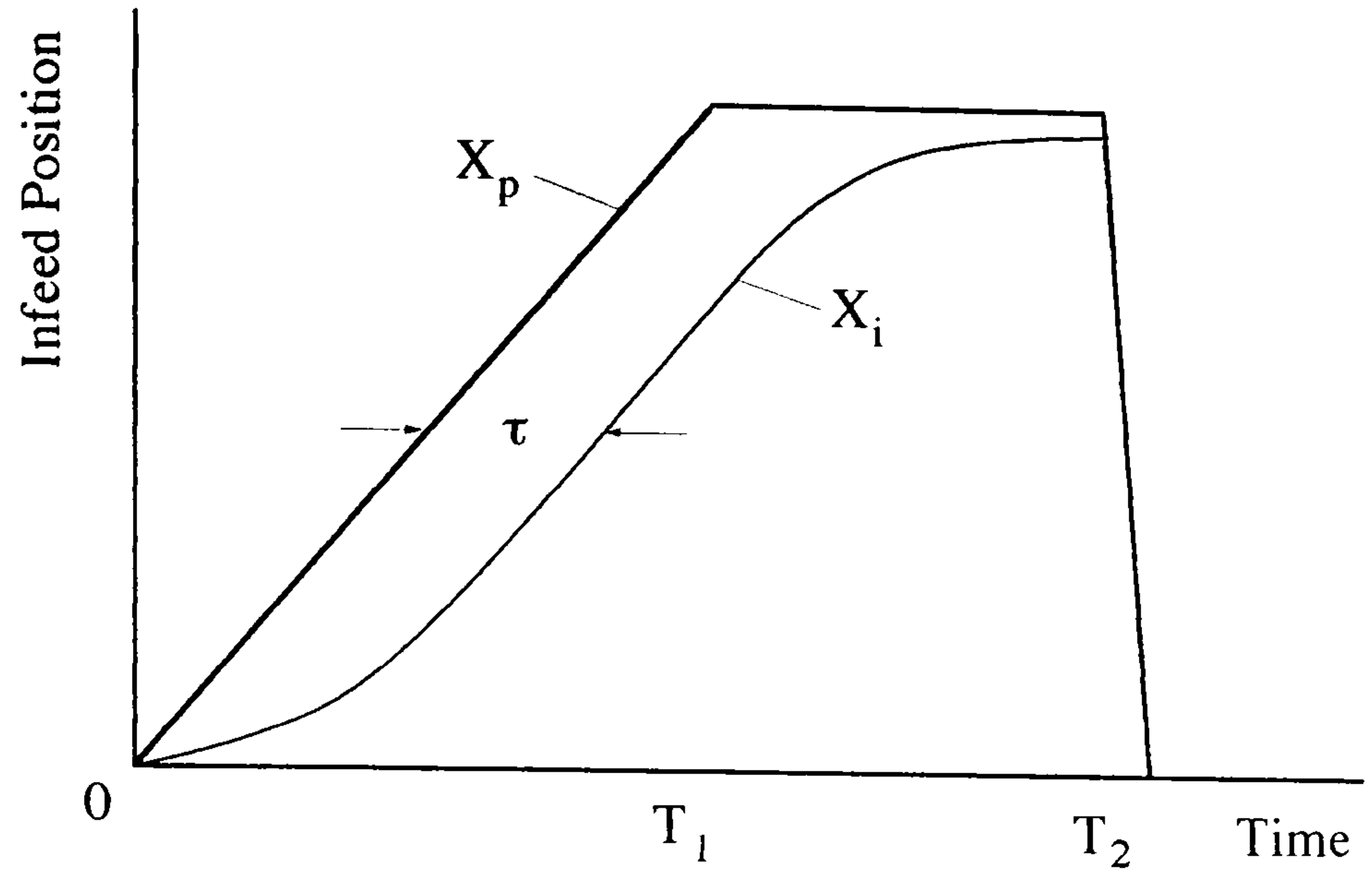


Figure 3.5 - The programmed and actual infeed positions during a typical infeed cycle

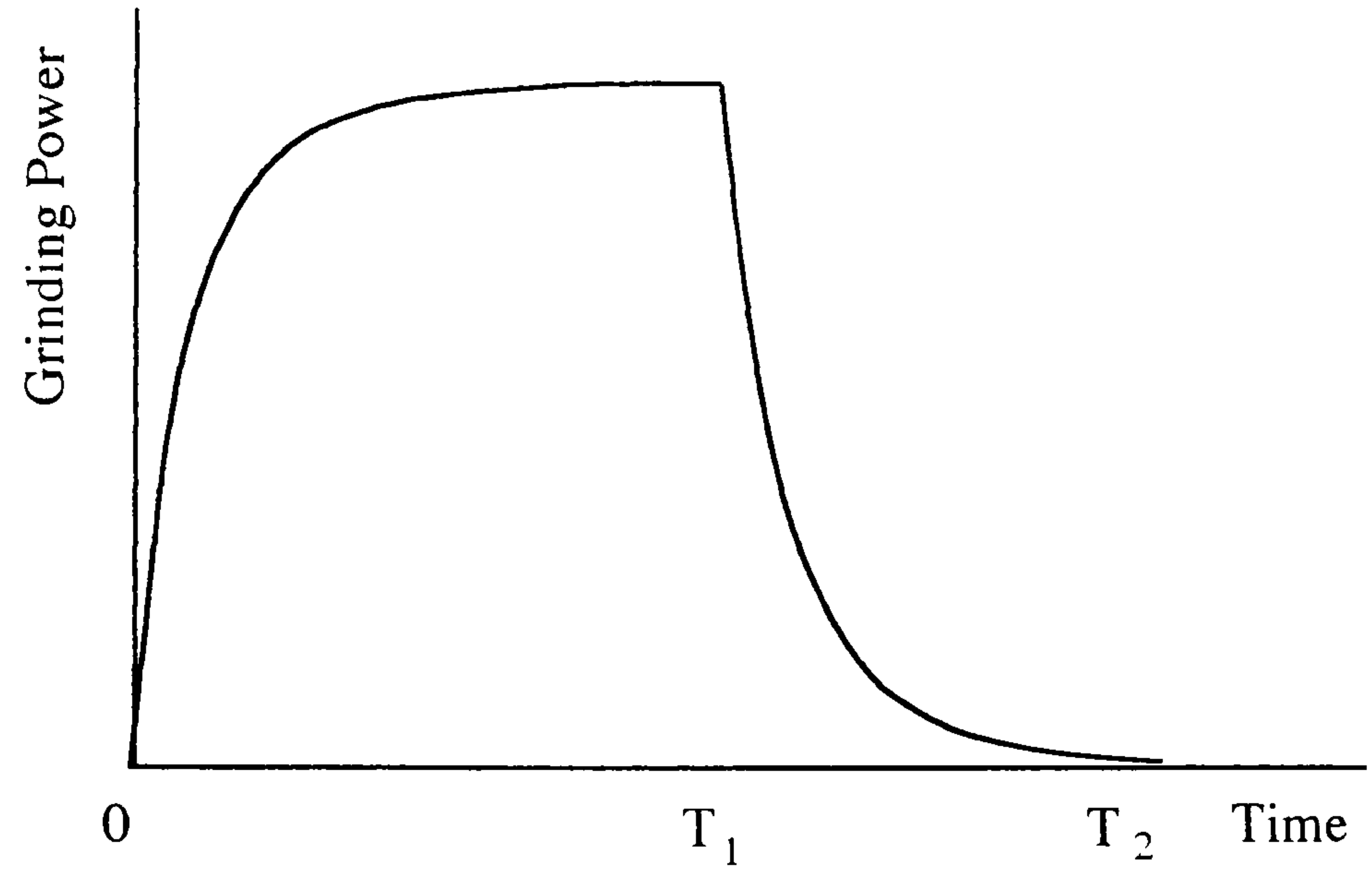


Figure 3.6 - The idealised grinding power during an infeed cycle

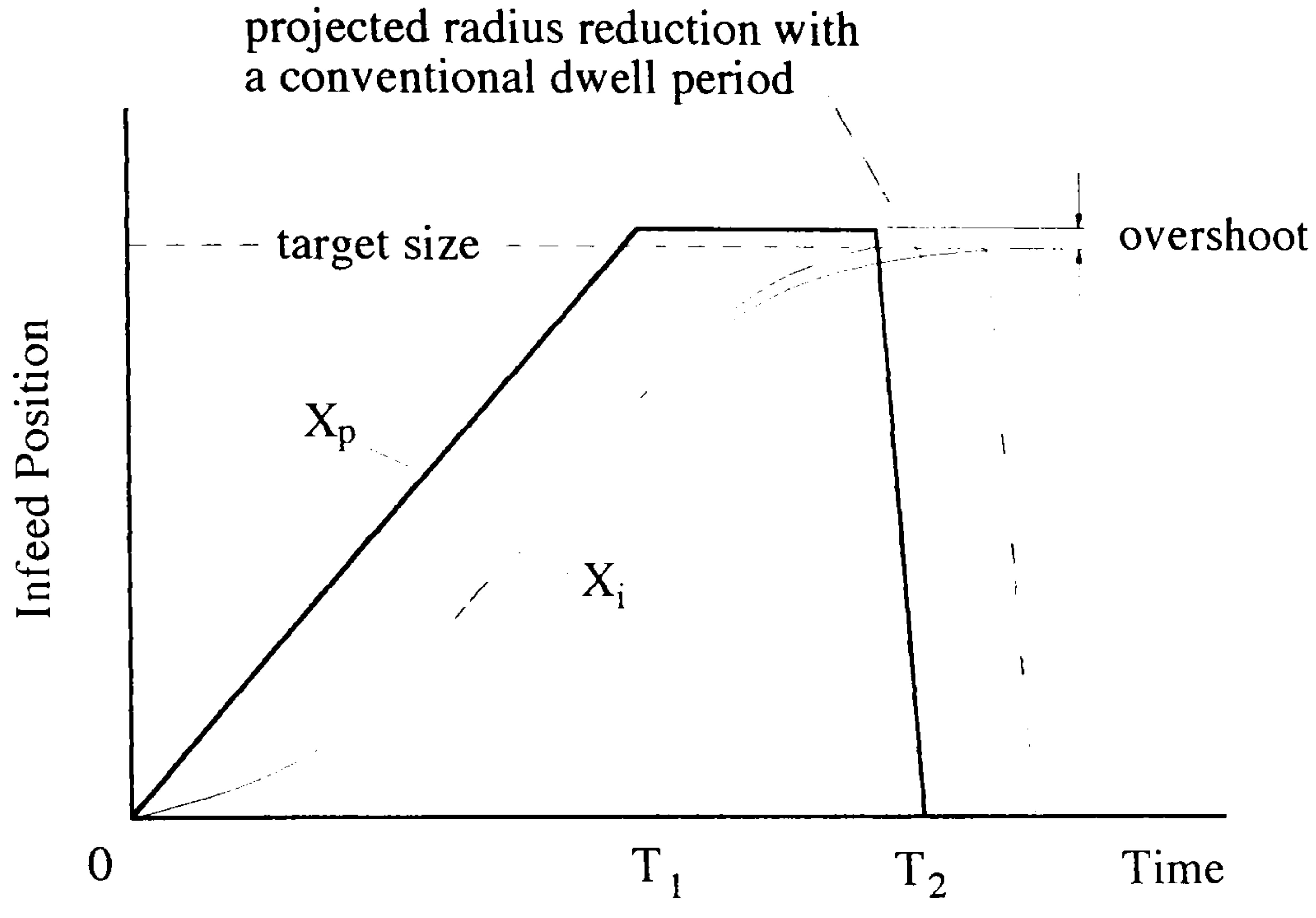


Figure 3.7 - Shortening the dwell period by extending the infeed period in order to apply an overshoot

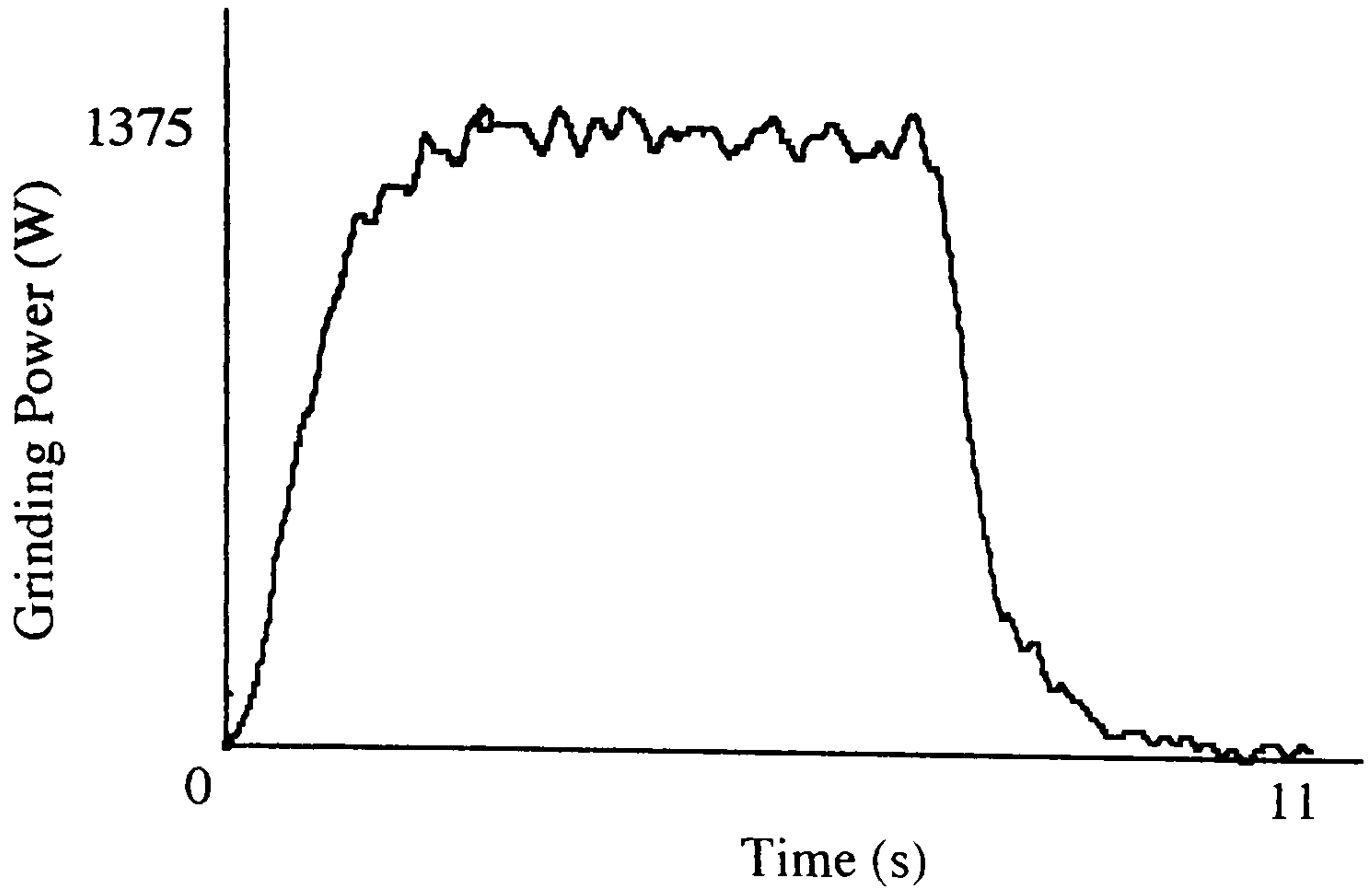


Figure 3.8 A data log showing the grinding power signal during a typical infeed cycle

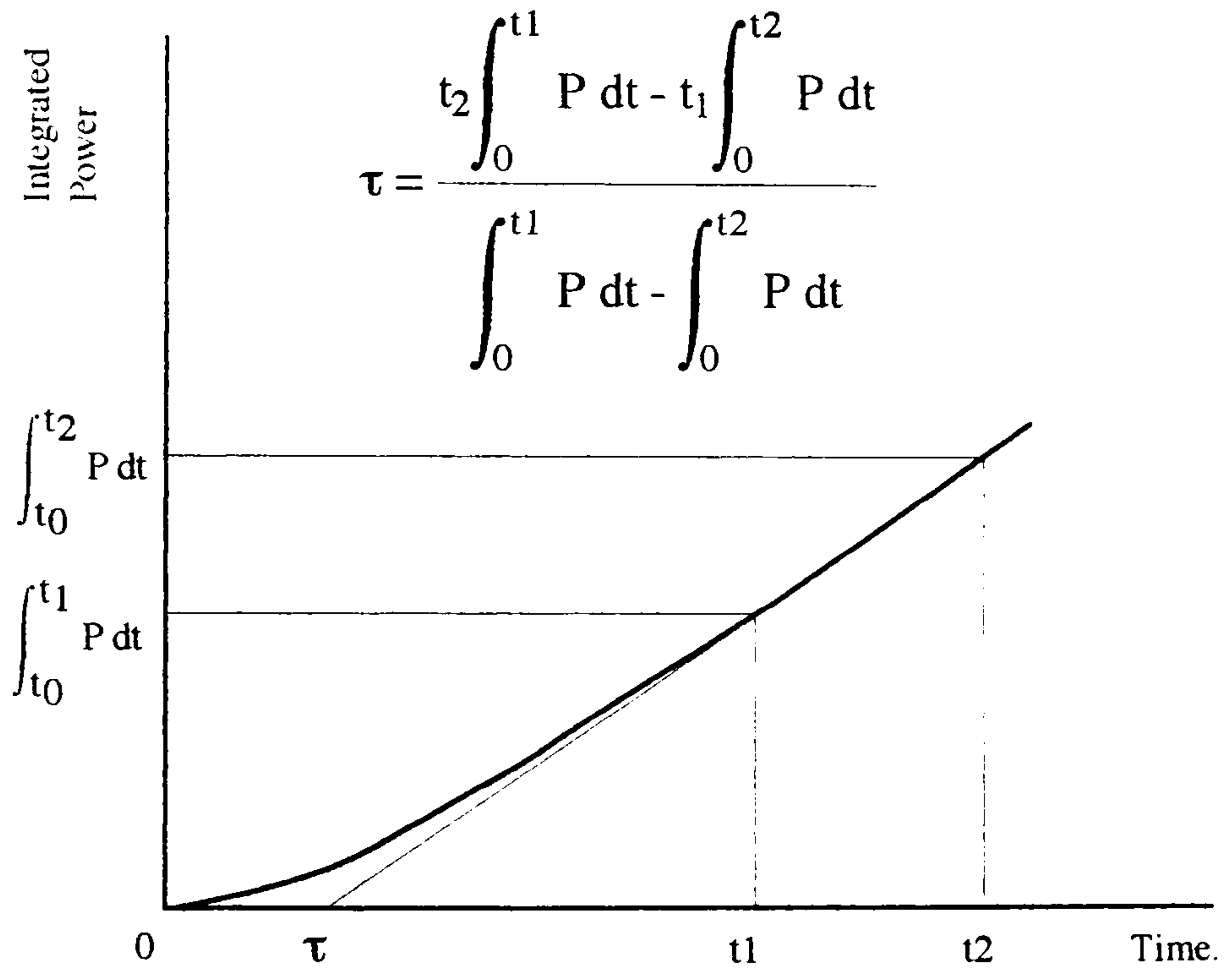
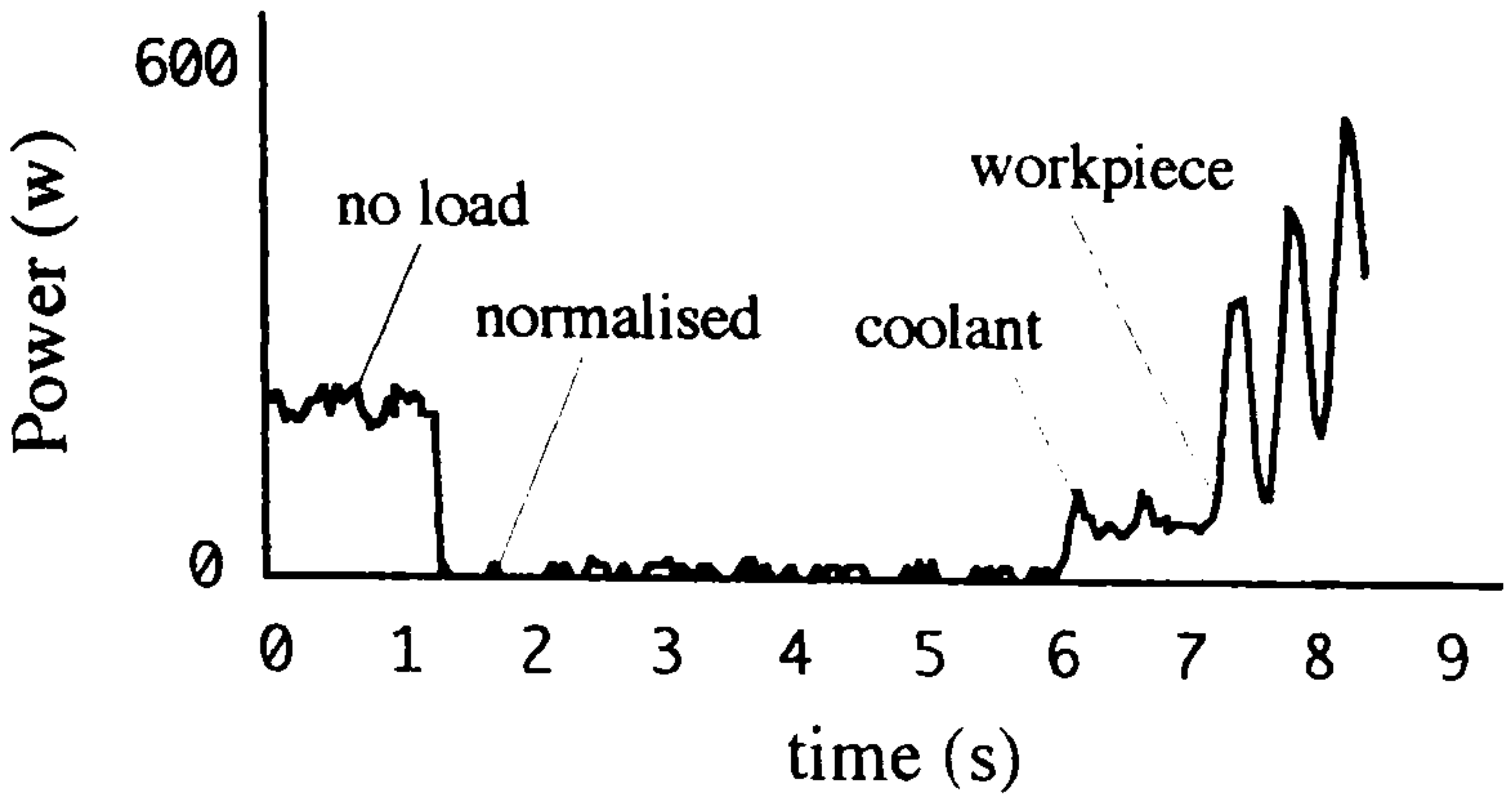
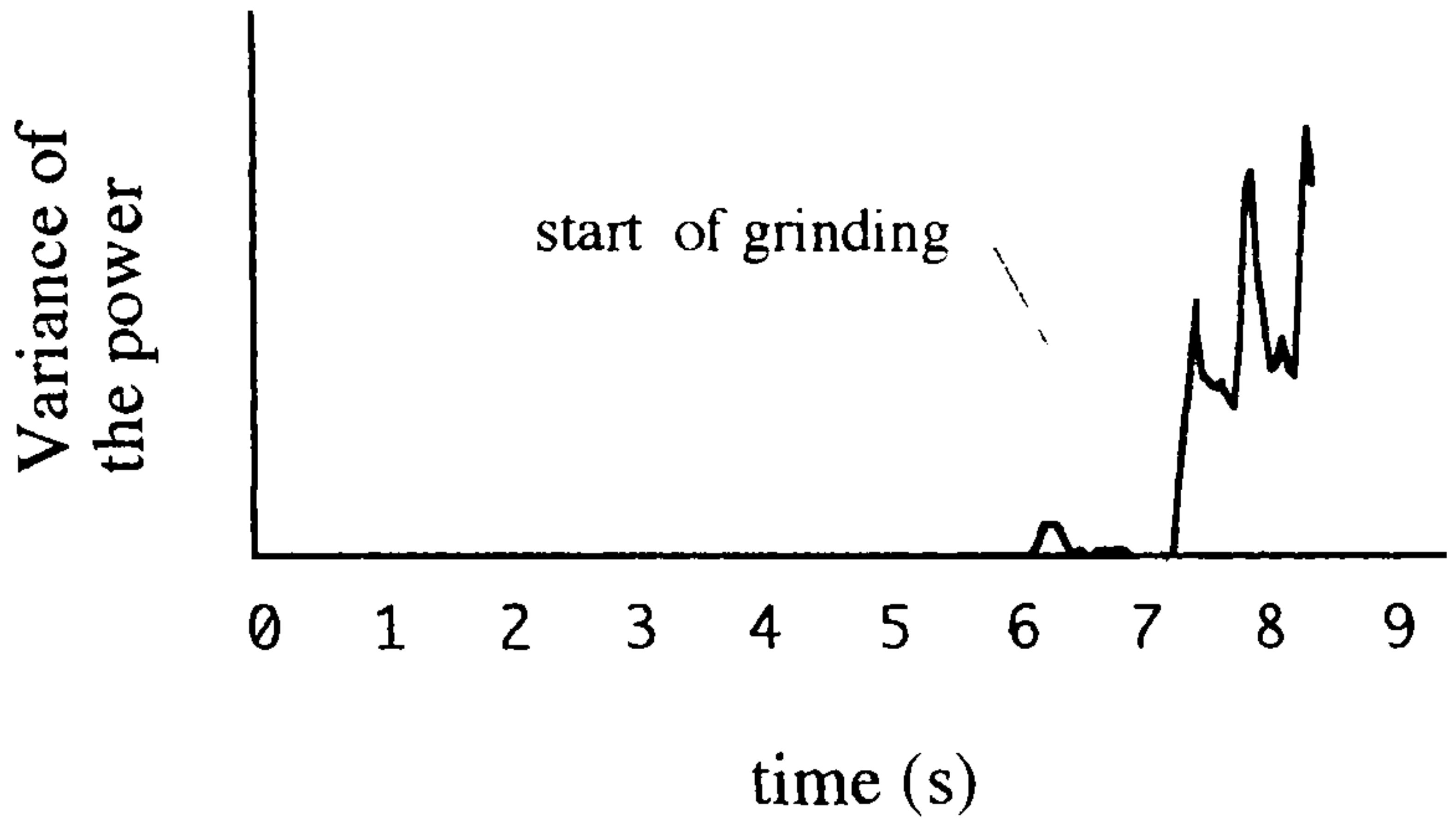


Figure 3.9 Calculating the time constant by integrating the grinding power during the infeed period



a) a typical power signal at the start of grinding



b) variance of the power signal at the start of grinding

Figure 3.10. Detection of the start of grinding using the variance of the power signal

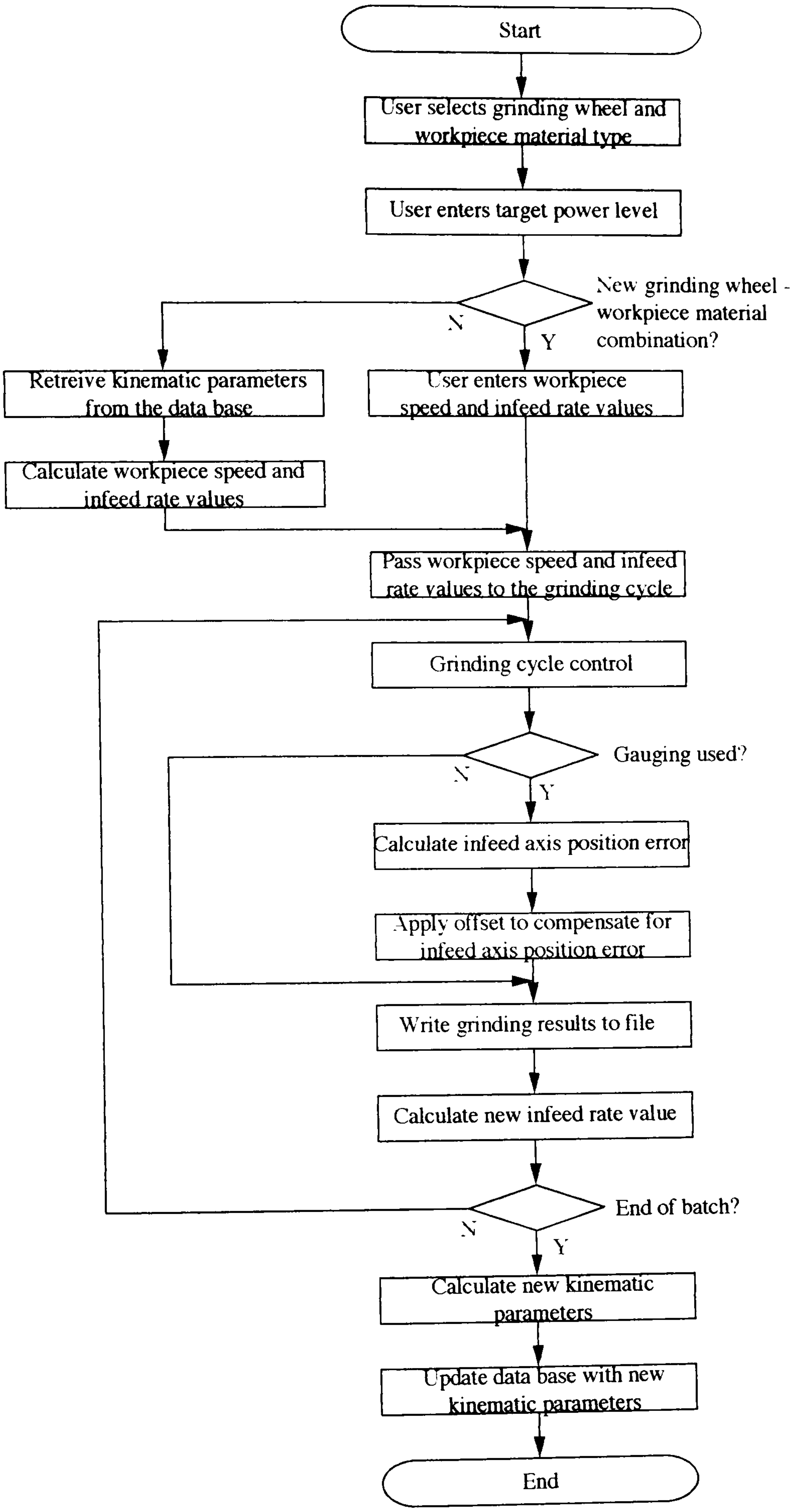


Figure 3.11 A Flow Chart Showing the Implementation of the Adaptive Strategies

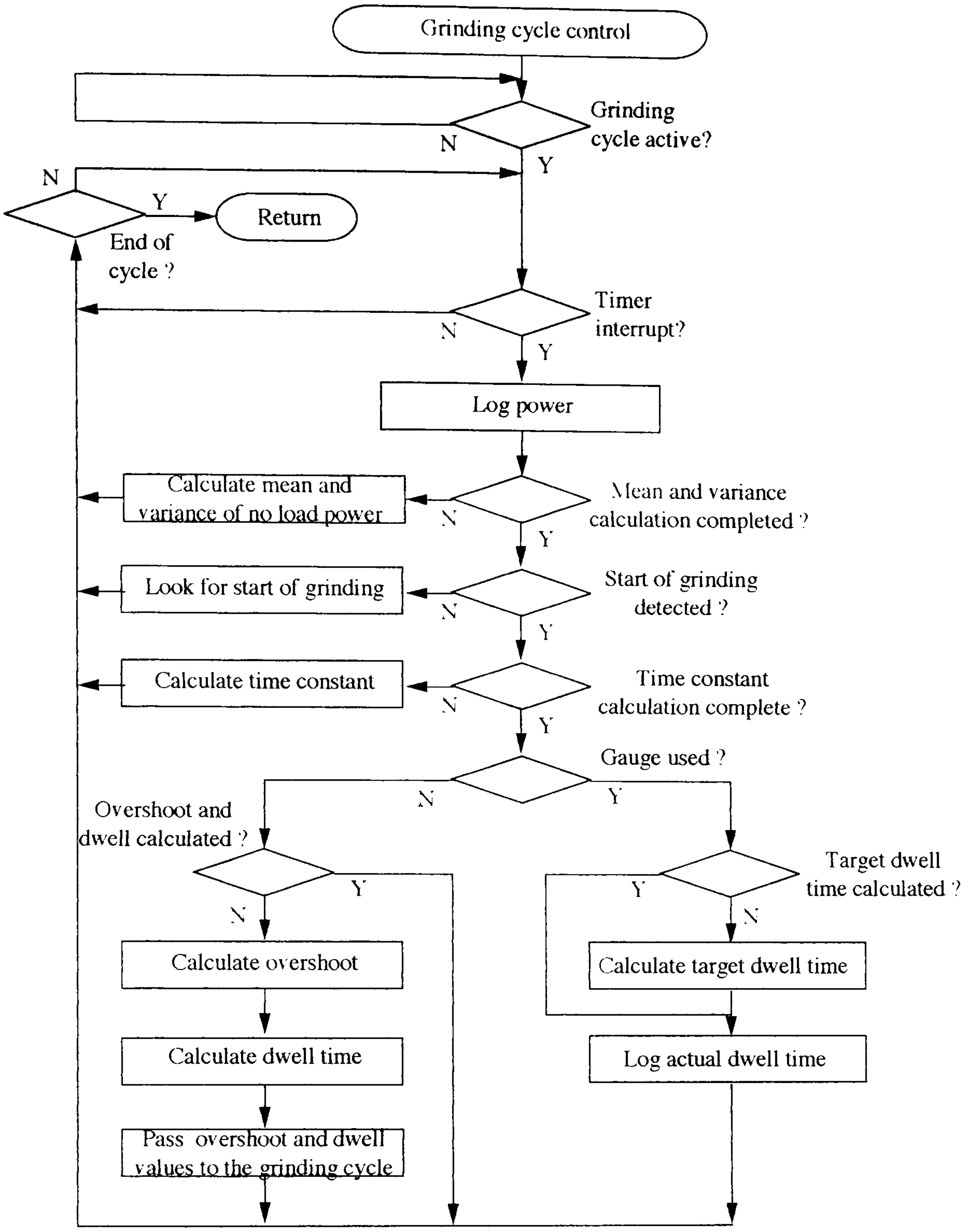


Figure 3.12 A Flow Chart Showing the In-process Operations Required to Implement the Adaptive Strategy

4 DEVELOPMENT OF THE ADAPTIVE CONTROL SYSTEM

4.1 Machine Configuration

The adaptive control system was based on the Series 10 cylindrical grinding machine similar to that shown in the photograph figure 4.1. Workpieces of up to 250 mm diameter could be held in a chuck or located between workhead and tailstock centres. The maximum distance between centres was 700 mm. The workhead and tailstock were mounted on the machine table. Traverse of the table in the Z axis was achieved by d.c.servo motor and ball screw drive with position feedback derived from 1 µm linear scales. Infeed of the wheelhead in the X axis was achieved by d.c.servo motor and ball screw drive with position feedback derived from 0.1 µm linear scales. A variety of plunge, traverse and face grinding cycles were provided by combining infeed and traverse motions. Infeed rates were programmable in the range of 0.06 to 5000 mm/min and traverse rates from 0.06 to 12000 mm/min. Grinding wheels up to 450 mm in diameter were rotated by a 7.5 kW a.c. motor via a belt and pulleys. The wheelhead motor was driven by a frequency inverter, allowing the rotational speed of the wheel to be varied with wheel diameter. In this way a constant surface speed of 33 m/s was maintained. The 1.1 kW d.c. workhead motor rotated the workpiece at rotational speeds of between 40 and 450 rpm. A full specification of the machine is given in Appendix II.

4.2 The Allen Bradley 8200 Controller

The control system for the Jones &Shipman Series 10 grinding cylindrical machine was built around an Allen Bradley 8200 controller, the operation of which was similar to many proprietary machine tool controllers. A part program written by the user specifies the movements of the machine tool axes required to produce a particular workpiece. Commonly, the part program is written on-line, that is input via an editor provided by the user interface of the controller. Alternatively the program is written off-line on another computer system and loaded via a tape reader or downloaded via a communications interface. The facility was provided to save a number of part programs to a bulk storage device.

As the part program was executed the axis movements were implemented by the partition of the control system responsible for motion control. The axis movements were displayed via the user interface along with an indication of the block of the part program currently being executed.

The Allen Bradley 8200 controller was comprised of a modular rack based system, as shown in figure 4.2. The first five slots in the rack were allocated to the processor section. This consisted of a memory module with 64k of battery backed RAM, a micro-instruction module, an arithmetic logic unit, a bus interface module and a processor panel interface. A bubble memory unit was also connected to the memory module for permanent storage of the system software and interface logic. On power down the system software and interface logic were downloaded to the bubble memory. On power up the contents of the bubble memory were written to the memory module.

There were an additional nine slots which were allocated to the interface section. Boards were allocated to these slots depending on the requirements for the particular machine tool application. The interface section for the Jones and Shipman Series 10 cylindrical grinding machine is shown in figure 4.2 and consisted of the following boards:

an operator panel interface for handling switches and indicators,
a CRT / keyboard module to handle the input and display of data,
a communications module to allow connection to peripheral devices,
a servo axes module for the closed loop control of multiple axes,
a digital input / output module for connecting switches, lamps, relays and contacts,
a bulk storage module with battery backed memory for storage of part programs.

Software for the control system was written by the machine tool builder to suit the requirements of a particular machine tool application. This software consisted of configuration, interface logic and part program macros.

Configuration software defined information such as the number of machine tool axes, the resolution of feed back devices, and drive parameters such as the gain and the allowable following error. This was accomplished through the Adjustable Machine Tool Parameters, or AMP.

The primary function of the interface logic was to handle the digital input, output and timing for implementing features such as interlocks, gauging, and the detection of limit switches and error conditions. The logic was also used for a variety of other features such as M word decoding, homing axes, setting feedrate and spindle speed overrides and initialising communications ports.

The logic was implemented using the proprietary language Programmable Application Logic, or PAL. Using the editor provided with the control system the logic program was written in the form of ladder logic. The entire logic was executed by the control system every ten milliseconds. Inputs and outputs were accessed by the logic by reading and writing to a number of PAL variables reserved specifically for this purpose. A number of PAL variables were also provided for performing calculations. System variables such as tool offsets and spindle speeds were accessed via PAL tables. An area of the PAL tables was also reserved for global PAL parameters which were used to synchronise the actions of the interface logic with the execution of the part program. This was particularly useful for features such as actuating in-process gauging and applying wear compensations.

Part programs specified the movements of the machine tool axes required to produce a particular workpiece. To simplify the writing of these programs a number of macros were provided with the control system that encapsulated the code required to implement specific infeed cycles. These part program macros were written using the paramacros facility of the AB 8200 controller.

From the brief description of the machine tool control system given above, it can be seen that the AB 8200 control system comprised of the following elements

part program storage,
part program execution,
motion control,
machine logic,
user interface,
peripheral interfaces, and
communications interfaces.

4.3 System Requirements for Adaptive Control

The purpose of the adaptive control system was to determine suitable grinding parameters, to monitor the process and modify the parameter values in order to maintain optimal operation of the grinding process.

The strategy adopted included the use of a data base together with a process model to determine initial values of workpiece speed and infeed rate. The infeed rate was updated from one grinding operation to the next in order to maintain the required grinding power level. A measure of the deflection of the machining system was given by the system time constant, that is the lag of the programmed and actual position of the wheel-workpiece interface. This was identified in-process from the characteristics of the grinding power during the infeed period. From this the dwell period was calculated to allow the deflection to relax and attain accurate workpiece size. The dwell period was also shortened by extending the infeed period to compensate for deflection.

A number of additional control system features were required in order to incorporate the adaptive strategy into the CNC machine. This included additional data entry that was required for the user of the machine to enter information required by the adaptive routines. Such data included the workpiece material type, the specification of the grinding wheel to be used, and the target grinding power level. Data entry was also required to provide the facility for the user to switch each adaptive feature on or off as required.

The implementation of a data base for the selection of grinding parameters required the permanent or bulk storage of data together with associated file handling facilities. The facility to pass the parameters to the partition of the control system responsible for the storage and execution of the part program was also required.

In order to monitor the grinding process, the ability to log data from sensors during an infeed cycle was also required. To accomplish this required signals from transducers to be sampled at regular intervals via digital and analogue inputs. The ability to temporarily store this data in memory was also required. The stored data was then processed in order to determine appropriate values of machining parameters such as infeed rate, workpiece speed, dwell time, and infeed position. In order to process the data mathematics functions were required such as those provided by the mathematics library of a high level language.

Because of the significant process variability caused by wheel wear and dressing, it was not sufficient to update the dwell time and final infeed position based on information gathered during the previous grinding operation. Rather, it was necessary to use parameter values calculated from data gathered during the current infeed cycle. It was evident that synchronisation was required between the execution of the part program, the logging and processing of data, and the passing of grinding parameters to the partition of the control system responsible for execution of the part program.

After the execution of a grinding cycle, further analysis was made of the data gathered during the grinding cycle. The peak grinding power value was compared to the target power value and the infeed for the next grinding cycle was calculated and passed to the partition of the control system responsible for the execution of the part program.

If diameter gauging was used an offset was applied to compensate for the infeed position error caused by wear and thermal effects.

From the above discussion it is evident that a number of additional features were required by the control system in order to implement the adaptive strategy. These features include

additional data entry by the user of the machine,
bulk storage of data,
file handling,
data logging from sensors during an infeed cycle,
temporary storage of logged data,
data processing using high level mathematics operations,
passing grinding parameters to the partition of the control system responsible for execution of the part program,
synchronisation of the adaptive routines with the execution of the part program.

4.4 Control System Modifications

The potential for implementing adaptive strategies on the AB 8200 control system was somewhat limited. There was little spare memory capacity for the storage and execution of additional software. Also, the proprietary languages provided for writing part program macros and interface logic only provided trigonometric and basic mathematics operations such as addition, subtraction, multiplication, division, and shift operations. There was no provision for the exponential and logarithmic operations required to implement the adaptive strategies. Although bulk storage was provided, this was limited only to part program files created through an on-line editor or downloaded from a peripheral or communications port. Furthermore there was no file handling capability provided for software written by the machine tool builder. Thus the creation and management of binary and text files required for implementing the data base was not possible.

However, it was anticipated that control systems would continue to follow a similar structure and mode of operation to that of the AB 8200, with the exception that the facility to write software using commonly used languages such as 'C' would be provided. This in turn would lead to increased flexibility of programming, give access to a range of mathematics operations and provide file handling capabilities. Furthermore, many man-hours had already been invested in developing a sophisticated grinding control system with a wide selection of grinding cycles and many advanced features such as in-process gauging, gap elimination, and automatic wheel balancing. It was for these reasons that, despite its limitations, the AB 8200 controller was used as the foundation on which to develop the adaptive control system.

The limitations of the AB 8200 controller were overcome by interfacing a second computer system to the controller. An IBM compatible personal computer was selected partly because of the familiarity with such computers, and also because of the wide selection of compilers, documentation, literature, data acquisition and input / output cards available. It was also anticipated that in the near future controllers would be capable of running DOS executable files, and that software developed on an IBM compatible would be readily transported to these platforms. In effect, interfacing an IBM compatible computer to the control system simulated the increased flexibility of programming expected with further development of machine tool controllers. Figure 4.3 shows how a personal computer was interfaced to the CNC machine in order to achieve adaptive control.

During the execution of a grinding cycle the AB 8200 controller carried out the normal functions of storing and executing part programs, controlling the machine tool axes, handling digital input and output, and displaying information regarding program execution and axis motion to the user. However, an additional task was communicating with the personal computer. The personal computer carried out the activities required for adaptive control, that is input / output to the user, executing data base routines, logging and processing data, calculating grinding parameters, and communicating with the controller.

It was evident that in order to implement the adaptive strategies, the ability was required to alter the infeed rate, workpiece speed, infeed positions and dwell time. Also, the dwell period and the infeed position values were calculated based on process measurements made during the infeed cycle. It was essential that these parameters were passed to the control system at the appropriate point during the grinding cycle.

To comply with these requirements, it was decided to implement communications via the input / output ports of the personal computer and controller. Values were output to ports of the personal computer and input to ports on the controller. These values were then used by the control system to set the grinding parameters. This approach allowed software running on the personal computer to set grinding parameter values while the infeed cycle was in progress.

Figure 4.4 shows in more detail the interface of the personal computer to the controller. A commercially available input / output card was installed in an expansion slot of the personal computer. The card used an 8255 programmable input / output device that was compatible with the TTL standard. An additional input / output card was installed in the rack of the controller. However, the ports of the controller required an external power supply and operated on 0 v to 24 V logic levels which were incompatible with the TTL standard. An interface card which converted the voltage levels of the two standards was required. A circuit diagram showing two lines of the interface is given in figure 4.5.

Because the port of the controller was read by the logic as a sixteen bit value, sixteen data lines were used. For negative values an additional control line was used to indicate the sign. In this way sixteen bit integers could be passed across the interface. Further control lines were provided between the controller and the personal computer. Some of these lines were used for timing signals to synchronise the adaptive control software with the grinding cycles. Others were used to control the passing of machining parameter values for use in the grinding cycle.

The values of various grinding parameters were set by first outputting a value and then setting the control lines to indicate which grinding parameter this represented. Grinding parameters could be written to at any time, allowing the adaptive control routines running on the personal computer to modify the currently active grinding cycle.

Axis positions were calculated in millimetres by the adaptive routines. They were converted to tenths of a micron, converted from floating point to integer values and then output to the port of the personal computer. Similarly, dwell times were calculated in seconds, converted to tenths of seconds, converted to integer values and output to the port of the personal computer. By following this procedure, infeed positions and dwell times could be set by the adaptive routines with resolutions of 0.1 μm and 0.1 s respectively.

Maximum values of infeed rate and workpiece speed were hard coded in the macros that defined the grinding cycles. These values were then reduced as required by writing to the infeed rate and workpiece speed override flags of the PAL logic. This gave the capability to change the infeed rate and workpiece speed at any time during the grinding cycle.

The override flags were set to an integer value between 0 and 16383, with 16383 representing 100 % of the value specified in the part program. The value of infeed rate coded in the macro was 0.020 mm/s, which allowed the adaptive routines to modify the infeed rate with a resolution of 0.00122 µm/s. Similarly, a workpiece surface speed value of 30 m/min was coded in the macro giving a resolution of 0.00183 m/min.

4.5 Software

The adaptive control software was written in 'C' and ran on the personal computer under the DOS operating system. A timing signal at a frequency of 18.2 Hz was derived from the system timer interrupt. Code to monitor and control the grinding cycle was was executed upon each interrupt. The control lines from the controller indicated which stage of the grinding cycle was active. Depending upon the active stage of the grinding cycle, the adaptive control software logged data, processed data, calculated grinding parameters or passed grinding parameters to the controller. At the end of the grinding cycle, further calculations were performed and new grinding parameter values passed to the controller for the next grinding cycle. Grinding parameters were passed by first outputting a value to the ports and then setting control lines to indicate which grinding parameter this represented.

To communicate with the personal computer, additional interface logic was written for the controller using the PAL language. This code was executed every 10 ms. Communication from the controller to the personal computer consisted of indicating which stage of the grinding cycle was active. This was accomplished by writing to output ports to set control lines. Communication from the personal computer to the controller consisted of reading grinding parameter values. Input ports were read to examine control lines set by the personal computer. If the control lines indicated that a value had been output from the personal computer, the data was read. The control lines also indicated which grinding parameter the data represented. A global PAL parameter was assigned to each grinding parameter and the value was copied to a particular PAL parameter depending on the state of the control lines.

Part program macros defined the axis movements required to execute grinding cycles. Macros were written using the paramacros feature of the controller that combined ISO M and G codes, control statements and reading and writing to parameters of the controller. Global variables were set to indicate the active stage of the grinding cycle to the interface logic. Global PAL parameters were also used to represent the grinding parameters. This allowed the currently active grinding cycle to be modified at any time via the interface logic.

4.6 Grinding Power Measurement

The wheelhead motor was driven by a variable frequency inverter. This allowed the rotational speed of the wheel to be varied and a constant grinding wheel surface speed maintained over a range of wheel diameters. Figure 4.6 shows how a commercially available power transducer was installed between the inverter and the motor. The voltages across the three phases and the current through two phases were measured by the transducer, and the power consumed by the motor was indicated by an analogue signal. This signal was sampled at a frequency of 18.2 Hz using the twelve bit analogue to digital converter of a commercially available data acquisition card installed in the expansion slot of the personal computer. The signal was first filtered with a low pass filter to avoid signal aliasing problems. A third order Butterworth filter with a cut-off frequency of 6 Hz was found to give satisfactory results without undue distortion of the signal. The circuit diagram of the filter is given in figure 4.7.

The output of the power sensor indicated the total power consumed by the wheelhead motor. When grinding was not in progress power was consumed due to the need to overcome frictional losses. This no-load power was subtracted from the total power consumed to give the power input to the process, that is the grinding power.

4.7 Diameter gauging

Diameter gauging was already provided with the CNC machine. The jaws of the gauge were set up on a datum component. During the grinding cycle the gauge was advanced onto the workpiece hydraulically. The gauge then operated as a comparator, indicating the difference in size from the datum part. Digital signals were output to the controller when pre-set amounts of stock remained. These signals were read by the part program macros via the interface logic and used to control the grinding cycle. The adaptive grinding cycles used the gauge in a similar manner, but the stock levels were set automatically and not by the user of the machine.

4.8 Summary

The Series 10 machine was provided with CNC capability by an AB 8200 controller. The X (infeed) and Z (table) axes were servo controlled. A number of grinding cycles were provided by combining motions of the two axes. The grinding wheel speed was varied by means of the a.c. wheelhead motor and a frequency inverter. Variable speed of the workpiece was achieved via the d.c. workhead motor and drive.

As a typical controller the AB 8200 offered a number of features in common with the majority of machine tool controllers, that is motion control, machine logic, user interface, peripheral interfaces, and communications interfaces. While these features were adequate for computer numerical control, additional features were required to implement adaptive control. In particular, additional capability was required for the user interface, bulk storage of data, file handling, data logging, and mathematics operations for processing data. These difficulties were overcome by interfacing a personal computer to the controller. This approach was adopted because of anticipated developments in controllers that would allow them to be programmed in commonly used languages such as 'C' and to run DOS executable files.

A diameter gauge was provided with the CNC system and this was also used by the adaptive control system. A power transducer was installed that measured the power consumed by the wheelhead motor. From this the grinding power was determined. The analogue output of the transducer was sampled by the personal computer via a data acquisition card with an analogue to digital converter. This data was used by the adaptive control routines to calculate grinding parameter values that were then passed to the controller.

Communications were established via the input / output ports of the personal computer and the controller. This synchronised the adaptive routines with the grinding cycle and allowed grinding parameters to be modified in-process, based on data logged during the currently active cycle.

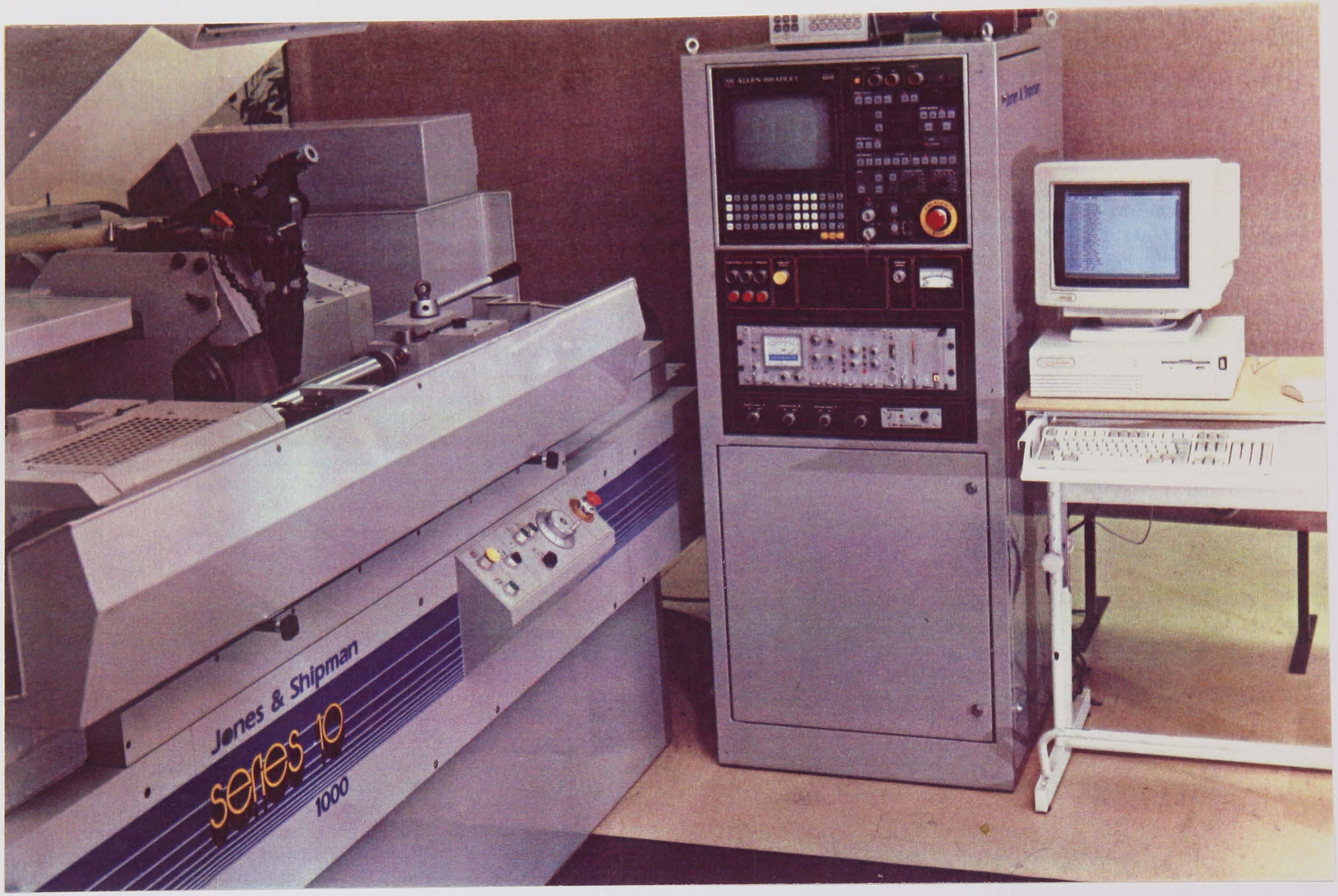


Figure 4.1 Jones & Shipman Series 10 cylindrical grinding machine.

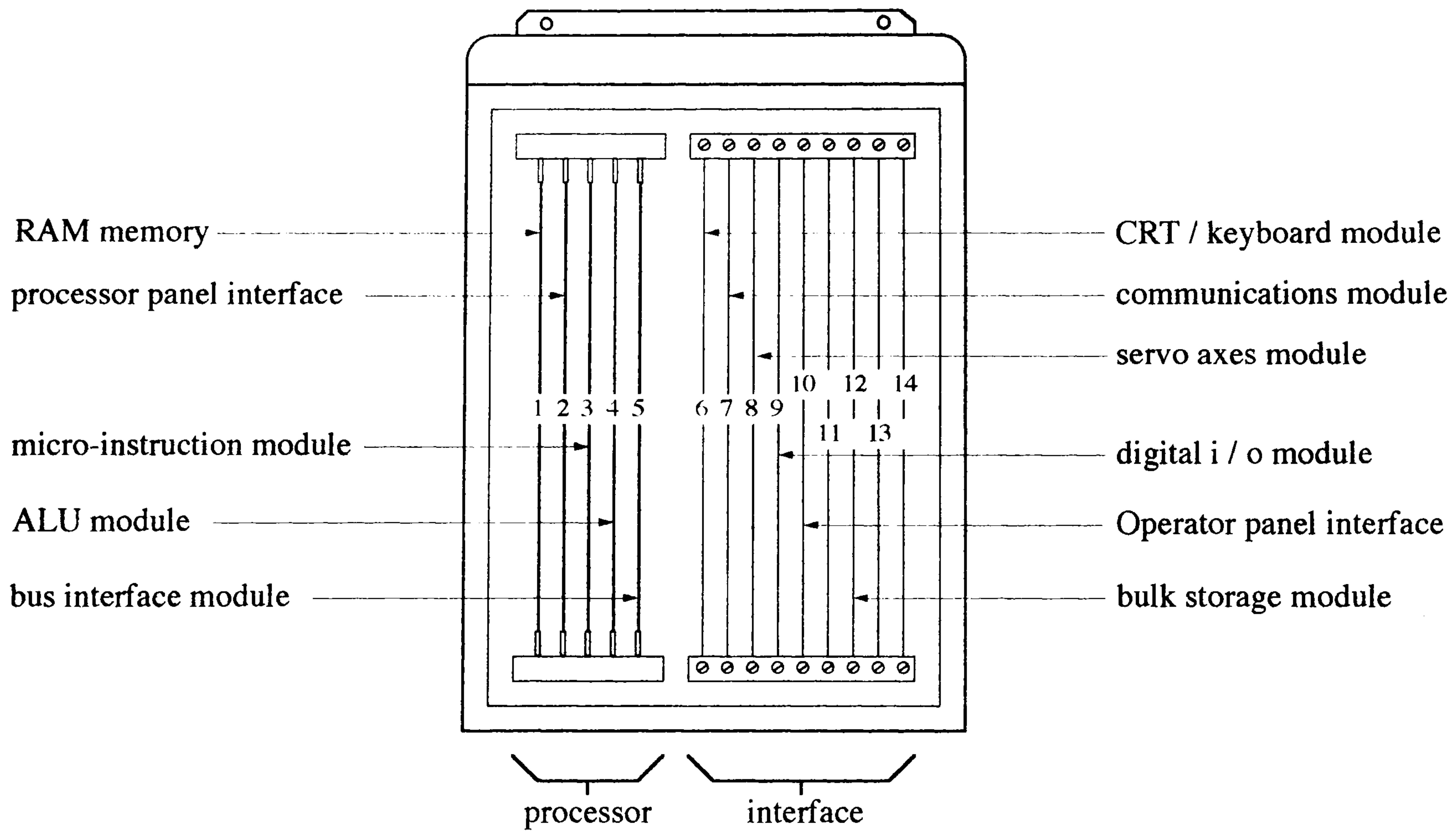


Figure 4.2 Allen Bradley 8200 controller rack.

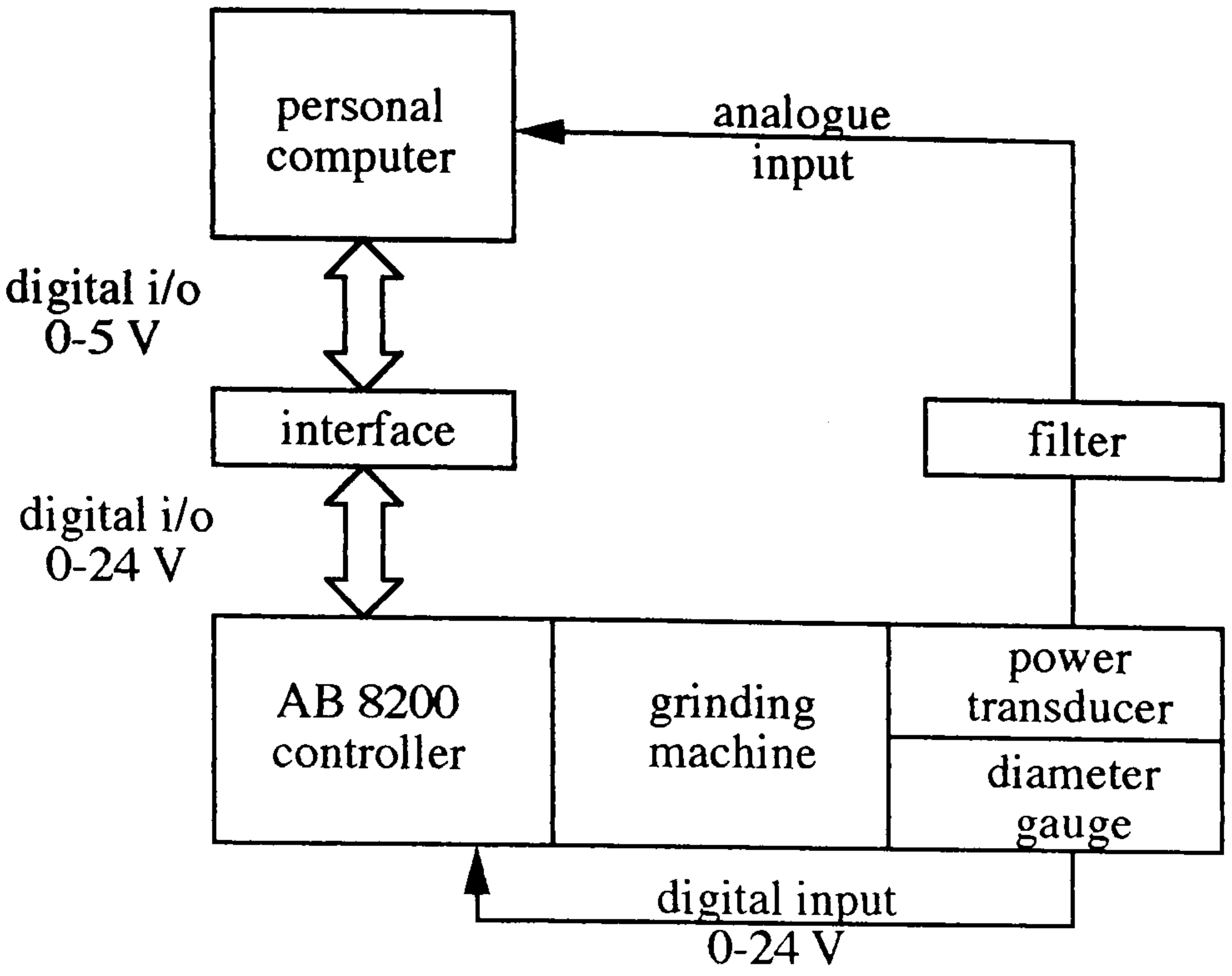


Figure 4.3 - Interfacing a personal computer to the CNC machine

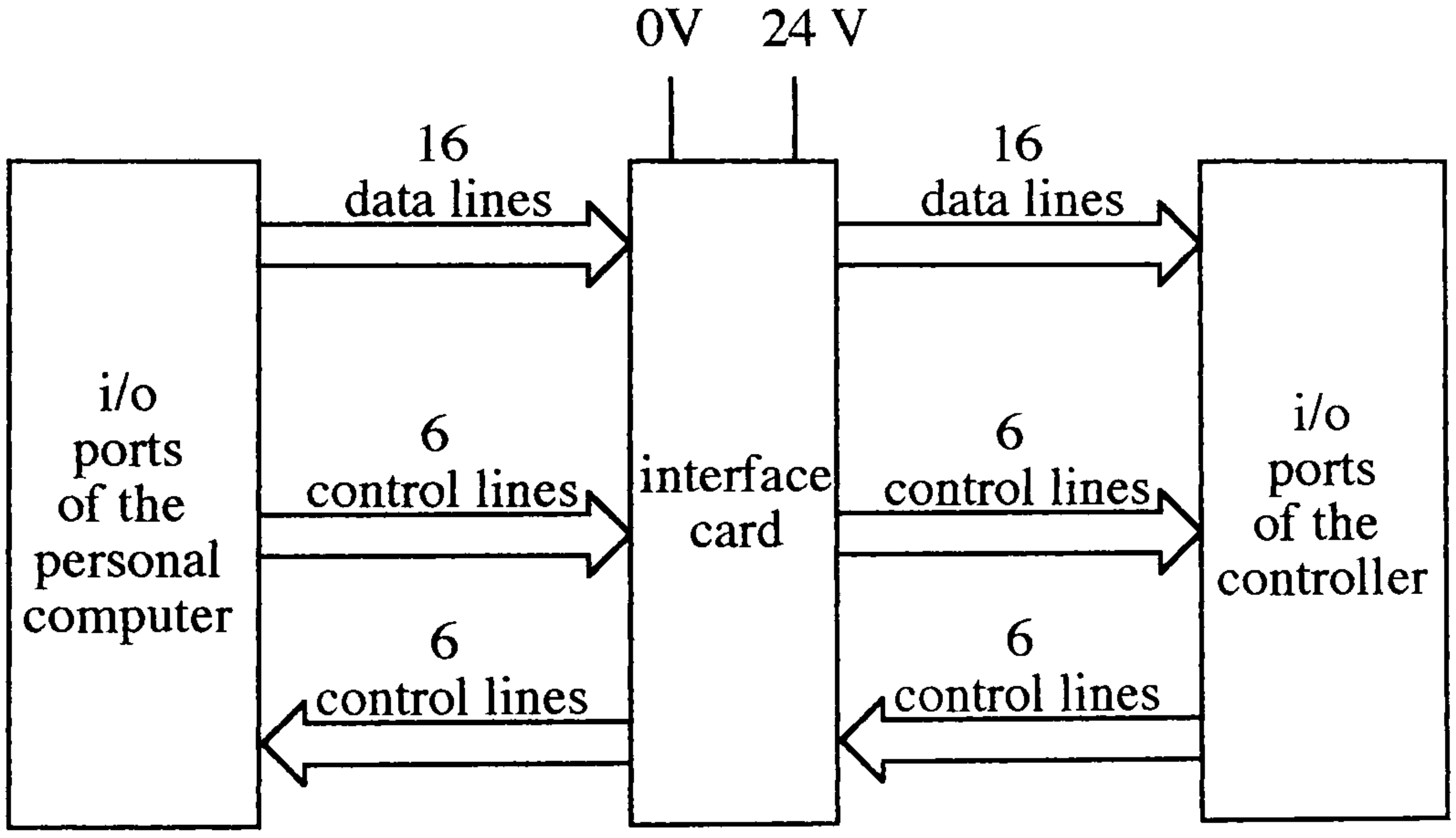


Figure 4.4 - detail of the interface between the personal computer and the controller

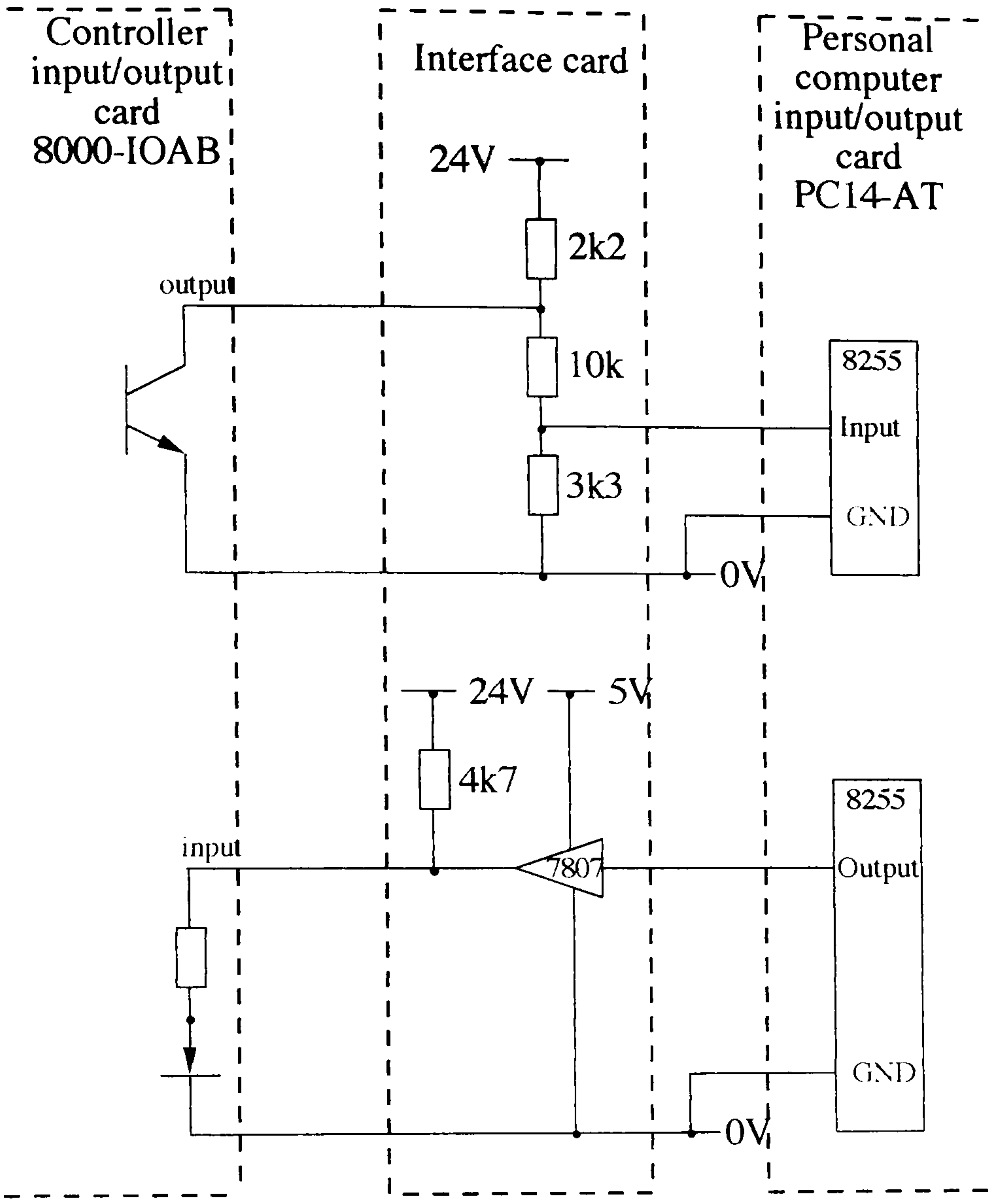


Figure 4.5 - Circuit diagram showing two lines of the PC to CNC interface

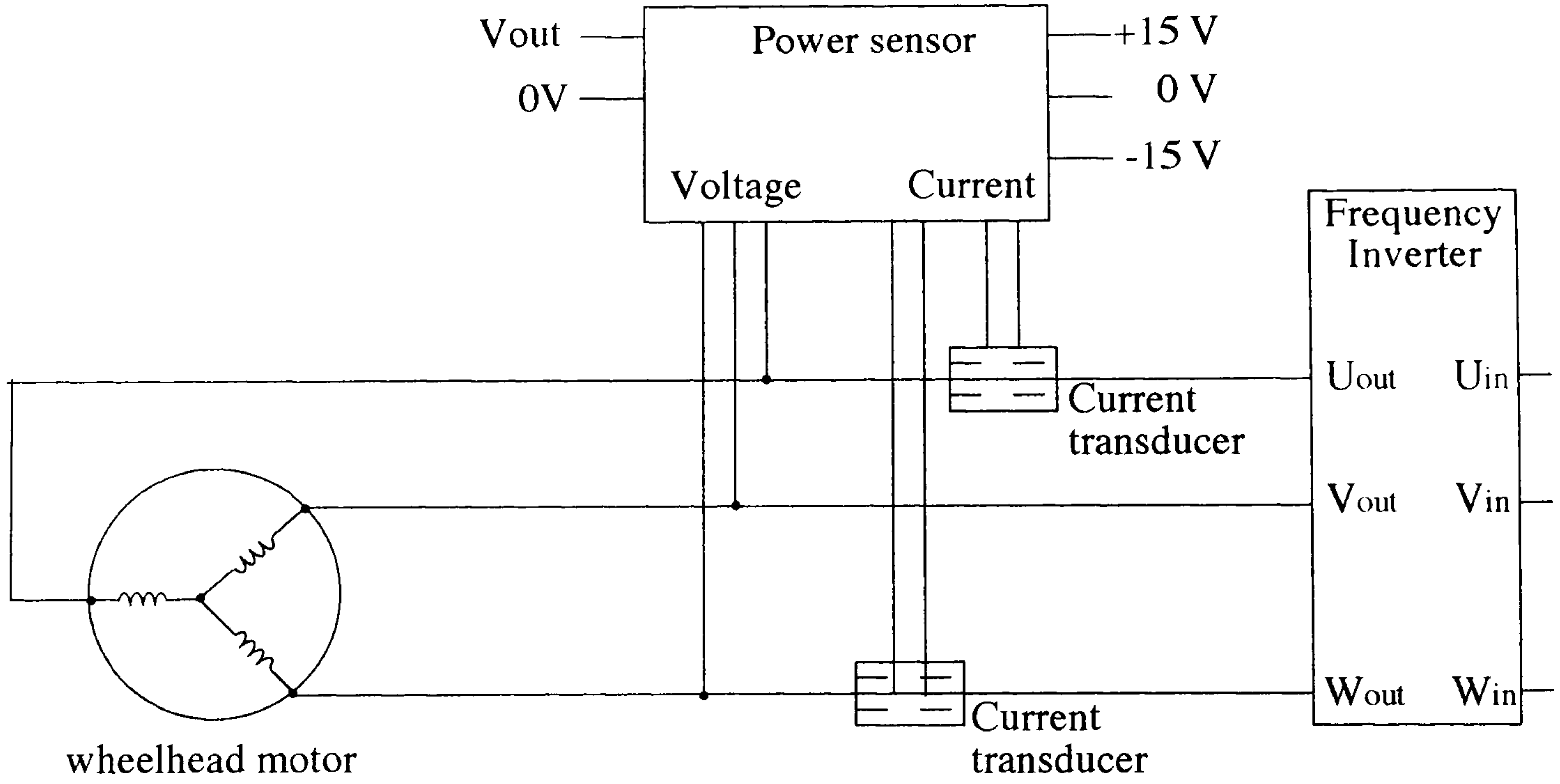


Figure 4.6 - Interconnection diagram for the power sensor

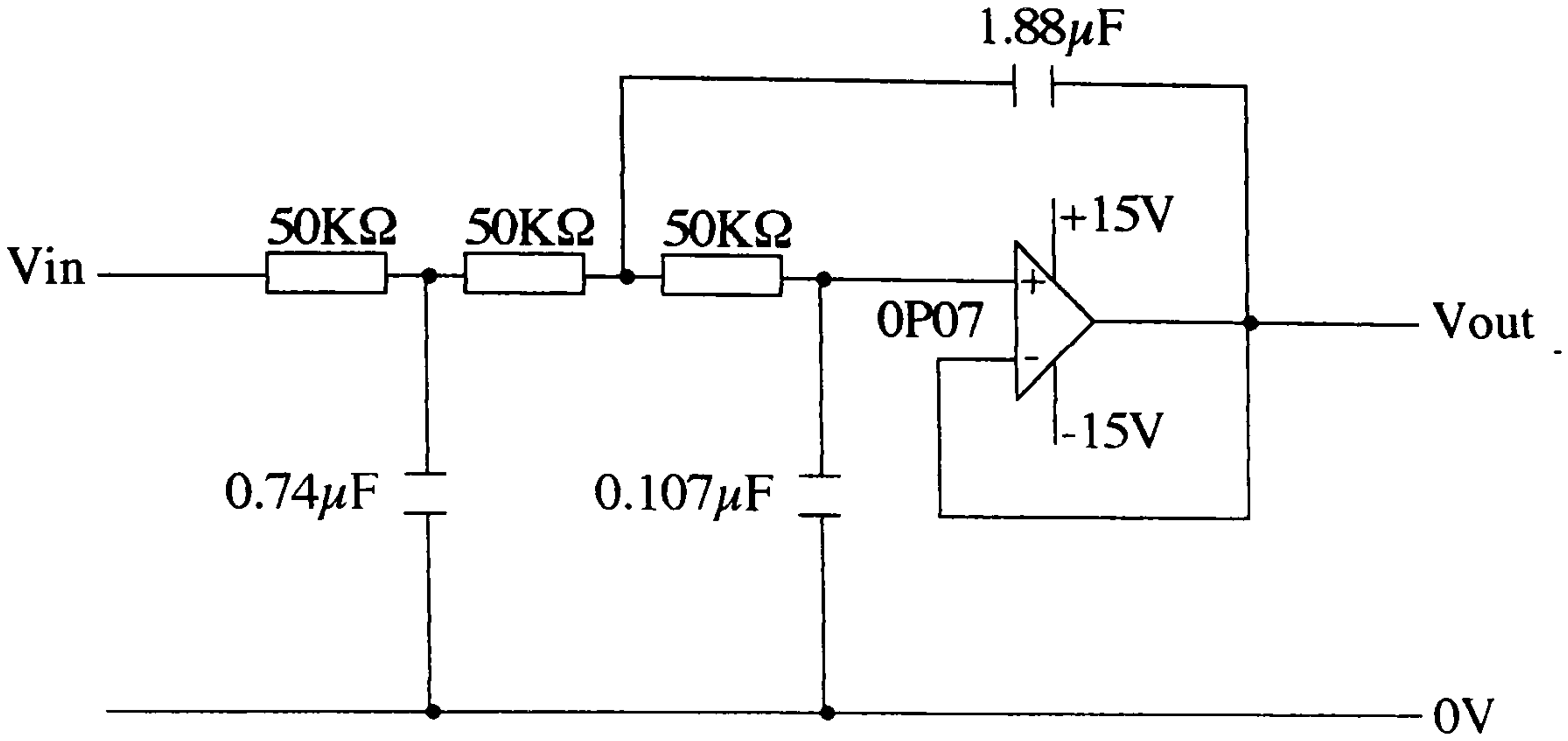


Figure 4.7 - Circuit diagram for the active filter with 6 Hz cut-off frequency used for the power signal

5 THE NON-ADAPTIVE CONTROL SYSTEM

5.1 Introduction

This chapter describes grinding cycles provided with the conventional CNC grinding machine. Grinding trials were undertaken to determine standards achievable with the conventional system. The performance of the grinding cycles both with and without diameter gauging was investigated. The results of these experiments were analysed in order to determine the controlling parameters of the process. The effects of grinding wheel wear and dressing diamond wear were considered, as were the effect of deflections of the machining system and of thermal expansion and contraction of the workpiece. Recommendations for improving the performance of the machine by the introduction of adaptive features were made.

5.2 The Plunge Grinding Cycles

A typical plunge grinding cycle consists of three infeed rates and a dwell period, as shown in figure 5.1a. The actual infeed position lags behind the programmed infeed position due to deflection of the machining system caused by the grinding forces. During the dwell period the deflection decays exponentially as further stock is removed to produce a finished workpiece of the required size.

Figure 5.1b shows a similar plunge grinding cycle which uses in-process diameter gauging. The user is required to specify the stock remaining when the final infeed period commences and the stock remaining when the dwell period commences. These values are set by potentiometers on the gauge unit. When these points are detected by the gauge, flags are set to signal the controller to change the infeed rate or stop the infeed. The end of the infeed cycle is also signalled by the gauge which sets a flag when the target diameter is attained, causing the controller to retract the grinding wheel. Although the grinding cycles appear the same, the cycle without gauging shown in figure 1a becomes inaccurate because of the cumulative effects of wheel wear and other factors. For the cycle with gauging shown in figure 1b, the final stages of the infeed cycle are triggered by the diameter gauge at positions relative to the target diameter. As a result any errors in the infeed position caused by wheel wear, dressing, machine set-up and thermal deformation of the machine are compensated for automatically. In addition the infeed position during the dwell period is compared to the programmed target diameter and the difference is used to calculate an offset for the infeed axis. In this way the error compensation is retained for future grinding operations.

For the plunge grinding cycles both with and without diameter gauging the user selected the workpiece speed, the infeed rates, the positions at which the infeed rates were changed and the dwell period based on experience and knowledge of the process. The grinding wheel surface speed is usually set to the default value of 33m/s.

5.3 Metrology Operations

The cylindrical grinding process is used to machine parts which are specified to fine size, roundness and surface texture tolerances. In order to avoid measurement errors due to thermal deformation of the workpiece, all metrology operations were made in a controlled environment with the temperature held at 20 °C. The measurements for this project were carried out in the metrology laboratory of the AMT Research Laboratory of Liverpool John Moores University.

5.3.1 Size Measurements

Size measurements were undertaken using a Rank Taylor Hobson Talymin Comparator. The comparator was set to a datum size using slip gauges. The workpiece was placed under the measuring probe and the difference in size from the datum was displayed on the dial. The resolution of the comparator was 0.2 μm, but readings were estimated to 0.1 μm by interpolating by eye between the graduations on the dial. The repeatability was determined by measuring a block of slip gauges a number of times. The results of figure 5.2 show that size could be measured repeatability within a range of 0.5 μm.

The CNC grinding machine was equipped with a diameter gauging system which could be used to control the plunge grinding cycle as described in section 5.2. The jaws of the gauge were set up on a datum component which was the same diameter as the target size of the workpiece to be ground. The gauge amplifier was adjusted so that this gave a zero reading. The gauge was advanced onto the workpiece hydraulically, either automatically or by the operator turning a switch. The gauge then functioned as a comparator, indicating the difference in size between the datum component and the component being measured.

The gauge reading was displayed on a dial on the controller front panel and a 0-10 V analogue output was also available. During the course of the research the analogue output was logged and the signal analysed to investigate the performance of the feed cycles. The repeatability of the diameter gauge was investigated by measuring the same workpiece a number of times. The workpiece was not removed from the centres for the duration of the experiment. The gauge was advanced onto the workpiece every thirty seconds and a total of 120 measurements were made over a period of one hour. The reading of the dial on the control panel was noted and the results of are shown in figure 5.3. The readings ranged from +0.3 μm to -0.7 μm. Likely causes of the trend of decreasing diameter measurements throughout the test are wear of the workpiece and thermal errors.

5.3.2 Roundness Measurements

A computer controlled Rank Taylor Hobson Talyrond was used for measuring workpiece roundness. The workpiece was held in jaws mounted on a table. A stylus was brought into contact with the workpiece and the table was rotated. In this way the profile of the workpiece was recorded and the roundness calculated. A display of the workpiece profile together with the roundness value was displayed on the computer screen and a printout could be obtained.

5.3.3 Surface Texture Measurements

For measuring the surface texture a computer controlled Rank Taylor Form Talysurf was used. The workpiece was placed on a V block and the stylus traversed across the workpiece surface. From the movement of the stylus the workpiece surface profile was recorded and the surface texture was calculated.

5.4 Machine Set-Up

The set-up procedure shown in figure 5.4 was required to be followed every time the machine was powered up, the grinding wheel was changed, the dressing diamond was changed or the tailstock or workhead were moved. For the purpose of discussing the errors introduced into the infeed axis position during the machine set-up, step 1 (touch dressing diamond onto the grinding wheel surface), step 3 (dress the grinding wheel) and step 5 (grind the workpiece, measure and input diameter) need to be considered.

Step 1 - touch dressing diamond onto the grinding wheel surface

The infeed axis position when the dressing diamond was in contact with the grinding wheel surface was stored. For discussion this will be called variable A. This variable is used to compute the infeed axis position when the grinding wheel was dressed.

Step 3 - dress the grinding wheel

The wheel was dressed by traversing the dressing diamond across the grinding wheel, using an infeed position equal to variable A minus the dressing increment. It was assumed that this had the effect of removing material from the wheel to a depth equal to the dressing increment.

Step 5 - grind the workpiece, measure and input diameter

The diameter of the ground workpiece was input into the controller and the diameter of the grinding wheel was computed and stored. This will be called variable B for the purpose of this discussion. The diameter was measured with a hand held micrometer and was subject to error which was carried over to the infeed position of the grinding wheel.

Every time the grinding wheel was dressed, the following calculations were performed:

variable A <= variable A - dressing increment 1
variable B <= variable B - dressing increment 2

The first calculation updated the variable which stored the infeed position at which the dressing diamond contacted the grinding wheel. The second calculation computed the new grinding wheel diameter. These calculations assumed that there was no wear of the dressing diamond and that there was no deflection of the diamond during the dressing operation. Therefore, any wear or deflection that did occur resulted in errors in the computed values of grinding wheel diameter and dressing infeed position.

5.5 Process Capability

Before the adaptive control system was designed it was necessary to assess the process capability of the machine with the non-adaptive control system and to determine the controlling parameters of the process. In order to accomplish this a set of machining trials was conducted using the infeed cycles provided with the standard control system.

The plunge grinding process may be operated in a number of ways. The wheel may be dressed between each grinding operation, or may be dressed only before grinding the first workpiece of a batch. Also, diameter gauging may be employed. Trials were carried out in order to assess the performance of the system when operated in each of the modes shown in figure 5.5a.

The capability of the machine to maintain size with the standard control system was determined under near ideal conditions using a standard testpiece and moderate infeed rates. The results are shown in figure 5.5b. Line A shows that when grinding without diameter gauging and without re-dressing the wheel before each operation there was an increase in the finished diameter throughout the batch. It was deduced that oversize workpieces were produced because of the cumulative effect of grinding wheel wear. Line D shows that when the wheel was re-dressed between each grinding operation there was a decrease in the finished diameter throughout the batch. This was considered to be due to wear of the dressing tool and possibly partly due to deflection of the dressing system during the dressing process. Lines B and C show the cases of re-dressing and not re-dressing the wheel between grinding operations when diameter gauging was used. In both cases the size accuracy of the process was dramatically improved by the use of in-process gauging.

5.6 The Effect of Deflection on Performance of the CNC Machine

Grinding forces cause the machine - grinding wheel - workpiece system to deflect. The steady state lag of the actual infeed rate from the programmed infeed rate was considered as the time constant of a first order system, as described in chapters 2 and 3. The workpiece geometry determined the stiffness of the workpiece, and therefore affected the stiffness of the machining system and the magnitude of the deflection. The grinding process is used to machine a wide variety of workpieces of differing stiffness, and a CNC grinding machine should be capable of producing good results over a range of stiffness values. To determine the effect of deflections on the performance of the CNC machine, trials were carried out on both stiff and flexible components. The range of testpieces used is shown in figure 5.6 together with typical values of time constant experienced when they were ground.

The stiffness of the machining system was not the only factor affecting the deflection. The grinding forces were dependent on the condition of the grinding wheel which varied considerably with wear and dressing. When the wheel was dressed at the start of the batch only, the variation in deflection varied significantly from workpiece to workpiece. This can be seen from the change in time constant with workpiece number shown in figure 5.7.

5.6.1 The Effect of Deflection on Plunge Grinding without Gauging

The effect of deflections on infeed cycle design was investigated by considering a basic infeed cycle consisting of a single infeed period followed by a dwell period. For workpieces of different geometries, varying amounts of deflection were experienced and as a result the dwell times required were not the same. The deflection x during the dwell period is given by the following equation where x_1 is the deflection at the start of the dwell period, t is the time since the start of the dwell period and τ is the time constant.

$$x = x_1 e^{-t/\tau} \qquad 5.1$$

As near steady state grinding conditions were assumed, the deflection at the start of the dwell period was given by the product of the infeed rate and the time constant. The dwell times required to finish workpieces to within 1 μm and 2 μm of target size were calculated for different time constant values when using an infeed rate of 10 μm/s. From the graphs shown in figure 5.8 it can be seen that the dwell periods required were approximately 10 s for a time constant of 3 s, 20 s for a time constant of 5 s, and 30 s for a time constant of 7 s.

Again considering a basic infeed cycle, the effect of the variations in time constant within a batch shown in figure 5.7 were examined. It was found that a fixed dwell period of 23 s would allow for the largest value of time constant and bring all the workpieces to within 1 μm of the target size. However, a dwell period of 8.56 s would have sufficed for the grinding operation with the shortest time constant. It was therefore deduced that the plunge grinding cycle produces satisfactory size holding results if a fixed dwell is used which is sufficiently long to account for the process variability. However, cycle times are non-optimal as the dwell period is longer than required for the grinding operations with the least deflection. This not only wastes time, it also leads to additional wheel wear, resulting in a requirement for more frequent wheel dressing.

5.6.2 The Effect of Deflection on Plunge Grinding with Gauging

The user was required to specify the stock remaining when the final infeed period commenced and the stock remaining when the dwell period commenced. These values were set by potentiometers on the gauge unit. The correct gauge settings depended on the deflection of the machining system. This may be explained by considering the stock to be removed when the dwell period commenced, shown by ΔX in figure 5.9.

For correct operation the stock Δx remaining at the start of the dwell period was set to be just less than the deflection at the start of the dwell period. This ensured that the grinding wheel was not retracted until the deflection was almost completely relieved, as shown in figure 5.9a.

However, if the stock remaining at the start of the dwell period was set to be equal to or greater than the deflection, target size was not achieved because of the exponential decay of the deflection. This is shown in figure 5.9b.

If the stock remaining at the start of the dwell period was set to be significantly less than the deflection, the grinding wheel was retracted before much of the deflection had been relieved. The grinding wheel overshot the target position as shown in figure 5.9c. This caused a 'step' to be created on the workpiece, resulting in poor roundness. Also the deflection remaining in the system, together with the delay in retracting the grinding wheel after the 'at size' signal, caused further material to be removed and resulted in under-size workpieces.

Once the gauge had been set, variations in deflection caused the grinding cycle to perform incorrectly. Variations in deflection were caused by changes in the grinding forces, and also by the user changing the infeed rate, the workpiece speed or the grinding wheel speed. All these actions change the time constant of the system.

In practice once suitable machining parameters were established they were seldom changed. However, the effect on performance of changes in the grinding forces was significant when grinding flexible workpieces at relatively high infeed rates. The stock allowance for start of the dwell period set on the gauge unit was correct for the first component of a batch. When the deflection varied throughout the batch the gauge settings were no longer correct and the cycle did not function correctly. This can be explained by considering the range of time constants shown in figure 5.7 for a dwell time of four time constants and for a single infeed rate of 10 μm/s. When grinding the first workpiece the infeed axis would overshoot by 1.04 μm. For the second workpiece the change in time constant from 5.7 s to 4.6 s would mean a decrease in deflection of 11 μm. The deflection would decrease to a value less than the stock allowance at the start of the dwell period set on the gauge unit, the cycle would fail as shown in figure 5.9b and the finished workpiece would be 9.76 μm oversize. Any significant change in the deflection of the system was required to be compensated for by altering the feed change points on the gauging system to ensure the correct operation of the feed cycle. In practice, conservative machining conditions are selected which ensure that the deflection of the system is small and that errors caused by the changes in deflection are minimised. This, however, is at the expense of cycle time.

Figure 5.10 shows the size results achieved when grinding flexible workpieces at high and low material removal rates. At the low removal rate all the workpieces were finished to within 1 μm of target size. However at the high removal rate the size error ranged from 7 μm to 9 μm below the target size. The gauge was more difficult to set because of the large variations in deflection with changes in the grinding forces. The stock remaining at the start of the dwell period was significantly less than the deflection as shown in figure 5.9a. The large size errors were attributed partly to incorrect setting of the gauge causing further material to be removed after the size signal had been detected, and partly to the workpiece continuing to cool to ambient temperature after the end of the dwell period. Indeed, the need to allow for this residual shrinkage has been identified by Peters and Aerons (1980). Different gauge are settings required, resulting in a longer dwell period, and allowing the deflection to relax and the workpiece to cool.

5.6.3 Multi-diameter Grinding

For workpieces which have more than one diameter to be ground, gauging is often applied to one diameter only. This is partly because of the expense of the gauging system, partly because of the increased set-up time associated with multiple gauging systems, and partly because of limited access to the workpiece because of the size of the gauge. Problems were experienced if the feed change points were set incorrectly for the gauging cycle as shown in figure 5.9c. The grinding wheel was found to feed in further than the target position and an axis offset was generated which was due to the incorrect setting of the feed change points. This had an adverse effect on the non-gauged diameter as the incorrect infeed offset was retained and resulted in significantly undersized workpieces being produced as shown in figure 5.11. The size errors for the gauged diameter were relatively small because the end of the cycle was triggered by the gauge.

5.7 Thermal Expansion of the Workpiece

It was found that during grinding energy input to the process caused the workpiece to heat up and expand. During the dwell period the depth of cut decreased and the workpiece was found to cool. It was found that if the workpiece was not given sufficient time to cool to near the ambient temperature before the system deflection had completely relaxed, the workpiece continued to contract causing a size error. The magnitude of this error depended upon the difference in workpiece temperature from ambient, and the coefficient of thermal expansion of the workpiece material. This error was calculated for a range of temperature differences for EN9 steel and is shown in figure 5.12.

5.8 Discussion and Conclusions

The controlling parameters of the grinding process were found to be deflection of the machining system, thermal expansion of the workpiece, and errors in the infeed position due to machine set-up errors, dressing tool wear and deflection, and grinding wheel wear.

The best performance of the CNC machine was found to be a size holding capability of 1 μm. This was achieved using the gauging cycle, which offsets the infeed axis to compensate for infeed position errors. However, the gauging cycle was prone to failure due to the variability of the grinding process and the requirement for the manual setting and adjustment of feed change points.

The selection of feed change points and machining parameter values was found to be difficult because of the changes in deflection that occur due to variations of the grinding force with the changing condition of the grinding wheel. In practice conservative values are used which result in long cycle times but ensure that every workpiece is produced to the required size.

It was decided that because of its variable nature the performance of the grinding process could be significantly improved by the use of an adaptive control system. Of particular benefit would be a system which characterised the deflection of the machining system and compensated by adjusting the feed cycle. For non-gauging cycles the dwell period should be set to the time required to produce a particular component to within the size tolerance, while improving productivity by avoiding unnecessarily long dwell times.

With knowledge of the system deflection the correct operation of the gauging cycle could be ensured. The time consuming gauge set-up procedure would be simplified and supervision requirements reduced. Also, a gauging cycle which was automatically adjusted to account for changes in deflection could be operated at higher removal rates without detriment to the size holding capability. For both gauging and non-gauging cycles the need for pre-production trials to optimise the process would be reduced.

Another useful feature would be the the prediction of wheel wear and dressing tool wear based on knowledge of G and D ratios. The G ratio is given by the volume of material worn from the wheel divided by the volume of material removed from the workpiece during a grinding operation. The D ratio is given by the volume of material worn from the dressing tool divided by the volume of material removed from the wheel during a dressing operation. Using the G and D ratios to predict wear would allow compensations to be introduced, substantially improving the size holding capability of the plunge grinding cycle when gauging was not in use. Also, the facility to automatically select the appropriate machining parameter values for a particular grinding wheel - workpiece combination from an on-line data base would reduce the need for pre-production trials in order to establish the correct values. A summary of adaptive features which would improve the performance of the grinding process is given in figure 5.13.

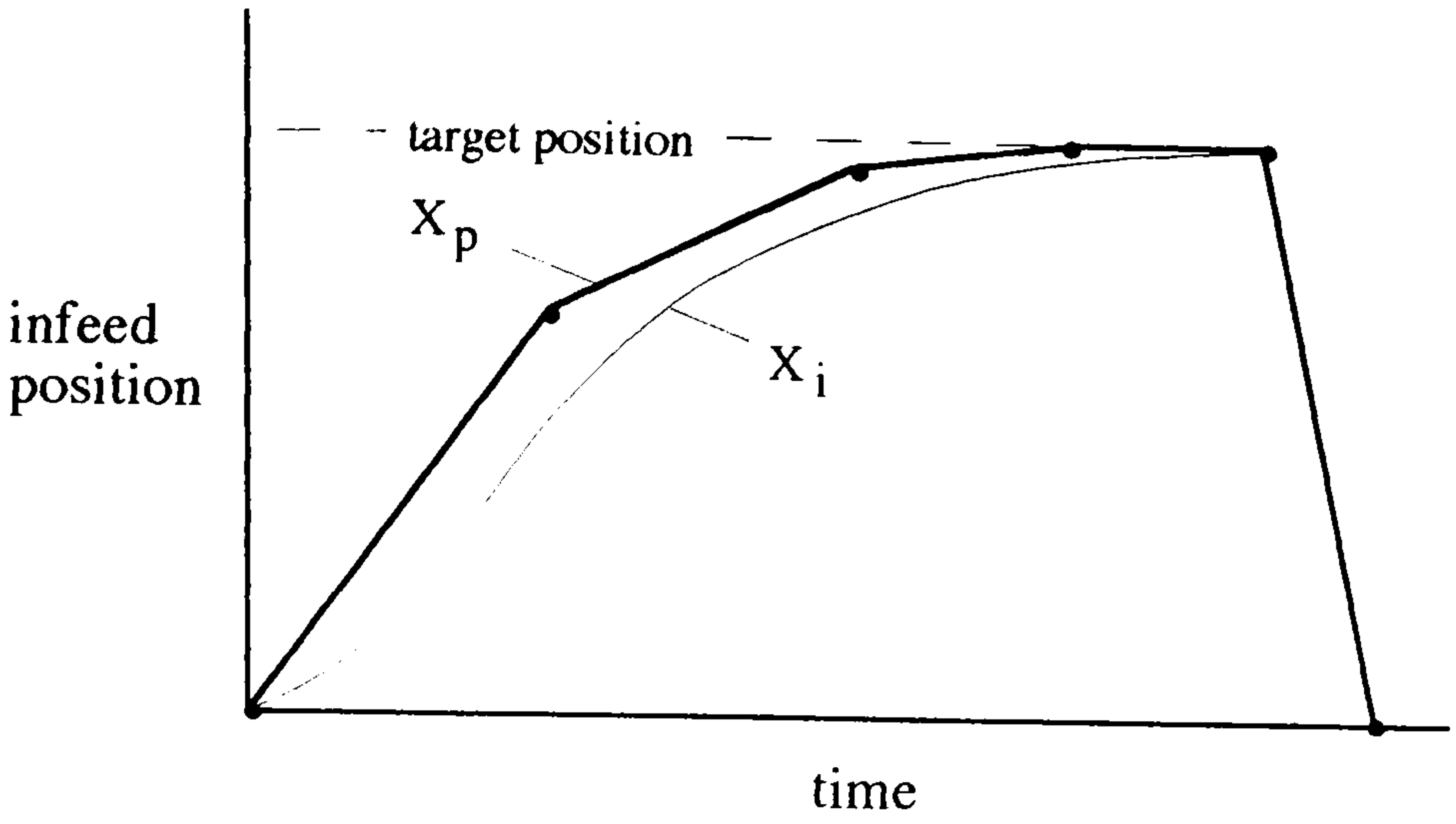


Figure 5.1a Plunge grinding cycle without diameter gauge

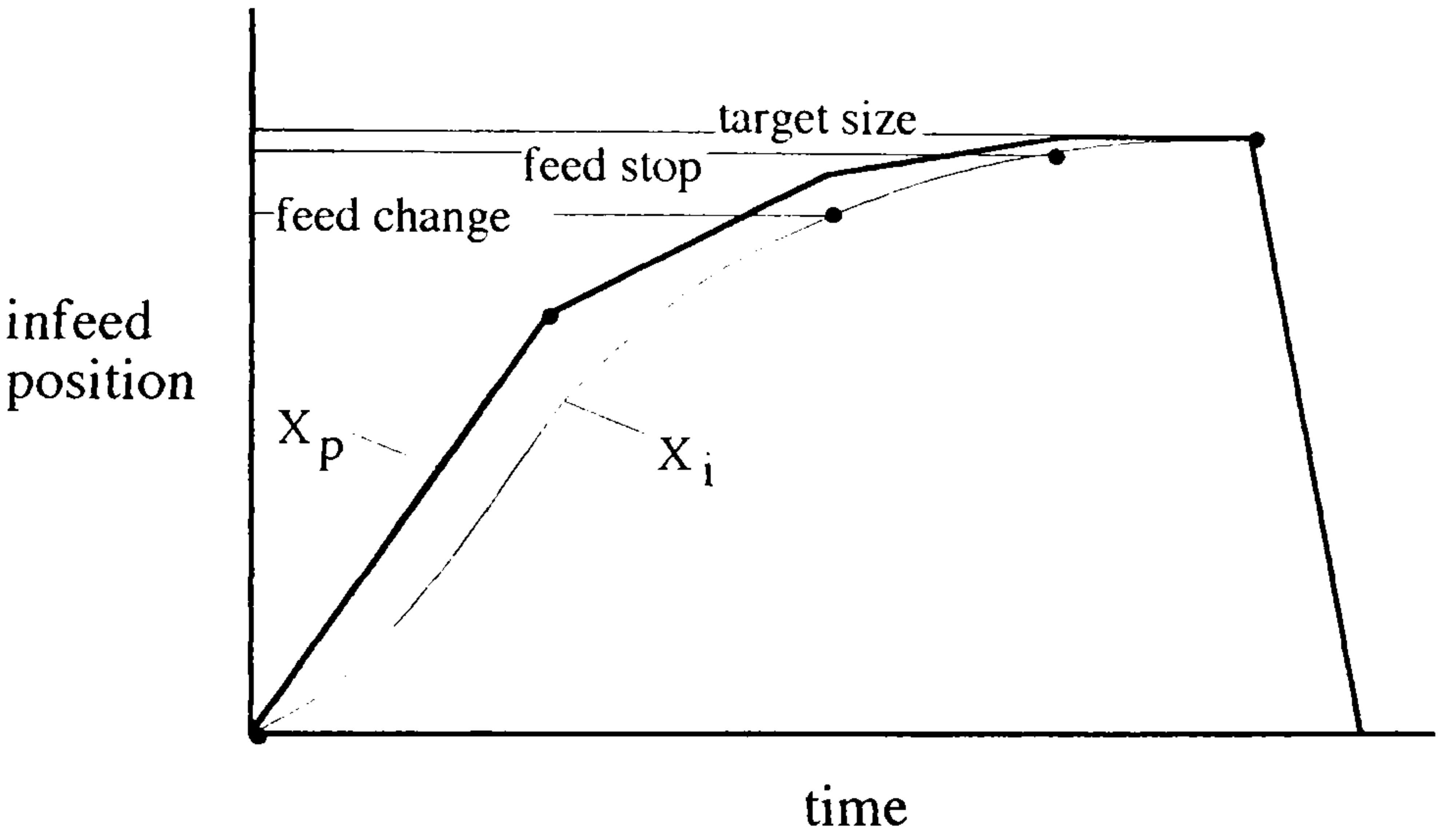


Figure 5.1b Plunge grinding cycle with diameter gauge

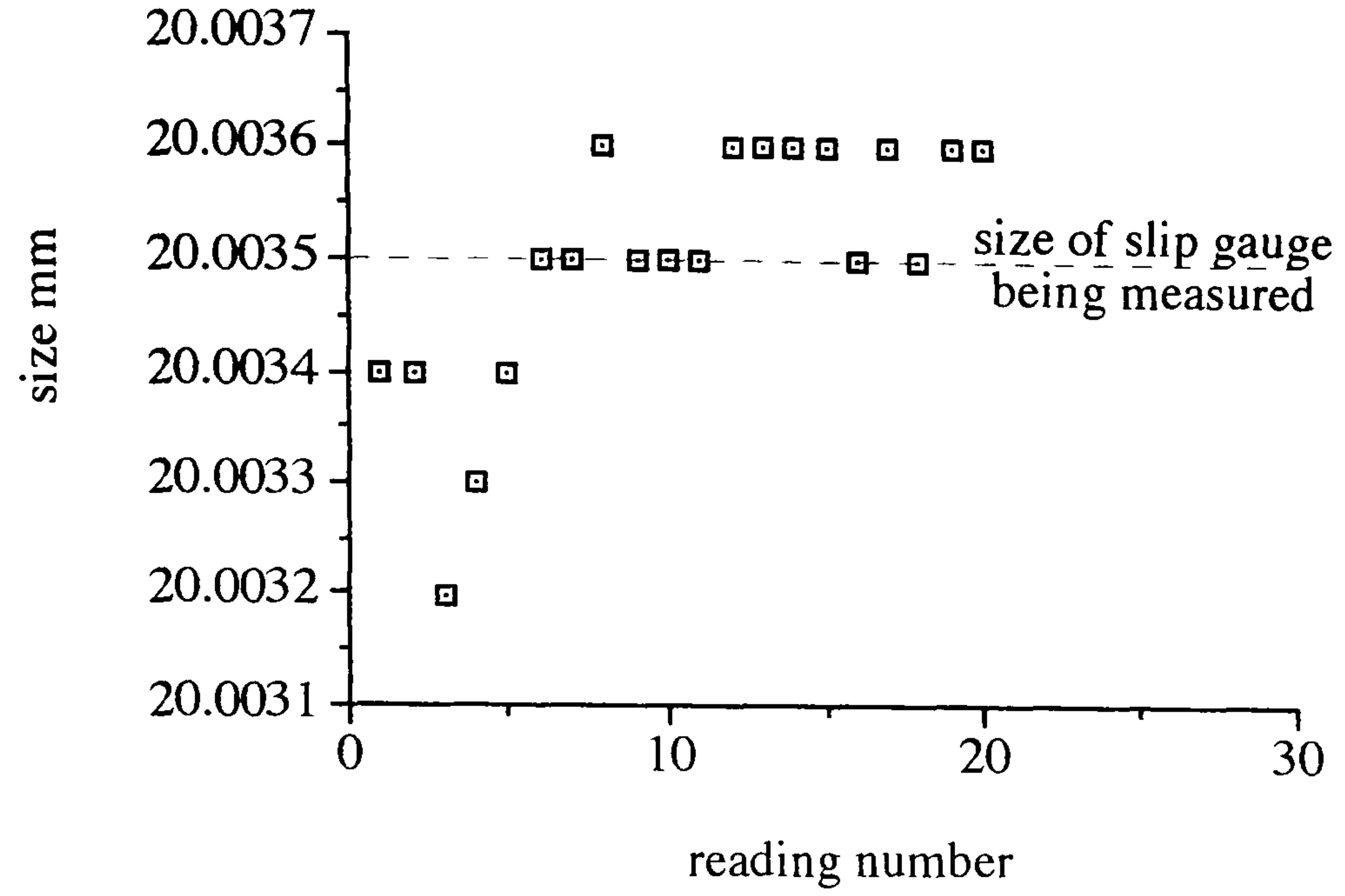


Figure 5.2 - Repeatability of the Talymin Comparator

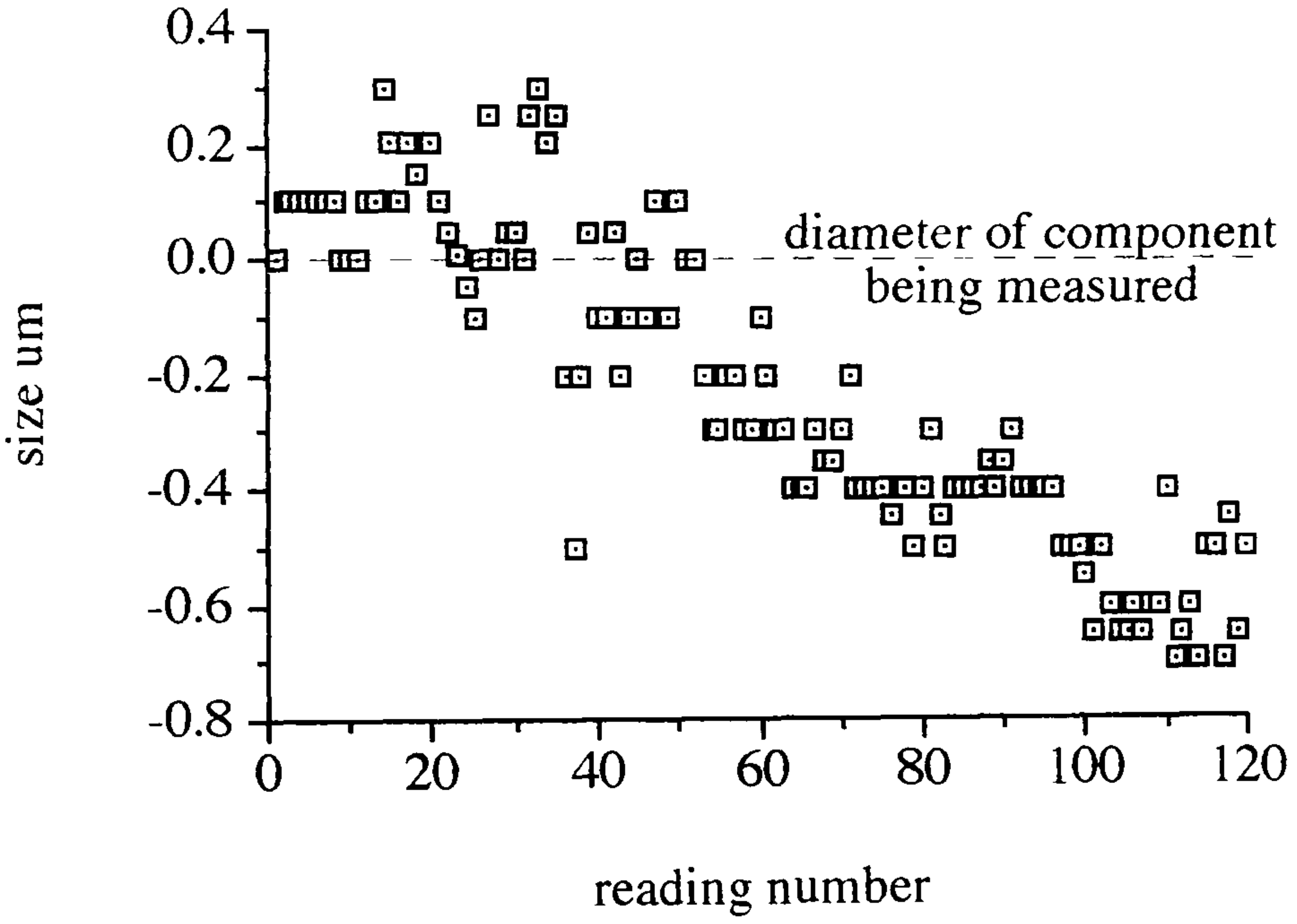
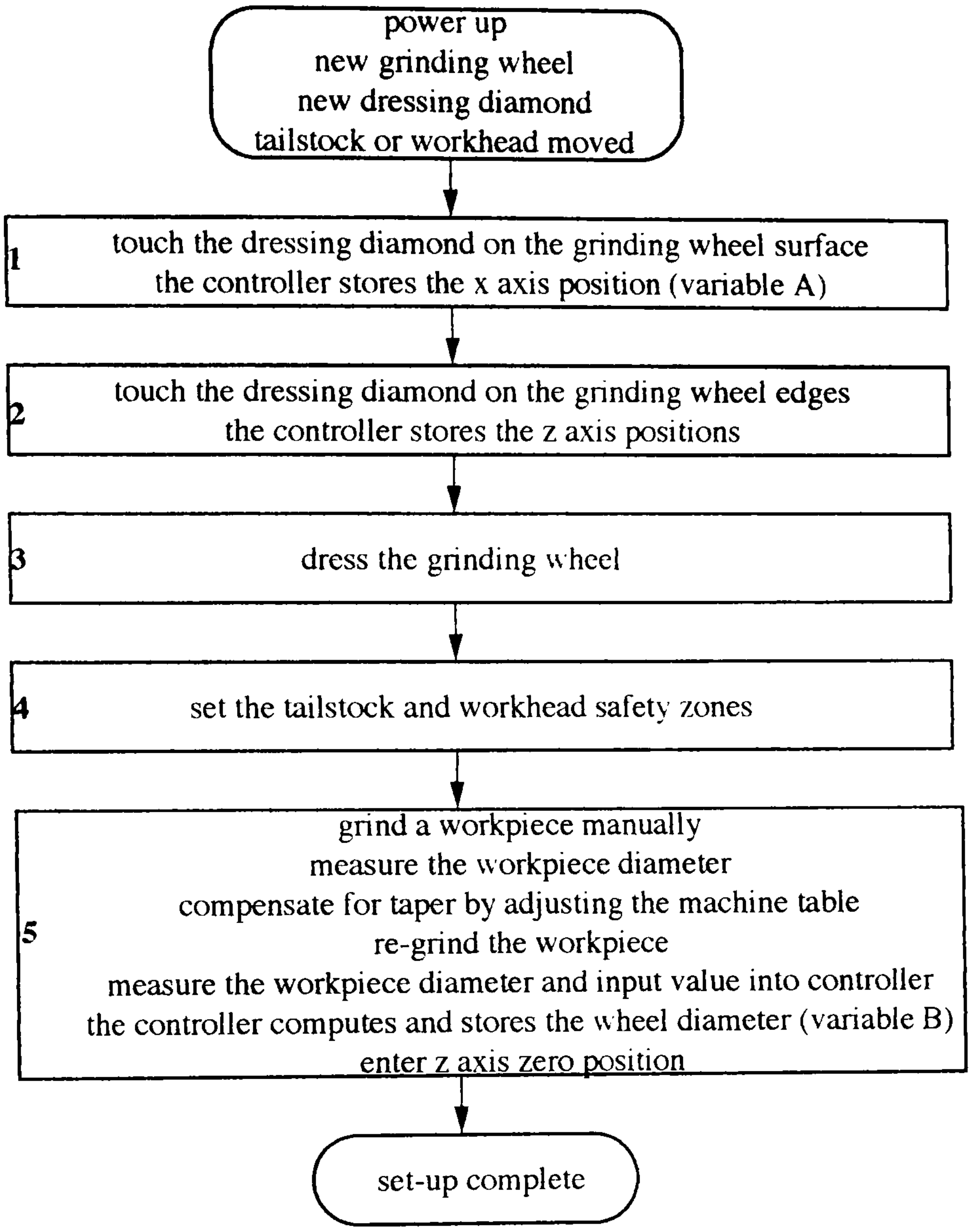


Figure 5.3 - Repeatability of the Movomatic diameter gauge



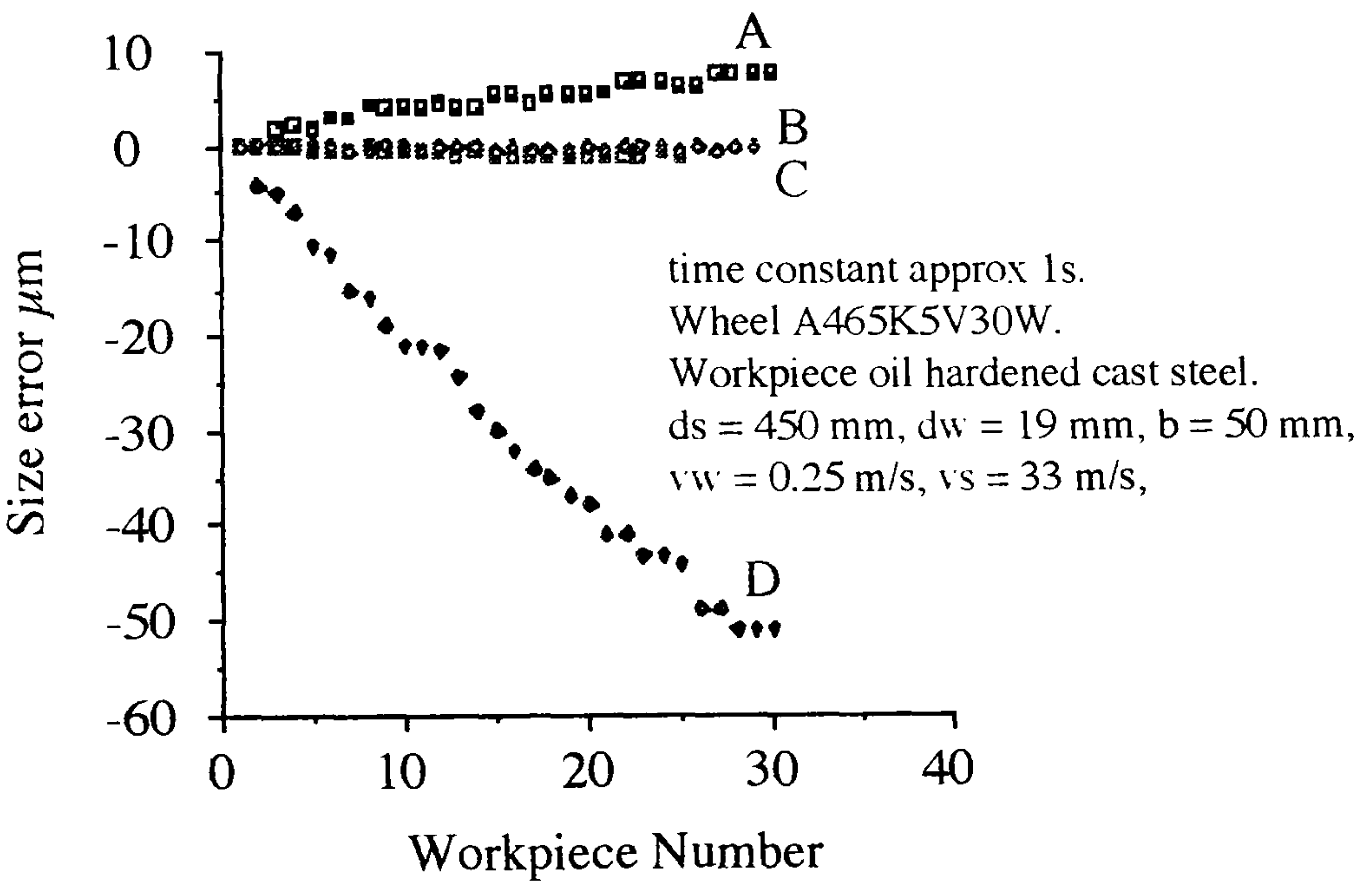
After every dressing procedure, the follwing calculations are performed:

variable A <= variable A - dressing increment
variable B <= variable B - dressing increment

Figure 5.4 - The machine set-up procedure

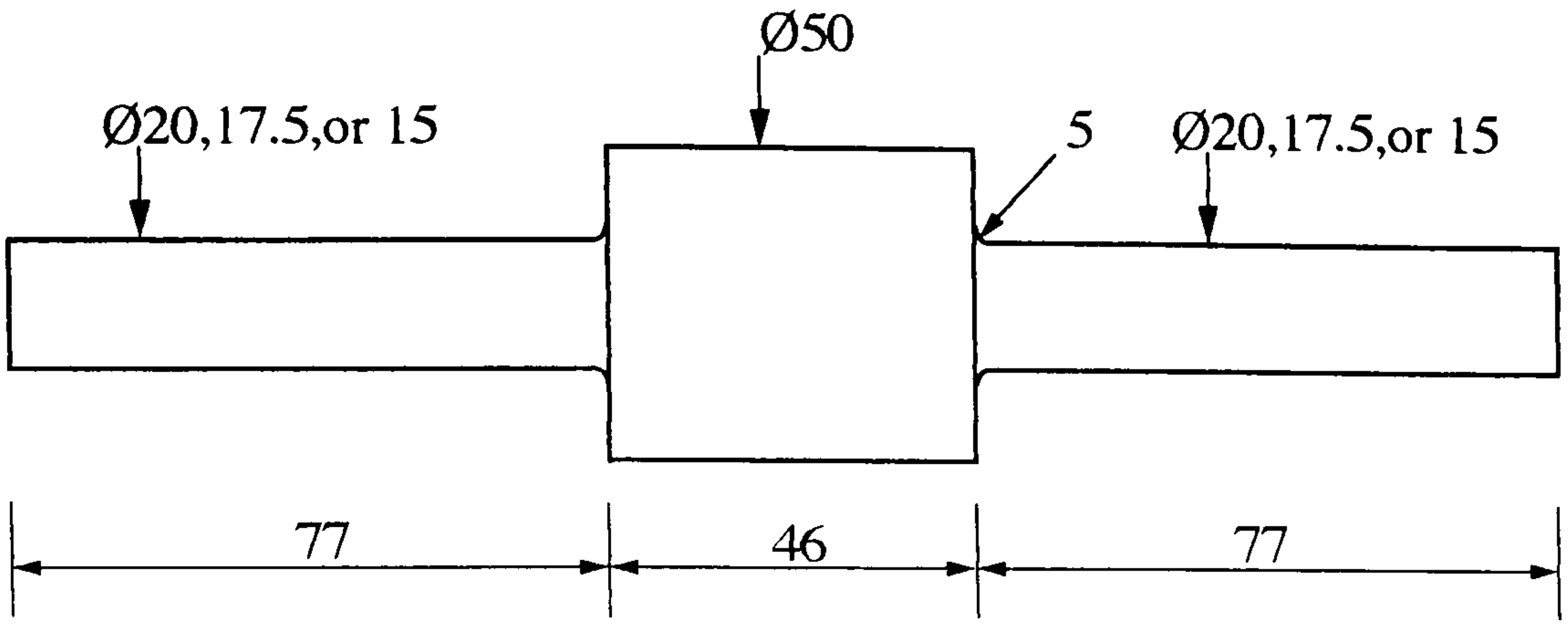
	Not Re-dressing	Re-dressing
Not Gauging	A	D
Gauging	B	C

Figure 5.5a - Modes of operation for plunge grinding

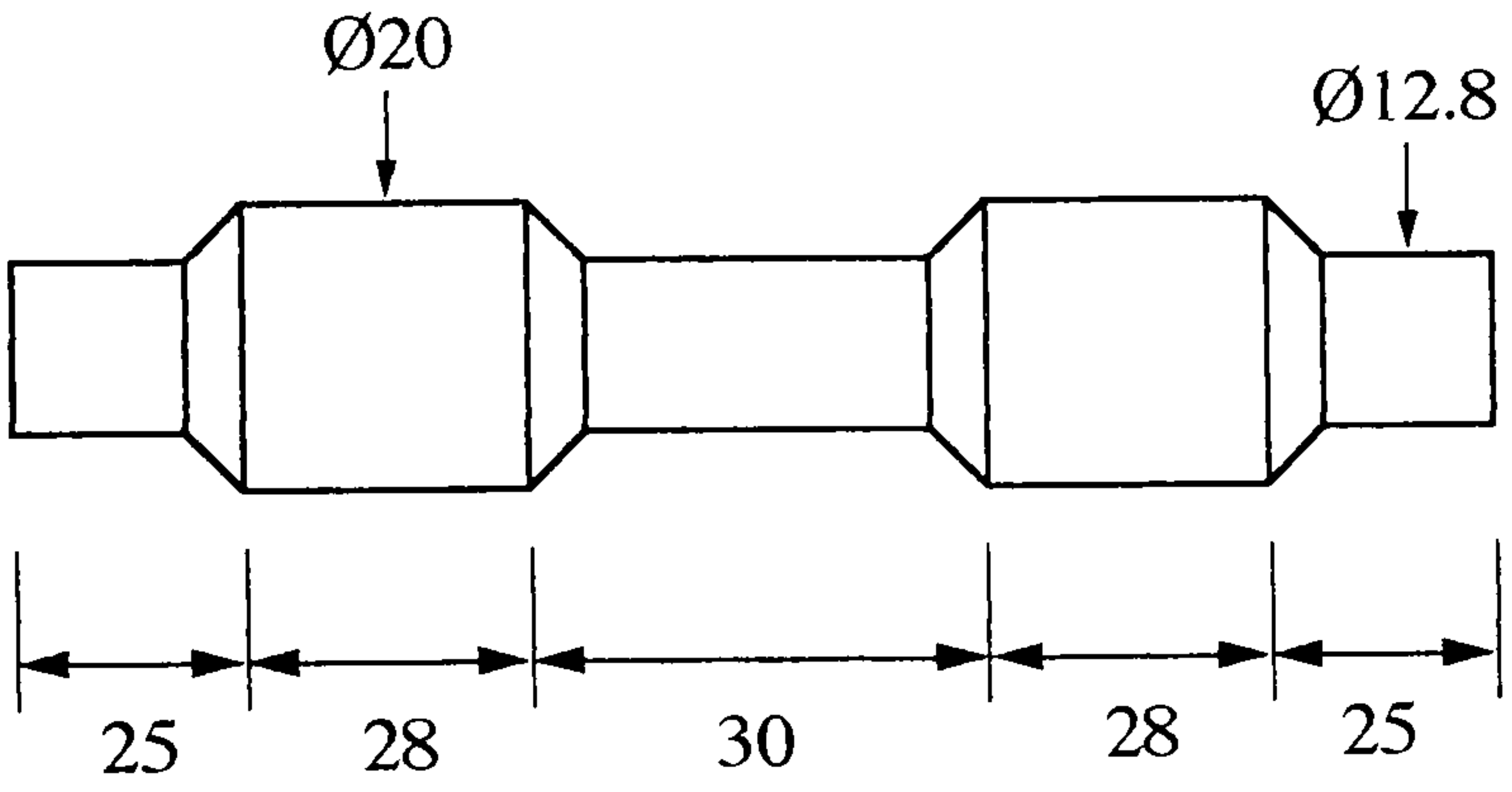


time constant approx 1s.
Wheel A465K5V30W.
Workpiece oil hardened cast steel.
ds = 450 mm, dw = 19 mm, b = 50 mm,
vw = 0.25 m/s, vs = 33 m/s,

Figure 5.5 b - Process capability with different modes of operation for plunge grinding



Ø 20, Time constant 3 s
Ø17.5,Time constant 5 s
Ø15, Time constant 7 s
Material En9
All diamensions in mm



Time constant 1 s
Material Oil Hardend Cast Steel
All diamensions in mm

Figure 5.6 - Workpieces used for testing the adaptive control system

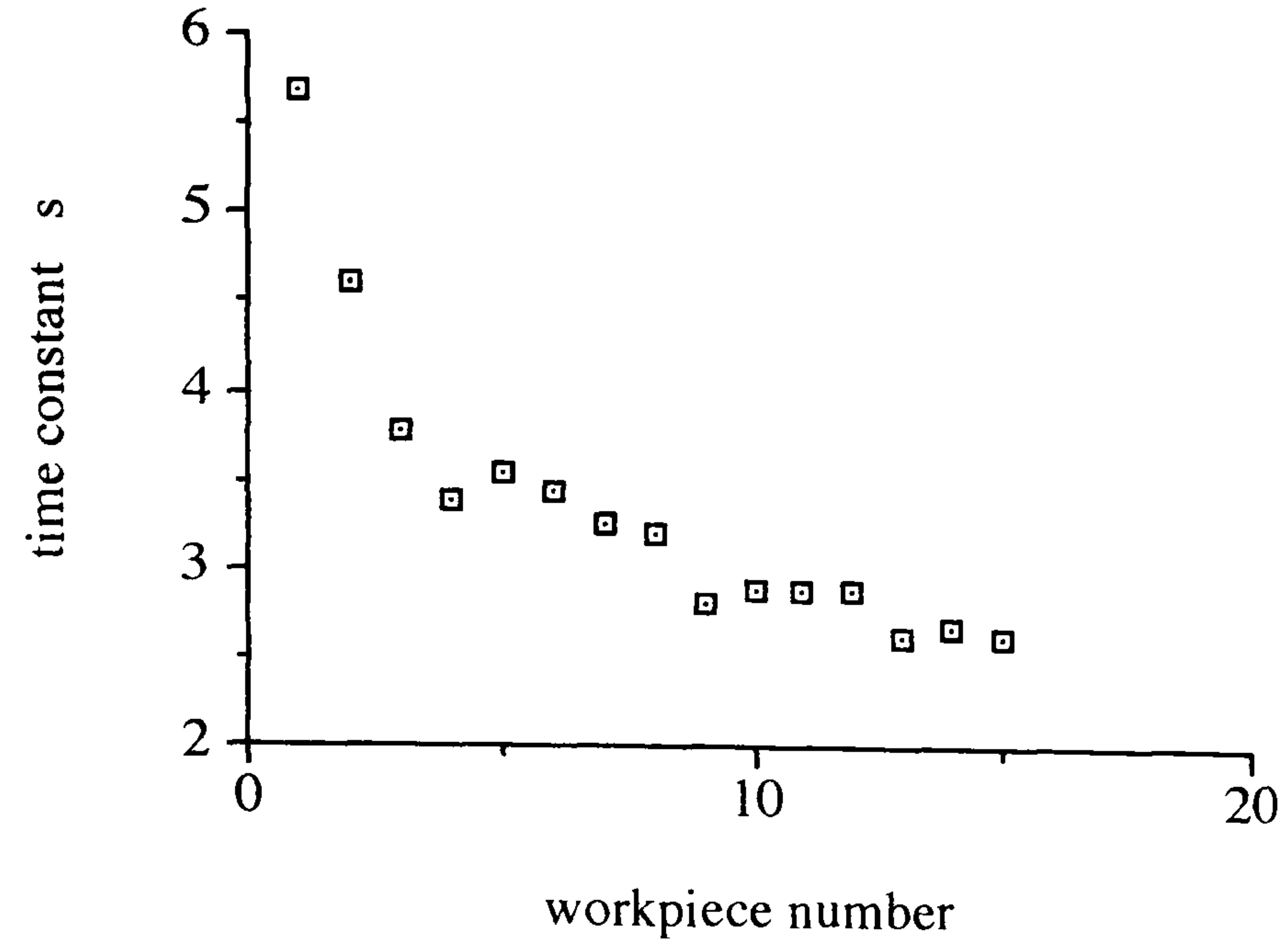


Figure 5.7 Change in system time constant with topography of the wheel

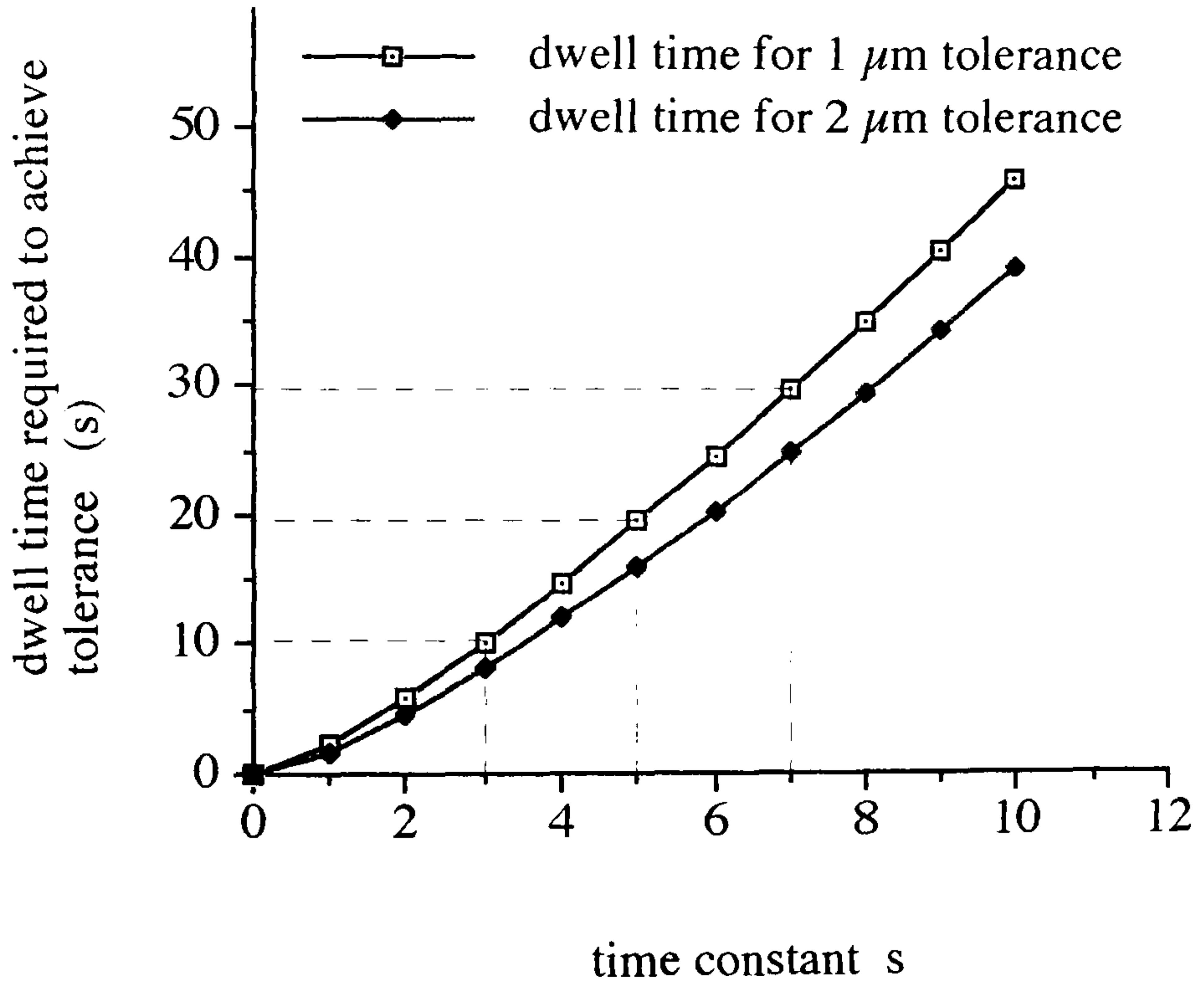
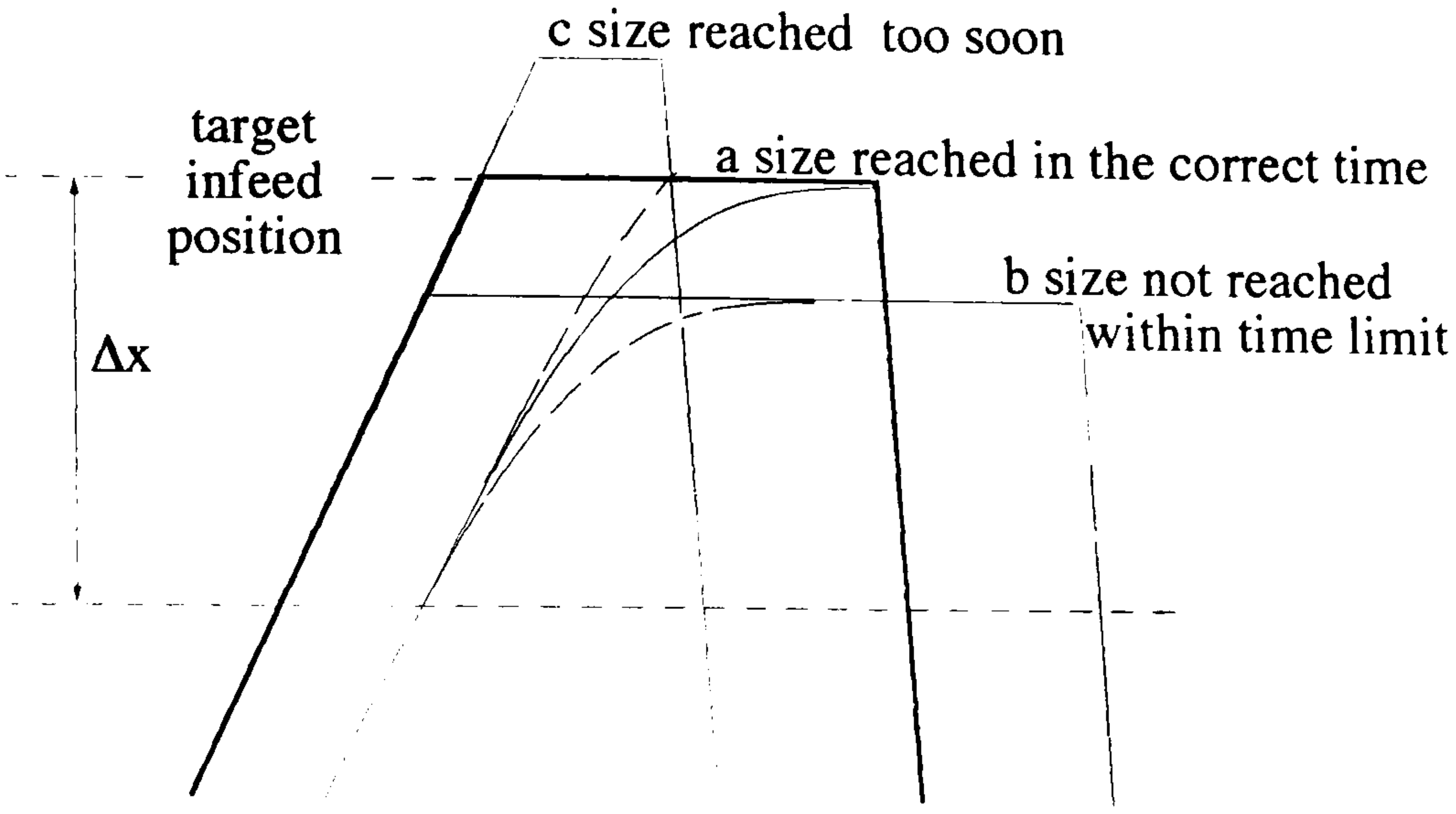


Figure 5.8 - Dwell time required to achieve a given tolerance



a Stock allowance set correctly $\Delta X = xi$
b Stock allowance set too large $\Delta X > xi$
c Stock allowance set too small $\Delta X < xi$

Figure 5.9 - A non-adaptive plunge feed cycle with diameter gauging - showing the effects of the setting of the feed stop point

time constant = 3 s approx.
Wheel A465K5V30W. Workpiece EN9, ds=450mm, dw=46mm, b=50mm, vw=0.25m/s, vs=33m/s, vf low=5, 3, 1μm/s, vf high=9, 7, 5 μm/s.

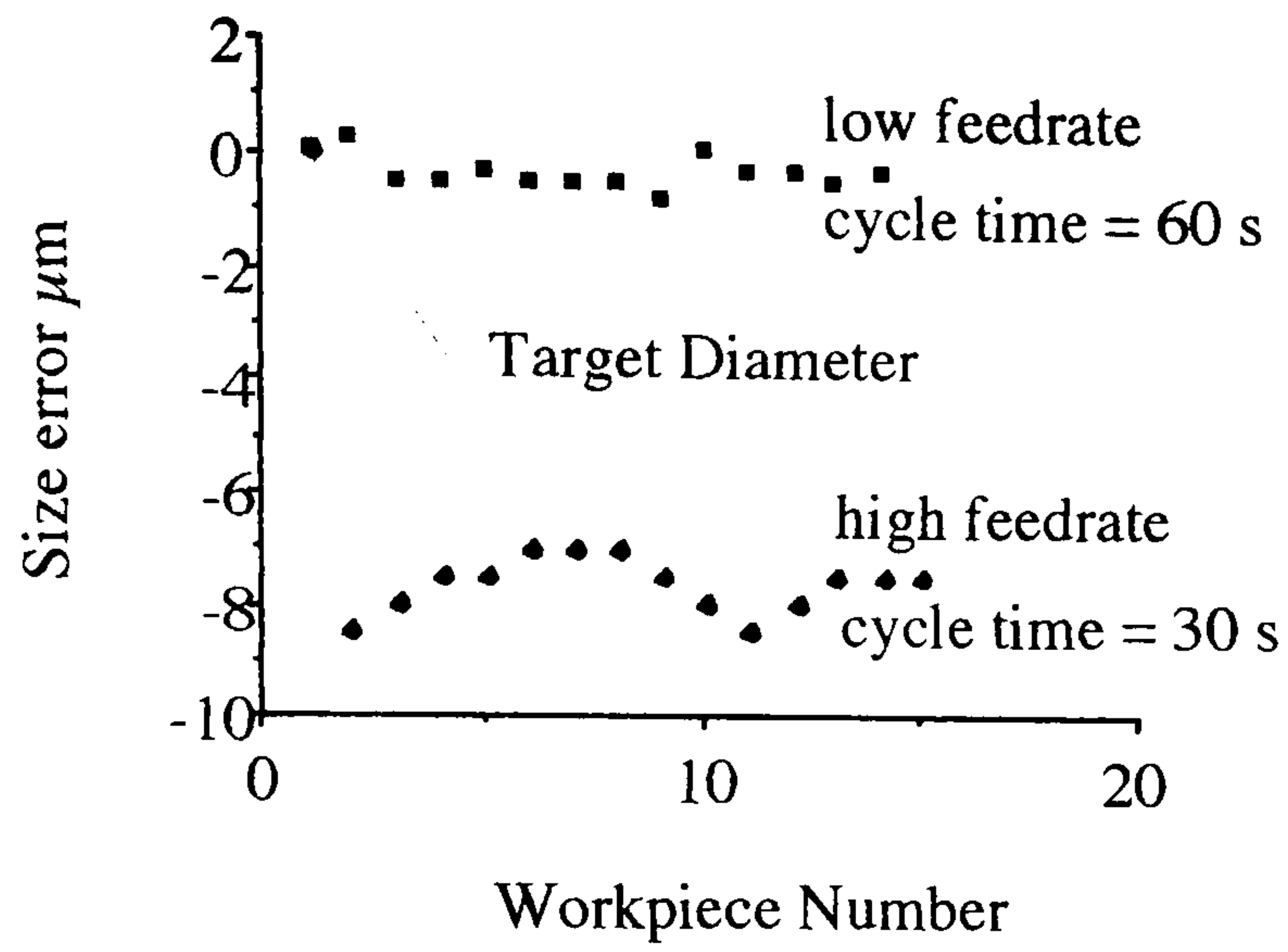


Figure 5.10 - Size error for the gauging cycle

time constant approx 3s .
Wheel A465K5V30W.
Workpiece EN9.
ds = 450 mm, dw = 46 mm, b = 21.4 mm,
vw = 0.25 m/s, vs = 33 m/s, vf = 10, 7, 5 μm/s.

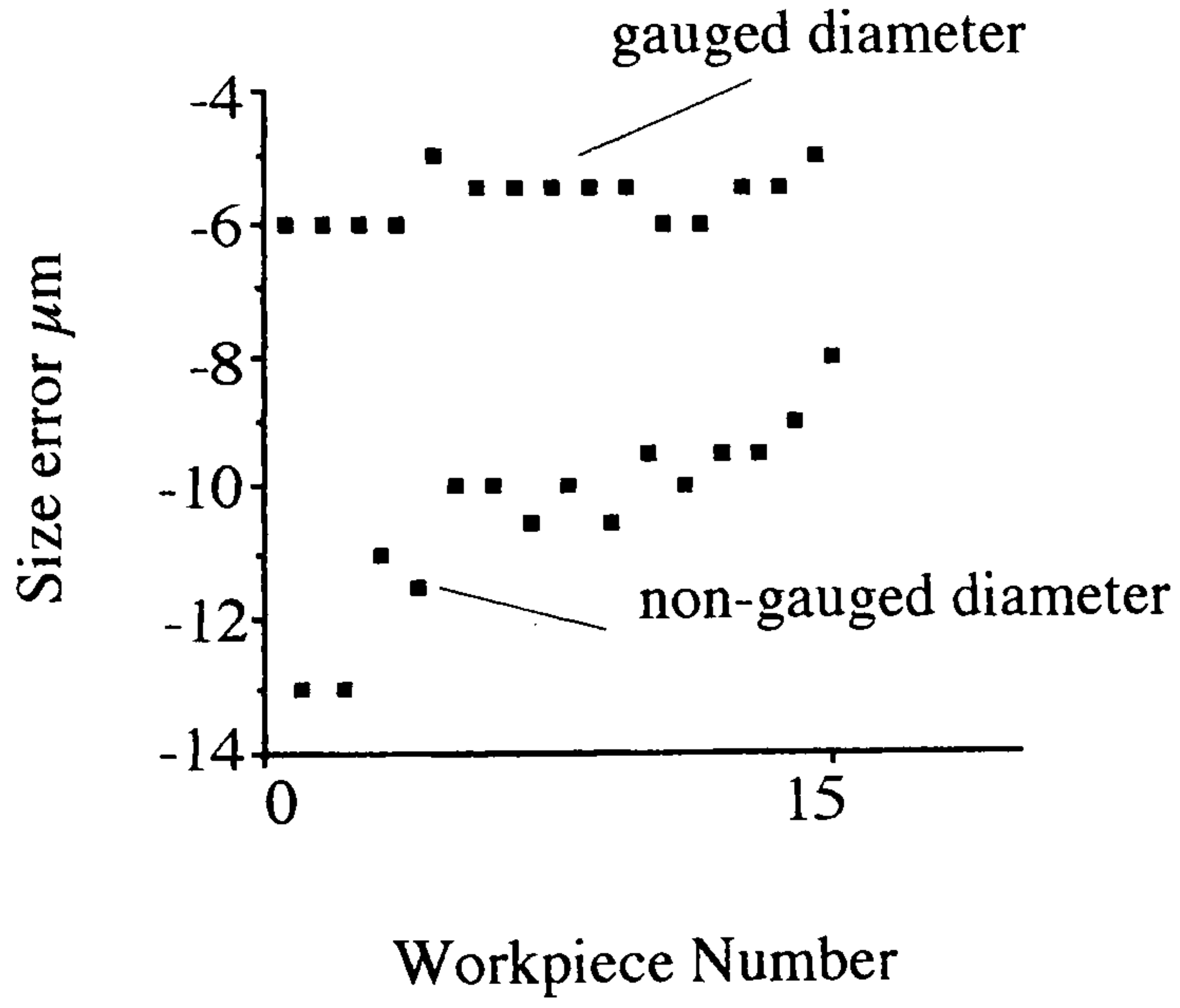


Figure 5.11 - Size error when grinding two diameters, using gauging on one diameter only

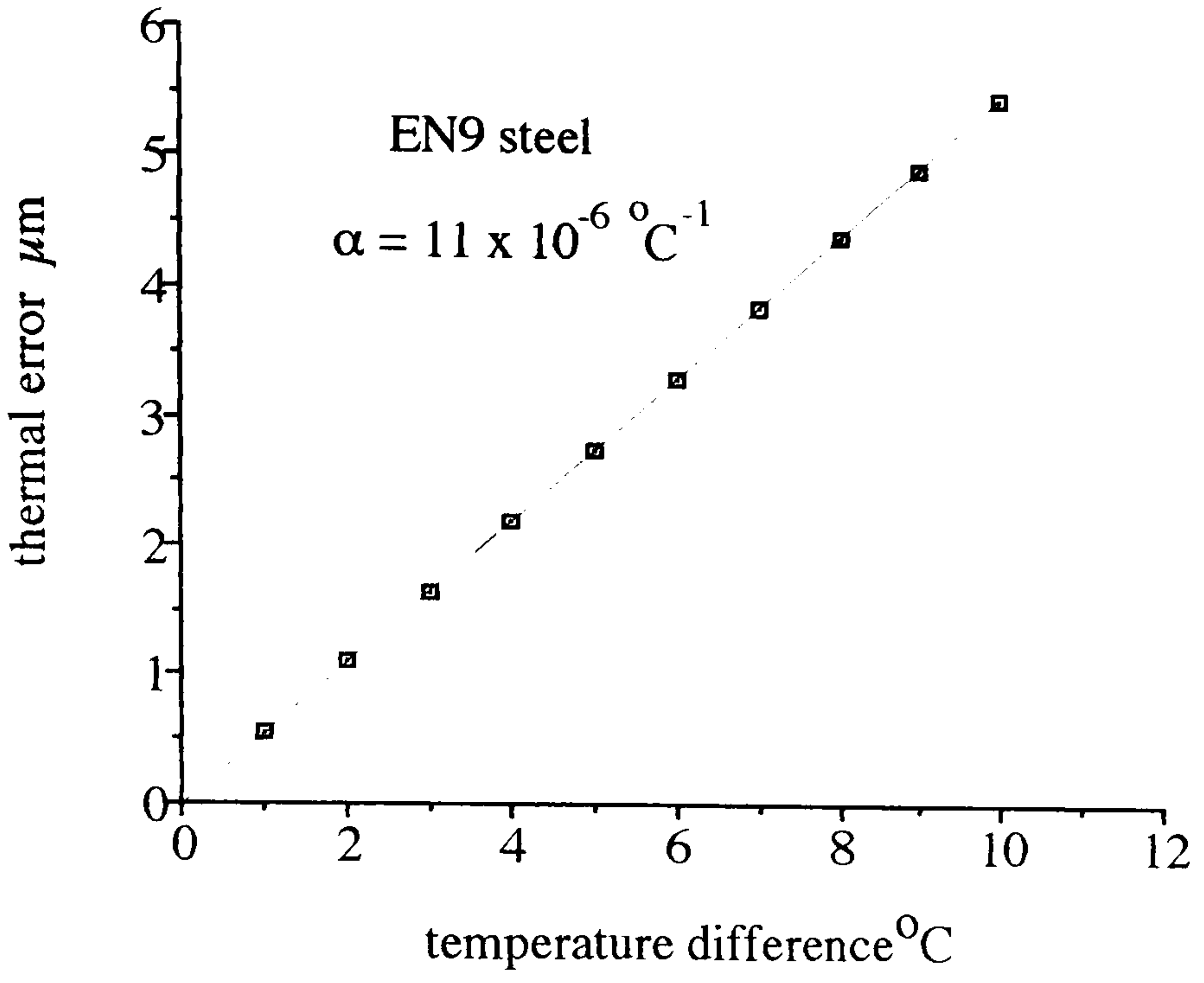


Figure 5.12 - Size error due to heating of the workpiece

Problem	Adaptive feature	Benefit
Variation in deflection of the machining system	non-gauging cycle - automatic setting of dwell time	improve productivity reduce pre-production trials
	gauging cycle - no reliance on the manual setting of feed change points	reduce pre-production trials reduce supervision requirements reduce set-up times reduce scrap improve productivity
wheel wear and dressing errors	compensation for wheel wear and dressing errors for non-gauging systems	improve quality lower cost option than gauging
thermal errors	complete cooling of the workpiece before the end of the machining cycle	improve quality

Figure 5.13 - A summary of adaptive features which would improve the performance of the grinding process

6 DESIGN AND TESTING OF THE ADAPTIVE GRINDING CYCLES

6.1 Introduction

This chapter describes how adaptive features were incorporated into infeed cycles both with and without diameter gauging. The results of grinding trials to evaluate the performance of the adaptive cycles are given. Results of the learning strategy are also given, showing how information from previous grinding operations was used to calculate the values of machining parameters for subsequent grinding operations.

6.2 Adaptive Grinding Cycles without Diameter Gauging

Figure 6.1 shows an infeed cycle providing the adaptive features of automatically setting the dwell period, updating the infeed rate and adapting the target infeed position. The facility was provided to enable or disable each adaptive feature as required.

6.2.1 Setting the dwell period

Knowledge of the deflection of machining the system was gained by measuring the time constant of the system from the characteristics of the grinding power during the infeed. The details of this technique are given in chapter 3.

The infeed position of the interface of the grinding wheel and the workpiece during the dwell period is given by

$$X_i = X_l + x_l \, e^{\frac{t-T_l}{\tau}} \qquad (6.1)$$

X_l is the infeed position of the the interface of the grinding wheel and the workpiece at the start of the dwell period. x_l is the deflection at the start of the dwell period and is given by

$$x_1 = v_f \tau \, (1 - e^{T_1/\tau}) \qquad (6.2)$$

Because of the exponential decay of the deflection, setting the dwell period to four time constants ensured that ninety eight percent of the deflection was relieved before the end of the machining cycle. In this way the target diameter was attained without excessive cycle time. The time constants and the dwell times for grinding a batch of components are shown in figure 6.2. The rapidly changing condition of the grinding wheel caused marked changes in the time constant. As a result the dwell time decreased dramatically for the first four workpieces and continued to decrease at a lower rate throughout the batch.

The effect on workpiece size of setting the dwell period in this manner is shown in figure 6.3. The size decreased for the first four workpieces and then increased for the rest of the batch. This produced a 'tick' shaped graph which can be explained by the effects of wheel wear and thermal deformation of the workpiece. The initial trend of decreasing size was attributed largely to thermal effects. Heating of the workpieces during the grinding process caused them to expand. During the dwell period the material removal rate decreased and the workpieces cooled and contracted. The dwell time for the first workpiece was 24 s. This decreased to 14 s for the fifth workpiece. It is believed that because of this rapid decrease in dwell time the workpieces were unable to cool to the ambient temperature before the end of the dwell period. Cooling after the end of the grinding cycle caused further contraction and resulted in undersize workpieces. For the remaining workpieces the dwell time decreased at a much lower rate from 15 s for the fifth workpiece to 11 s for the fifteenth workpiece. The trend of increasing size from the fifth workpiece was attributed to wheel wear.

Figure 6.4 illustrates an idealised case showing the size error, the component due to wheel wear and the component due to thermal expansion of the workpiece. For the size results of figure 6.3 an estimate of the wheel wear is 1 μm per workpiece. An estimate of the error due to thermal contraction is 8 μm for the fifth and subsequent workpieces, assuming that the first workpiece was cooled to ambient temperature before the end of the dwell period. For an error due to thermal contraction of this magnitude the workpiece temperature at the end of the dwell period would be 14 ^{0} C above ambient.

In addition to thermal deformation of the workpiece, another factor effecting workpiece size was the change in magnitude of the deflection throughout the batch. The time constant when grinding the first workpiece was around six seconds, compared with about three seconds for the fifth and subsequent workpieces. As a consequence, the deflections were around 60 μm for the fifth workpiece and 30 μm for the fifth workpiece. At the end of each dwell period two per cent of the deflection remained in the system, that is 1.2 μm and 0.6 μm for the first and fifth workpieces. But for the effect of wheel wear and thermal deformation this would have resulted in the first workpiece being 0.6 μm larger than the fifth workpiece.

In this case the effect of changes in deflection on workpiece size was not significant compared to the effect of thermal contraction of the workpieces and of wheel wear. However when grinding extremely flexible workpieces, changes in deflection would pose more of a problem. A remedy would be to terminate the dwell time when a pre-programmed magnitude of deflection remained in the system rather than setting the dwell time to a multiple of the time constant value. Alternatively the dwell period could be lengthened from say four to six time constants.

6.2.2 Achieving the Desired Power Level

The cycle time was further reduced by updating the infeed rate in order to attain a desired power limit. The first workpiece of a batch was ground using an infeed rate value provided by the learning strategy or by the user of the machine. The maximum grinding power measured during the machining cycle was recorded. It was assumed that the grinding power was proportional to infeed rate and the infeed rate required to give the desired grinding power level was calculated as follows

$$v_{fn} = \frac{P_t}{P_{n-1}} v_{fn-1} \tag{6.3}$$

where P_t was the target grinding power, P the grinding power, v_f the infeed rate and the subscript n indicated the workpiece number. The maximum grinding power was measured and the infeed rate updated again for the next operation. This resulted in the desired power level being maintained at the target power level throughout the batch as shown in figure 6.5.

6.2.3 Modifying the Target Infeed Position

The dwell period was set to two time constants. Fourteen percent of the deflection remained in the system at the end of the dwell period. The infeed period was extended in order to overshoot the target infeed position and compensate for the deflection remaining at the end of the dwell period. The required overshoot OS was calculated as follows

$$OS = x_1 \, e^{-T_d/\tau} \tag{6.4}$$

where x_1 was the deflection at the start of the dwell period, T_d was the dwell time and τ was the time constant. Figure 6.6 shows the size results achieved with this cycle when the dwell period was set to two time constants. The size results show a trend of increasing workpiece size due to wear of the grinding wheel. There is also some variability which was attributed to small errors in the estimated value of the time constant.

6.3 Adaptive Grinding Cycles with Diameter Gauging

6.3.1 An Infeed Cycle with Dwell and Overshoot

Figure 6.7 shows an infeed cycle consisting of a single infeed rate followed by a dwell period. When the "at size" signal was detected from the diameter gauge during the dwell period the grinding wheel was retracted, ending the grinding cycle.

An overshoot was always applied to the infeed axis to ensure that target size was achieved. The duration of the dwell period was set to the required value by varying the magnitude of the overshoot. The facility to update the infeed rate was provided. This feature could be enabled or disabled by the user.

The value of the overshoot was set by the control system to cause the workpiece to reach target size after a dwell time of three times the value of the system time constant, at which time ninety five percent of the deflection had been relieved. The dwell time T_d' was measured and any difference from the expected dwell time T_d was attributed to errors in the infeed position. The following equation expresses the infeed position error X_e as the difference between the intended overshoot and the overshoot which was actually applied.

$$X_e = x_l \left(e^{-T_d/\tau} - e^{-T_d'/\tau} \right) \qquad (6.5)$$

A negative infeed position error value indicated that the grinding wheel surface had fed in further than expected, a positive value meant that it had fed in less than expected.

An offset was applied to the infeed axis to compensate for the position error. The causes of this error were wheel wear, dressing, machine set-up and thermal deformation of the machine. These are explained in more detail in chapter 4. It should be noted that it was only possible to measure errors within a certain range in this way. From figure 6.8 it can be seen that the infeed position error had to lie within the following limits.

$$-(x_1 - OS) < X_e < +OS \qquad (6.6)$$

If the error exceeded + OS the target size was never attained. If the error exceeded -$(x_1$ - OS) target size was achieved before the start of the dwell period.

The size results achieved with this infeed cycle are shown in figure 6.9. The mean size is 2 μm under the target size, with a scatter of + - 1μm about the mean. The two possible causes for the undersized workpieces are as follows

- the control system delay in retracting the grinding wheel after detecting the "at size" signal from the gauge, together with the remaining deflection of the machining system caused further material to be removed. The maximum error resulting from this effect would be equal to the overshoot employed, that is 1.5 μm.

- Incomplete cooling of the workpiece during the dwell period. Cooling of the workpiece after the end of the machining cycle caused a further reduction in diameter and undersize workpieces were produced. To account for an error of 3 μm a workpiece temperature of 6 ^{o}C at the end of the dwell period would be required.

The cause of the undersize components was assumed to be mainly due to incomplete cooling of the workpiece during the dwell period.

6.3.2 An Infeed Cycle with the Dwell Period Replaced by a Very Fine Infeed Rate.

In order to overcome the effect of delays in the control system and the thermal expansion of the workpiece during the grinding process, it was decided to increase the programmed dwell time from three to six time constants. This reduced the deflection remaining in the system at the end of the dwell period and allowed the workpiece to cool before the end of the machining cycle.

However, the use of a long dwell period severely limited the range of infeed position errors for which the control system could compensate. Also, the performance of the cycle was sensitive to errors in the infeed position, as even a small error resulted in a large difference in the actual dwell time from the programmed value. To overcome these problems the dwell was replaced by a very fine infeed rate of 0.1 μm/s (0.2 μm/s diameter reduction). This infeed cycle is shown in figure 6.10. The very fine infeed rate represents a very small infeed rate considering that the resolution of the infeed position measurement is 0.1µm and the following error is several microns. The effect is to gradually advance the mean infeed position in steps of 0.1um.

It was necessary to modify the calculation of the infeed axis error as follows to account for the modification to the infeed cycle.

$$X_e = x_1 \left(e^{-T_d/\tau} - e^{-T_d'/\tau}\right) + v_{ff}(T_d' - T_d) \qquad (6.7)$$

Replacing the dwell period by the very fine infeed rate ensured that final size was always attained. Also, the only limit on the range of axis infeed error that could be measured was

$$X_e > -(x_1 - OS) \qquad (6.8)$$

To ensure that this error was not exceeded a positive offset larger than the maximum expected error was applied before grinding the first workpiece. This resulted in a long dwell time for the first grinding operation but this was rectified for subsequent operations. The initial offset was set allow a worst case set-up error of 20 µm. This set a minimum value to 0.1 µm/s for the very fine infeed rate, to maintain the dwell period for the first part below 100 s in the worst case. Thus the very fine infeed rate was set as small as possible, without incurring an unacceptably long dwell period for the first workpiece due to the initial offset for set-up errors.

The size results achieved with this infeed cycle at high and low target power levels are shown in figure 6.11 and figure 6.12 respectively. It can be seen that with a high target power the majority of the workpieces were finished to within 2 μm of target size, and with a low target power all the workpieces were finished to within 1 μm of target size. This shows a great improvement over the adaptive grinding cycle with diameter gauging which used a conventional dwell period without the very fine infeed rate.

6.4 The Learning Strategy

The purpose of the learning strategy was to store the optimum machining conditions achieved by the adaptive system so that they could be used for future grinding operations. The first time that a particular grinding wheel and workpiece material combination was used, the machine user was prompted for the values of machining parameters to be used. These values were used for grinding the first workpiece of the batch. The kinematic parameters of chip aspect ratio and chip length for the grinding operation were calculated and stored in a data base. The next time that this combination of grinding wheel and workpiece material was used the machine user was not prompted for values of machining parameters. Rather, the kinematic parameters were retrieved from the data base and used to calculate the values of machining parameters to be used. The calculations are given in chapter 3.

Storing the kinematic parameters in this way allowed machining conditions to be reproduced for any grinding operation which used the same combination of grinding wheel type and workpiece material. By using this as a starting point the adaptive system quickly achieved the desired operating conditions after grinding a small number of workpieces.

To test the kinematic model the following trial was carried out. Two workpieces were manufactured from the same material type. The workpieces were of different diameters but had the same width of contact with the grinding wheel. Suitable grinding parameters for grinding the largest workpiece were determined by experiment. The grinding wheel was dressed and the workpiece was ground a number of times. The grinding power was recorded each time.

The kinematic parameters of chip aspect ratio and chip length for grinding the large workpiece were calculated. Grinding parameter values for the smaller workpiece were chosen to give the same kinematic parameter values. The wheel was dressed and the small workpiece was ground a number of times. The grinding power was again recorded. Figure 6.13 shows the grinding powers for grinding the large and small workpiece. Similar grinding powers were achieved for grinding both the large and the small workpieces, showing that the kinematic model was suitable as a basis for the learning strategy.

6.6 Discussion and Conclusions

Infeed cycles with a number of adaptive features were introduced for grinding with or without a diameter gauge. Setting the dwell time according to the deflection of the machining system ensured that parts were produced to the required size without incurring excessive cycle times. Cycle time was further reduced by updating the infeed rate from one grinding operation to the next in order to maintain a target grinding power. The facility was also provided to reduce dwell times by overshooting the target infeed position. These features could be enabled or disabled by the operator as required.

When using diameter gauging the dwell period was replaced by a very fine infeed rate and the grinding wheel was retracted when target size was indicated. This ensured that the system deflection was relaxed and that the workpiece cooled down sufficiently for the target size to be achieved. The infeed position error was calculated from the difference in the expected and the actual duration of the very fine infeed rate "dwell" period and the axis was offset to compensate for the error. An initial offset was applied to allow for initial set-up errors. This offset determined the minimum value of the very fine infeed rate that could be used without incurring an unacceptably long dwell period for the first workpiece.

The grinding parameters achieved by the adaptive strategy after grinding a number of workpieces were stored in a data base. By using these conditions as a starting point the adaptive system was able to quickly achieve the desired operating conditions over a small number of grinding operations.

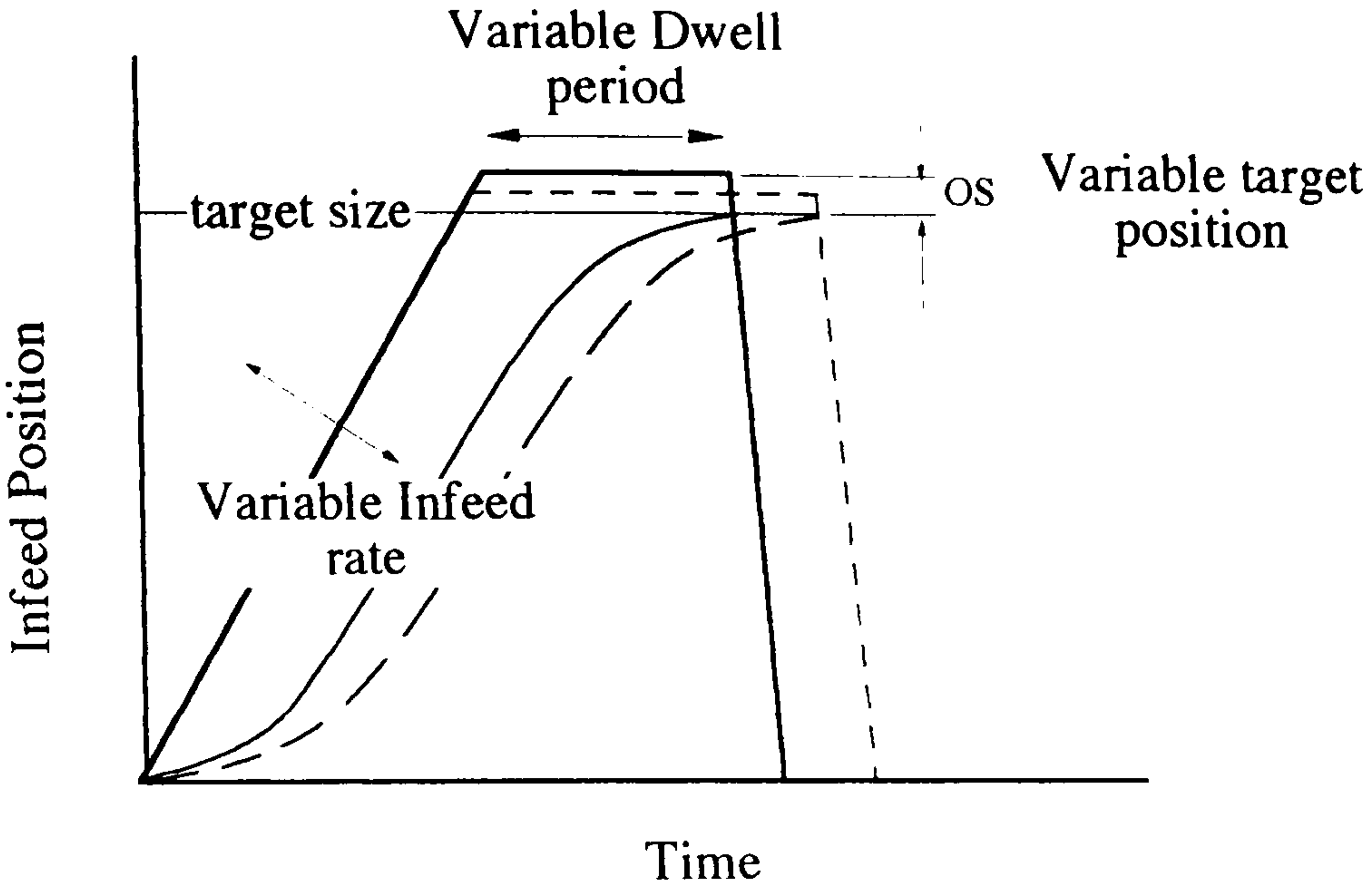
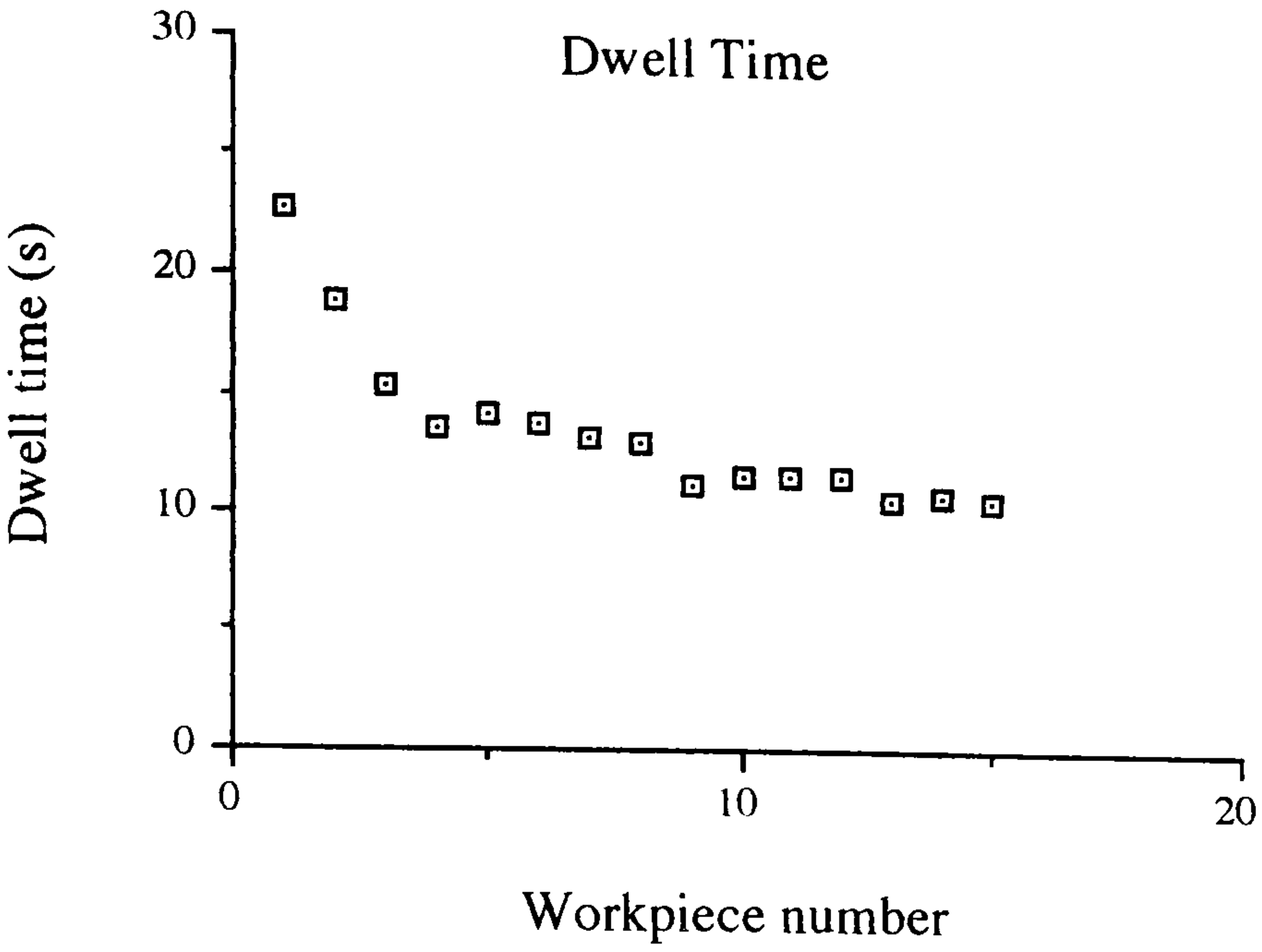
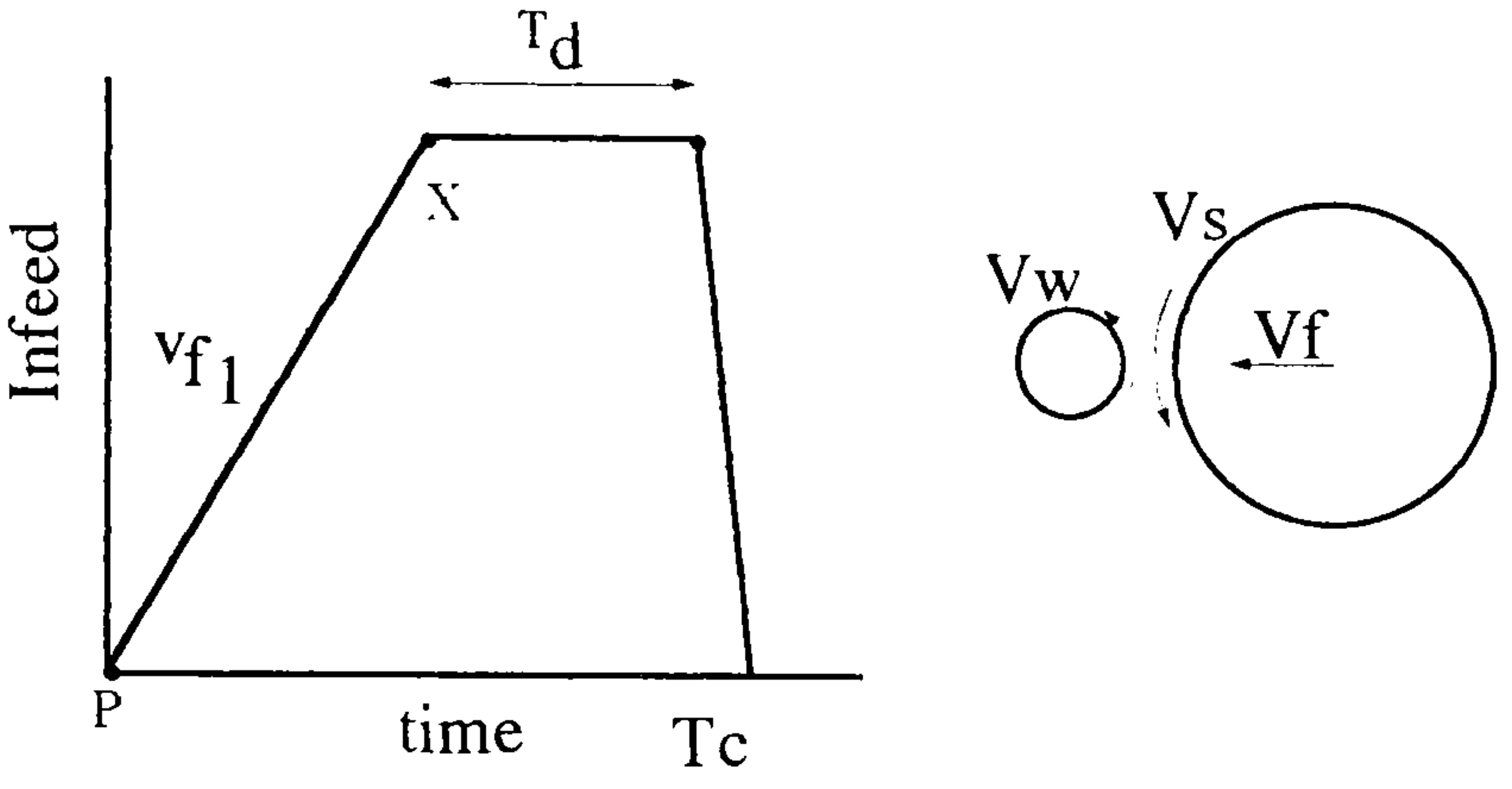


Figure 6.1 - A grinding cycle with adapted dwell time, infeed rate and infeed position



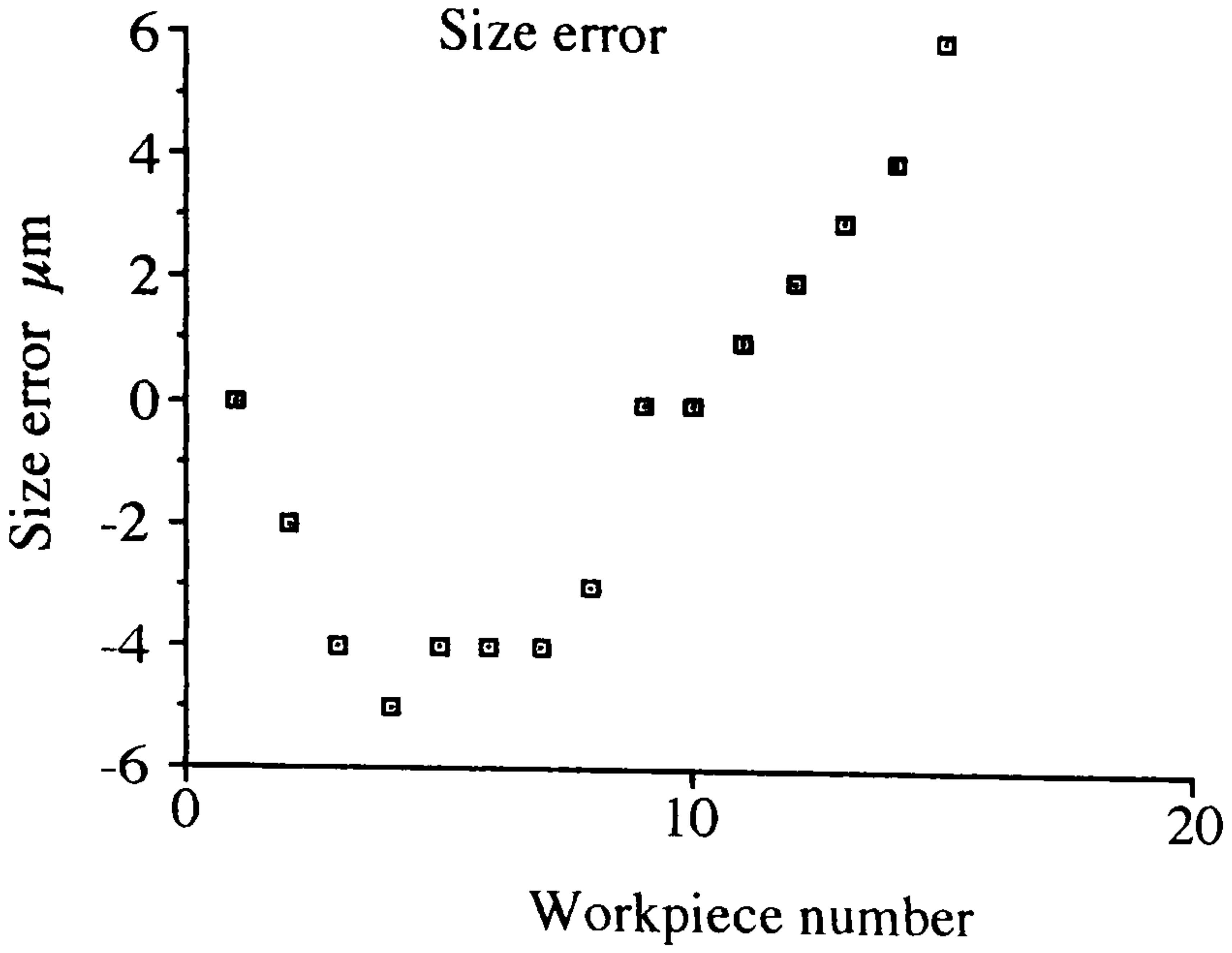
In-feed cycle



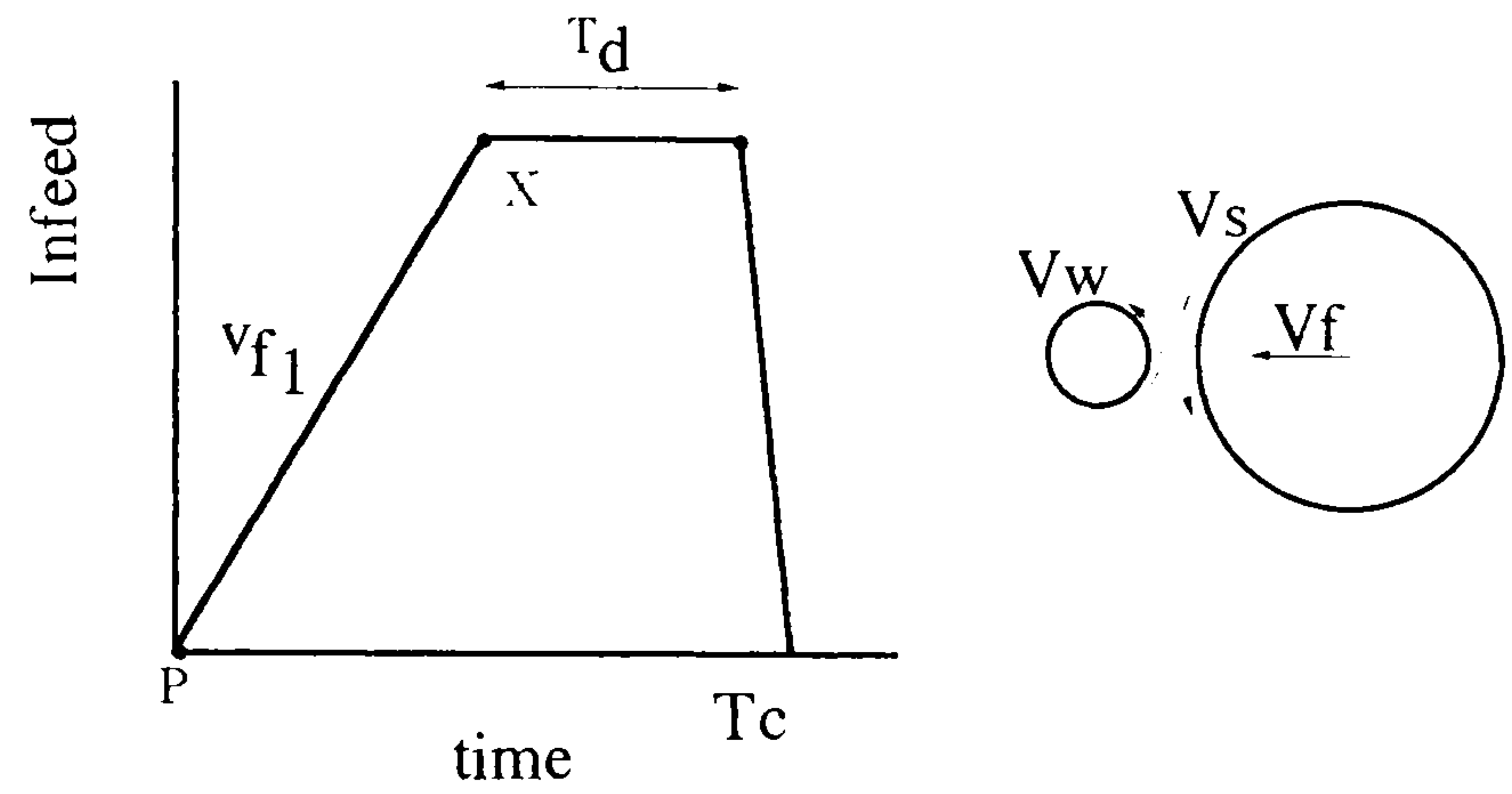
Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 0.005 μm/s	P 48.638 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~3 s
Vw 15 m/min	X 48.338 mm	every time	
Vs 33 m/s	Tc ~42 s	once only *	
Td 4τ	Pt -		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 6.2 - Adapting the dwell period when grinding flexible workpieces without diameter gauging.



In-feed cycle



Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 0.005 μm/s	P 48.638 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~3 s
Vw 15 m/min	X 48.338 mm	every time ☐	
Vs 33 m/s	Tc ~42 s	once only *	
Td 4τ	Pt -		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 6.3 - Size error. Adapting the dwell period when grinding flexible workpieces without diameter gauging.

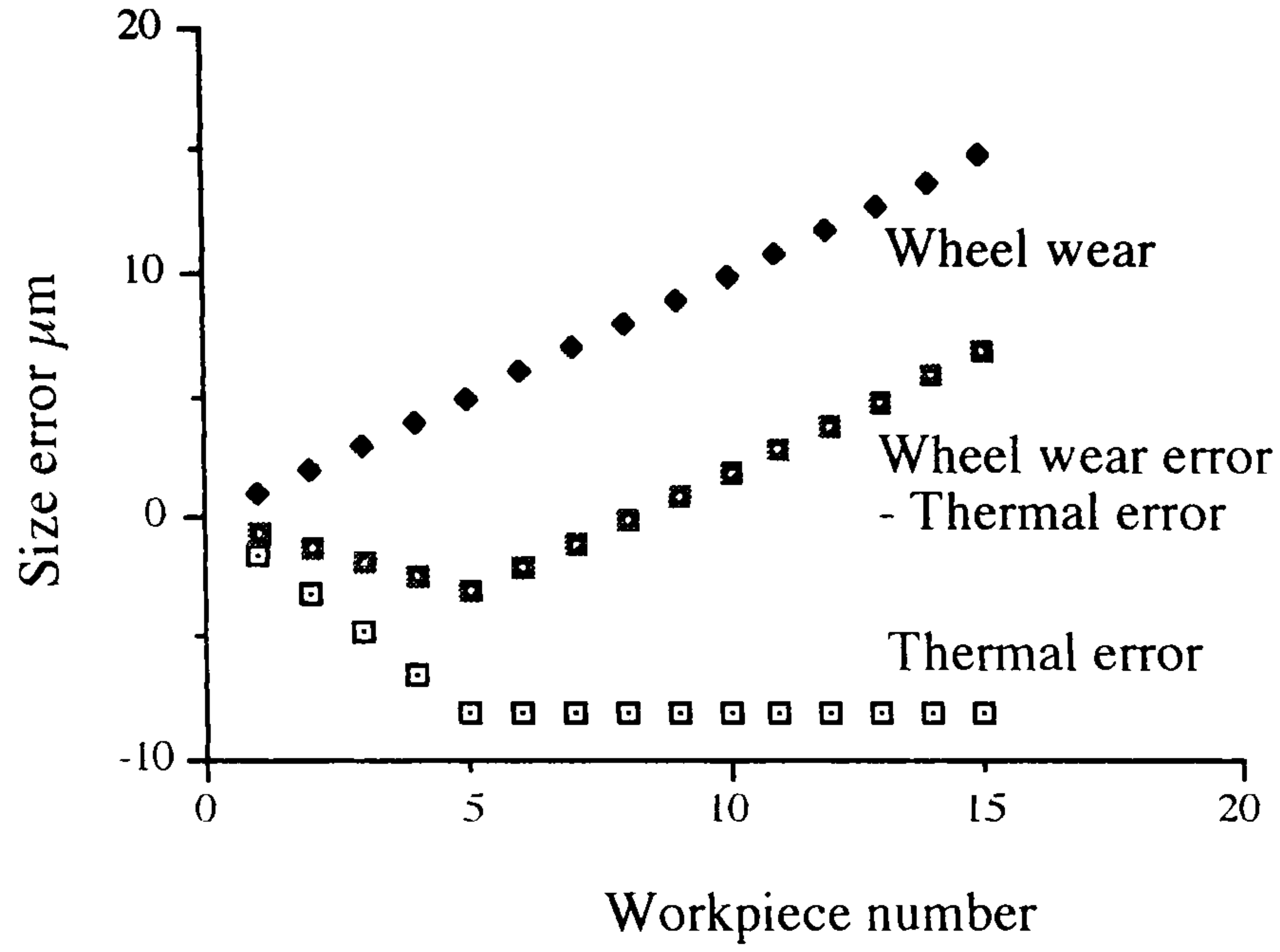
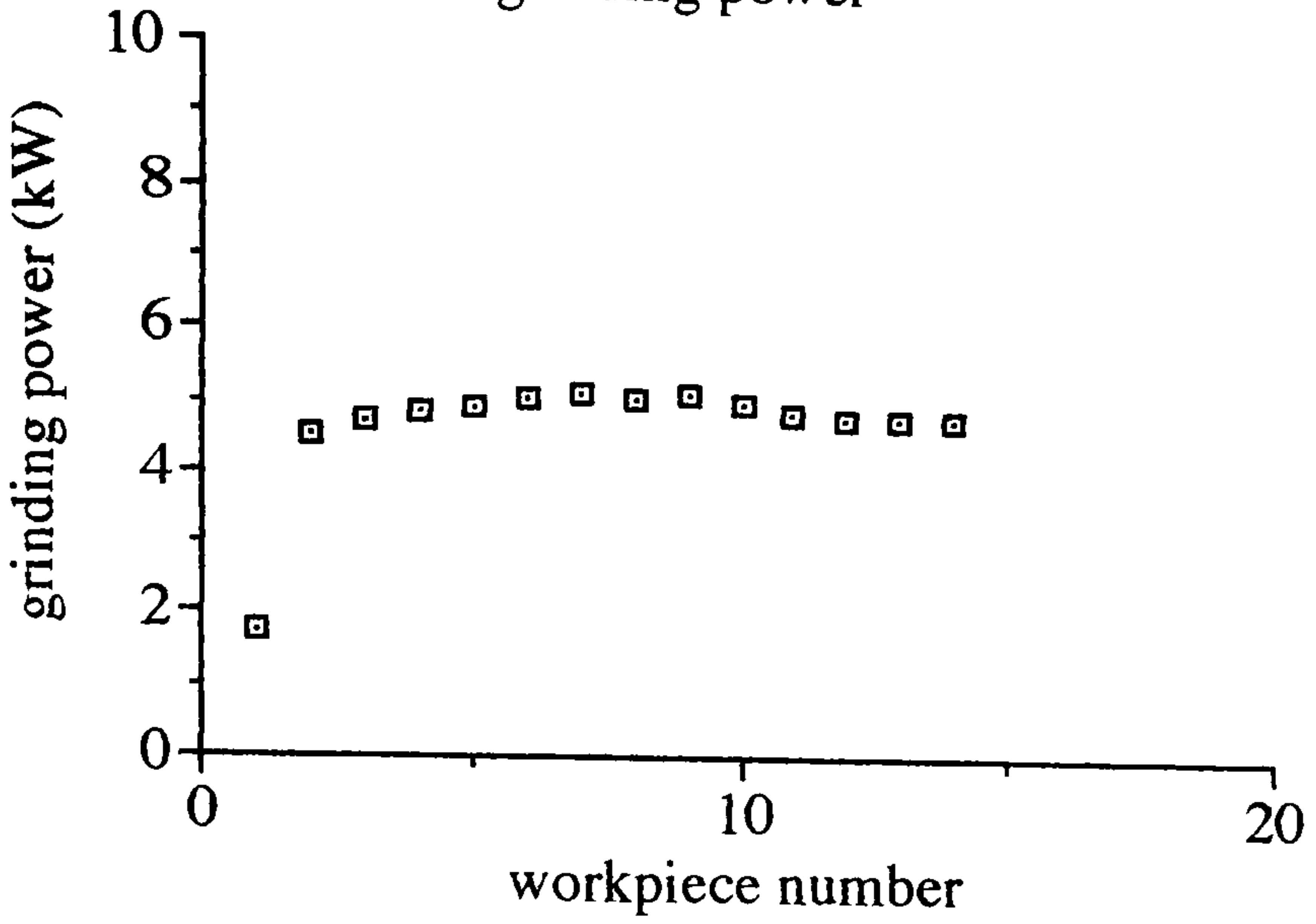
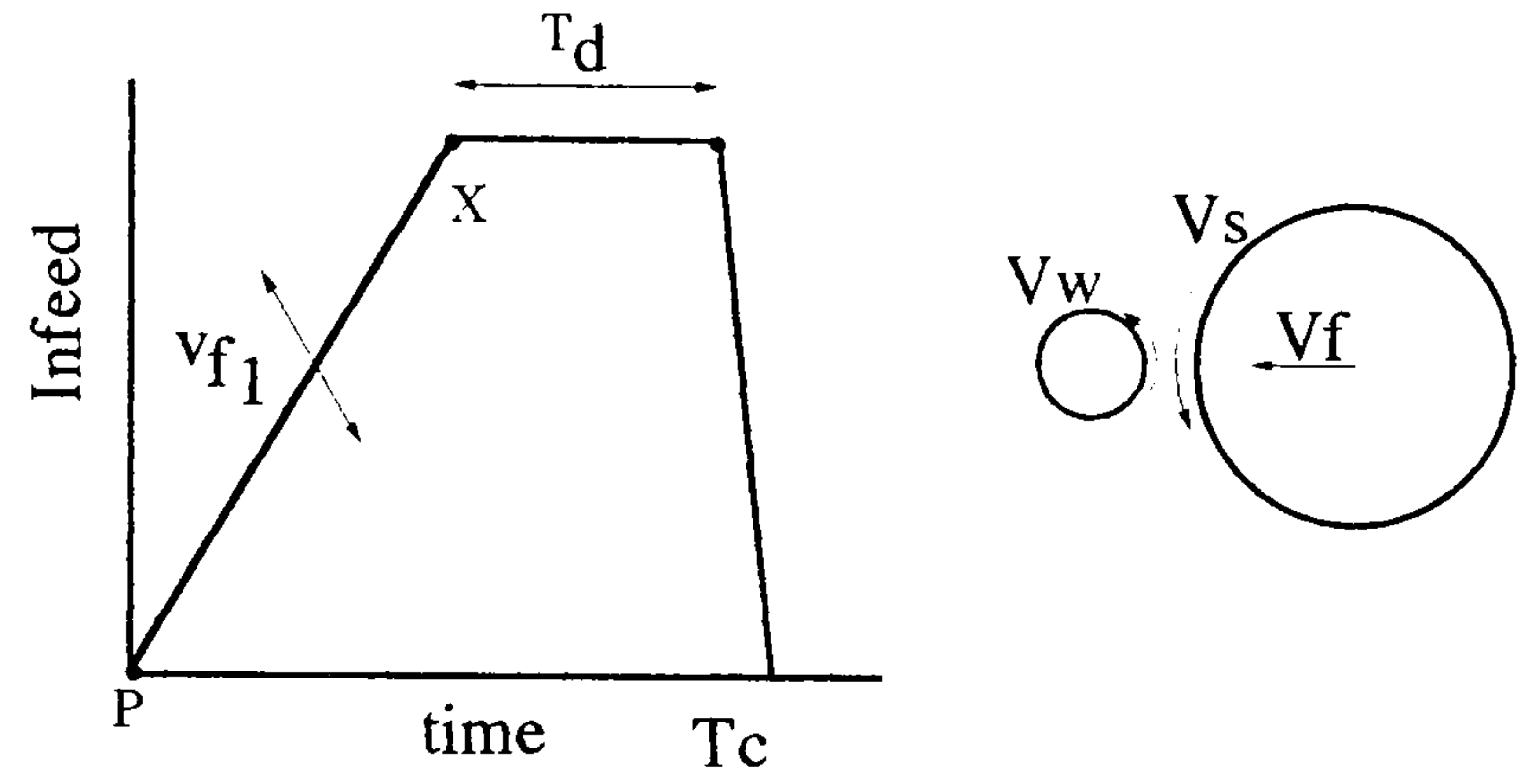


Figure 6.4 - Breakdown of the size error into thermal error and wheel wear error. Adapting the dwell period when grinding flexible workpieces without diameter gauging.

grinding power



In-feed cycle

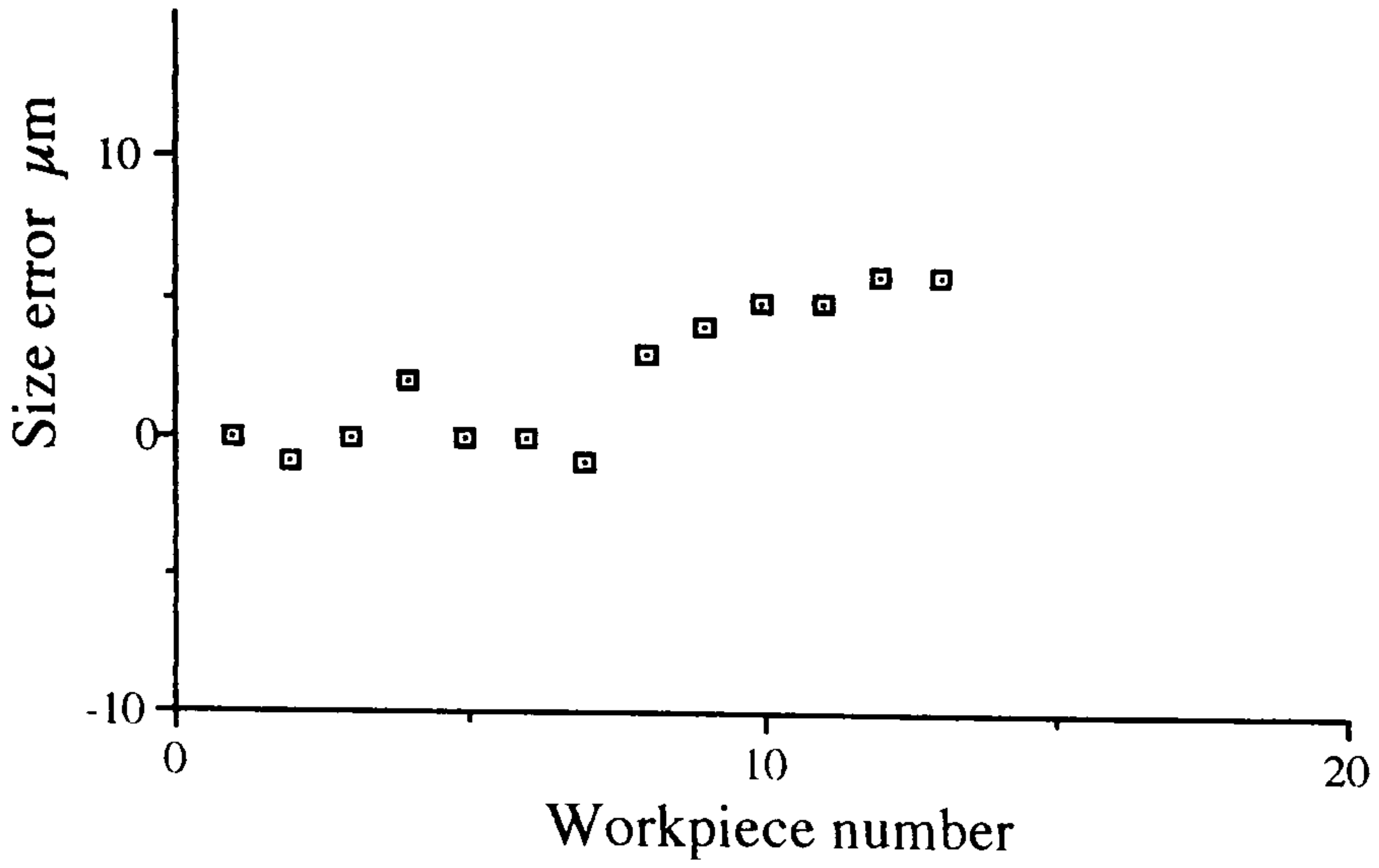


Experimental conditions

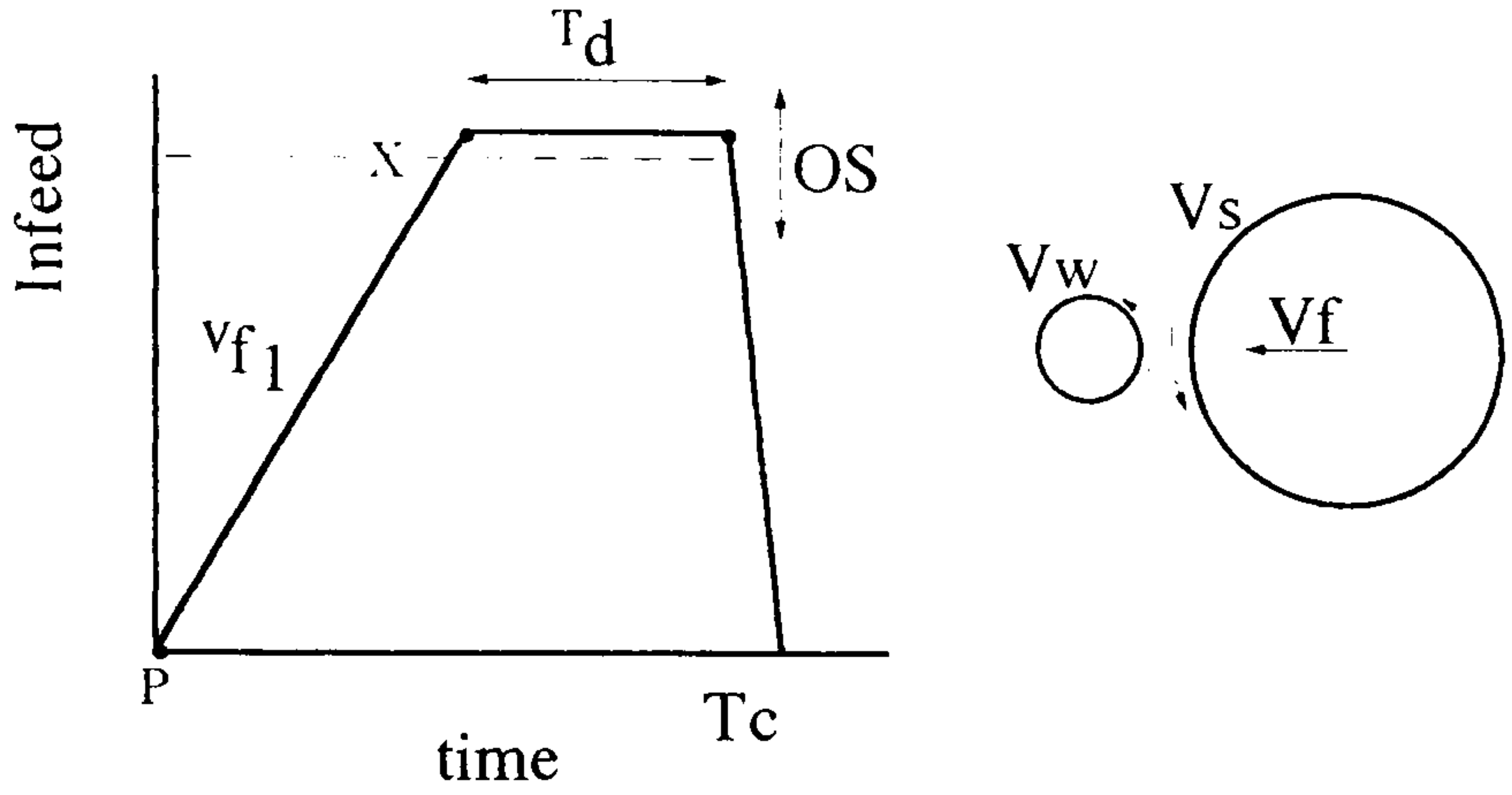
grinding parameters		dressing parameters	workpiece information
Vf1 1-8.5 μm/s	P 48.335 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~3 s
Vw 15 m/min	X 48.035 mm	every time ☐	
Vs 33 m/s	Tc 194 - 25 s	once only *	
Td 4τ	Pt 6 kW		
grinding wheel: A465K5V30W, ds = 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 6.5 - Updating infeed rate to achieve a target power level.

Size error



In-feed cycle



Experimental conditions

grinding parameters	dressing parameters	workpiece information
Vf1 0.005 μm/s P 46.490 mm Vf2 - I - Vf3 - J - Vw 15 m/min X 46.190 mm Vs 33 m/s Tc ~ 44 s Td 2τ Pt -	E 0.15 mm/rev I 0.005 mm N 5 every time ☐ once only *	material EN9 contact width 46 mm time constant ~7 s
grinding wheel: A465K5V30W, ds 450 mm	dressing tool: multi point diamond	coolant: synthetic

Figure 6.6 - Size error when adapting the dwell period and overshooting the target infeed position.

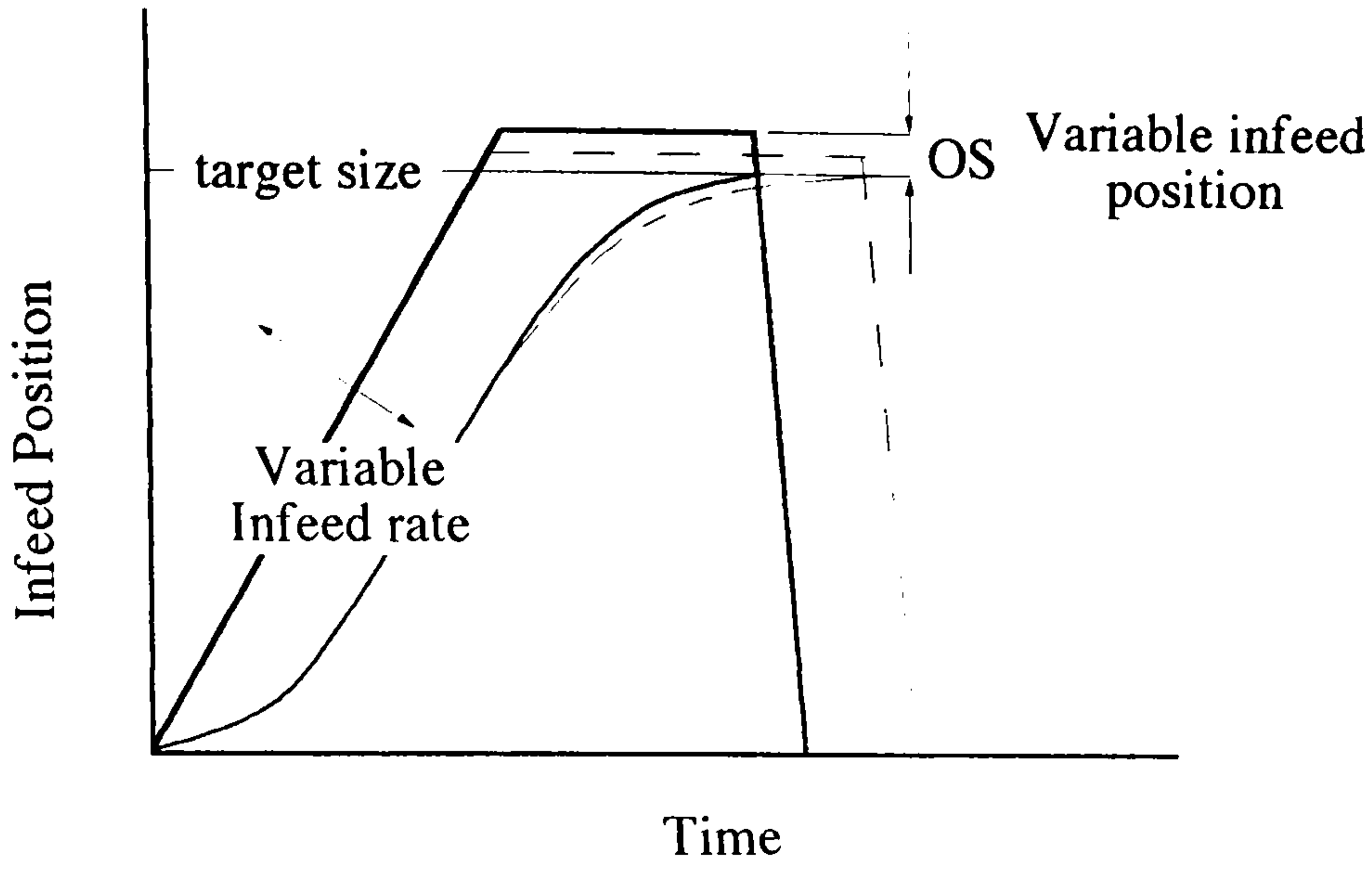
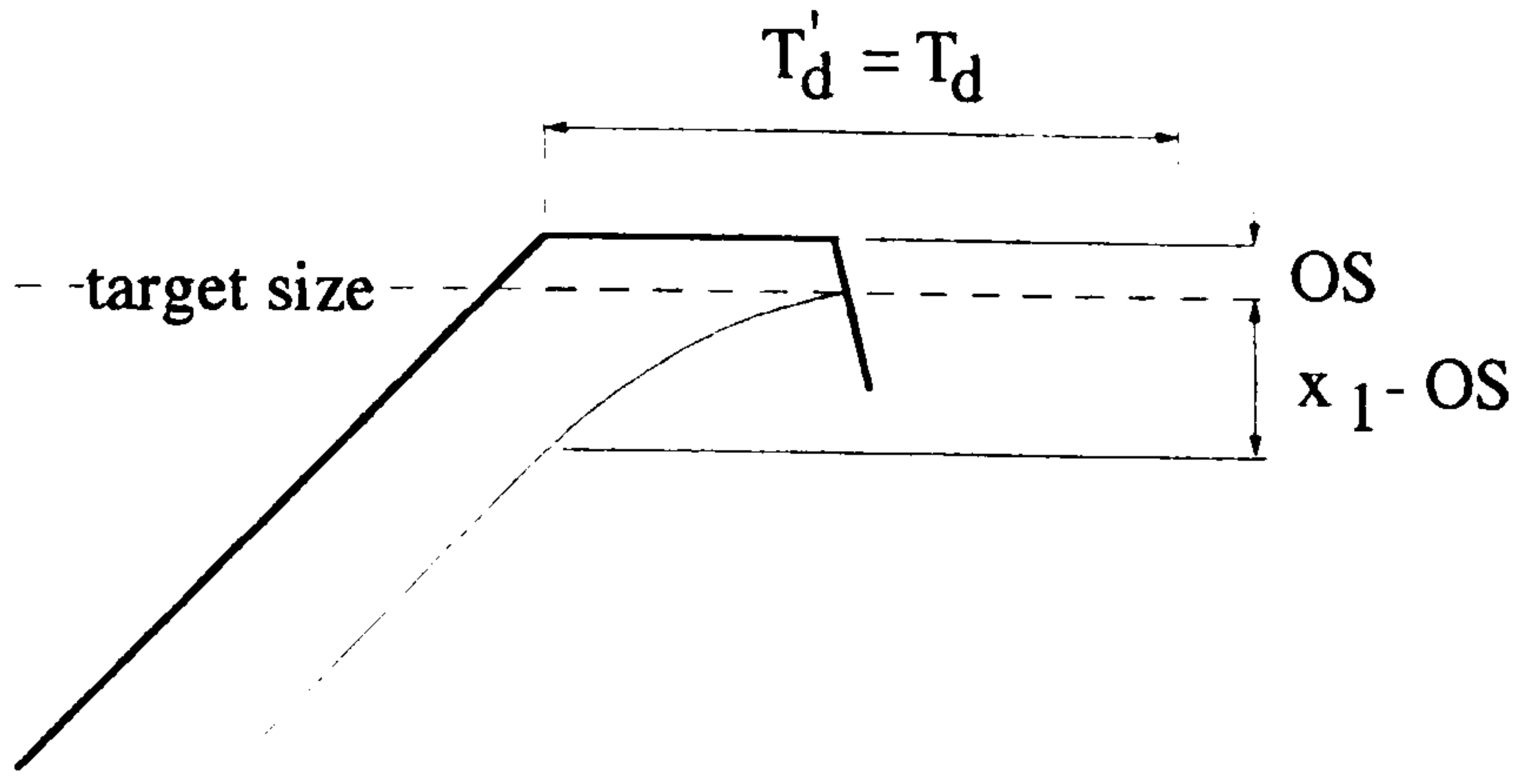
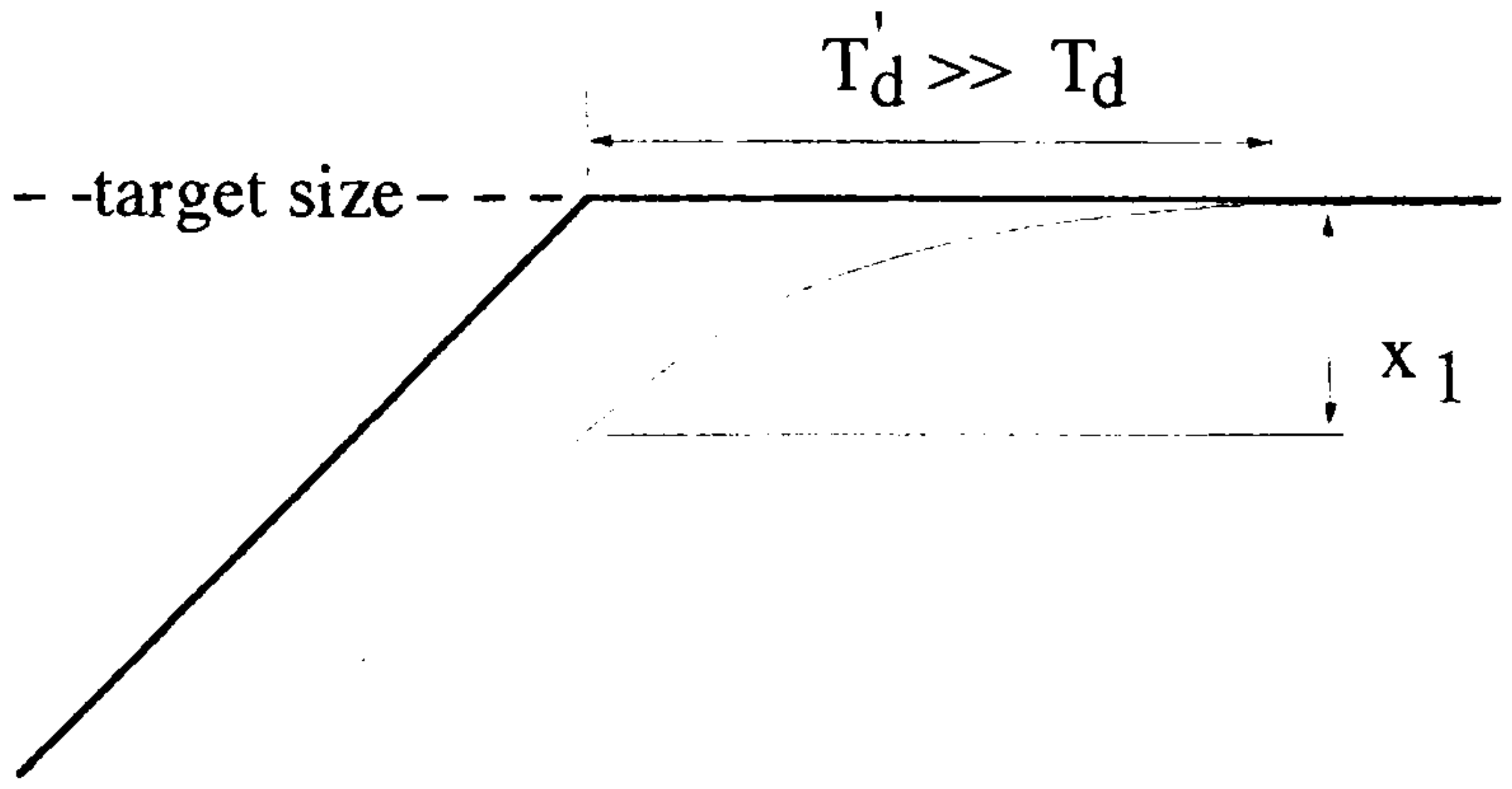


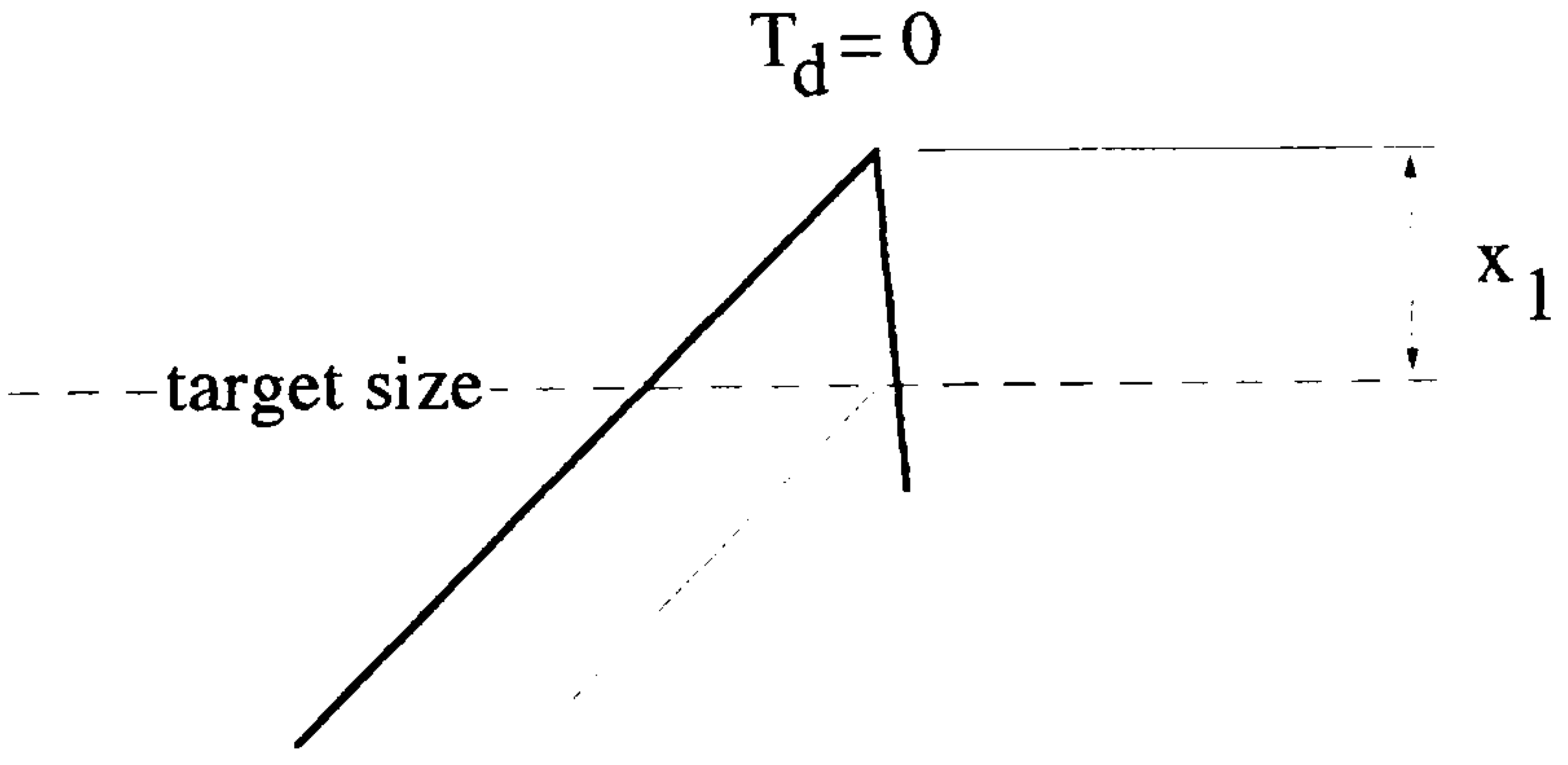
Figure 6.7 - A grinding cycle with diameter gauging. Infeed position was adapted to maintain a target dwell time, infeed rate may also be adapted.



Actual overshoot = intended overshoot
Infeed position error = 0

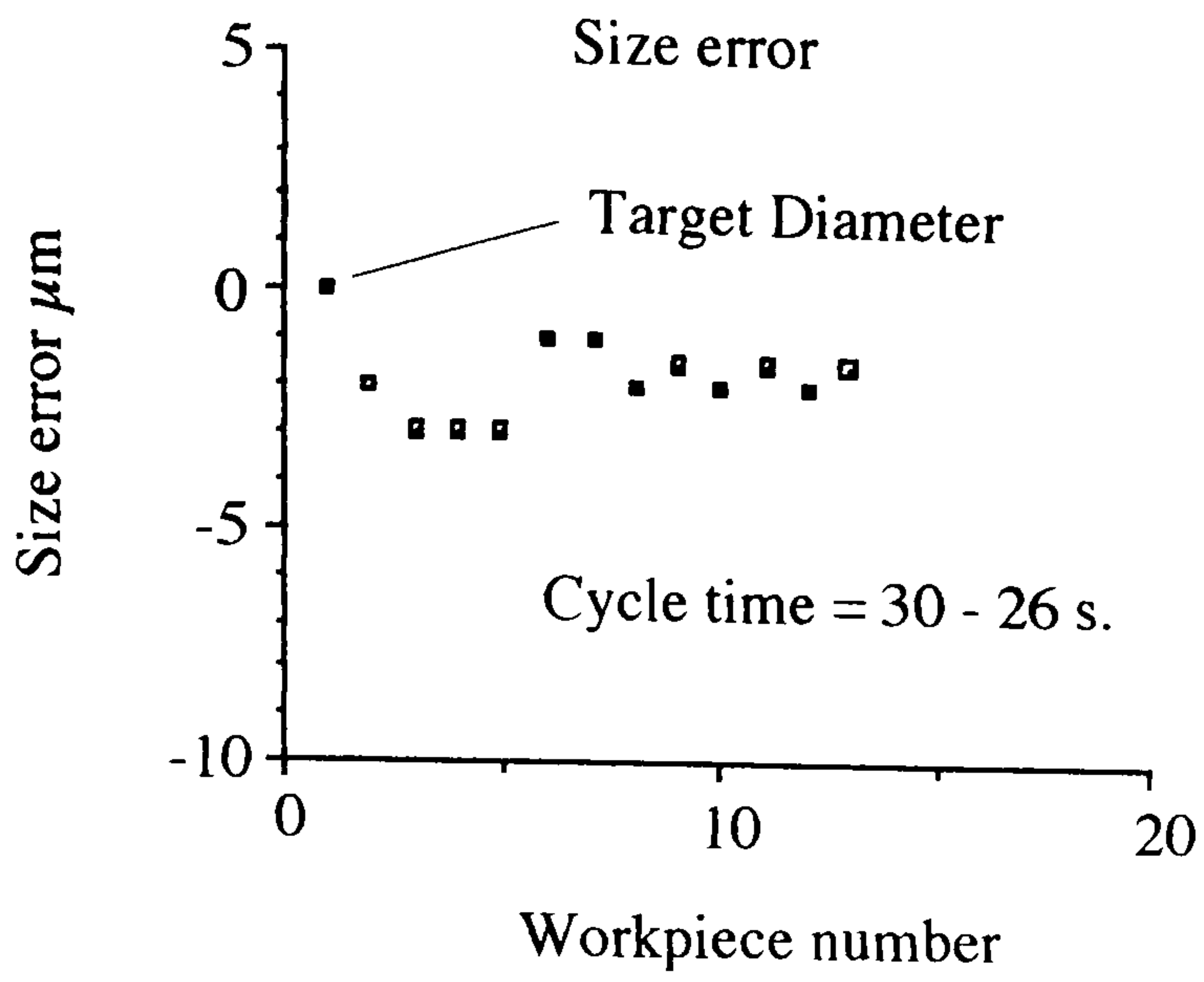


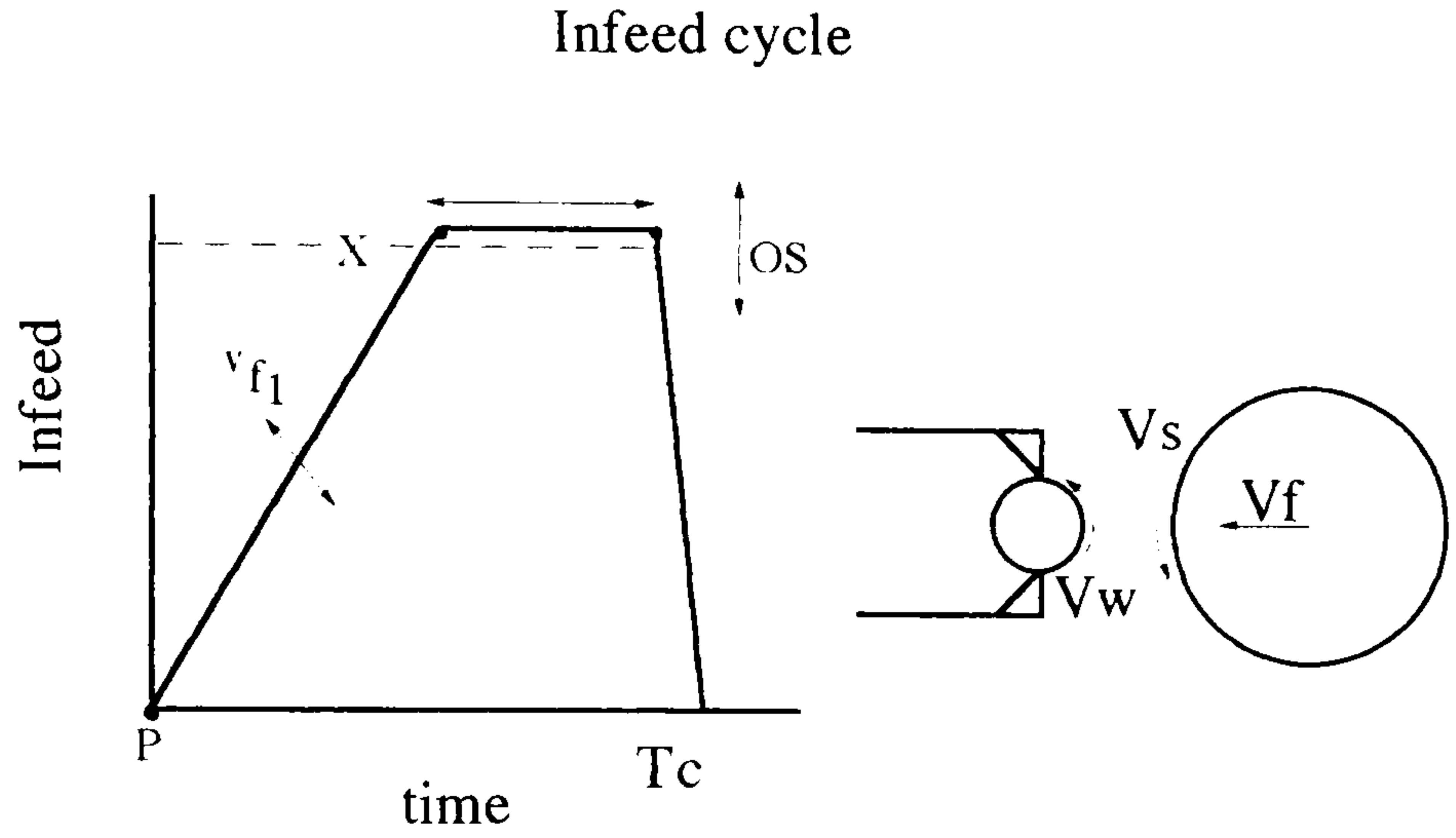
Actual overshoot = 0
Infeed position error = +intended overshoot



Actual overshoot = x_1
Infeed position error = - (x_1 - intended overshoot)

Figure 6.8 - The range of infeed position error that can be measured by the adaptive infeed cycle with gauging





Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 4 - 8.6 μm/s	P 43.995 mm	E 0.1 mm/rev	material EN9
Vf2 -	I -	I 0.010 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~2 s
Vw 15 m/min	X 43.634 mm	every time ☐	
Vs 33 m/s	Tc ~ 30 s		
Td 3 τ	Pt -	once only *	
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 6.9 - Size error for the adaptive gauging cycle.

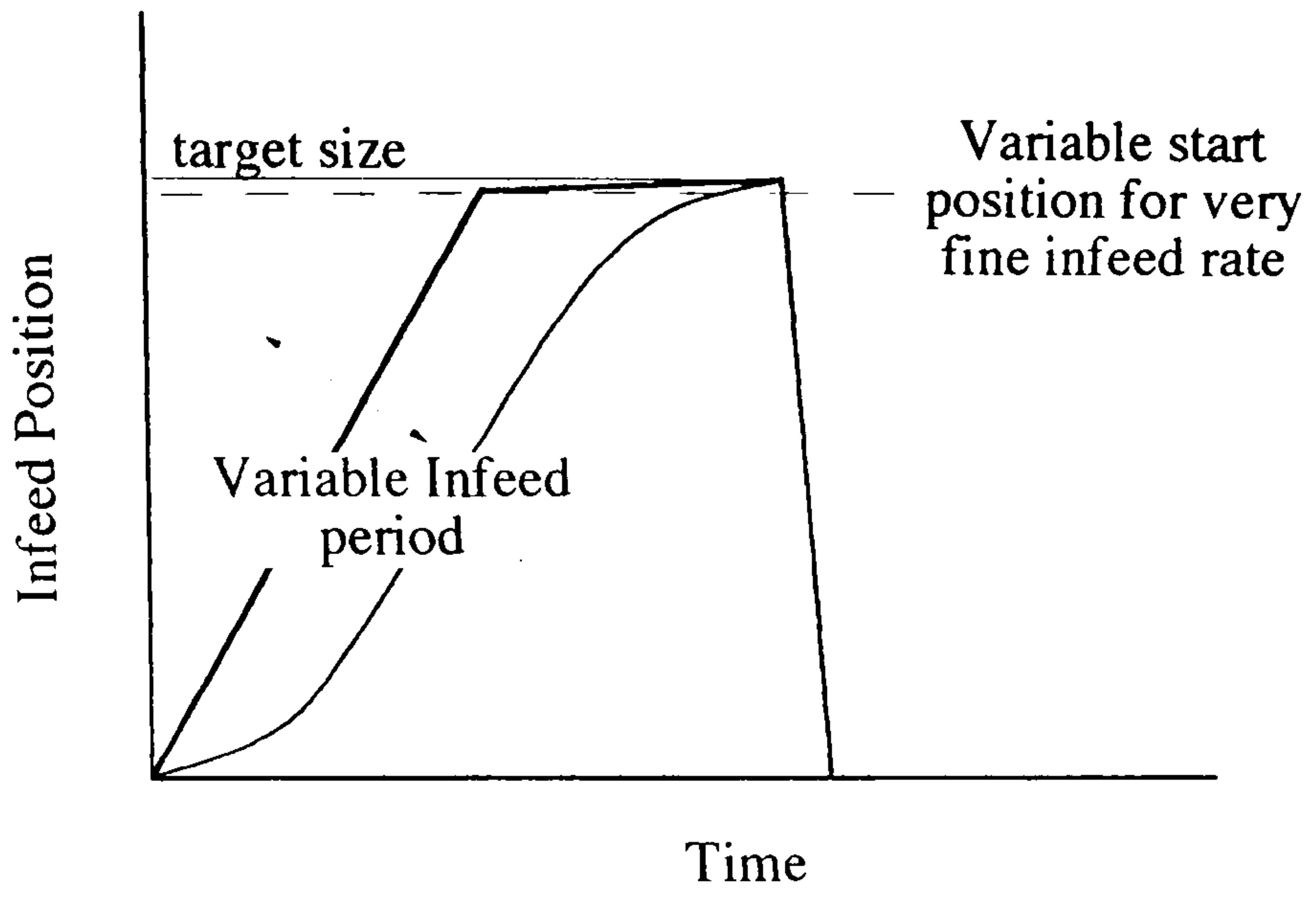
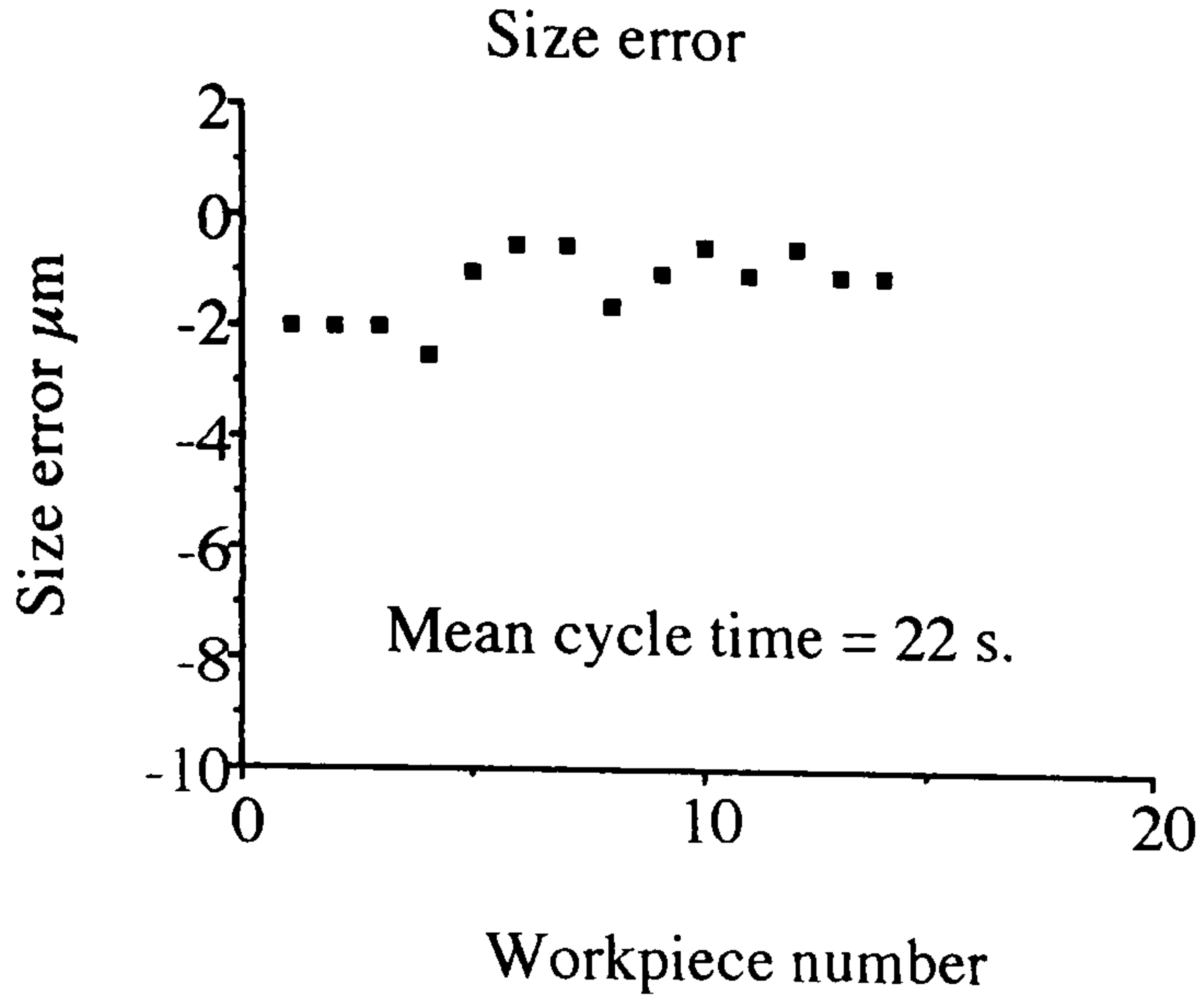
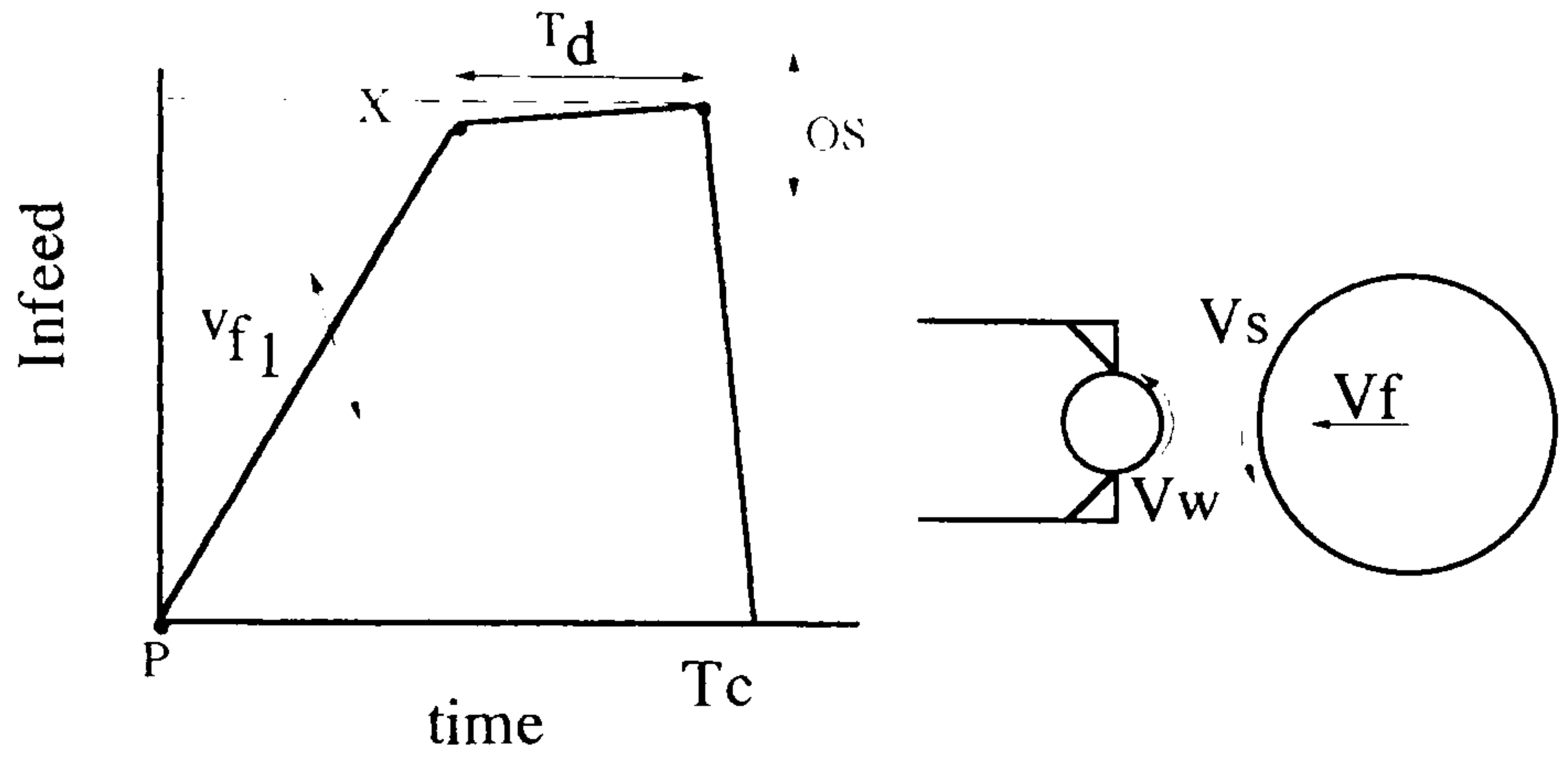


Figure 6.10 - A grinding cycle with diameter gauging. The start of the very fine infeed rate was varied to maintain a target 'dwell time'. The infeed rate may also be adapted.

Size error



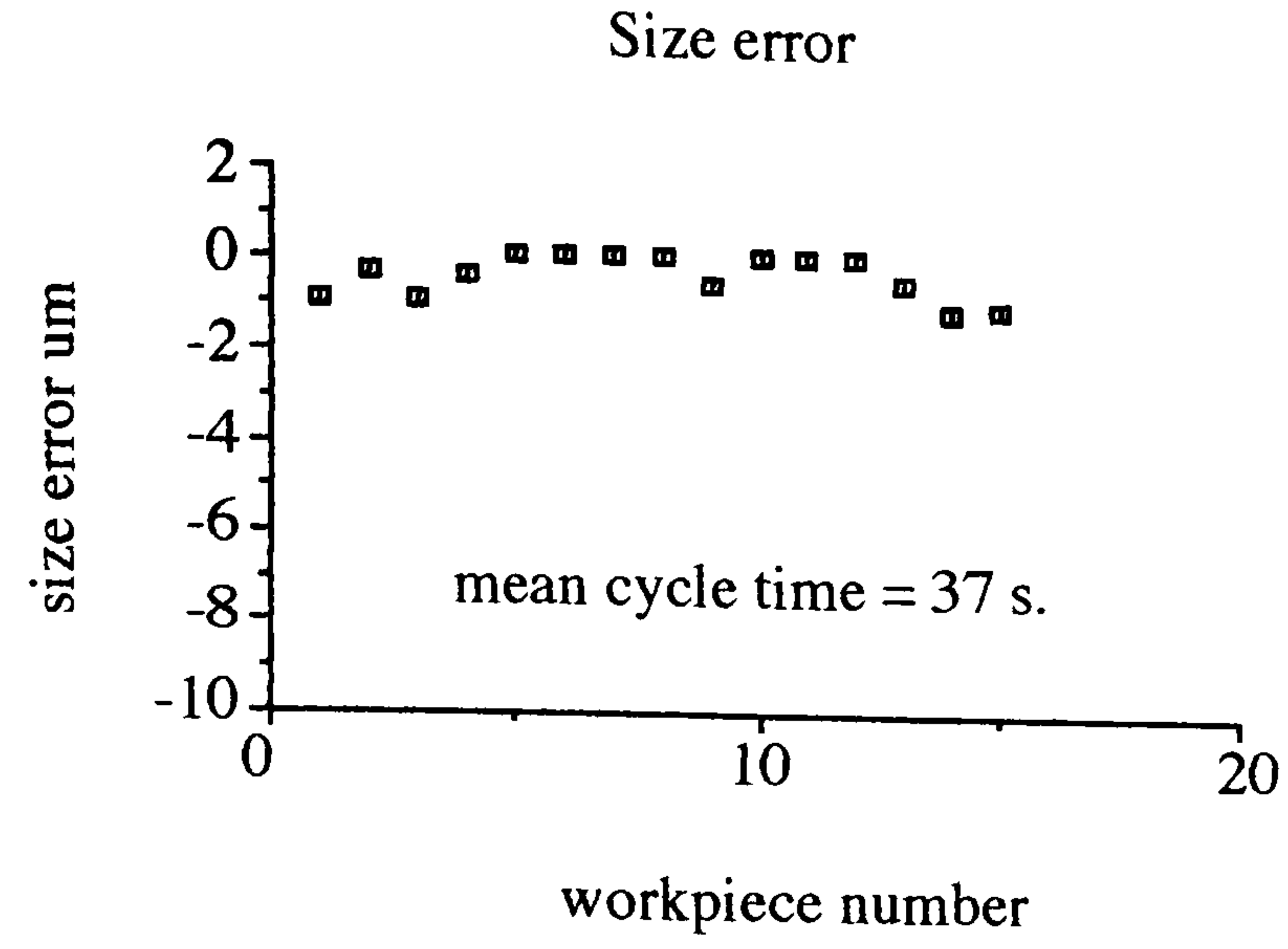
Infeed cycle

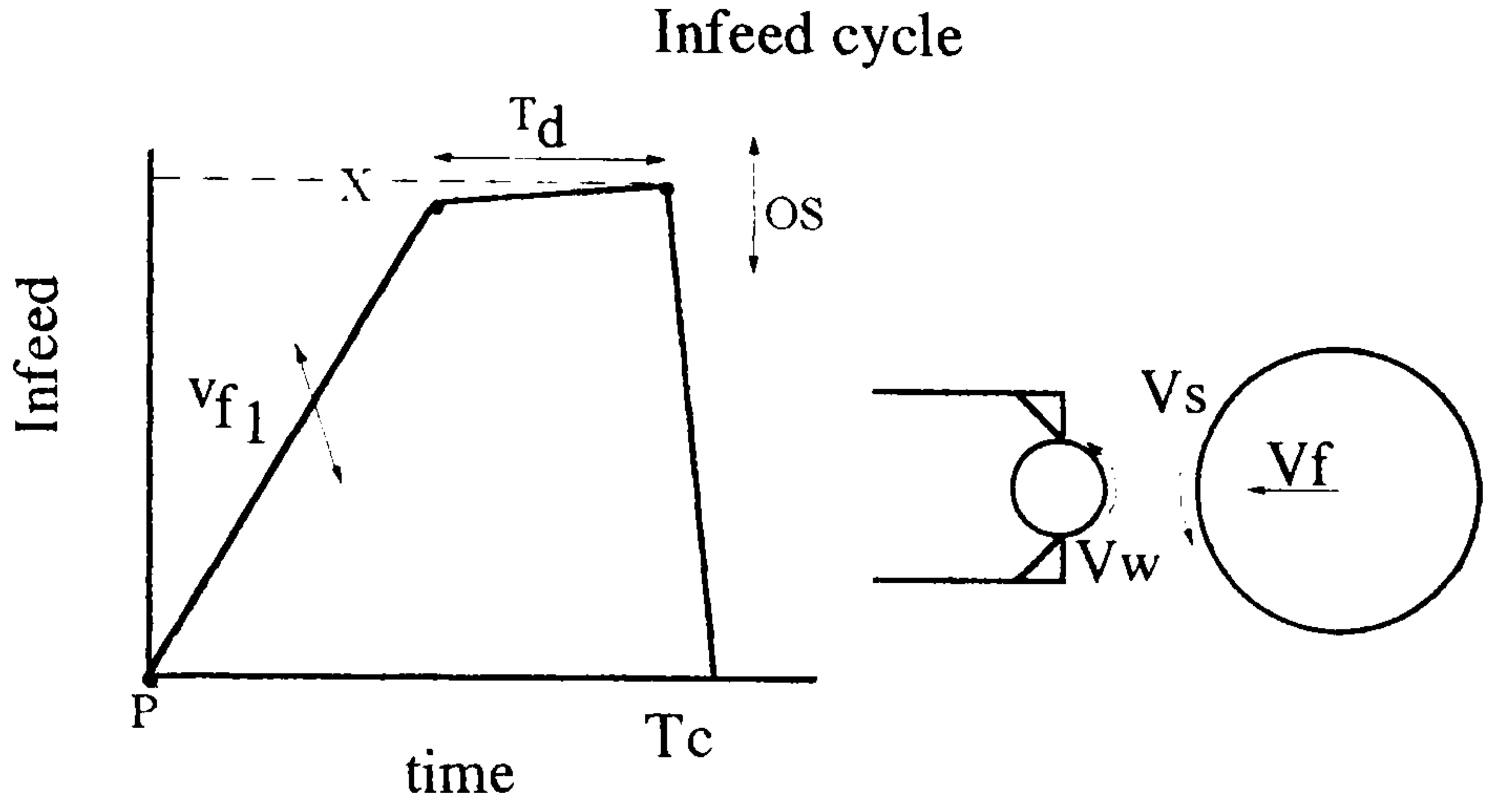


Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 10 - 13 μm/s	P 38.566 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~1-2 s
Vw 15 m/min	X 38.226 mm	every time ☐	
Vs 33 m/s	Tc ~ 22 s	once only *	
Td 6 τ	Pt - 5 kW		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 6.11 - Size error when the dwell period of the gauging cycle was replaced by a fine infeed rate. High target power level.





Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 -	P 36.501 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~2 s
Vw 15 m/min	X 36.181 mm	every time ☐	
Vs 33 m/s	Tc ~ 37 s	once only *	
Td 6 τ	Pt - 2.5 kW		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 6.12- Size error when the dwell period of the gauging cycle was replaced by a fine infeed rate. Low taret power level.

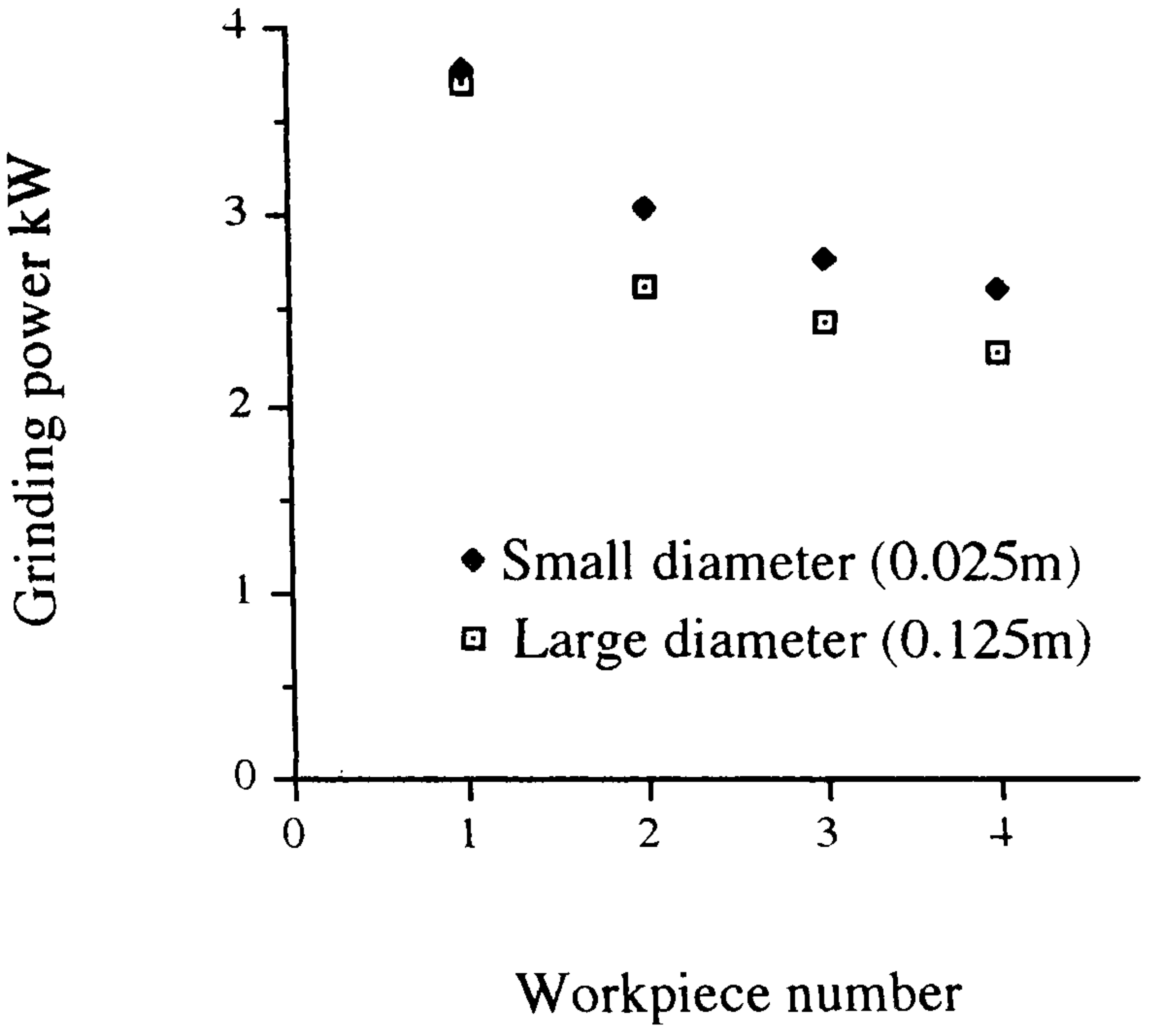


Figure 6.13 - Grinding power for the trials to test the kinematic model.

7 COMPARISON OF THE ADAPTIVE AND NON-ADAPTIVE SYSTEMS

7.1 Introduction

A brief description of the features of the adaptive and non-adaptive systems is given in this chapter. Results of grinding trials are given which compare the cycle times and workpiece quality achieved with the adaptive and the non-adaptive systems. The advantages and limitations of each system are summarised.

7.2 A Brief Description of the Non-Adaptive System

7.2.1 Grinding cycles

The plunge grinding cycle for the non-adaptive system consisted of coarse, medium and fine infeed periods followed by a dwell period as shown in figure 7.1. The actual infeed position lagged behind the programmed infeed position due to deflection of the machining system caused by grinding forces. During the dwell period tension in the system caused further stock to be removed until the deflection was relieved, producing a finished workpiece of the required size.

The plunge grinding cycle with diameter gauging for the non-adaptive system is shown in figure 7.2. The fine infeed period and the dwell period were commenced when preset workpiece sizes were attained. When the target diameter was attained the grinding wheel was retracted. Because the final stages of the infeed cycle were triggered by signals from the diameter gauge, it was possible to effectively eliminate the errors in the infeed position caused by wheel wear, dressing, machine set-up and thermal deformation of the machine. By comparing the infeed position during the dwell period to the programmed infeed position and applying the difference as an axis offset, the error compensation was retained for subsequent grinding operations.

7.2.2 Selection of Grinding Parameters

Typically the user selected initial grinding parameters based on his previous experience of the grinding process, and then optimised the grinding cycle by experimentation. Parameters that the user was required to select included

the grinding wheel speed,
the workpiece speed,
the positions at which grinding commenced and ended,
the positions at which the coarse, medium and fine infeed rates commenced,
the coarse, medium and fine infeed rates,
and the dwell period.

In the absence of programmed values, defaults were provided for

the grinding wheel speed,
the positions at which the medium and fine infeed rates commenced,
the medium and fine infeed rates,
and the dwell period.

Although these defaults were satisfactory they were unlikely unlikely to be optimal.

7.3 A Brief Description of the Adaptive System

7.3.1 Grinding Cycles

Figure 7.3 shows an adaptive infeed cycle consisting of a single infeed rate followed by a dwell period. The time constant or lag of the system τ was measured from the grinding power characteristics. This value was then used to calculate the dwell time required to attain size without incurring excessive cycle time.

Two strategies were provided for setting the dwell period. In the first strategy the dwell time was set to four time constants. This was long enough for most of the deflection to be relieved. Alternatively the dwell time was shortened to two time constants so that some deflection remained at the end of the grinding cycle. In this case an overshoot was applied to the infeed axis to compensate for the remaining deflection.

Cycle time was further reduced by updating the infeed rate from one grinding operation to the next in order to maintain a preset power level throughout a batch of workpieces.

The adaptive plunge grinding cycle with diameter gauging is shown in figure 7.4. The cycle consisted of a single infeed rate followed by a very fine infeed rate of 0.1 μm/s which was maintained until most of the deflection was relieved and the workpiece had cooled to near the ambient temperature. It was found that a dwell period of six time constants was generally sufficient. When the target diameter was attained the grinding wheel was retracted. The duration of the very fine infeed rate was maintained at the desired value by altering the position at which the very fine infeed rate was commenced. The feature of updating the infeed rate to maintain a target power level was also provided for this grinding cycle.

7.3.2 Selection of Grinding Parameters

When suitable grinding conditions were achieved the kinematic parameters chip aspect ratio and chip length were calculated and stored in a data base. Subsequently, when the same combination of grinding wheel and workpiece material was used the kinematic parameters were retrieved from the data base and used to calculate machining parameter values. Storing kinematic parameters allowed appropriate machining parameter values to be calculated for any diameter of workpiece and grinding wheel. This was preferable to storing machining parameter values which were valid only for specific workpiece and grinding wheel diameters. Using initial machining parameter values generated from the data base the adaptive system quickly achieved the desired operating conditions after grinding only a small number of workpieces.

The infeed rate and workpiece speed were selected from the data base and the dwell time was set automatically by the grinding cycles. As the default grinding wheel speed of 33 m/s was usually satisfactory, this only left the user to select the positions at which grinding commenced and ended.

7.4 Comparison of Grinding Results for the Adaptive and Non-Adaptive Systems

7.4.1 Plunge Grinding without Diameter Gauging

Figure 7.5 shows the size results obtained when grinding workpieces using the non-adaptive plunge grinding cycle without gauging. The upper line shows the case when the grinding wheel was dressed only before grinding the first workpiece. The trend of increasing size with workpiece number was attributed to wear of the grinding wheel. The lower line shows the case when the grinding wheel was dressed before grinding each workpiece. The trend of decreasing size with workpiece number was attributed to wear of the dressing tool.

Figure 7.6 shows the size results obtained when adapting the dwell period. The grinding wheel was dressed before grinding the first workpiece only. Again the overall trend was an increase in workpiece size caused by grinding wheel wear. However, for the first four workpieces the size decreased. This can be explained by the change in dwell times throughout the batch, as shown in figure 7.7. Because of rapidly changing grinding forces the time constant decreased markedly for the first four workpieces. The dwell times were shorter for the fifth and subsequent workpieces and consequently these workpieces were not completely cooled during the dwell period. Rather they continued to cool after the end of the grinding cycle and undersize workpieces were produced.

The size results shown in figure 7.8 were obtained when adapting the dwell period and applying an overshoot to decrease the dwell time. The grinding wheel was dressed before grinding the first workpiece only. The overall trend was an increase in workpiece size caused by grinding wheel wear. Some variability was superimposed on this trend. This was attributed to small differences in the actual time constant and to small errors in the measured value of the time constant. The differences in dwell period from workpiece to workpiece caused the variability of the size results.

7.4.2 Plunge Grinding with Diameter Gauging

Figure 7.9a shows the size results obtained when using the non-adaptive plunge grinding cycle with gauging to grind workpieces using a low infeed rate. All the workpieces were finished to within 1 μm of the target diameter and the average cycle time was 60 s. At high infeed rates the average cycle time was reduced to 30 s, but as shown in figure 7.9b the workpieces were not finished accurately. The workpieces were on average 8 μm under size. The cause of size error was attributed to incomplete cooling of the workpiece and incomplete relaxation of the machining system during the dwell period.

Figure 7.10 shows the size results obtained when using the adaptive plunge grinding cycle with gauging to grind workpieces at a low power level. All the workpieces were finished to within 1 μm of the target diameter and the average cycle time was 37 s. At high power levels the average cycle time was reduced to 22 s, and as shown in figure 7.11 all the workpieces were finished to within 1 μm of the target diameter. Using the adaptive cycle accuracy was maintained at high power levels because the workpiece cooled sufficiently and most of the deflection of the machining system was relieved before the end of the grinding cycle.

7.5 Discussion

The best size results for both the non-adaptive and the adaptive grinding cycles were achieved when using diameter gauging. With both cycles it was possible to maintain accuracies of less than 1 μm throughout a batch of workpieces.

With the non-adaptive plunge grinding cycle with gauging the accuracy that could be attained was effected by the thermal expansion of the workpiece. When high infeed rates were used the workpiece did not cool sufficiently before the end of the dwell period and subsequent cooling resulted in undersize workpieces being produced. Also, because the gauge was used to signal the start of the fine infeed rate and the dwell period, changes in deflection affected the accuracy that was attained. Because these two factors adversely affected the performance of the cycle at high infeed rates, it was necessary to use conservative grinding parameters to ensure that consistently good size results were achieved.

The period of very fine infeed rate at the end of the the adaptive plunge grinding cycle with gauging allowed the deflection to relax and the workpiece to cool. Because the gauge was not used to signal the start of the fine infeed rate or the dwell period, the sensitivity of the cycle to changes in deflection was reduced. This allowed higher infeed rates to be used, giving shorter cycle times. In addition the need to empirically determine the positions at which to start the fine infeed rate and the dwell period was eliminated, reducing set up times. However, to allow for set-up errors it was necessary to apply a positive offset for the first workpiece to be ground. This resulted in a long dwell period but this was corrected for grinding subsequent workpieces.

The size results obtained with the non-adaptive cycle without gauging showed the effect of grinding wheel wear and dressing tool wear. These effects were also evident with the adaptive cycle without gauging, but in this case additional variation was introduced. This was due to variations in the actual time constant combined with thermal expansion of the workpiece, and also to small errors in the measured time constant. It is likely that this variability could be overcome by lengthening the dwell period or by introducing a finishing infeed rate to allow the workpiece to cool. Alternatively a lower material removal rate could be used to reduce the workpiece temperature during grinding. The adaptive cycle resulted in faster cycle times because the dwell time was set to the minimum value required to relax the deflection and also no finishing infeed rate was used. Set-up time was decreased because the user did not have to determine the correct dwell time.

The automatic selection of infeed rate and workpiece speed from a database, together with updating the infeed rate to maintain a target power level decreased the set-up time as the user was not required to select grinding parameters or determine the optimum grinding conditions.

7.6 Conclusions

Excellent size results were achieved using the non-adaptive plunge grinding cycle with gauging. However because of deflection and thermal effects, size results were inferior when grinding flexible workpieces at high removal rates. This problem was overcome for the adaptive cycle by replacing the dwell period with a very fine infeed rate. The adaptive cycle also simplified the use of the diameter gauge, reducing set-up times. However, a long dwell period was experienced for the first workpiece to be ground.

Without gauging the effects of wheel wear and dressing tool wear were evident for both the non-adaptive and the adaptive cycles. The adaptive cycle automatically set the dwell period to relieve most of the deflection without incurring excessive cycle times. However, the effect of altering the dwell time combined with the thermal effects resulted in additional variations being introduced. It is likely that this could be rectified by using lower removal rates or by lengthening the dwell period.

With the non-adaptive system the user was required to select appropriate infeed rates and workpiece speed. With the adaptive system a data base automatically selected the initial values of infeed rate and workpiece speed. Also, updating the infeed rate from one workpiece to the next accounted for conditioning of the grinding wheel, maximising the removal within the constraint of a target power level.

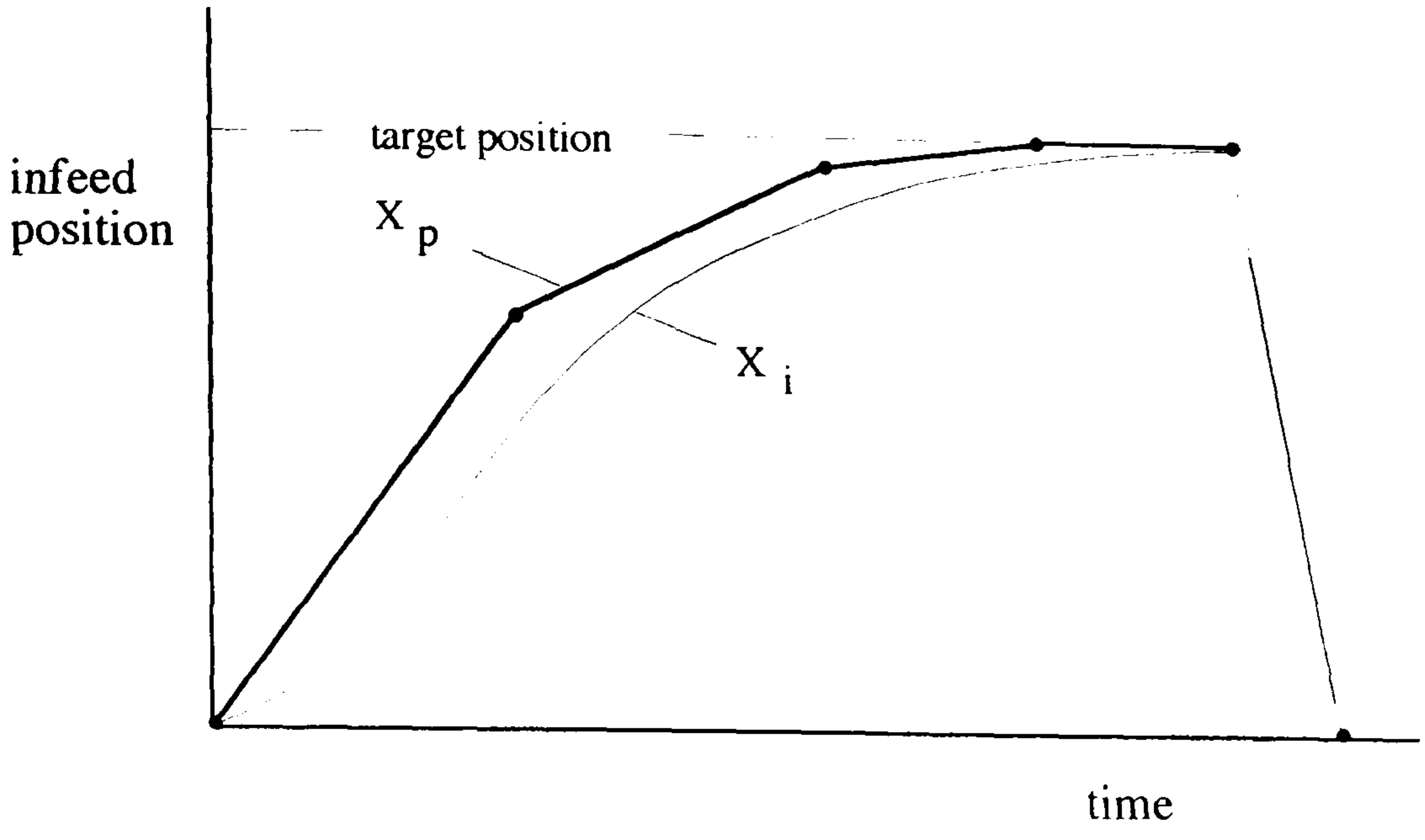


Figure 7.1 Non - Adaptive Plunge Grinding Cycle without Diameter Gauge

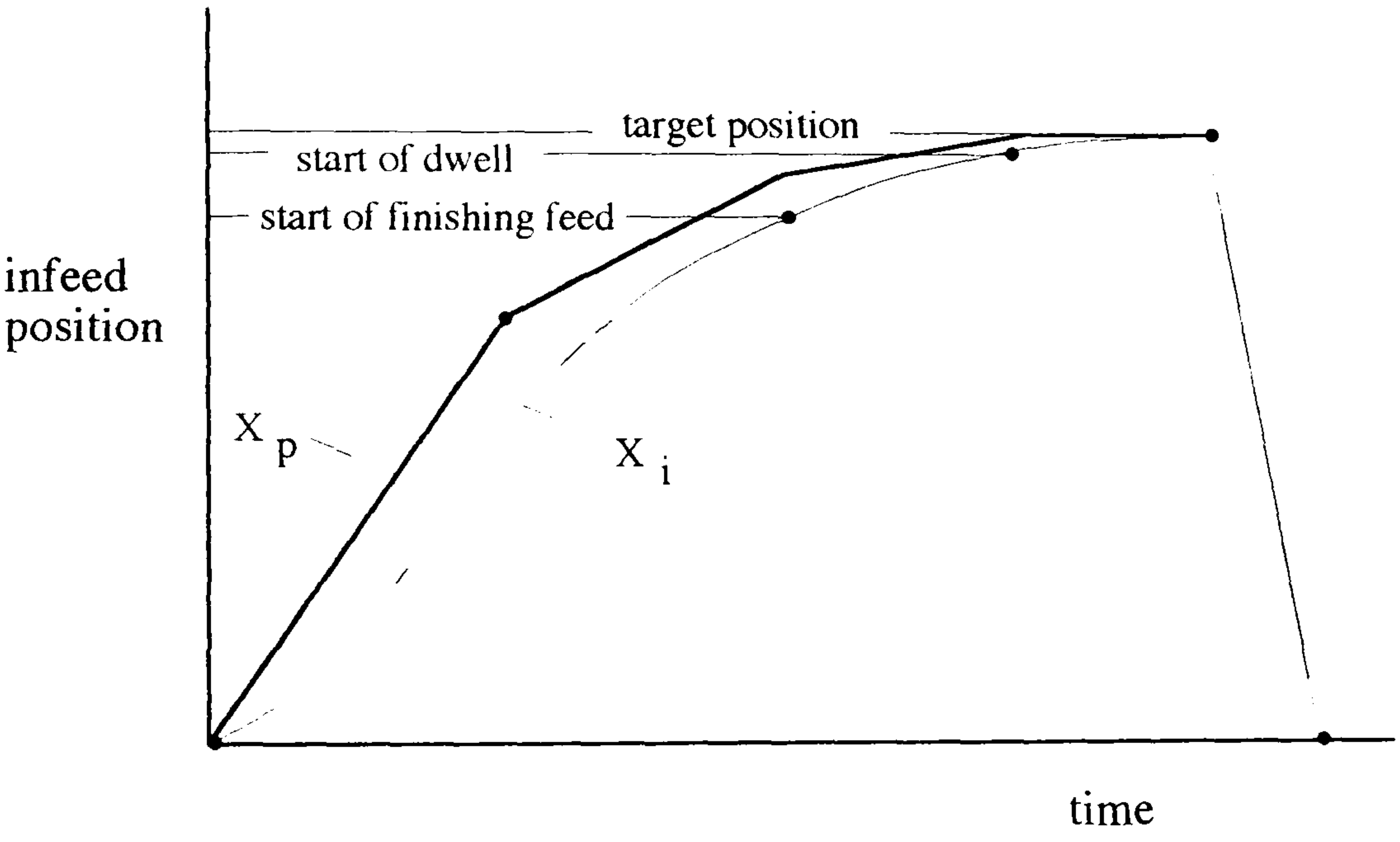


Figure 7.2 Non - Adaptive Plunge Grinding Cycle with Diameter Gauge

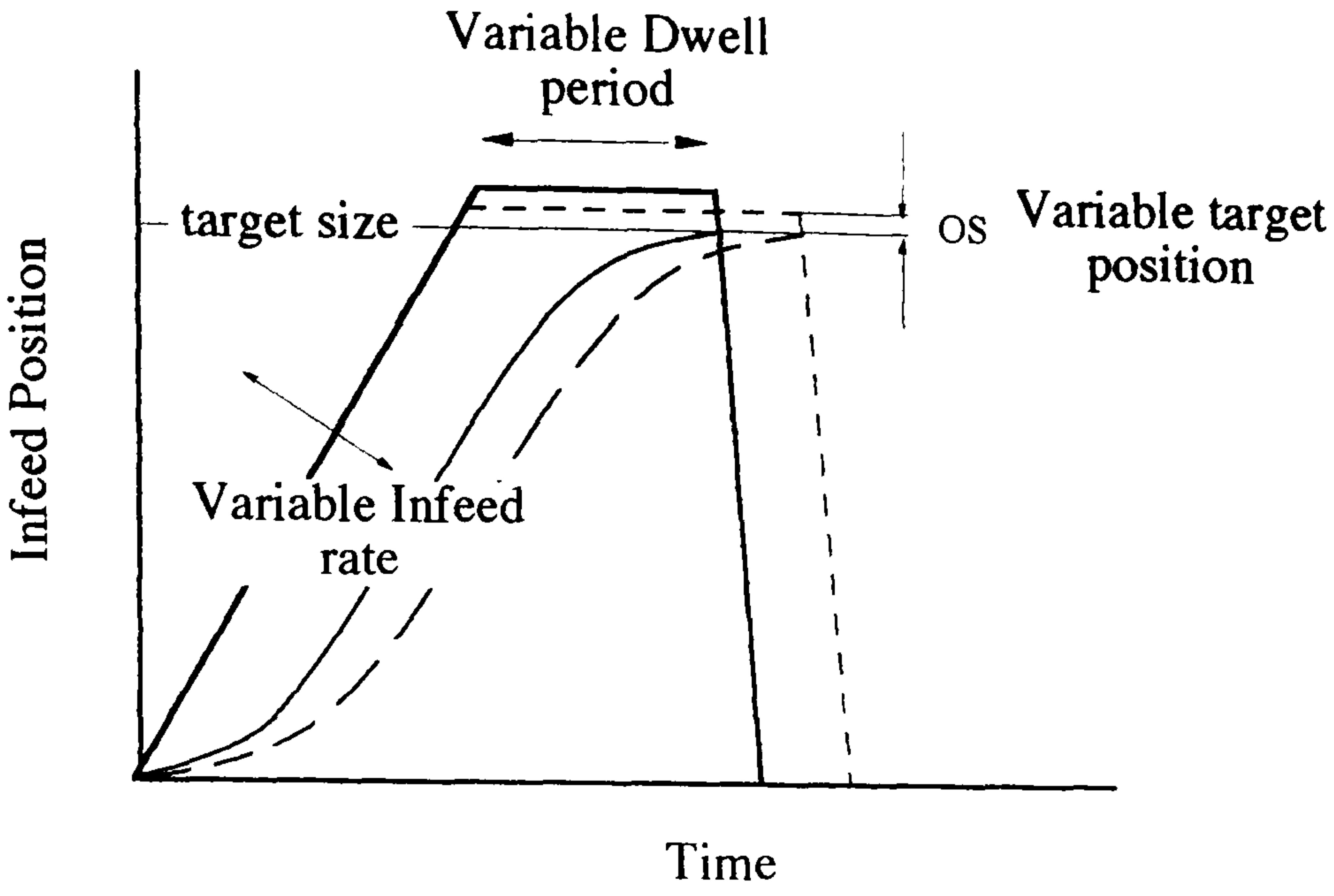


Figure 7.3 - A grinding cycle with adapted dwell time, infeed rate and infeed position

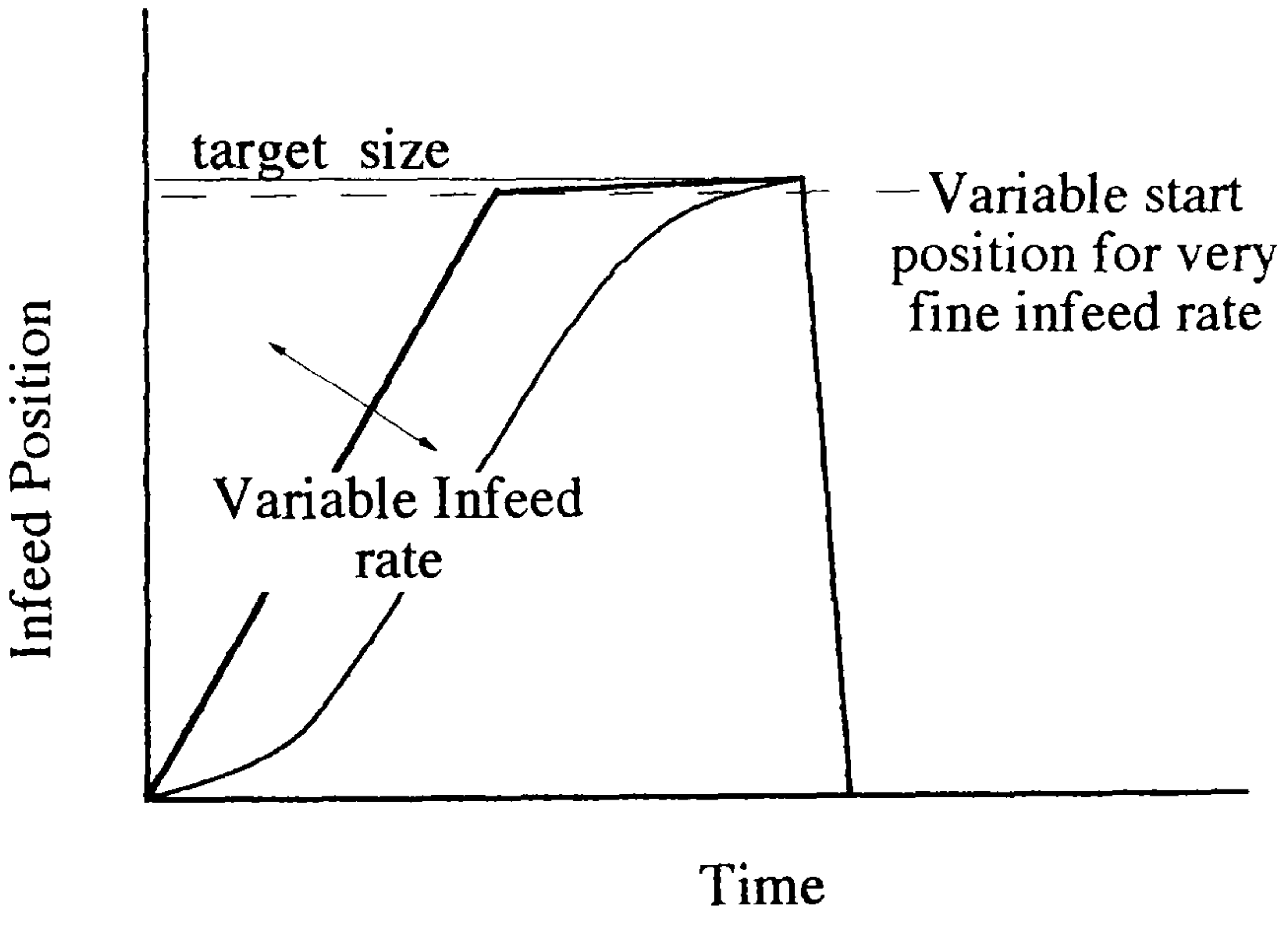
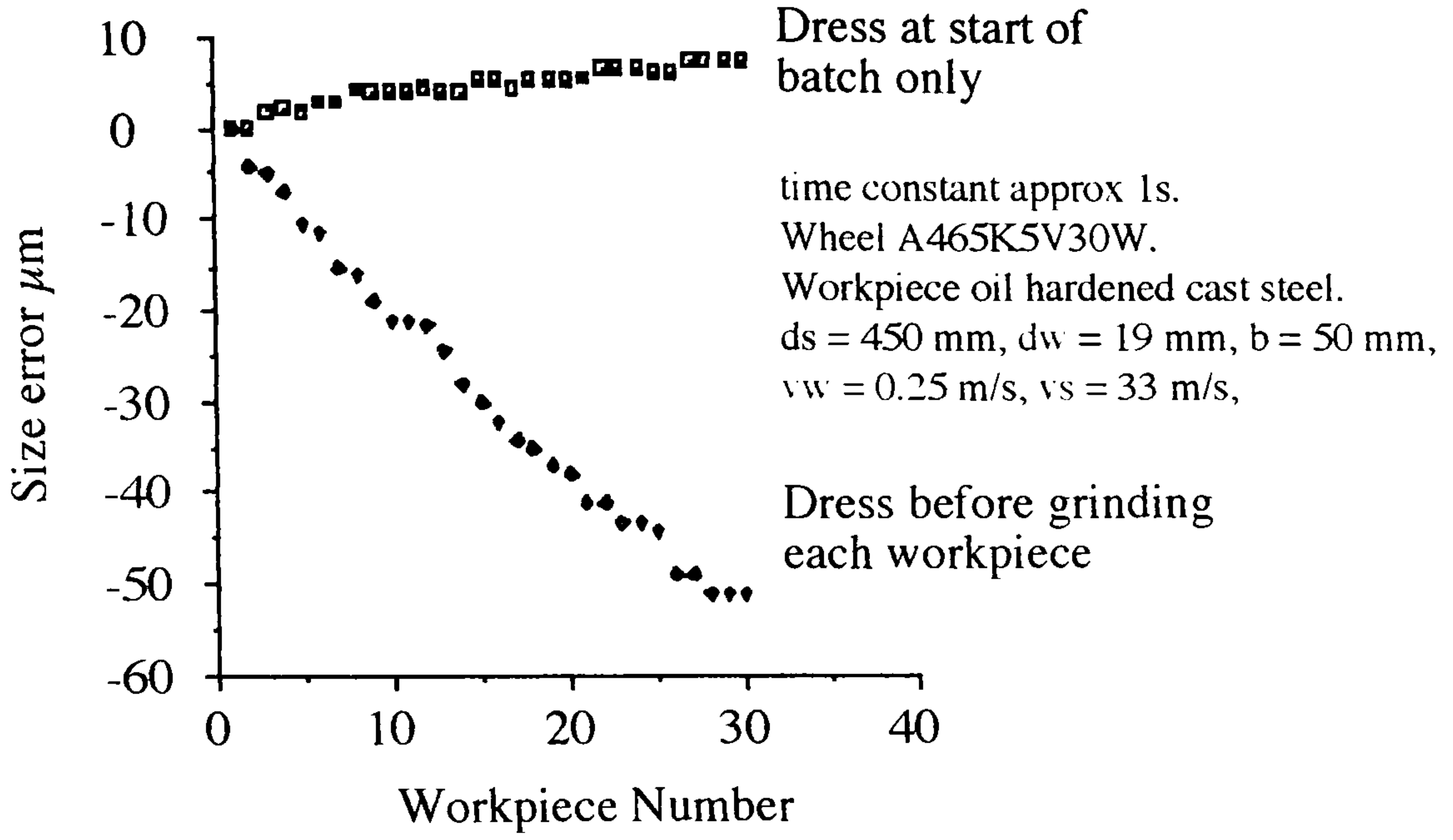
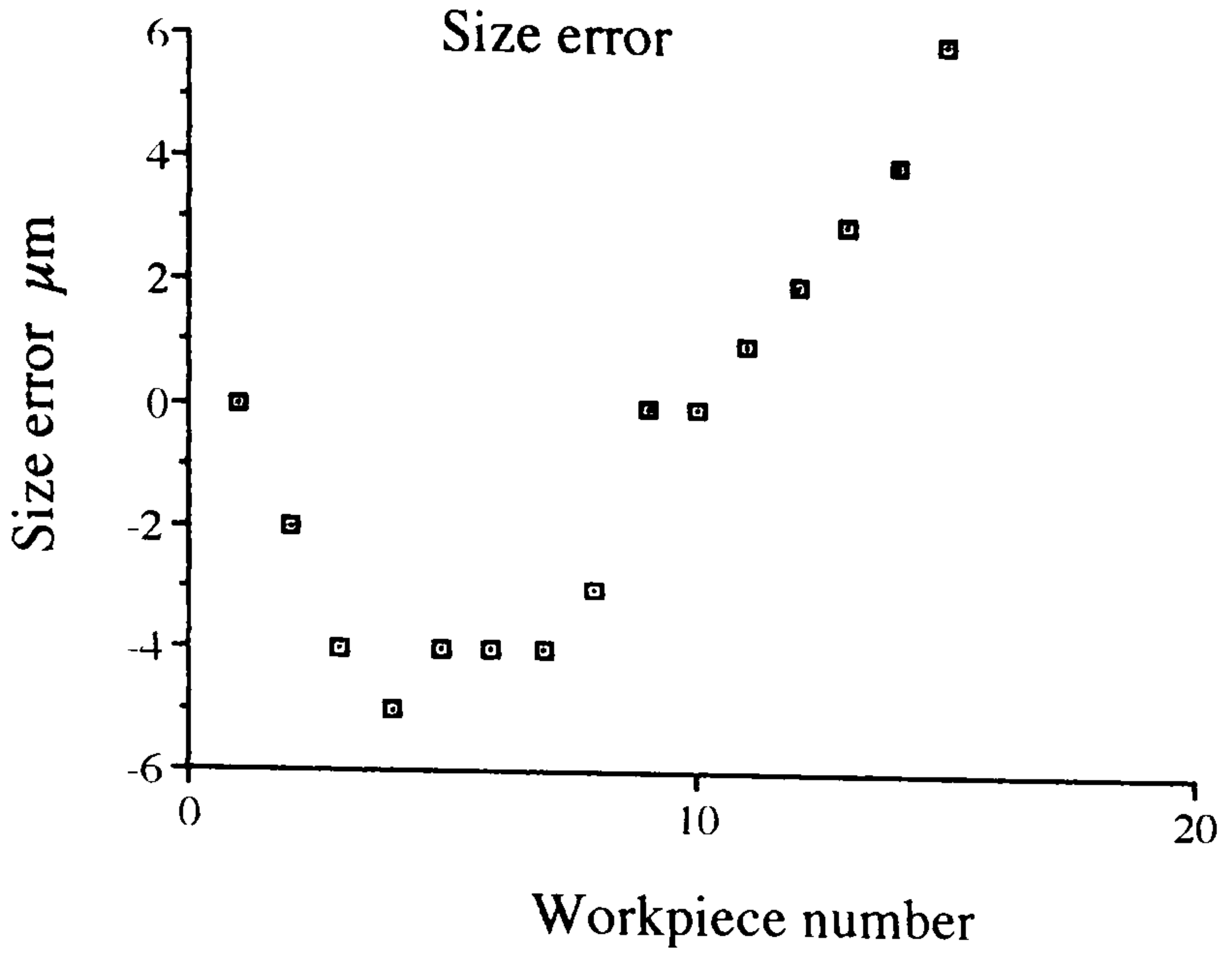


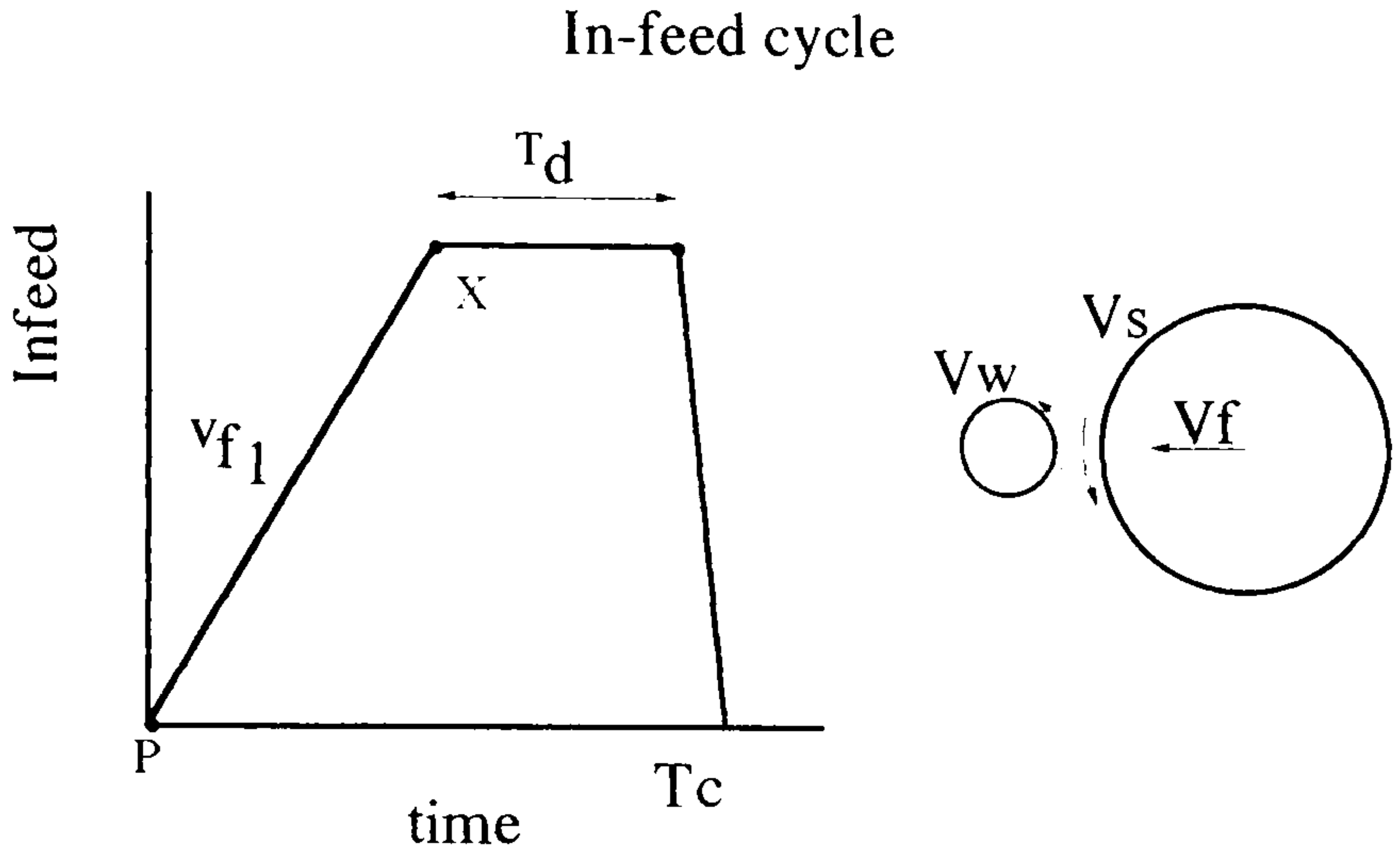
Figure 7.4 - A grinding cycle with diameter gauging. The start of the very fine infeed rate is varied to maintain a target the 'dwell time'. The infeed rate may also be adapted.



time constant approx 1s.
Wheel A465K5V30W.
Workpiece oil hardened cast steel.
ds = 450 mm, dw = 19 mm, b = 50 mm,
vw = 0.25 m/s, vs = 33 m/s,

Figure 7.5 - Size errors. Non - adaptive plunge grinding cycle without gauging

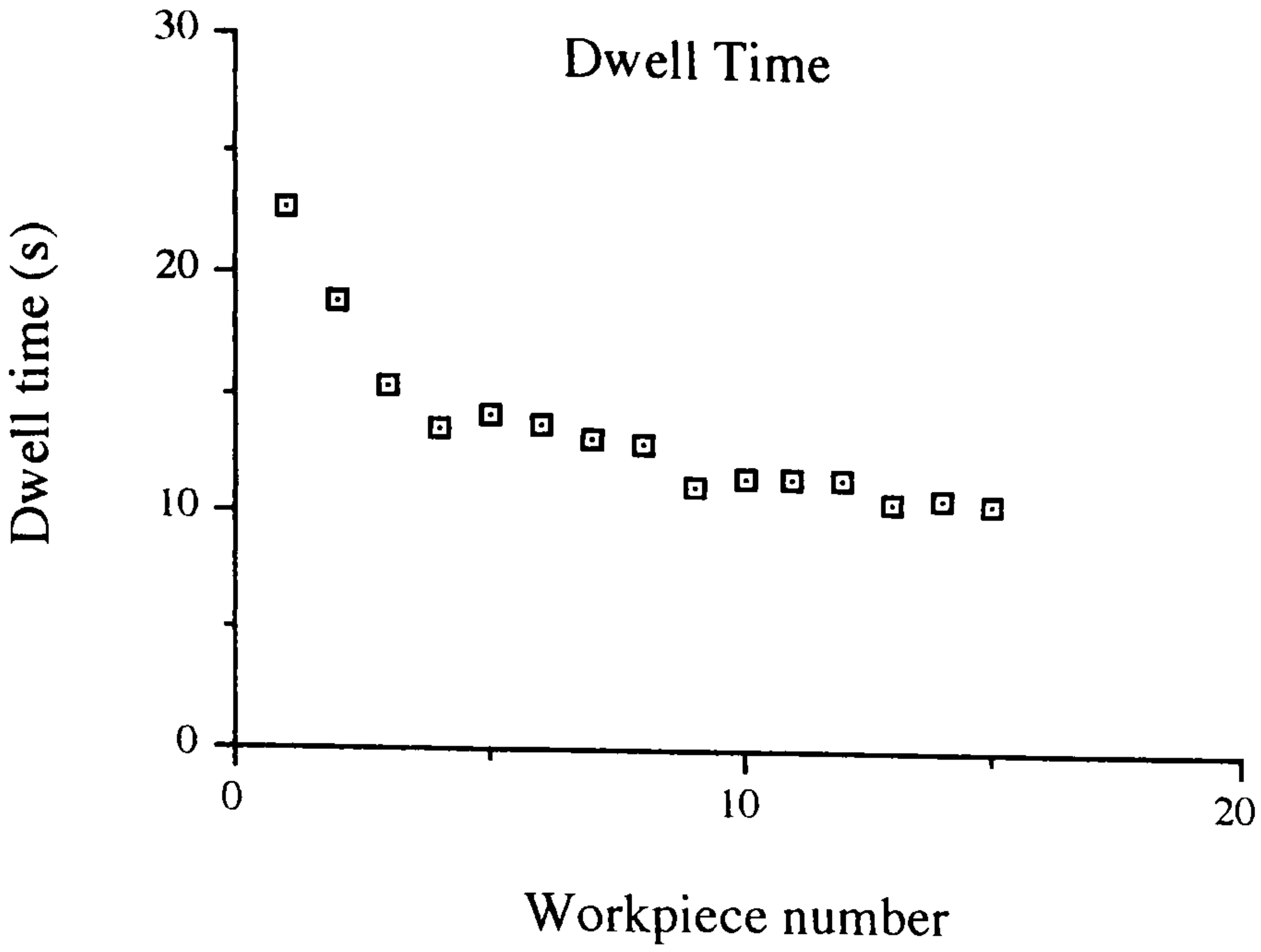


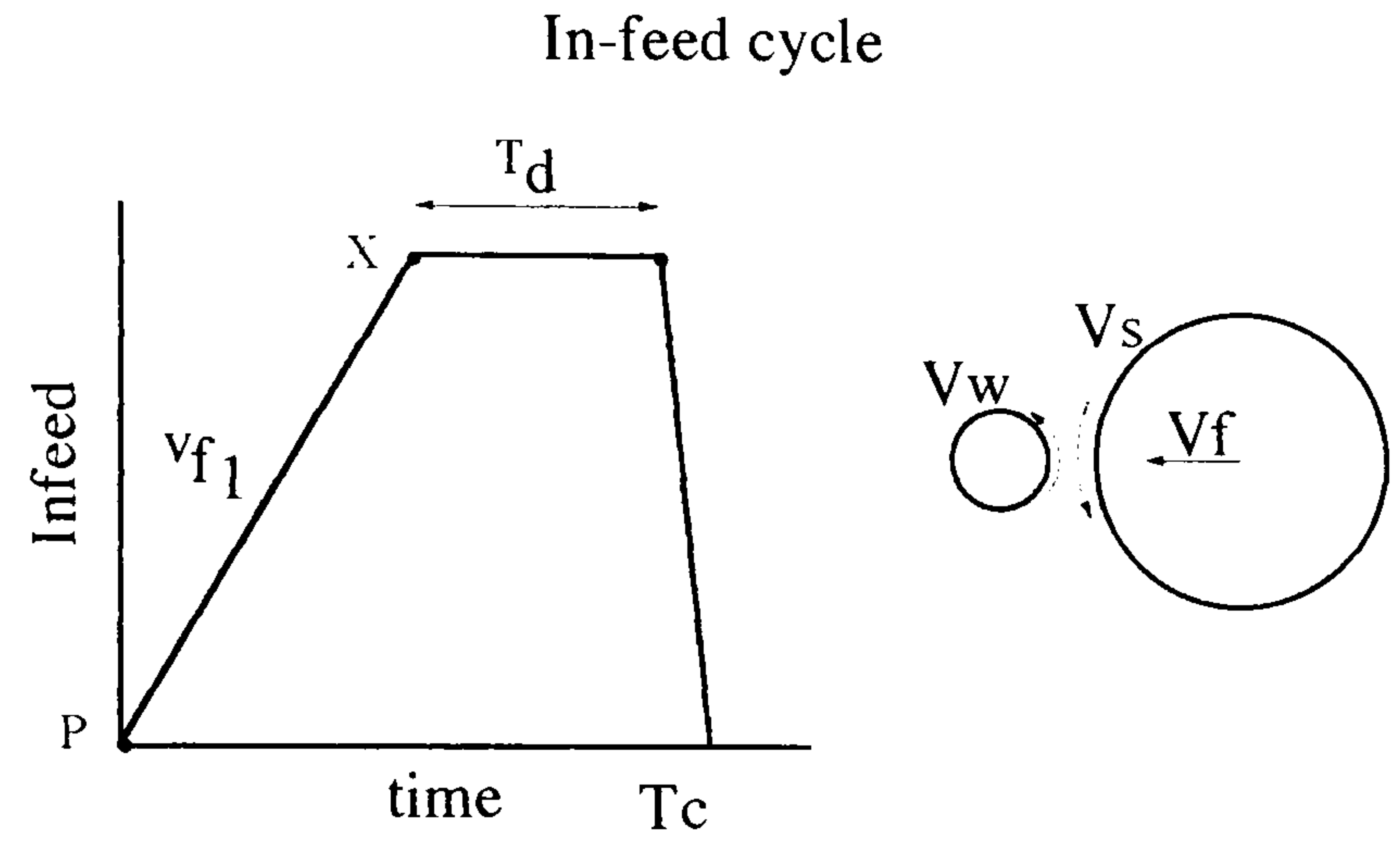


Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 0.005 μm/s Vf2 - Vf3 - Vw 15 m/min Vs 33 m/s Td 4 τ	P 48.638 mm I - J - X 48.338 mm Tc ~42 s Pt -	E 0.15 mm/rev I 0.005 mm N 5 every time ☐ once only *	material EN9 contact width 46 mm time constant ~3 s
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 7.6 - Size error. Adapting the dwell period when grinding flexible workpieces without diameter gauging.



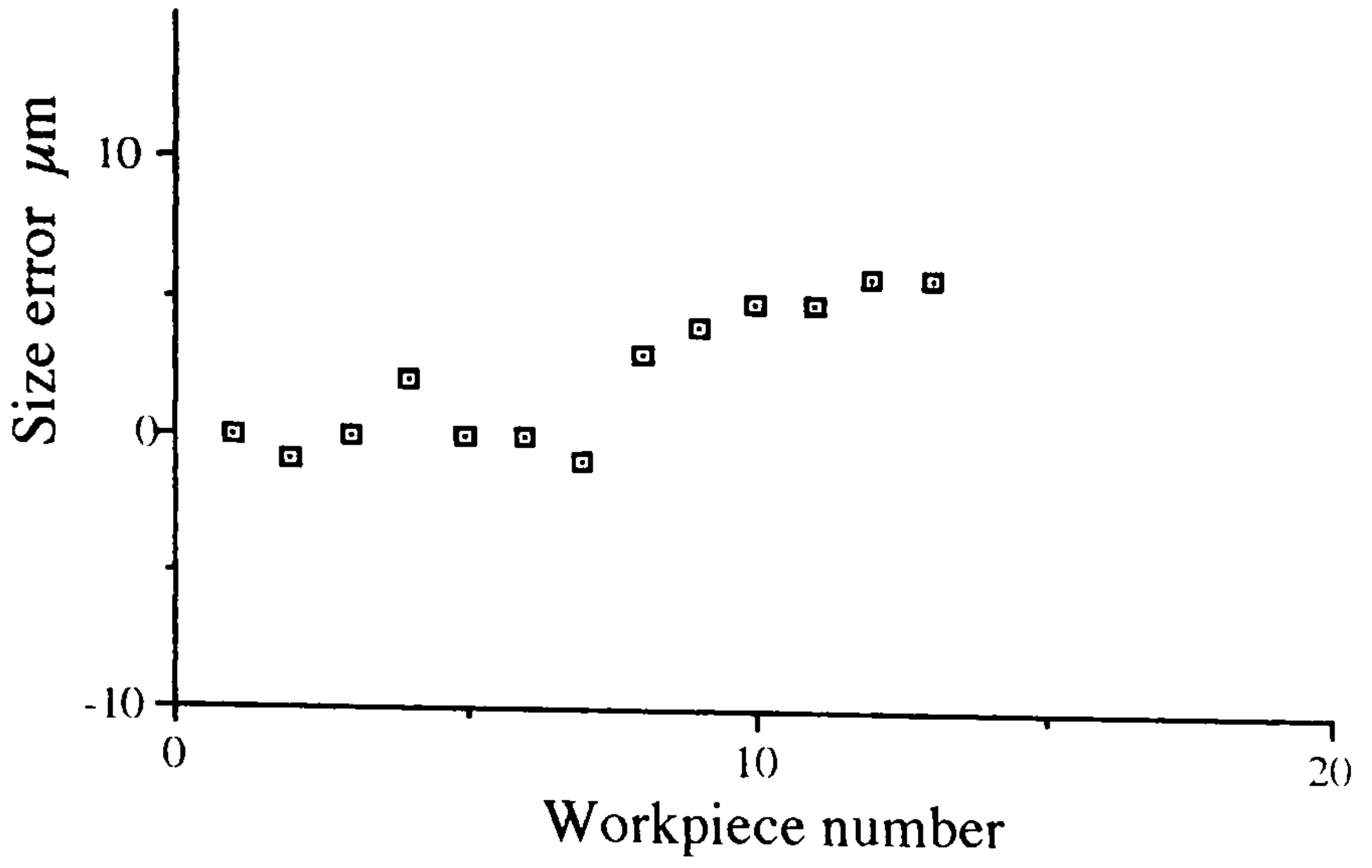


Experimental conditions

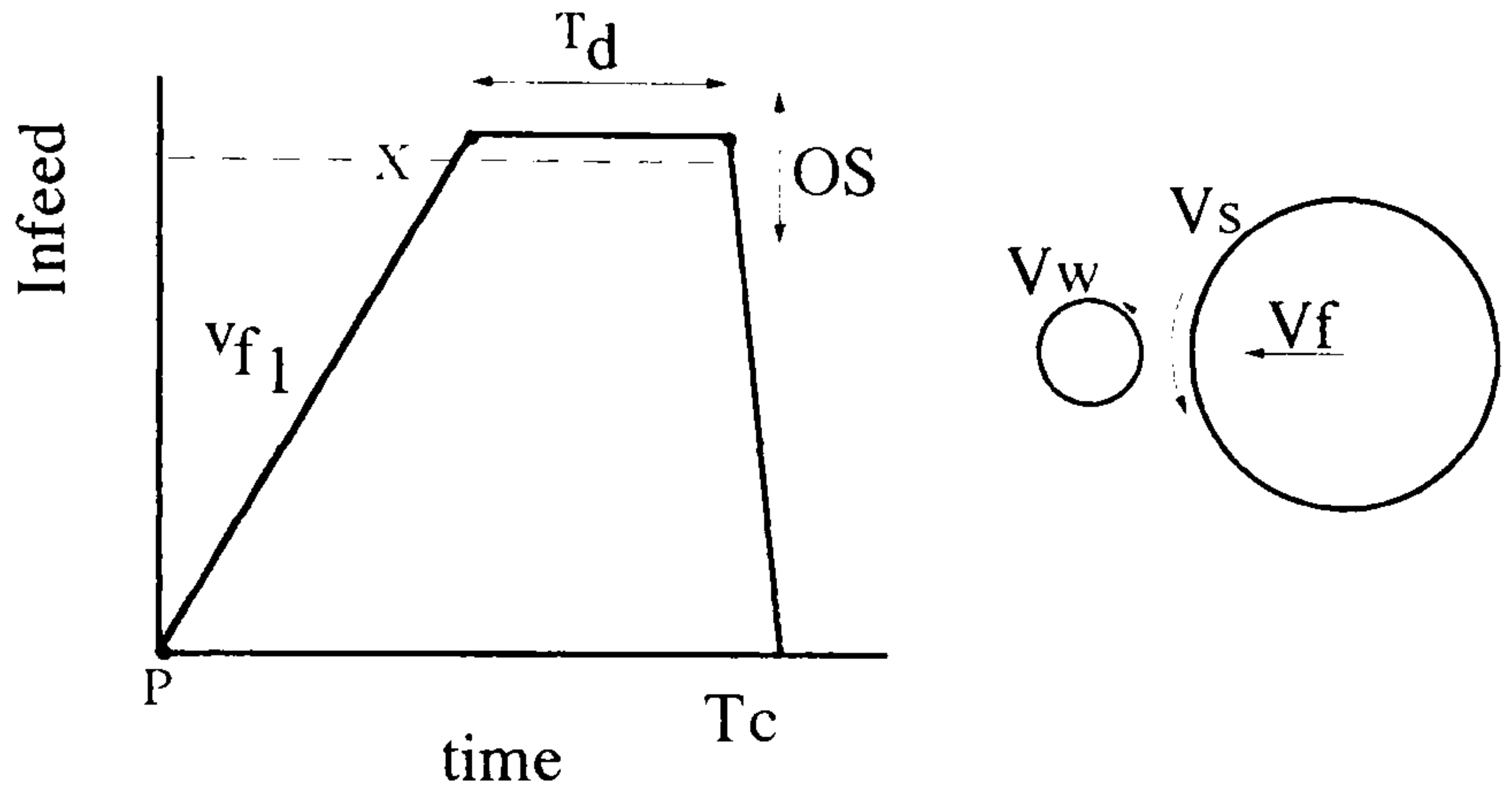
grinding parameters		dressing parameters	workpiece information
Vf1 0.005 μm/s	P 48.638 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~3 s
Vw 15 m/min	X 48.338 mm	every time	
Vs 33 m/s	Tc ~42 s	once only *	
Td 4 τ	Pt -		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 7.7 - Adapting the dwell period when grinding flexible workpieces without diameter gauging.

Size error



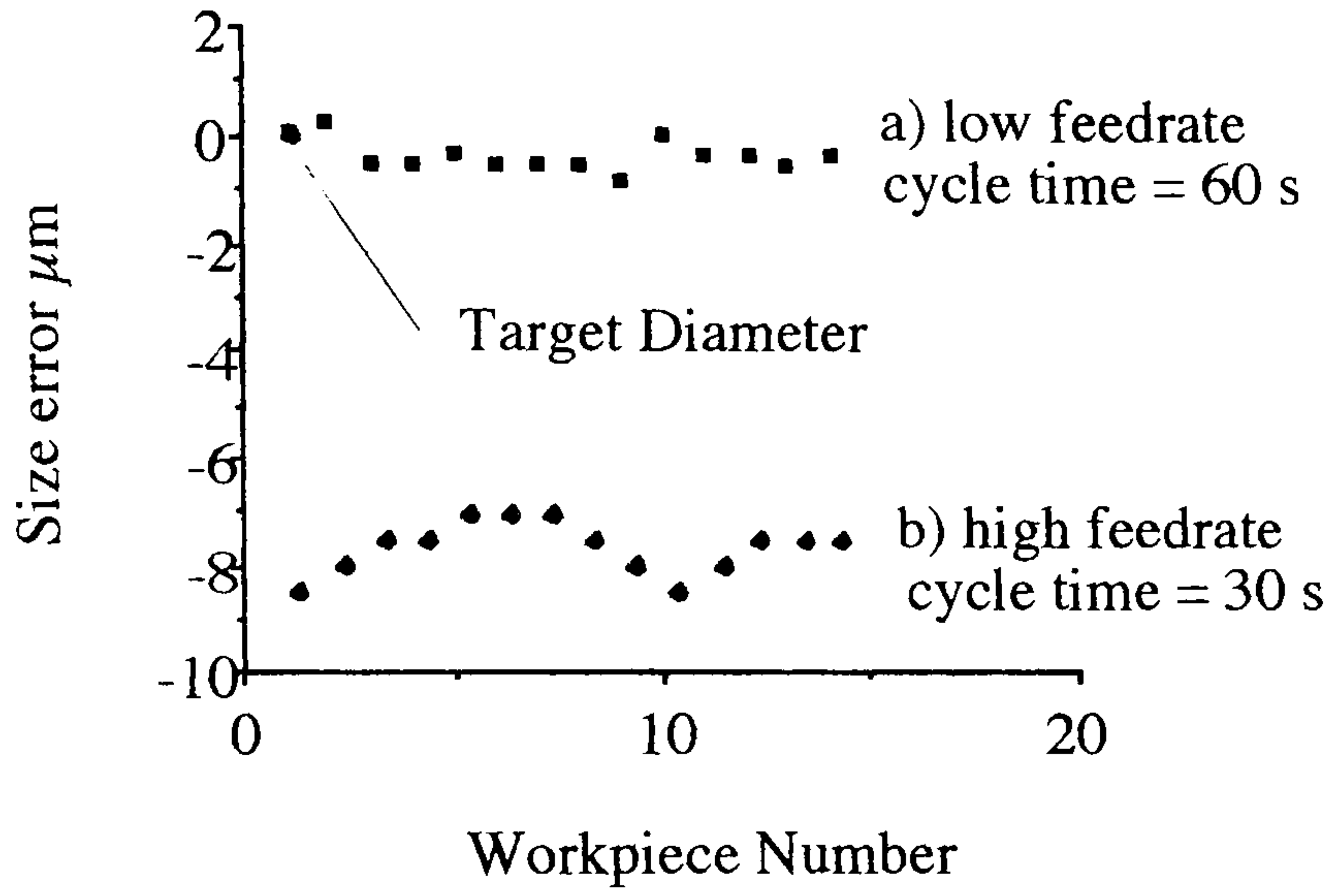
In-feed cycle



Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 0.005 μm/s	P 46.490 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~7 s
Vw 15 m/min	X 46.190 mm	every time ☐	
Vs 33 m/s	Tc ~ 44 s	once only *	
Td 2τ	Pt -		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

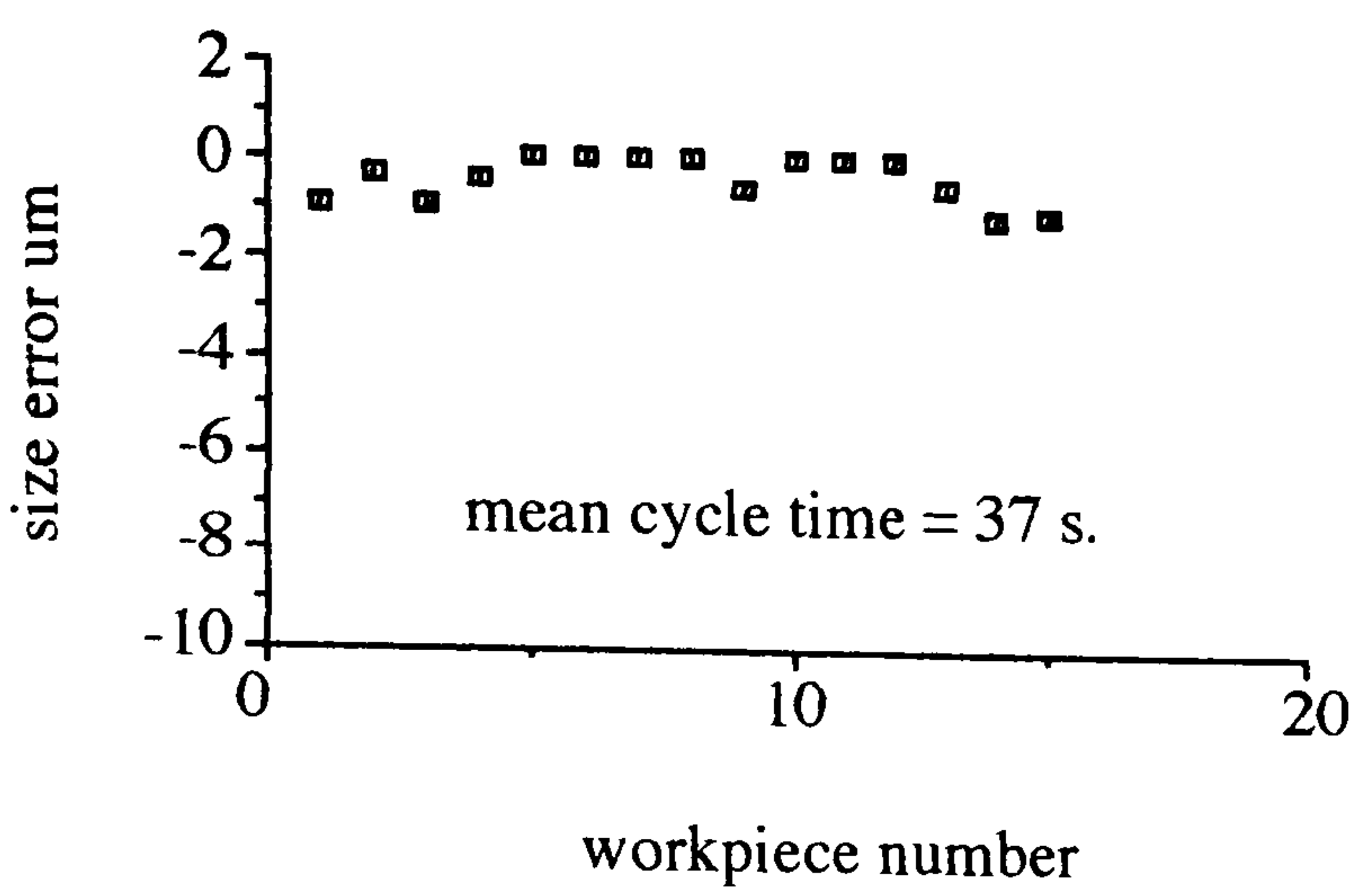
Figure 7.8 - Size error when adapting the dwell period and overshooting the target infeed position.



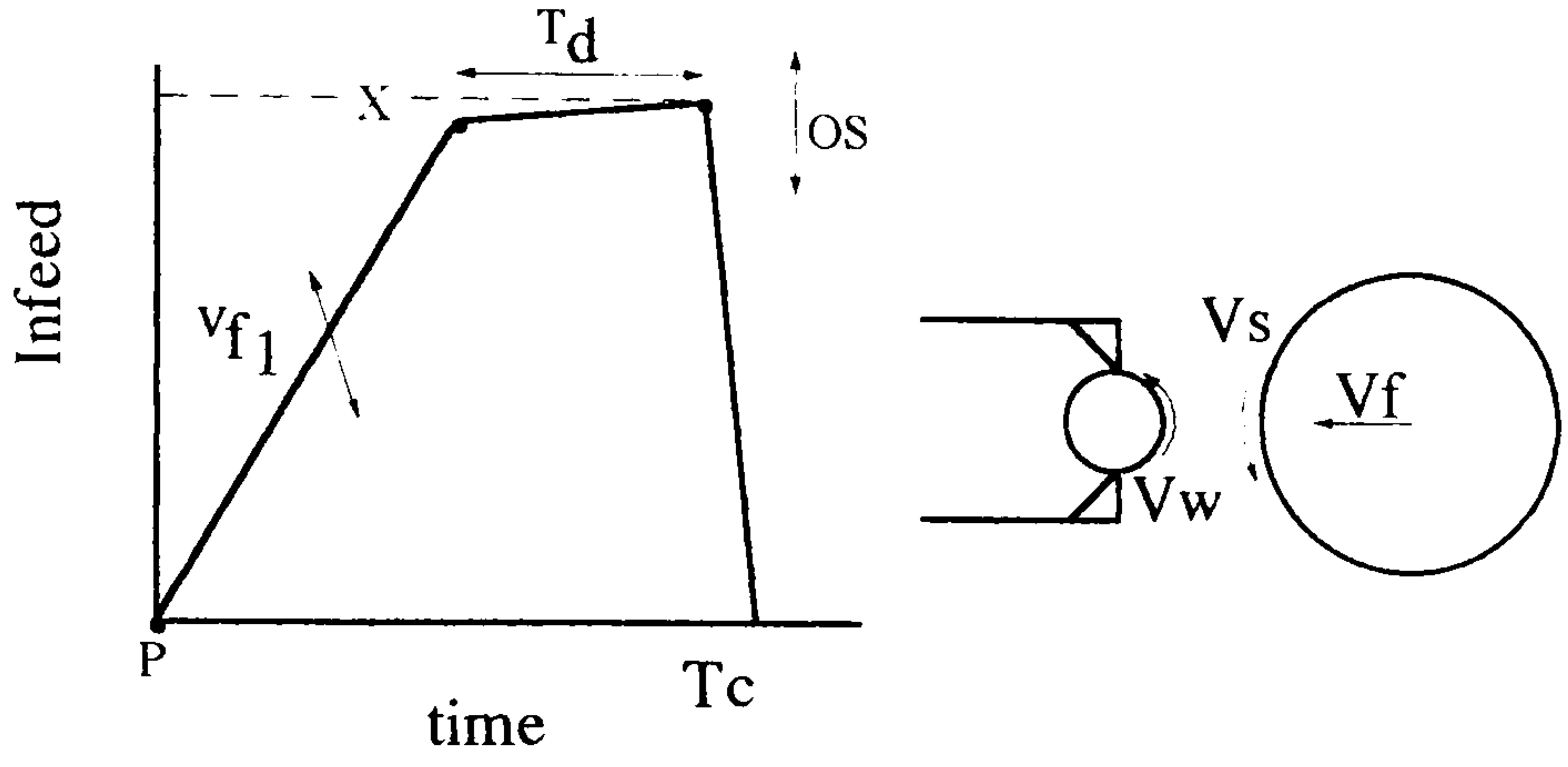
time constant = 3 s approx.
Wheel A465K5V30W. Workpiece EN9, ds=450mm, dw=46mm, b=50mm, vw=0.25m/s, vs=33m/s, vf low=5, 3, 1μm/s, vf high=9, 7, 5 μm/s.

Figure 7.9 - Size error. Non- Adaptive Plunge Grinding cycle with diameter gauging

Size error



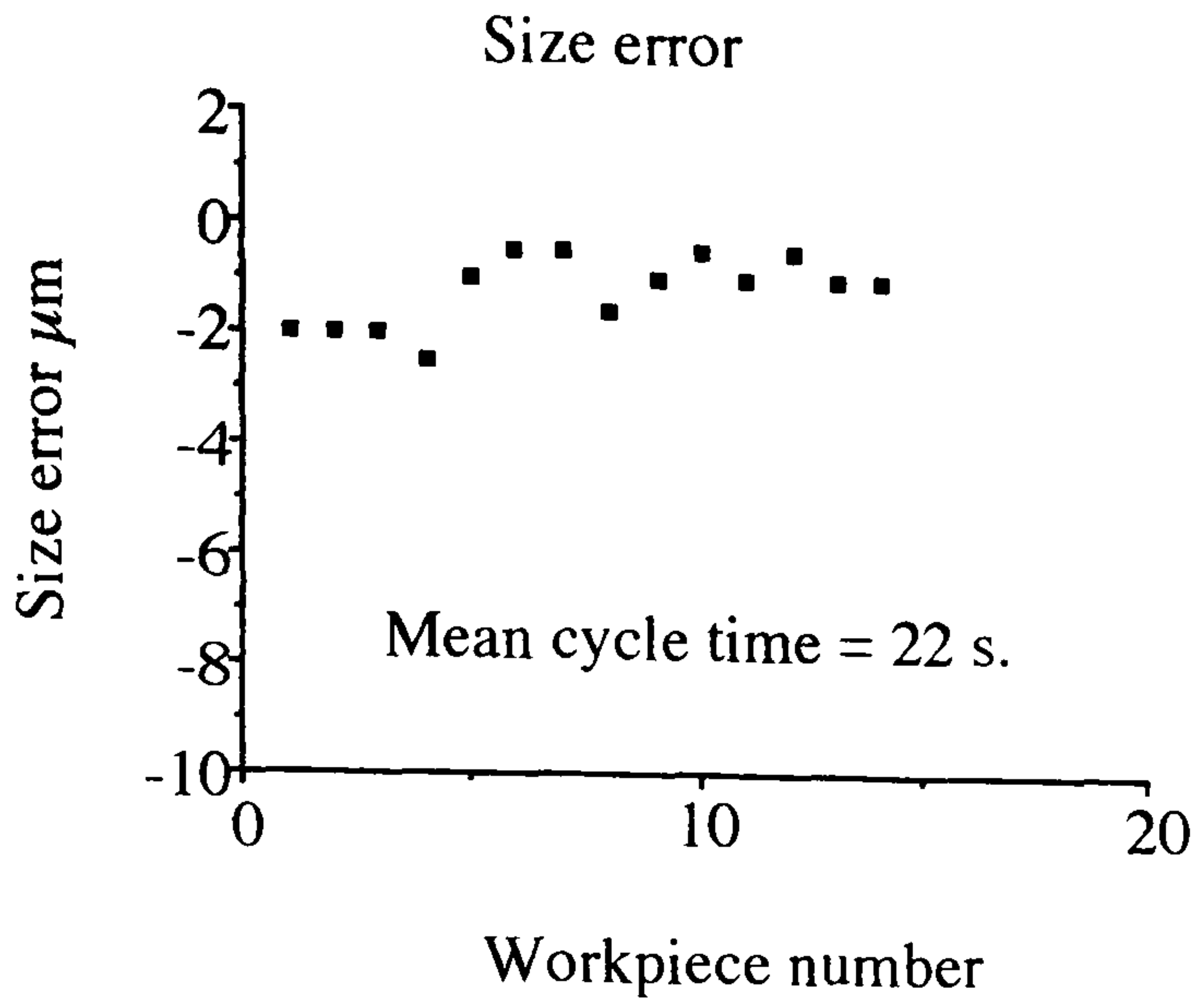
Infeed cycle

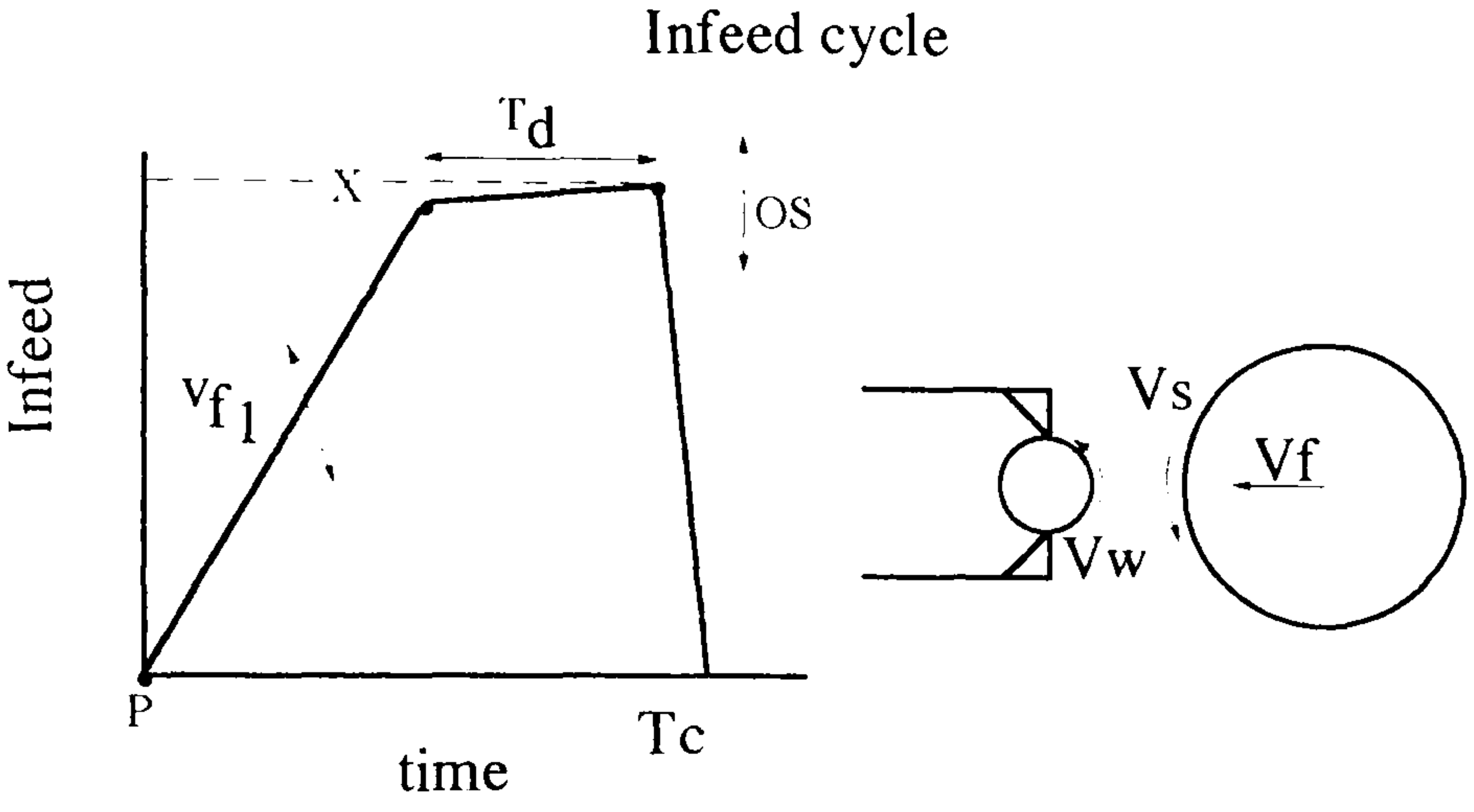


Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 -	P 36.501 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~2 s
Vw 15 m/min	X 36.181 mm	every time ☐	
Vs 33 m/s	Tc ~ 37 s	once only *	
Td 6τ	Pt - 2.5 kW		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 7.10- Size error when the dwell period of the gauging cycle was replaced by a fine infeed rate. Low taret power level.





Experimental conditions

grinding parameters		dressing parameters	workpiece information
Vf1 10 - 13 μm/s	P 38.566 mm	E 0.15 mm/rev	material EN9
Vf2 -	I -	I 0.005 mm	contact width 46 mm
Vf3 -	J -	N 5	time constant ~1-2 s
Vw 15 m/min	X 38.226 mm	every time ☐	
Vs 33 m/s	Tc ~ 22 s	once only *	
Td 6 τ	Pt - 5 kW		
grinding wheel: A465K5V30W, ds 450 mm		dressing tool: multi point diamond	coolant: synthetic

Figure 7.11 - Size error. Adaptive plunge grinding cycle with gauging. High target power level.

8 CONCLUSIONS

It has been shown that adaptive control offers substantial advantages for productivity compared to conventional CNC grinding, while attaining the high accuracy levels required of precision grinding. Initial trials have shown significant improvements in terms of reduced cycle times and set-up times, reduced supervision requirements, improved size holding capabilities and ease of use.

The concept of an intelligent data base, based on storing kinematic parameters, has been explored. It has been shown that is possible to select initial values of infeed rate and workpiece speed for various workpieces ground using the same material and type of grinding wheel. This is the first step towards providing a fully intelligent system for the selection of grinding conditions.

The strategy of adapting infeed rate from one grinding operation to the next to maintain the grinding power level is a relatively simple strategy to incorporate into a CNC system. It can be readily implemented on machine tool controllers, which conventionally move machine tool axes from point to point at a constant feedrate. The application of adaptive feedrate allows removal rate to be increased to the maximum rate consistent with the desired quality level, and also to be maintained at the maximum rate consistent with the surface condition of the grinding wheel. Shorter cycle times and reduced process variability have been achieved.

Controlling the spark-out process by adapting the dwell period and the final infeed position, has allowed good size holding capability without incurring excessive cycle time. A new method for in-process identification of the system time constant from the grinding power allows real-time adjustment of the sparkout period both with and without diameter gauging. This contributes towards a practical, widely applicable system, and represents a major advantage over previous systems that relied on in-process diameter gauging.

A new plunge grinding cycle with gauging has been proposed, with the dwell period replaced by a very fine infeed rate. This allows the deflection of the machining system to relax and the workpiece to cool. The grinding wheel is retracted when the required workpiece size is indicated by the gauge. The cycle compensates for infeed position errors caused by wear of the wheel and dressing tool. At low removal rates the accuracy is comparable to the non-adaptive gauging cycle. Furthermore, at high removal rates the adaptive cycle is considerably more accurate than the non-adaptive cycle. In addition set-up time is reduced, because the user is not required to experiment with gauge settings to achieve correct operation of the grinding cycle.

An adaptive control system has been designed, based on interfacing a personal computer to a CNC grinding machine. The new system has been developed with suitability for commercialisation as an important pre-requisite, and is broadly equivalent to the latest CNC systems incorporating a p.c. partition. A practical and widely applicable system has been achieved through the use of sensors that can be installed without major modifications, and do not interfere with the operation of the machine. In addition, algorithms and strategies have been designed specifically for implementation on the latest generation of machine tool controllers.

9 RECOMMENDATIONS FOR FURTHER WORK

The development of adaptive control systems draws on techniques from a number of fields, including process modelling, the formulation of adaptive strategies, control system design and instrumentation. Regarding process theory, there remains considerable scope for the development of process models using conventional techniques. However, there is also scope for the application of artificial intelligence techniques such as neural networks, fuzzy logic and expert systems to adaptive control systems. Rowe, Yan and Malkin (1994) consider future directions for knowledge based systems, adaptive control optimisation and artificial intelligence.

There are also opportunities for developing the adaptive strategies. New advances in gauging systems allow full communications with the control system. The gauge points may now be set by the control system and as a result it is now feasible to implement more advanced adaptive strategies for gauging. It is also feasible to compensate for wear without the use of a diameter gauge, based on workpiece size measurements made by the operator and input to the control system.

In order to reduce the time taken for deflection to build up at the start of the grinding cycle, a high infeed rate could be used at start of cycle. This requires a high infeed rate to be maintained until the radius reduction or the grinding power approaches a desired value. A suitable grinding feed rate can then be resumed. The use of a high infeed rate at start of cycle to reduce the time taken for deflection to build up, combined with the identification of the system time constant, would represent an advance in controlling the grinding process. However, a very reliable or a failsafe method will be required to ensure the safety of this strategy.

The development of strategies for traverse grinding and face grinding would further enhance performance. Adaptive control optimisation of the wheel dressing process is likely to improve the results that can be achieved. Also, the development and evaluation of strategies for internal grinding represents an opportunity for further work.

The adaptive control strategies and algorithms proposed in this thesis were designed for implementation on modern controllers with the high level mathematics and file handling capabilities required for adaptive control. Appendix 4 outlines how the adaptive control software has been incorporated into the Allen Bradley 10 Series controller that has a p.c. partition. Further developments should include the adoption of an open system approach to control system design would allow adaptive control software to be incorporated more easily onto a range of different platforms, promising a reduction in development times and associated costs.

REFERENCES

Allanson D.R., Kelly S., Terry S., Moruzzi J.L. and Rowe W.B., Coping with Compliance in the Control of the Grinding Process, Annals of the CIRP Vol 38/1/89, pp311-314.

Amitay G., Malkin S., Koren Y., Adaptive Control Optimization of Grinding, Journal of Engineering for Industry, Vol 103, February 1981, pp 103-108.

Bell W.F., Lambert E.L., Practical Achievement and Monitoring of High Rate Internal Grinding, Part 1 - Machine Instrumentation and Data Acquisition, SME Technical paper MR88-611, presented at the 3rd International Grinding Conference, October, 1988.

Brinksmeier E., Popp C., A Selftuning Adaptive Control System for Grinding Processes, Annals of the CIRP, vol. 40/1/1991, pp 355-358.

Elbestawi M.A., Yuen A.K., Srivastava H.D., Adaptive Force Control for Robotic Disk Grinding, Annals of the CIRP, Vol. 40/1/1991, pp 391-394.

Gao Y., Jones B., An integrated Sensor System for Size and Roundness Control in Plunge Grinding, Int. J. Mach. Tools Manufact., Vol. 32, No. 3, pp 281-290, 1992.

Gao Y., Jones B., Webster J., An Integrated Size and Roundness Adaptive Control System for the Plunge Grinding Process, Int. J. Mach. Tools Manufact., Vol. 32, No. 3, pp 291-303, 1992.

Gao Y., Jones B., An Optimum Size and Roundness Adaptive Control Method for the Plunge Grinding Process, Proc Instn Mech Engrs, Vol 206, pp107-116, 1992.

Groover M.P., Zimmers E.W., CAD / CAM: Computer Aided Design and Manufacturing, 1984, Published by Prentice Hall, Englewood Cliffs, New Jersey, U.S.A.

Hahn R.S., Controlled Force Grinding - A New Technique for Precision Internal Grinding, J. Eng. for Industry, Trans. ASME, series B, 86, pp 287-293, 1964.

Hahn R.S., Some Characteristics of Controlled Force Grinding, Proc. 6th Int. Machine Tool Design and Research Conf., 1965.

Hahn R.S., Graham G., An Application of Force-Adaptive Grinding, SME Technical paper MR84-530 presented at the International Grinding Conference, Fontana, Wisconsin 1984.

Hahn R.S., Improving Perormance with Force-adaptive Grinding, Manufacturing Engineering, October 1986, p73.

He Xiu-Shou, The Research of a Practical Adaptive Control System for External Cylindrical Grinding Process, Proceedings of the 25th International Machine Tool Design and Research Conference, Birmingham 1985, pp 169-175.

Hideo Inoue, Kazutaka Tamakohri, Tetsuya Sutoh, Hohsei Noguchi, Tohru Waida, An Adaptive System of Grinding Process, Proceedings of the International Conference on Production Engineering, Tokyo 1974, part 1, pp 671-676.

Inasaki I., Monitoring and Optimisation of Internal Grinding Process, Annals of the CIRP, Vol. 40/1/91., pp 359-362.

Kaliszer H., Mishina O., Webster J., Adaptively Controlled Surface Roughness and Roundness During Grinding, 20th MTDR Conference, 1979.

Kaliszer H., Adaptive Control in Grinding Processes, Proceedings of the 4th International Conference on Production Engineering, Tokyo 1980, pp 579-593.

Kelly S., Rowe W.B., Moruzzi J.L., Adaptive Grinding Control, Adv. Manuf. Eng., Vol 1, October 1989, pp 287-295.

Kim S.W., Shumsheruddin A.A., Adaptive Computerised Numerical Control of Grinding Process for Industrial Applications, Proceedings of the 24th International Machine Tool Design and Research Conference 1983, pp 239-246.

Koelsch J.R., Ease the Grind in Small Shops, Manufacturing Engineering, February 1992, pp 35-40.

Konig W., Werner G., Adaptive Control Automisation of High Efficiency External Grinding - Concept, Technological Basics and Application, Annals of the CIRP, Vol. 23/1/1974., pp101-102.

Liverton J., Major Improvements to Precision Grinding Brought About by the Application of CNC, SME Technical Paper MR90-521, presented at the 4th International Grinding Conference, Dearborn, Michigan, October 1990.

Malkin S., Koren Y., Off-line Grinding Optimisation with a Micro-Computer, Annals of the CIRP, Vol. 29/1/1980, pp 213 - 216.

Malkin S., Grinding Cycle Optimisation, Annals of the CIRP, Vol. 30/1/1981, p222-226.

Malkin S., Koren Y., Optimal Infeed Control for Accelerated Spark-Out in Plunge Grinding, Journal of Engineering for Industry, Vol. 106, February 1984, pp 70-74.

Malkin S., Practical Grinding Optimisation, SME Technical Paper MR86-637, presented at the International Grinding Conference, June 1986.

Peters J., Aerons R., Optimisation Procedure of Three Phase Grinding Cycles of a Series without Intermediate Dressing, Annals of the CIRP, Vol. 29/1/1980, pp 195-

197.

Ralston P.A.S., Ward T.L. , Adaptive Control of Machine Tools: The Past and Projected Role of Numerical Control Computers, Computers ind. Engng, Vol.1, No.2, 1988, pp 85-94.

Rao G.R., Malkin S., Process Monitoring for Intelligent Control of Grinding, SME Technical paper MR90-512, presented at the 4th International Grinding Conference, October 1990.

Rowe W.B., Bell W.F., Brough D., Limit Charts for High Removal Rate Centreless Grinding, Int. J. Mach. Tools Manufact., Vol. 27, No. 1, 1987, pp 15-25.

Rowe W.B., Pettit J.A., Boyle A., Moruzzi J.L., Avoidance of Thermal Damage in Grinding and Prediction of the Damage Threshold, Annals of the CIRP, Vol. 37/1/1988, pp 327 - 330.

Rowe W.B., Allanson D.R., Pettit J.A., Moruzzi J.L. and Kelly S., Intelligent CNC for Grinding, Proc Instn Mech Engrs, Vol 205, 1991, pp 233-239.

Rowe W.B., Yan L., Malkin S., Applications of Artificial Intelligence in Grinding, Annals of the CIRP, Vol. 43/2/1994.

Smith R.L., Energy-Adaptive CNC of Precision Grinding, Cutting Tool Engineering, January / February 1980, pp 3, 4, 6,7,10.

Spiewak S., Kaliszer H., Multi-microprocessor Control for Plunge Grinding, Proceedings of 24th International MTDR Conference, 1983, pp 247-257.

Spiewak S., Kaliszer H., In-process measurement of Roughness in Plunge Grinding Operations, Proc. 24th Int. MTDR conference, 1983.

Sprow E., Grinding Controls Go CNC, Tooling and Production, May 1991, pp 48-51.

Stelson T.S., Komanduri R., Shaw M.C., Manual Adaptive Control of a Centreless Grinding Operation, Int. J. Prod. Res., Vol. 17, No. 2, pp 111-121, 1979.

Storm T., Adaptive Control in cut-off Grinding, Proceedings of the MTDR Conference, 1970, pp 455-464.

TenClay D.,CNC Grinding for the U.S., Tooling and Production, November 1989, pp 92-94.

Terada K., What's Happening in CNC Grinders, Metalworking Engineering and Marketing, May 1990, pp18-23.

Toenshoff H.K., Process Control in Internal Grinding, Annals of the CIRP, Vol. 29/1/80.

Toenshoff H.K., Zinngrebe M., Kemmerling M., Optimisation of Internal Grinding by Microcomputer-Based Force Control, Annals of the CIRP Vol. 35/1/1986, pp 293-296.

Trmal G.J., In-process Control of Size of a Ground Component, Proc. 20th Int. MTDR Conf., 1979, pp 405-411.

Ulsoy A.G., Koren Y., Rasmussen F., Principal Developments in the Adaptive Control of Machine Tools, Journal of Dynamic Systems, Measurement, and Control, June 1983, Vol. 105, pp 107-112.

Ulsoy A.G., Koren Y., Applications of Adaptive Control to Machine Tool Process Control, IEEE Control Systems Magazine, June 1989, pp 33-37.

Wada R., Kodama H., Adaptive Control in Grinding, Bull. Japan Soc. Prec. Eng., Vol. 11 No.1, Mar 1977, pp1-10.

Webster J., Zhao Y.W., Time Optimum Adaptive Control of Plunge Grinding, Int. J. Mach. Tools Manufact., Vol. 30, No 3, pp 413-421, 1990.

Xiao G., Malkin, S., Danai, K., An Autonomous system for Cylindrical Plunge Grinding, Proceedings of the NSF Design and Manufacturing Systems Conference, 1993, pp 399-403.

Younis M.A., An Equivalent Chip Coefficient Towards an Adaptive Controlled Grinding Process, Proc Instn Mech /engrs, Vol 204, pp 61-70, 1990.

Zimmers E.W., Groover M.P., CAD/CAM: Computer Aided Design and Manufacturing, Prentice Hall International.

Zhao Y.W., Webster J., Kaliszer H., In-process Size and Roundness Measuring System for the Adaptive Control of Grinding, proc. 27th MTDR conference 1988.

Zhu J.Y., Shumsheruddin A., Optical technique for In-Process Measurement for Surface Roughness during A.C.C. Grinding, Proc. 22nd Int. MTDR Conference 1981.

APPENDIX 1 Specification of the Jones & Shipman Series 10 Cylindrical Grinding Machine

(Imperial dimensions unless taken to decimal are approximate)

Dimensions		Series 10 450	Series 10 700	Series 10 1000	Series 10 2000
Grinding length between centres					
(parallel wheelhead)	mm(")	450(18)	700(27)	1000(39)	2000(79)
(angled wheelhead)	mm(")	200 (8)	450(18)	750(30)	1750(69)
Maximum diameter ground with new new wheel	mm(")	250(10)	250(10)	250(10)	250(10)
Height from table top to centres					
(parallel wheelhead)	mm(")	127 (5)*	127 (5)*	127 (5)*	127 (5)*
(angled wheelhead)	mm(")	175 (7)	175 (7)	175 (7)	175 (7)
Table swivel		1° 1°	1° 1°	1° 1°	1° 1°
Net weight (approx.)	kg/lb	2040/4500	2310/5100	2630/5800	3080/6800
Gross weight (approx.)	kg/lb	2580/5700	3000/6600	3630/8000	4540/10000

* available with 178mm (7") centre height as an option

COMMON TO ALL MACHINES

Workhead (Dead Centre)

Workhead speed range continuously variable	40-450 rpm	40-450 rpm
Motor (D.C.)	1,1 kW	1½ hp

Table (Z Axis)

Traverse speed, per min	0,06 to 12000mm	0.002" to 4762.5"
Minimum programmable increment	0,001mm*	0.0001"
Servo input resolution	0,001mm*	0.00004"

* Optional 0,001mm programming is available

Wheelhead (X Axis)

Wheelhead Motor	5,6 kW	7.5hp
Infeed amount	200mm	8"
Infeed speed range (linear) per min.	0,06 to 5000mm	0.002 to 197"
Minimum programmable increment (diameter)	0,001mm*	0.00004"
Servo input resolution (linear)	0,0002mm*	0.00001"

* Optional 0,0001mm programming is available.

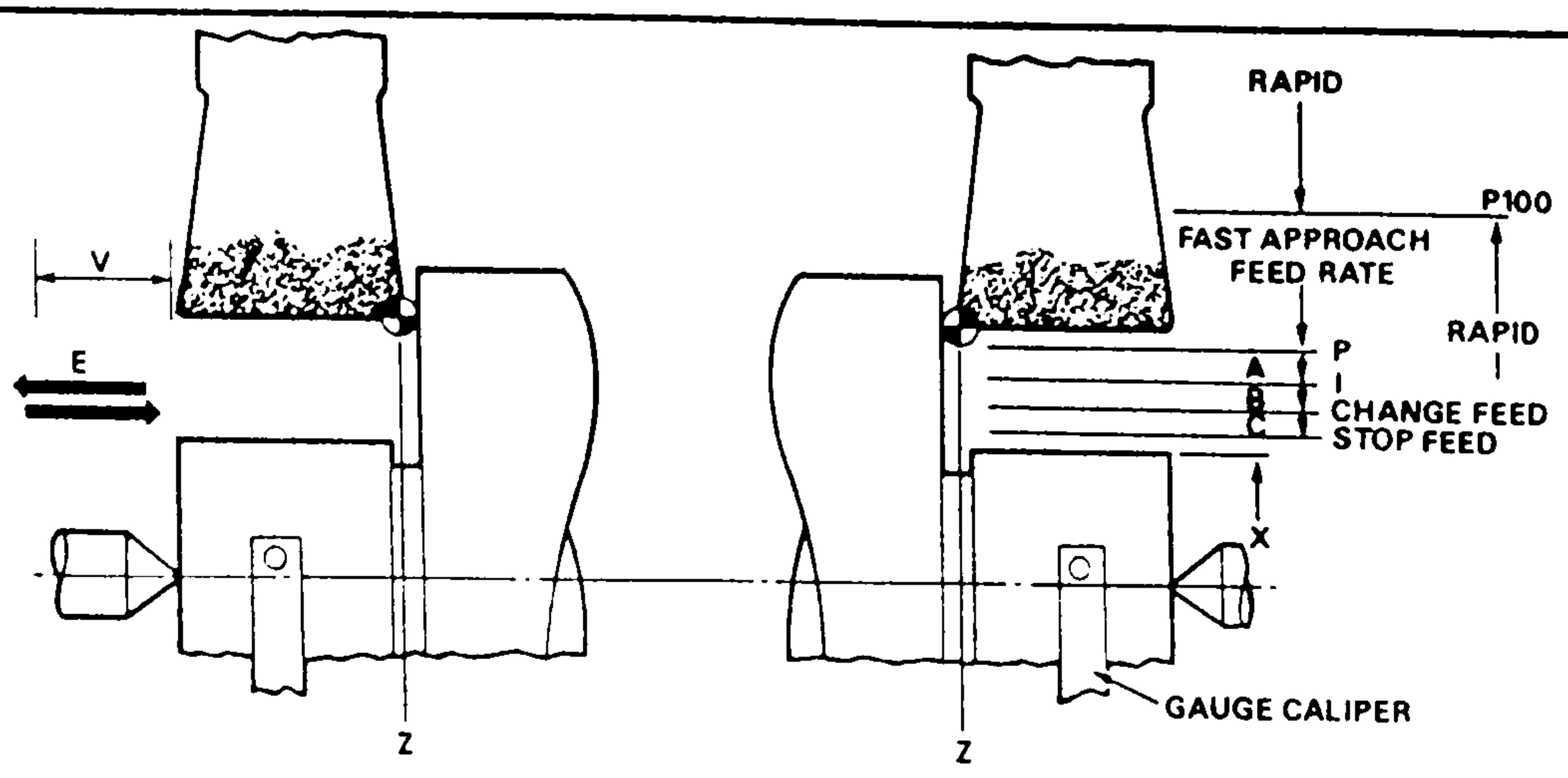
Grinding Wheel

Wheel diameter	450mm	18"
Wheel bore (standard)	127mm	5"
Wheel bore (option)	203mm	8"
Wheel width (standard)	50mm	2"
Wheel width (maximum)	80mm	3 1/8"
Wheel peripheral speed (standard)	33m/s	6500ft/min
Wheel peripheral speed (standard)	45m/s	9000ft/min

APPENDIX 2 Specification of Plunge Grinding Cycles for the Jones & Shipman Series 10 Cylindrical Grinding Machine

A 2.1 G82 Plunge Grinding Using Diameter Gauge and Auto Offset

G82	PLUNGE GRINDING USING DIAMETER GAUGE AND AUTO OFFSET



DATUM ON RH FACE OF WHEEL
Q1

DATUM ON LH FACE OF WHEEL
QO

WORDS THAT MUST BE PROGRAMMED	X Z P Q I A

WORD	DESCRIPTION	Words that must be programmed ● or assumed value if not programmed.
X	Final diameter size as signalled by gauge (mm)	●
Z	Z axis position of left or right hand wheel face. (mm)	●
P	Coarse grinding feed start point. (mm)	●
Q	Format modifier: Datum LH or RH of wheel Q = 1 RH edge Q = 0 LH edge	●
I	First feed change point (coarse to medium). Gauge actuated to contact workpiece. (mm)	●
A	Coarse grinding feedrate. (mm/s)	●
B	Medium grinding feed rate. (mm/s)	50% of feed rate A
C	Fine grinding feed rate. (mm/s)	50% of feed rate B
E	Table oscillation feedrate (mm per sec)	0 (zero)
V	Table oscillation distance (mm)	0 (zero)

SEQUENCE

1. Wheel moves to P100 at rapid feedrate
2. Table moves at rapid feedrate to Z
3. Wheel moves to P at fast approach feedrate.
4. Wheel moves to first feed change point I at coarse grinding feed rate.
5. Diameter gauge contacts workpiece. (If undersize is signalled then **'AT SIZE'** appears on the CRT, the wheel retracts to P100 and the program is stopped).
6. Wheel moves towards X at medium grinding feedrate B.
7. When first gauge signal is received the wheel moves towards diameter X at feedrate C.
8. When the "stop feed" gauge signal is received, the wheel stops and sparkout begins.
9. Table oscillation commences if E is programmed.
10. As the component sparks out its size is reduced. When the size signal is received from the gauge the current CAR X value is compared with the programmed X value, and if different the control automatically re-datums the wheel. The difference (offset) is displayed as OS on the CRT. The gauge retracts and the wheel also retracts to P100.
11. If during sparkout the size signal is not received after 30 seconds (default value of P118), the wheel and gauge are retracted and SIZING FAILURE 000003 appears on the CRT. As the size signal has not been received automatic re-datuming of the wheel position does not therefore take place.

EXAMPLE

G82	X50.210	Z30.000	A.010	I50.300	P50.500	Q0

EXAMPLE OF CYCLE WITHOUT DEFAULT VALUES

G82	X50.210	Z30.000	A0.010	I50.300	B0.004	C0.001	P50.500	Q0

EXAMPLE OF CYCLE WITH TABLE (Z AXIS) OSCILLATION

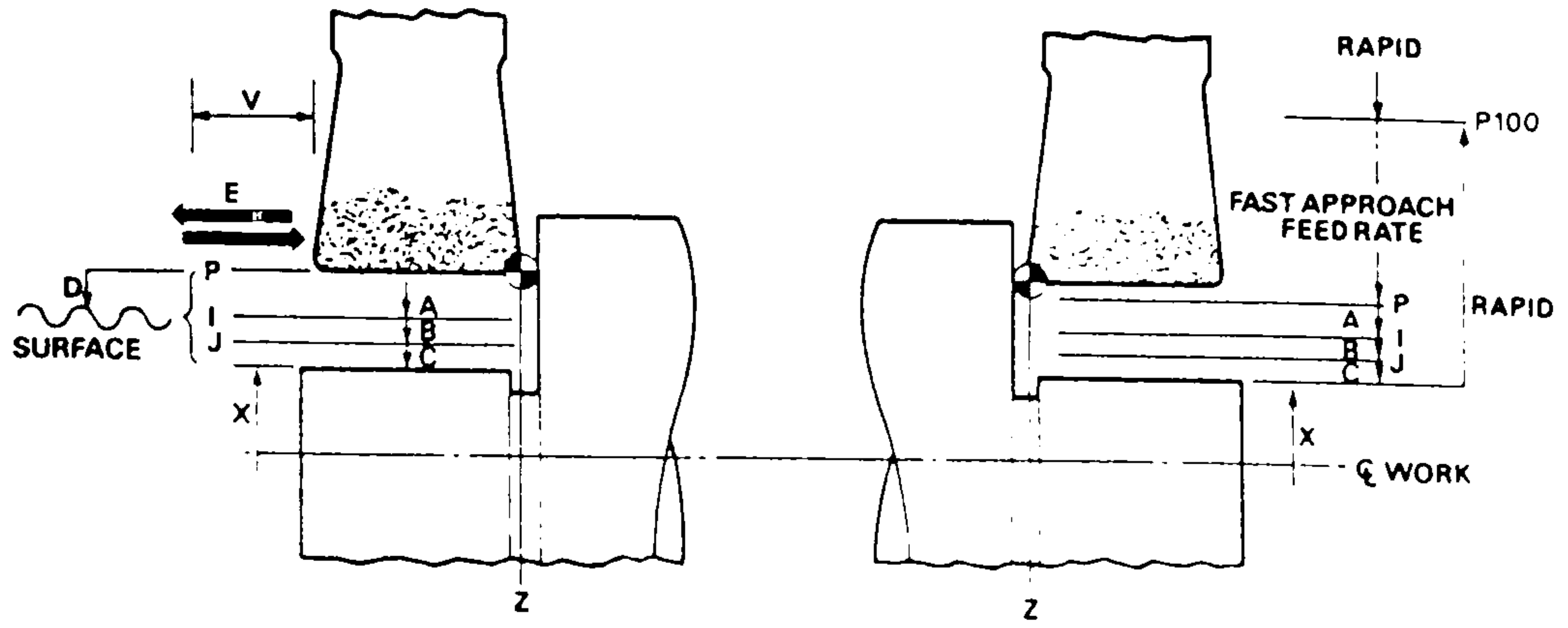
G82	X30	Z100.1	Q0	P30.25	I30.15	A.008	E3	V3

PROGRAMMING NOTES

1. Various checks for errors are made in G82. When an error is detected a message is displayed on line 1 of the CRT.
   The messages are:-
   GAUGE ERROR 000001 - first gauge point not found
   GAUGE ERROR 000002 - second gauge point not found
   SIZING FAILURE - size not found after 30 seconds
   AT SIZE 000001 - size found before first gauge signal
   AT SIZE 000002 - size found before second gauge signal
   AT SIZE 000003 - size found immediately after second gauge signal
2. When an error is detected the part program halts. It can however be re-started by pressing the cycle start key so that subsequent part program blocks can be executed.
3. Ensure Q is correctly entered. If programmed incorrectly the wheel can move at semi-rapid from P100 to P on the metal side of the shoulder.
4. When oscillation is programmed the direction of oscillation moves the shoulder away from the datum edge of the wheel. ie, if Q0 the table moves to the left; if Q1 the table moves to the right. The programmer should always ensure that sufficient tolerance exists on the other side of the wheel to accommodate the programmed oscillation distance.

A 2.2 G88 Plunge Grinding

G88	PLUNGE GRINDING



DATUM ON RH EDGE OF WHEEL Q=1

DATUM ON LH EDGE OF WHEEL Q=0

WORDS THAT MUST BE PROGRAMMED	X Z P Q A

WORD	DESCRIPTION	**Words that must be programmed ● or assumed value if not programmed.**
X	Final diameter size (mm)	●
Z	Z axis position of left or right hand wheel face (mm)	●
P	Coarse feed grinding start point. (mm)	●
Q	Format Modifier: Datum LH or RH of wheel Q = 1 RH Edge Q = 0 LH Edge	●
I	Feed change point - coarse to medium (mm)	After 75% of stock removal
J	Feed change point - medium to fine (mm)	After 90% of stock removal
D	Gap elimination feedrate (mm per sec)	No gap elimination
A	Coarse grinding feedrate (mm per sec)	●
B	Medium grinding feedrate (mm per sec)	50% of feedrate A
C	Fine grinding feedrate (mm per sec)	50% of feedrate B
S	Sparkout time at final size (sec)	0 (zero)
E	Table oscillation feedrate (mm per sec)	0 (zero)
V	Table oscillation distance (mm)	0 (zero)
R	Number of oscillation cycles	0 (zero)

SEQUENCE

1. Wheel moves to P100 at rapid.
2. Table moves to Z at rapid.
3. Wheel moves to P at fast approach feedrate.
4. If gap elimination is programmed wheel moves towards X at gap elimination feedrate D. When the wheel touches the surface the gap eliminator is triggered. (See Section 2.3.3 for the correct setting procedure for the gap eliminator). The control then selects feedrate A, B or C depending on the position of the surface.
5. The wheel moves to I at coarse grinding feedrate A.
6. Wheel moves to the second feedchange point J at medium grinding feedrate B.
7. Wheel moves to final size X at fine grinding feedrate C.
8. Sparkout if S is programmed.
9. Table (Z axis) oscillation commences if E is programmed, together with V and R.
10. Wheel retracts to P100 at rapid.

EXAMPLE

G88	X25.4	Z50.000	A.008	P25.7	Q0

EXAMPLE OF CYCLE WITHOUT DEFAULT VALUES

G88	X25.4	Z50.000	D.050	A.010	B.002	C.0005	P25.500	J25.410	S10	Q0

EXAMPLE OF CYCLE WITH TABLE (Z AXIS) OSCILLATION

G88	X12.25	Z65	Q1	P12.5	A.010	E4	V2.5	R5

PROGRAMMING NOTES

1. Ensure that Q is programmed correctly. If programmed in error the wheel can move at semi-rapid to a point one wheel width away from its correct position.

2. If feedrate D is programmed, gap elimination error checks are made in G88. When an error is detected a message is displayed on line 1 of the CRT. The messages are:-

   GAP ELIMINATION ERROR 000001 - Gap elimination triggered before wheel starts feeding in.
   GAP ELIMINATION ERROR 000002 - Gap elimination not triggered during wheel infeed to X.

3. When an error is detected the part program halts. It can however be continued by pressing the cycle start key so that subsequent part program blocks can be executed.

4. When oscillation is programmed the direction of oscillation moves the shoulder away from the datum edge of the wheel. ie, if Q0 the table moves to the left; if QI the table moves to the right. The programmer should always ensure that sufficient clearance exists on the other side of the wheel to accommodate the programmed oscillation distance.

APPENDIX 3 Implementing Adaptive Control on the Allen Bradley 10 Series Control System.

A3.1 The 10 Series Controller

The 10 Series controller is based on the hardware of an IBM compatible personal computer running a multi-tasking operating system, and is available in a number of configurations including modular rack based systems and single board systems. DOS is run as a task under the multi-tasking operating system, and the facility is provided to run utilities written by the original equipment manufacturer (OEM). These utilities take the form of DOS executable files, written in the 'C' language and compiled and linked with Allen Bradley libraries. The OEM utilities have access to system resources such as hard disc, floppy disc, keyboard, screen and communications ports.

Interface Logic is written using the PLUS language. This takes the form of function block / ladder in conjunction with instruction lists. The ladder diagrams specify the inputs and outputs to function blocks. Each function block encapsulates code for a particular module, and is written using instruction list, a mnemonic type language similar to assembler. The interface logic is translated into 'C' code and compiled and linked into an executable file. At the compilation stage, it is possible to include additional functions written in the 'C' language. Programming, translation and compilation are all performed on the control system. Foreground logic was executed on an interrupt every 10 ms. Foreground logic was executed within several milliseconds, and the background logic was implemented in the remaining processing time.

The motions of the axes required to implement the grinding cycles are defined in the form of part program macros, which consist of ISO G and M codes together with conditional branch statements and subroutine calls. PLUS global variables are provided for passing data between the logic and the part program macros. Functions are also provided for reading and writing to global variables from the OEM utilities.

A 3.2 Adaptive Control Software for the Allen Bradley 10 Series Controller

It was decided to implement the user interface and the data base routines as an OEM utility, because of the facility to access the hard disc, keyboard, and screen. From the OEM utility, the user performs data entry tasks such as selecting from menus the workpiece material type, the grinding wheel type, target power level, and size data for computing wear offsets. The facility is also provided for enabling or disabling each of the adaptive control features. This data was entered for each diameter to be ground, as specified in the part program. To save unnecessary data entry, the data entered for the first diameter was used as a default for subsequent diameters.

The OEM utility opened the currently active part program file on the hard disc and read data such as the workpiece diameter, infeed rate, and workpiece speed. Control system data such as the grinding wheel diameter diameter was also read from the PLUS interface logic environment. This data was stored together with the data entered by the user in the form of a data structure.

Workpiece material properties and grinding wheel properties were read from the data base files stored on the hard disc. For the automatic selection of infeed rate and workpiece speed, the data base was interrogated for appropriate kinematic parameter values, and infeed rate and workpiece speed values were calculated for each diameter. The kinematic parameters and the workpiece and infeed rate were also stored in the data structure.

On exiting the OEM utility, the new infeed rates and workpiece speed were written into the part program file. Data concerning the target power level, wear offsets, workpiece material properties and grinding wheel properties were copied to a data array in the PLUS environment. Handshaking was used between the OEM utility and PLUS logic, to transfer the data one item at a time via global variables. Also stored was a factor for multiplying the infeed rate. The data was stored in a two dimensional array in order to store for each diameter to be ground.

The OEM utility was executed before the first part of a batch was ground. Subsequently, the logic carried out all the adaptive functions. Data logging and time constant identification were implemented in foreground logic as an accurate timing signal was required. Calculations for gauge offsets, wear offsets and adapting the infeed rate, were carried out on a post process basis at the end of the grinding cycle, and were implemented in background logic. All the adaptive control software was written as 'C' code that was called from the PLUS function block / ladder.

The part program macros were interfaced with the logic by the use of global variables. The data logging and time constant identification was initiated by flags set in the part program, and the post process calculations were initiated by a flag set at the end of the infeed cycle. The infeed rate for each diameter was multiplied by a factor calculated by the logic. The dwell period was ended when a global flag was set by the logic.

The overall design of the adaptive control software for the 10 Series controller is shown in figure A3.1. It is evident that the adaptive control system developed on the Allen Bradley 10 Series controller is broadly equivalent to the prototype adaptive control system that consisted of Allen Bradley 8200 controller interfaced with a personal computer.

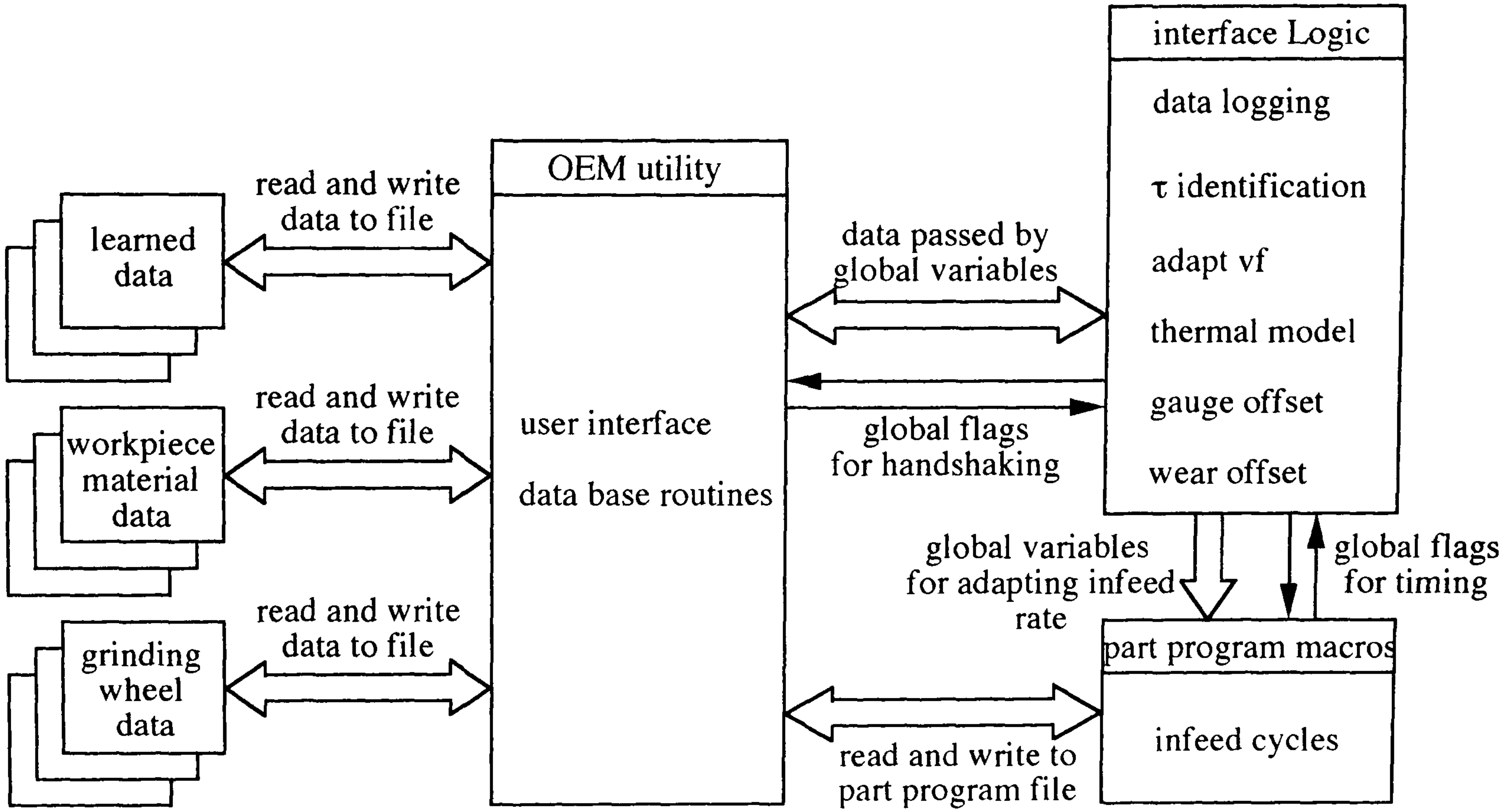


Figure A3.1 - Schematic diagram of the adaptive control software for the AB 10 Series controller

APPENDIX 4 Supporting Papers

A 4.1 The paper published in the Journal of Engineering for Industry, Vol. 117, May 1995, pp 194-201.

D. A. Thomas

D. R. Allanson

J. L. Moruzzi

W. Brian Rowe

Liverpool John Moores University,
Liverpool, England

In-process Identification of System Time Constant for the Adaptive Control of Grinding

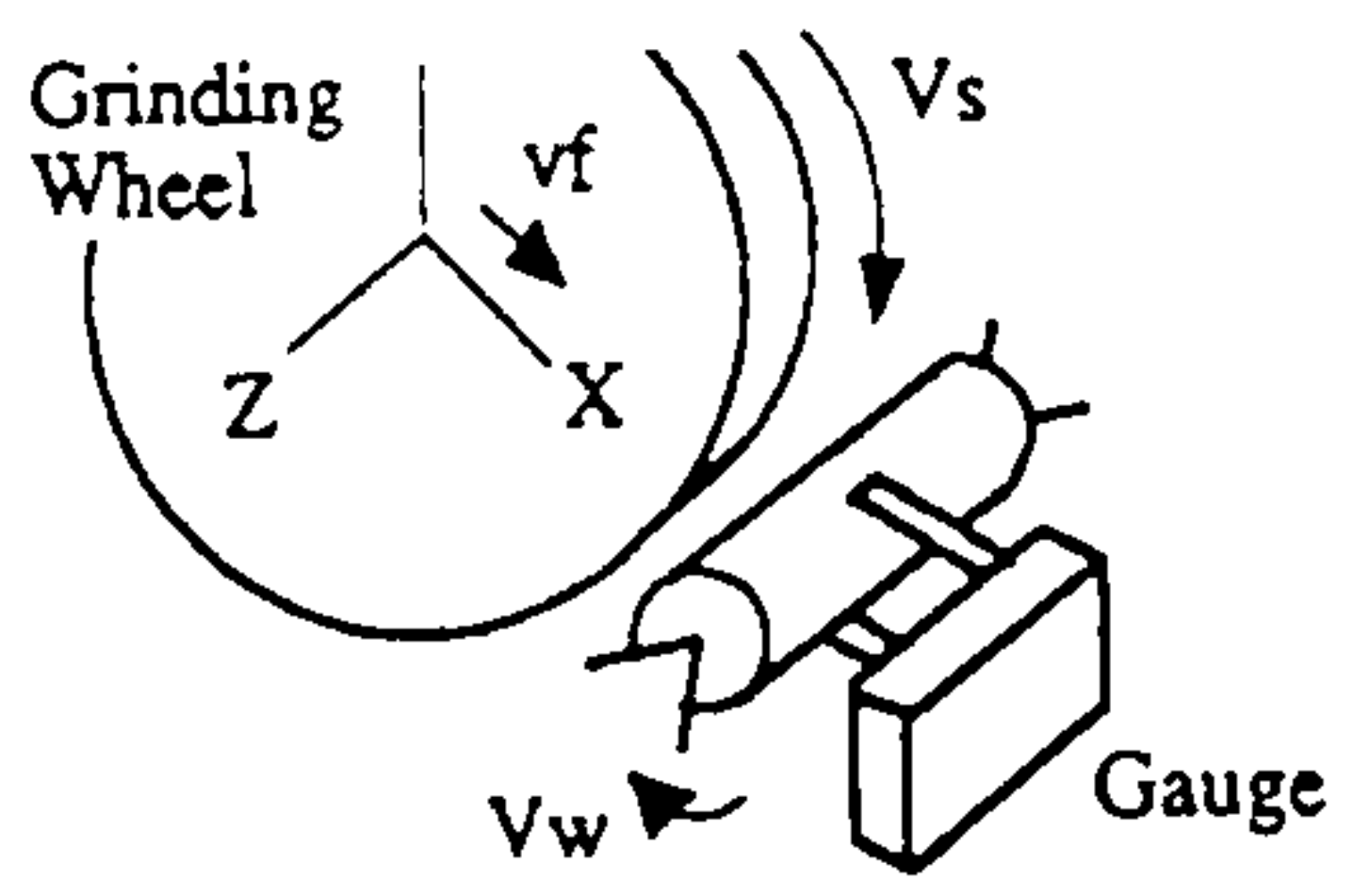
The forces generated during the grinding process cause deflections of the machine-grinding wheel-workpiece system which are large compared to the accuracies required. The deflections cannot be precisely predicted and the optimum grinding conditions vary because the grinding wheel sharpness changes with grinding wheel wear and dressing. In practice conservative machining conditions and feed cycles are used in order to maintain the quality of the finished workpieces. This paper presents a new method of characterizing the time constant of the system from the grinding power consumption during the infeed section of a grinding cycle. Adaptive grinding cycles have been implemented which use the measured value of system time constant to control the target axis position and the dwell time. In this way the control system adapts the machining cycle for the wheel condition at the time of grinding, and can cope with the large variations in deflection that occur when using high feedrates.

Introduction

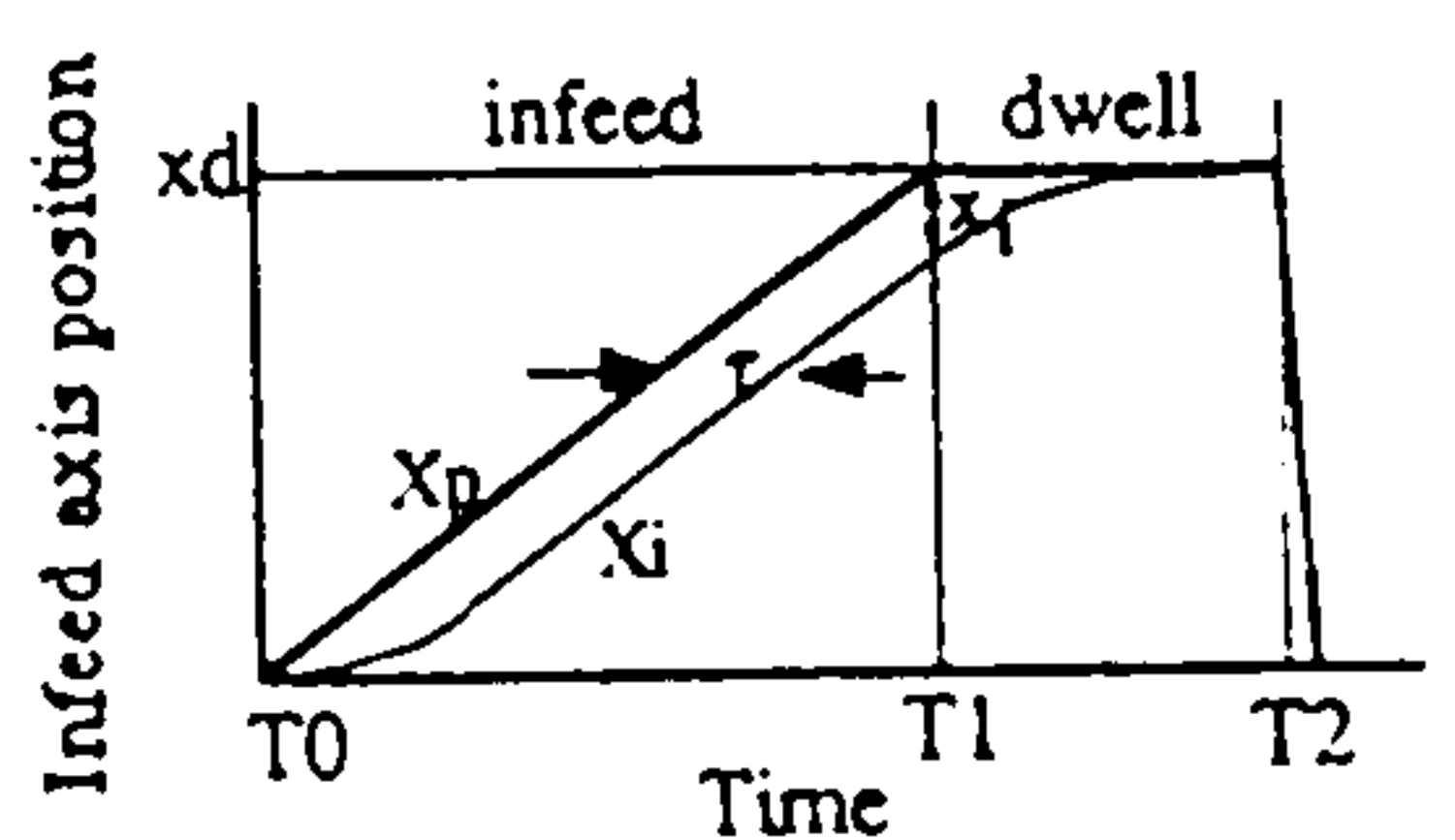
The cylindrical grinding process is a finishing operation used extensively in the aerospace and automotive industries because of the fine tolerances which can be achieved. If components are scrapped the cost can be high due to the expense of the materials involved and the number of hours of work that may have been incurred in the production of the components. It is therefore important that the control system makes it possible to maintain high accuracy and high productivity. A schematic diagram of the process is shown in Fig. 1. In-process diameter gaging may optionally be used for high accuracy work.

The grinding force causes deflection [1] which is variable and large in comparison to the accuracy required. The magnitude of the deflection is dependent on a number of factors, including the stiffness of the machine, the workpiece geometry, the workpiece material properties, the wheel type, the wheel sharpness and the machining parameters used. The deflection results in errors in size and roundness of the workpiece. These errors are reduced in conventional grinding control systems by the selection of conservative machining parameters in order to approach size at a low feedrate with a small depth of cut and by the use of a dwell period at the end of the machining cycle. During the dwell period the axis is held at the target position and the final stock removal is achieved by the relaxation of the deflections in the system, bringing the workpiece within the size and roundness requirements. This can be a time consuming operation, particularly with flexible workpieces [2].

The deflections are difficult to predict because of the variability of the grinding forces due to the change in wheel sharpness with wheel wear and dressing [3, 4]. The forces can vary by more than one hundred percent for the same removal rate which introduces considerable uncertainty into the system. Diameter gaging systems which trigger the retraction of the grinding wheel when size is reached can help improve size holding capability. However, the use of diameter gaging is limited by expense, longer set-up times, and by the fact that diameter gaging can often only be applied to one or two diameters on a workpiece because of the physical size of the gage. Furthermore, conservative removal rates must still be used because the stock to be removed during the dwell period is set manually and is difficult to predict. There is also the risk of poor roundness if the final size is approached too rapidly.



(a) Schematic layout of grinding between centres



(b) A basic feed cycle

Fig. 1 The cylindrical grinding process

Contributed by the Production Engineering Division for publication in the JOURNAL OF ENGINEERING FOR INDUSTRY. Manuscript received Dec. 1992; revised Nov. 1993. Associate Technical Editor: S. Chandrasekar.

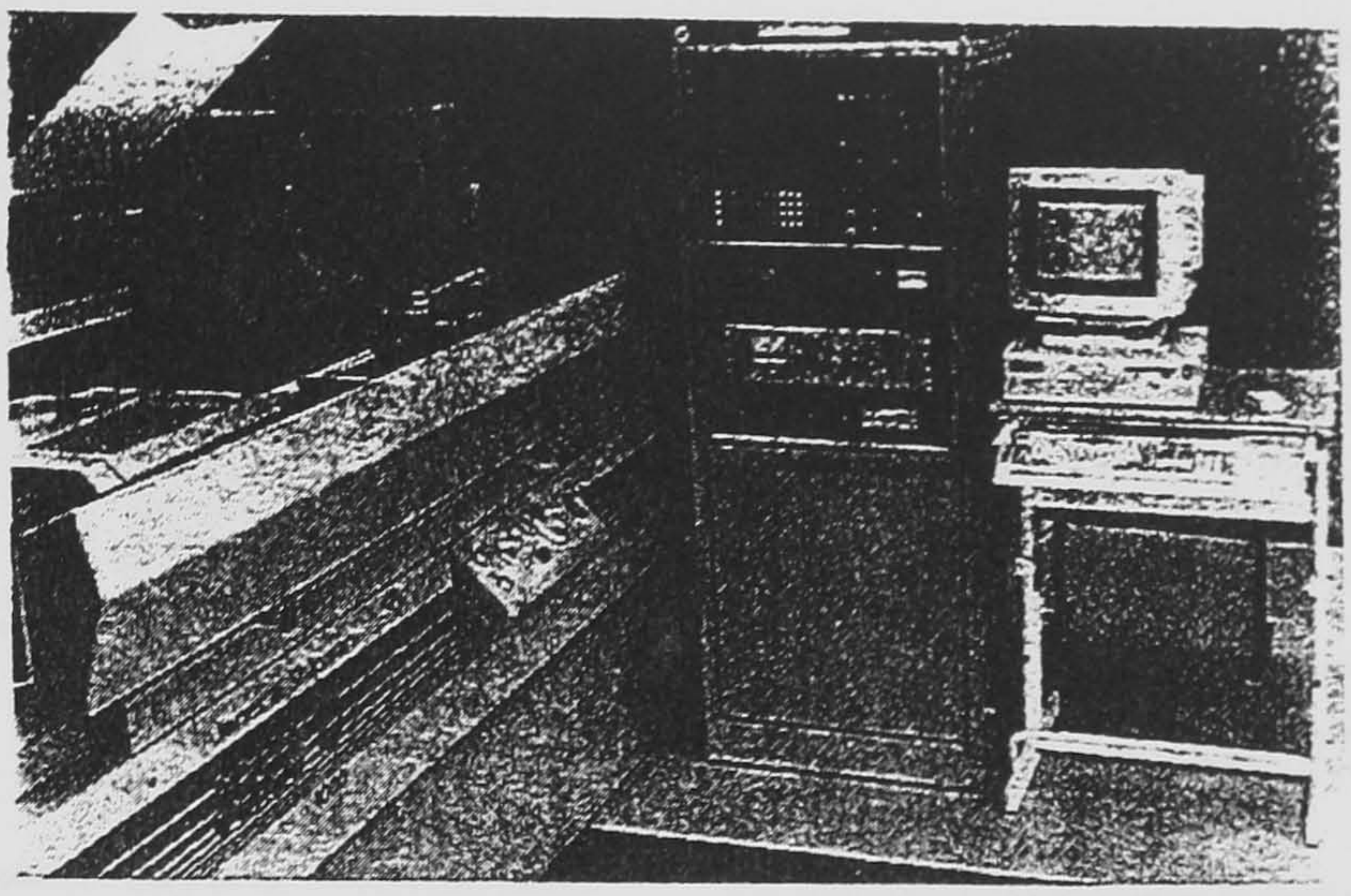


Fig. 2 The machine and control system

This paper presents a method of characterizing the response of the system during the initial stage of a machining cycle. This information can be used to optimize the machining cycle in-process in order to ensure the required accuracy of each workpiece and achieved reduced cycle times. The system demonstrates advantages when grinding both with and without diameter gaging.

The Machine and Control System

The research work was conducted on a Jones and Shipman Series 10 cylindrical grinding machine with CNC capability provided by an Allen Bradley 8200 control system. Infeed and table axes were driven by d.c. servo drives and position feedback was derived from linear scales. The resolution of the position feedback was 0.1 μm for the infeed axis and 1 μm for the table axis. A 7.5 kW grinding wheel motor was driven by a frequency inverter to give a variable speed drive. Sensors already fitted to the standard machine were used to measure workpiece size and axis position. An additional sensor was fitted to the grinding machine in order to make in-process measurements of grinding power. The information from these sensors was sampled at a frequency of 100 Hz and was recorded using a data logging package running on a personal computer system. Analog power and size signals were input via 12 bit analog to digital converters.

Workpiece size was measured by a commercially available caliper gaging system which was actuated hydraulically by the CNC at the start of the machining cycle. The gage gave a signal to the controller to start the dwell at a given stock allowance, and another signal at target size. When target size was indicated by the gage the grinding wheel was retracted and the infeed axis updated to compensate for errors. The gage also gave a 0-10 v analog output over a range of 200 μm of stock removal which was logged for experimental results.

The grinding power is related to the grinding forces and yields valuable information about the process. Grinding power was measured by subtracting the no-load power from the power consumption during the grinding operation. A commercially available power sensor was employed which samples the voltages across and the current through the phases of the motor. From these inputs the value of the power consumed by the motor was determined and output as a 0-1 v analog signal. The power signal was found to contain high frequency noise generated by the frequency inverter. The signal also had a low frequency component due to the response of the drive when loaded. Simulation was used to select a filter which gave acceptable attenuation of the noise without significantly distorting the power curve. A third order Butterworth filter with a cut off frequency of 6 Hz was selected. The filter also served to prevent signal aliasing. The axis position was accessed directly from the system software of the controller. The machine and control system is shown in Fig. 2 and a schematic diagram is shown in Fig. 3.

The Compliance Model

Because of the deflection of the machining system the actual position of the wheel-workpiece interface lags behind the programmed position as shown in Fig. 1(*b*). Modeling of the relationship between the programmed infeed rate and the normal grinding force as a first order system [1] has shown that the actual infeed position can be found from the solution of the equation

$$\tau \frac{dX_i}{dt} + Xi = Xp \qquad (1)$$

Nomenclature

X_i = actual position of the wheel/workpiece interface
X_p = programmed position of the wheel/workpiece interface
x_i = system deflection
ΔX_i = stock to be removed during the dwell period of a conventional grinding cycle with gaging
v_f = infeed rate
t = time from the grinding wheel contacting the workpiece
$T1$ = time at the start of the dwell period
τ = system time constant
v_W = workpiece speed
k_S = normal grinding force coefficient
d_w = workpiece diameter
λ_e = stiffness of the machining system
P = grinding power
k_p = a constant of proportionality relating infeed rate to grinding power
OS = infeed axis overshoot
X_e = infeed axis position error
Td = dwell time

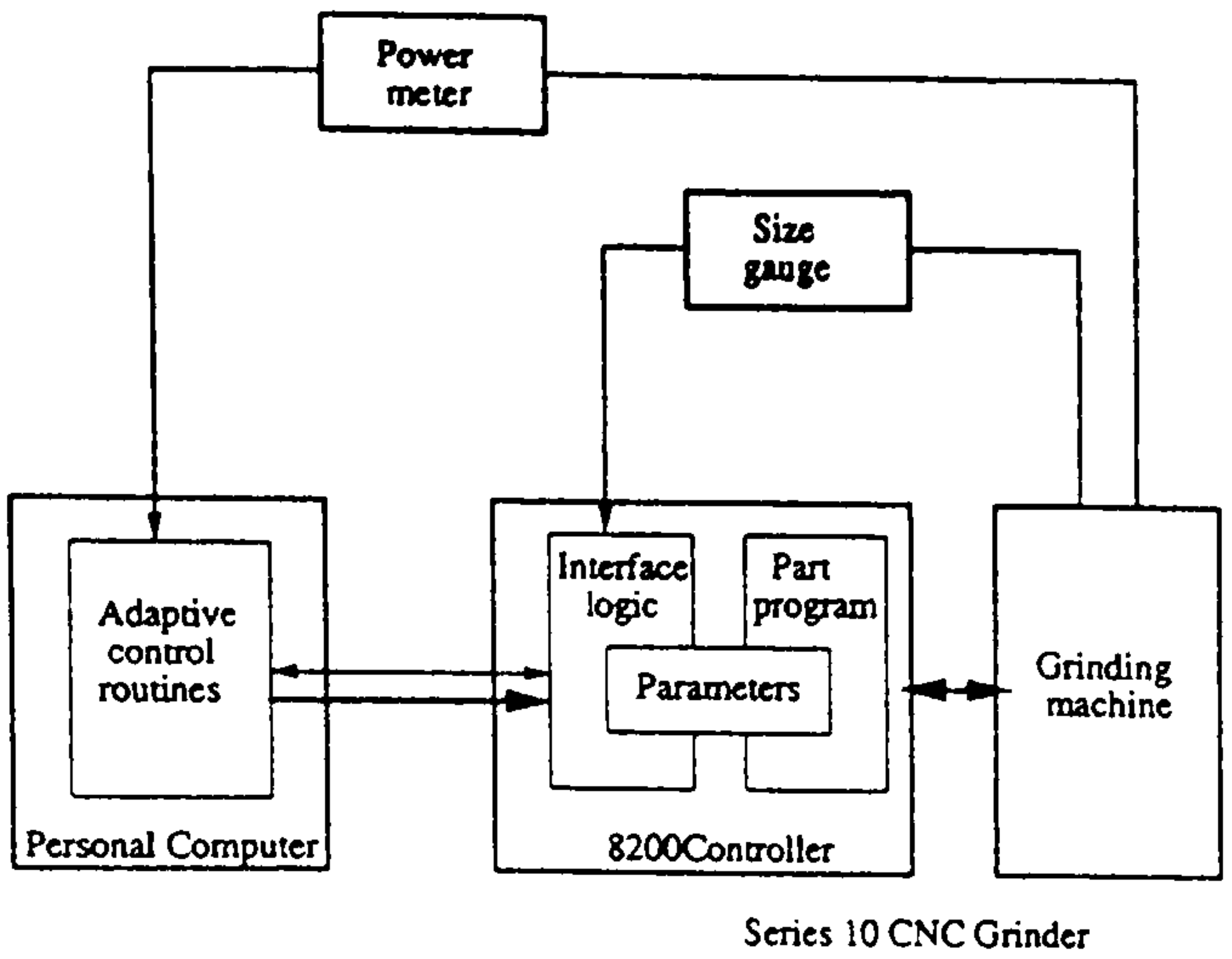


Fig. 3 A schematic diagram of the control system

where

$$\tau = \frac{\pi d_w k_s}{v_w \lambda_e} \tag{2}$$

The solution of Eq. (1) for a constant infeed rate gives

$$X_i = v_f(t - \tau + \tau e^{-t/\tau}) \quad 0<t<T1 \tag{3}$$

where

$$v_f = \frac{dX_p}{dt} \tag{4}$$

The system deflection is given by

$$x_i = X_p - X_i = v_f\,\tau(1 - e^{-t/\tau}) \quad 0<t<T1 \tag{5}$$

At the start of the dwell period the demanded depth of cut is a step input which is equal to the deflection of the system

$$x_1 = vf\,\tau(1 - e^{-T1/\tau}) \tag{6}$$

and the actual infeed position during the dwell period is given by

$$X_i = X_1 + x_1(1 - e^{-(t-T1)/\tau}) \quad T1<t<T2 \tag{7}$$

Computer simulation of the grinding process [5] was used to show the effect of the time constant on the dwell time required to reach the specified size within a tolerance of 2 μm. The grinding cycle evaluated was a single infeed of 10 μm/s followed by a dwell period of sufficient duration to bring the workpiece diameter within 2 μm of the target diameter. The results of the simulation are shown in Fig. 4. The deflections in the system and the dwell time required to produce components within the size tolerance are clearly dependent on the system time constant. Knowledge of the system time constant is therefore essential in optimizing the grinding cycle.

The grinding force coefficient k_S varies with the type of wheel and also changes with the wheel sharpness. The stiffness of the machining system λ_e has three components, the stiffness of the machine, the stiffness of the grinding wheel and the stiffness of the workpiece. It is not practical to calculate the time constant from Eq. (2) because the grinding force coefficient is constantly varying. To allow the machining cycle to be optimized for every grinding operation, a method was required of measuring the system time constant in real-time from readily available process data.

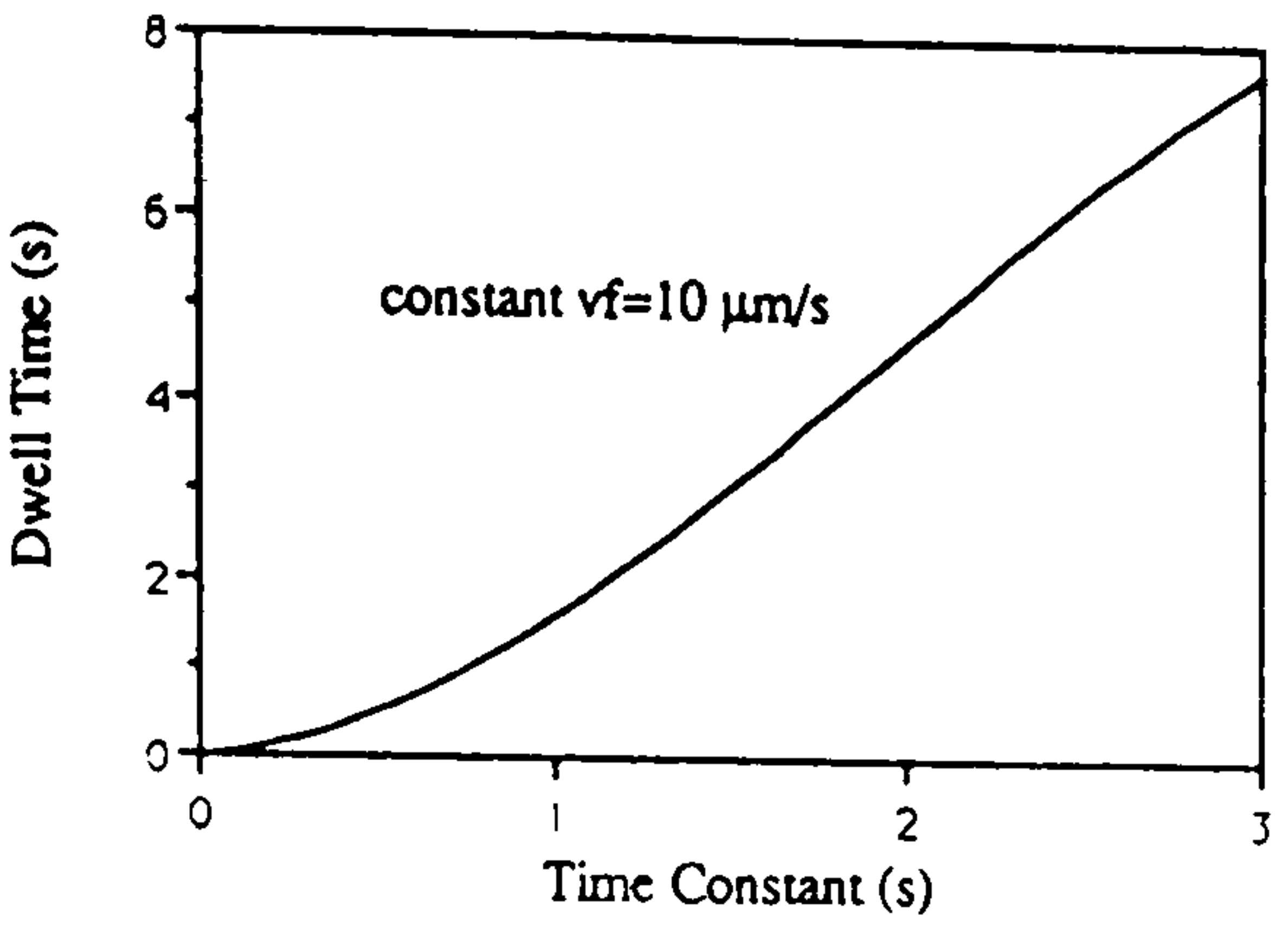


Fig. 4 Simulation results showing the dwell time required to reduce the workpiece diameter to within 2 μm of the target value

Measurement of the System Time Constant

Gao and Jones [6] propose a control method which estimates the value of the system time constant at the end of the grinding cycle from the nominal wheel infeed rate and the achieved size reduction. The value of the time constant can also be determined in real time by monitoring the deflection of the system. This may be achieved by monitoring the infeed position and the size of the workpiece [7]. Using this method wheel wear would result in a measured value which is larger than the real value of time constant. Also, gaging systems are expensive and gage set-up times as well as the difficulties posed by multi-diameter workpieces limit the usefulness of a control system that relies on diameter gaging for all operations.

The normal force is often used for the adaptive control of grinding [8]. It is possible to measure the time constant from the force signal but the output from a force transducer is dependent on the position of installation and the use of a force transducer requires modification of the machine structure. The use of force transducers is less convenient in a production environment.

An alternative method is to measure the time constant from the grinding power characteristics [9]. It is possible to measure the system time constant from the grinding power during the dwell period [1] and this method is shown in Fig. 5(*a*). However, a control system using the dwell period method has to optimize the feed cycle using the value of time constant computed from previous grinding operations rather than from the operation which is currently being undertaken. A more useful method was developed which identifies the time constant from the power during the initial stage of the infeed cycle.

The mathematical relationships required for the new method were derived as follows. The grinding power is proportional to the depth of cut if the grinding force coefficient is constant for all depths of cut. This is not exactly true but works very well for the purposes of characterizing the system performance.

$$P \propto \frac{dX_i}{dt} \tag{8}$$

By differentiating Eq. (3)

$$P = k_p v_f(1 - e^{-t/\tau}) \quad 0<t<T1 \tag{9}$$

The constant of proportionality k_p links the infeed rate to the grinding power.

Equation (9) implies that the grinding power characteristic has a transient section during which the material removal rate approaches the value corresponding to the programmed infeed rate after which point a constant depth of cut is achieved. Data logging of the power signal (Fig. 6) shows that the transient section of the grinding power follows this exponential model well. By analysis of this power characteristic accurate values of the system time constant have been obtained.

A method of calculating the time constant by differentiating the power signal is shown in Fig. 5(*b*). This method is inaccurate in the presence of small levels of noise remaining after filtering

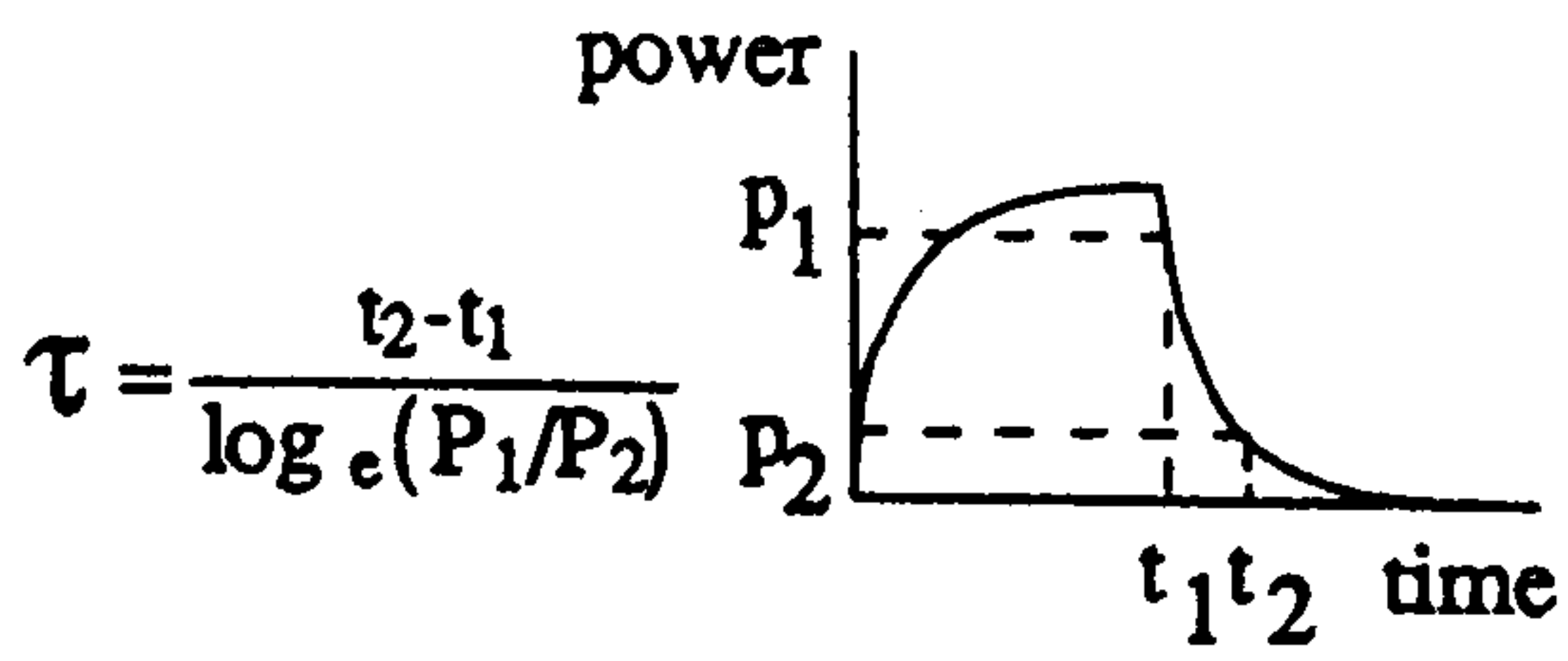


Fig. 5(a) Calculation of the time constant during the dwell period

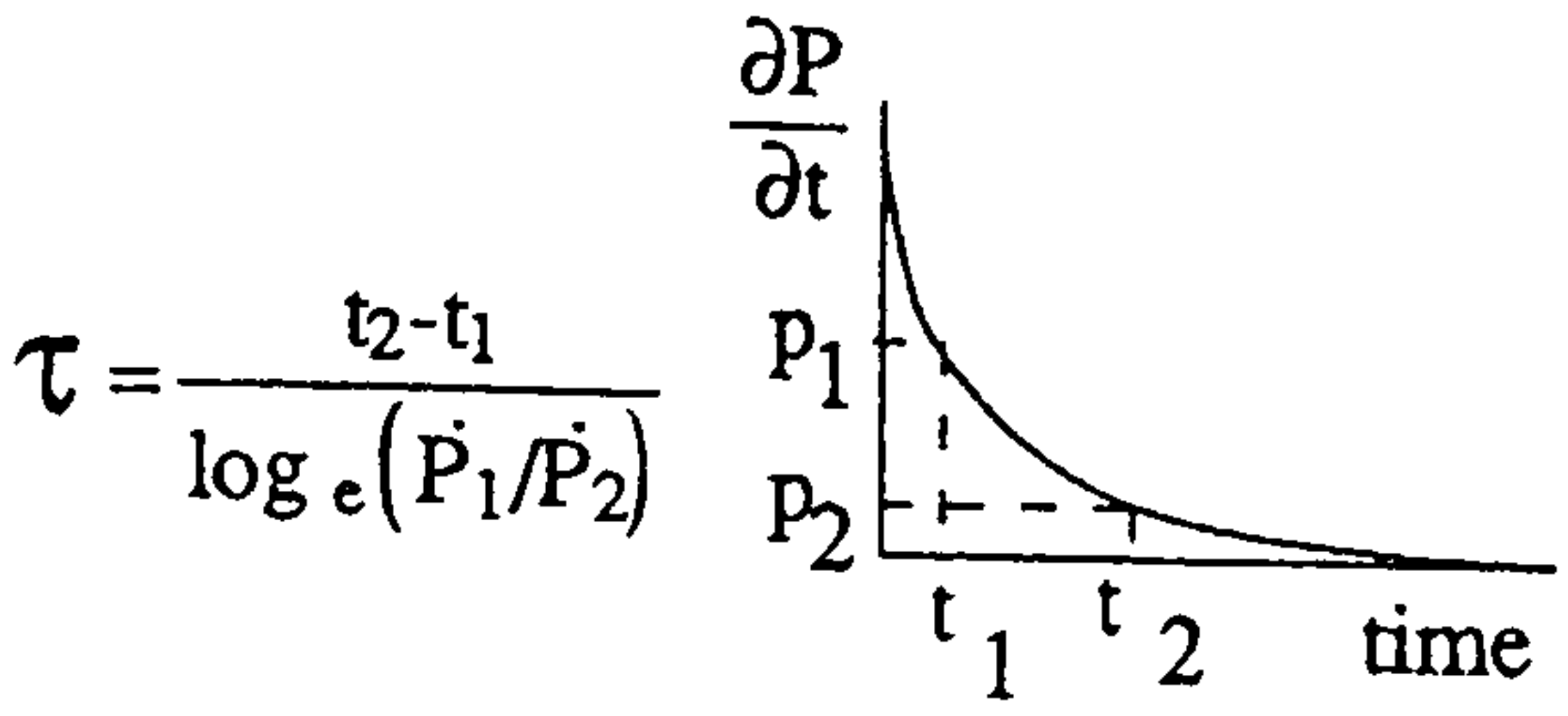


Fig. 5(b) Calculation of the time constant during the infeed period

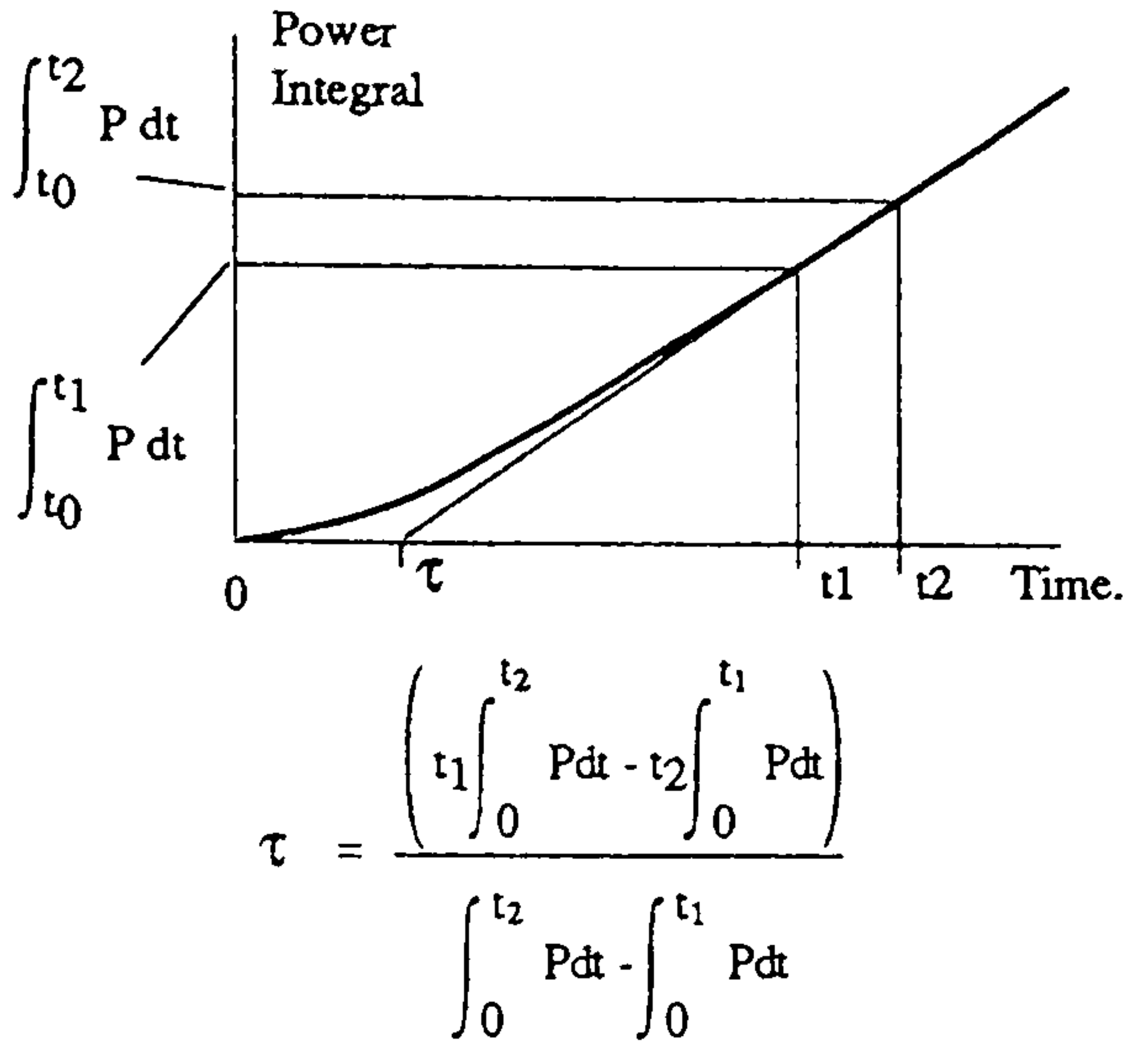


Fig. 5(c) The calculation of time constant by integrating the process power signal

the power signal and did not give satisfactory results on real data. Improved results were obtained by integrating the power signal.

Integrating Eq. (9) gives

$$\int_0^t P\,dt = k_p v_f (t - \tau + \tau e^{-t/\tau}) \qquad (10)$$

Steady state grinding conditions are established when a constant depth of cut is achieved. At this time t is large compared to τ and

$$\int_0^t P\,dt = k_p v_f (t - \tau) \qquad (11)$$

The method of determining the system time constant from the integral of the grinding power is shown in Fig. 5(*c*). From Eq. (11) it can be seen that the value of the system time constant is given by the intercept of the integral of the grinding power at steady state conditions when extrapolated to meet the time axis.

To obtain the value of the time constant using this method requires the start of grinding to be known. A commercially available gap elimination device based on an accelerometer was used initially for this purpose. However, it was found that the precise start of grinding was difficult to detect to the required accuracy because noise from the grinding wheel contacting the coolant resulted in a false indication of the start of grinding. A method was devised for detecting the start of grinding from the variance of the grinding power. As each new power sample was logged the variance of the last *n* samples was calculated. Figure 7 shows that two large increases in the variance occurred. The first was due to the contact of the grinding wheel with the coolant and the second was due to the contact of the grinding wheel with the workpiece. The second increase in the variance was taken as the start of grinding. Using this method it was possible to accurately detect the start of grinding. This method can also be used for dry grinding applications by detecting the first increase in the variance.

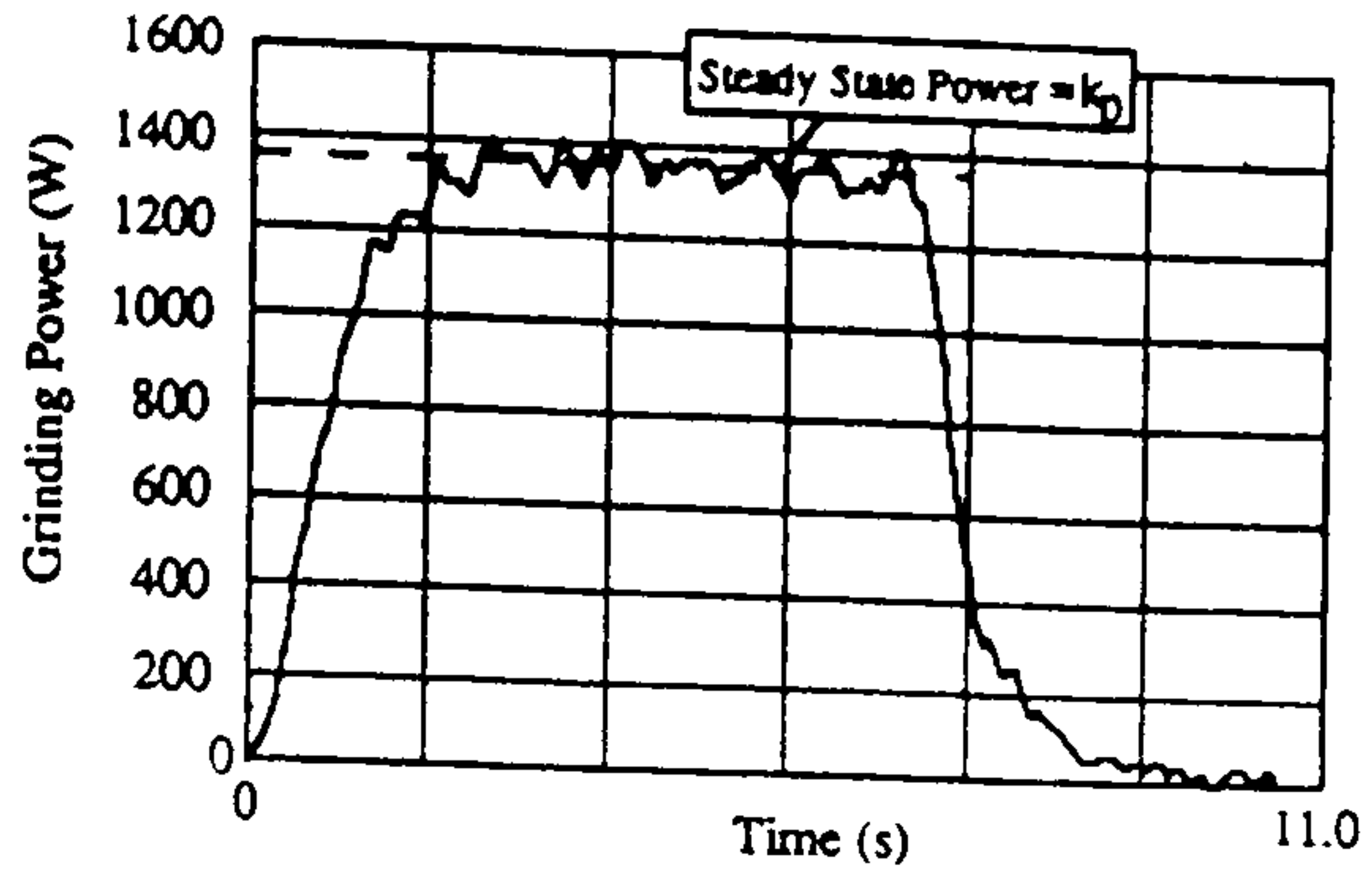


Fig. 6 A typical power signal

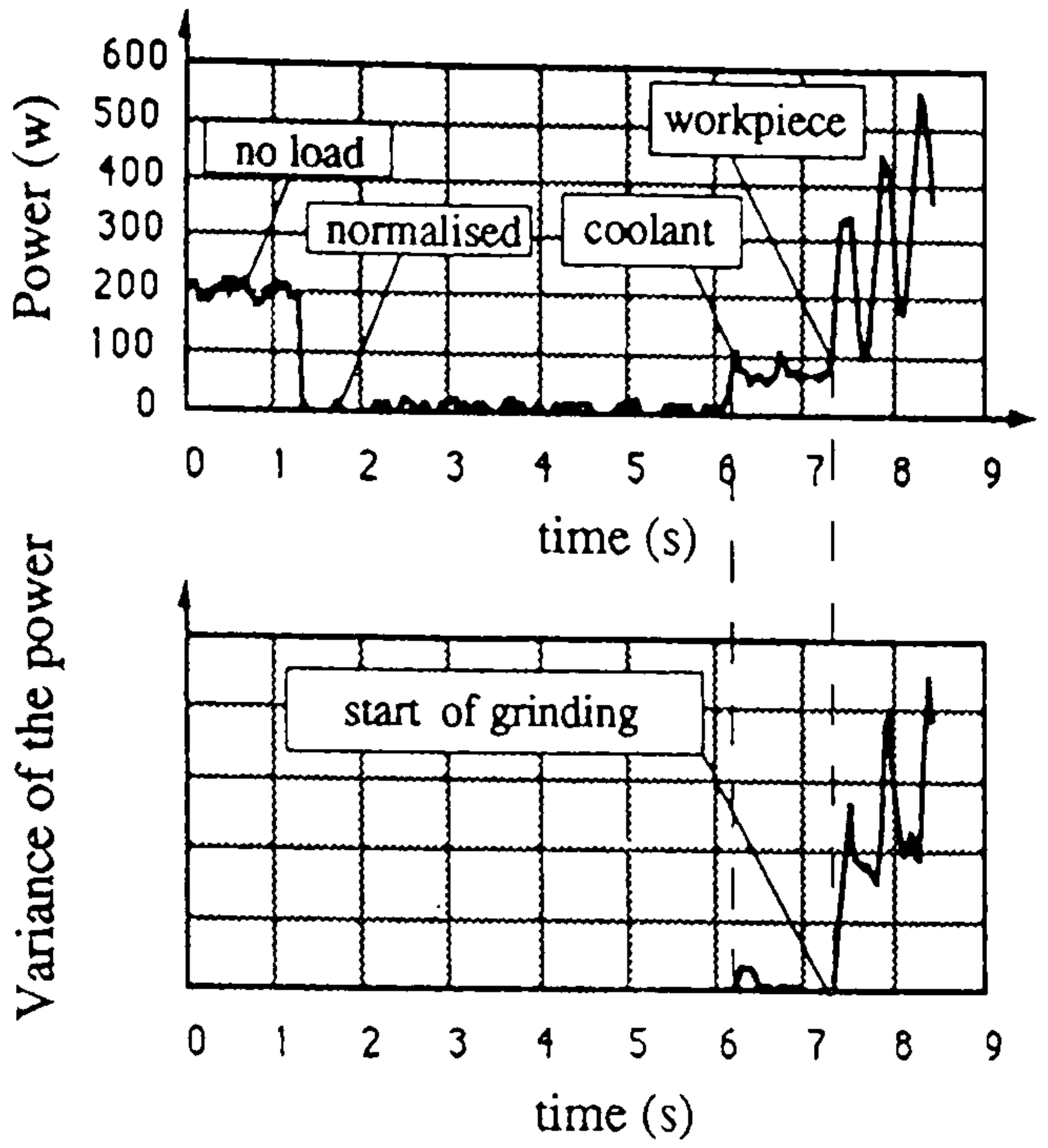
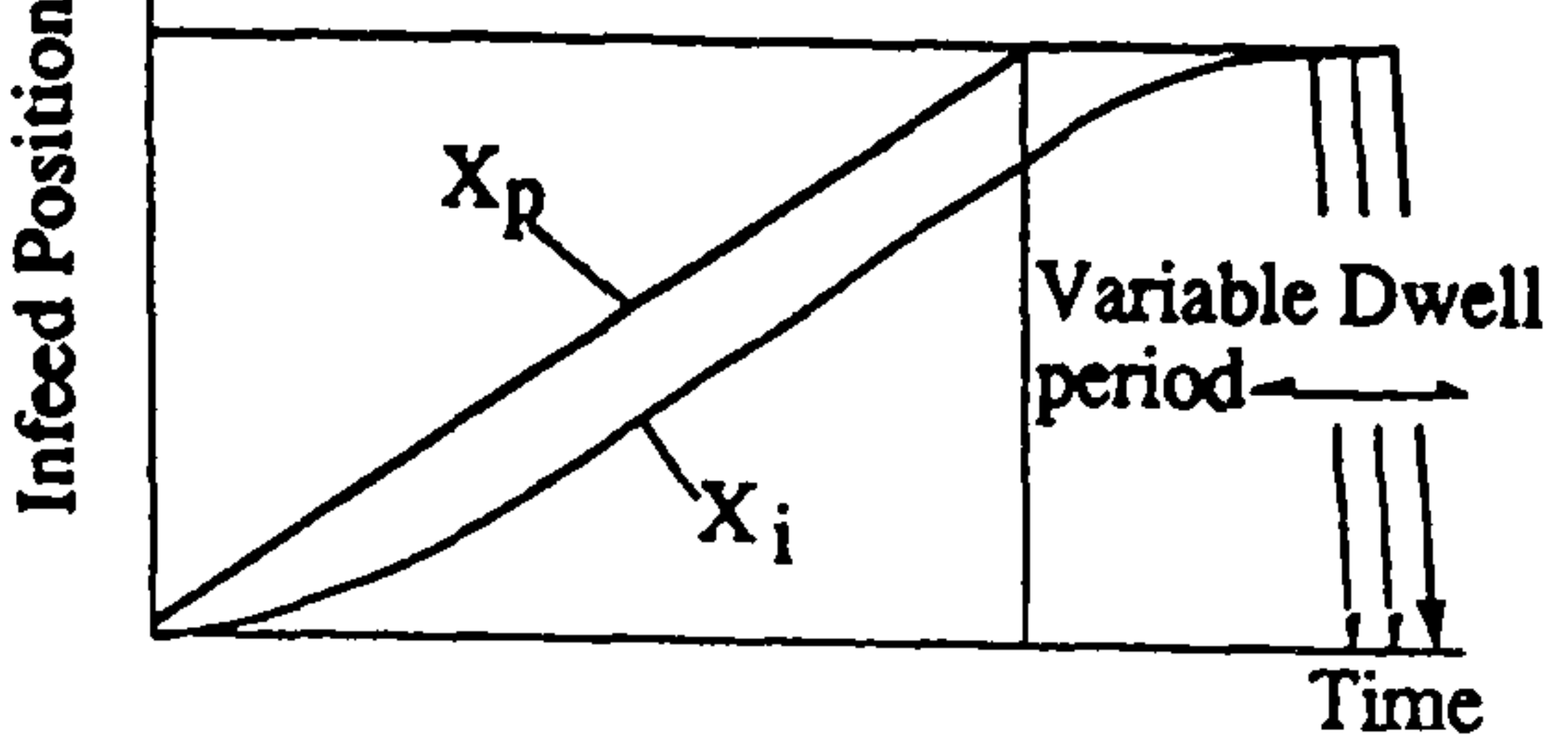


Fig. 7 The detection of the start of grinding (*a*) the typical power curve (*b*) the variance of the power signal

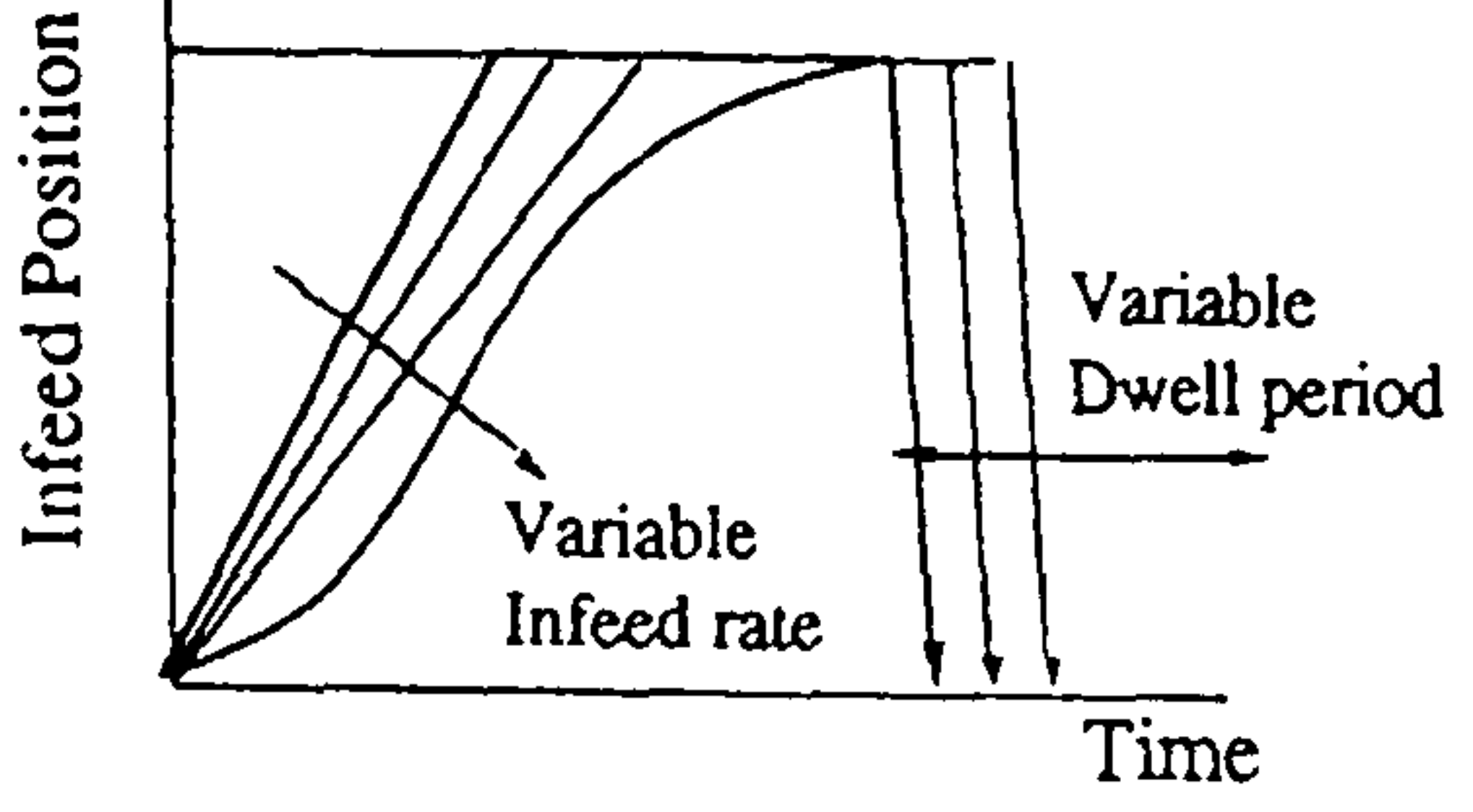
Grinding Cycles

In the basic infeed cycle shown in Fig. 1(*b*) the wheel is moved to the target position at a single infeed rate and is held at this position for a constant dwell period before being retracted at rapid speed. During the dwell period the system deflection is relieved and the workpiece diameter is reduced to the target size. As the grinding force is variable and the de-

a) Adaptive control of dwell time



b) Adaptive control of infeed rate and dwell time



c) Adaptive control of infeed rate, dwell time, and target position

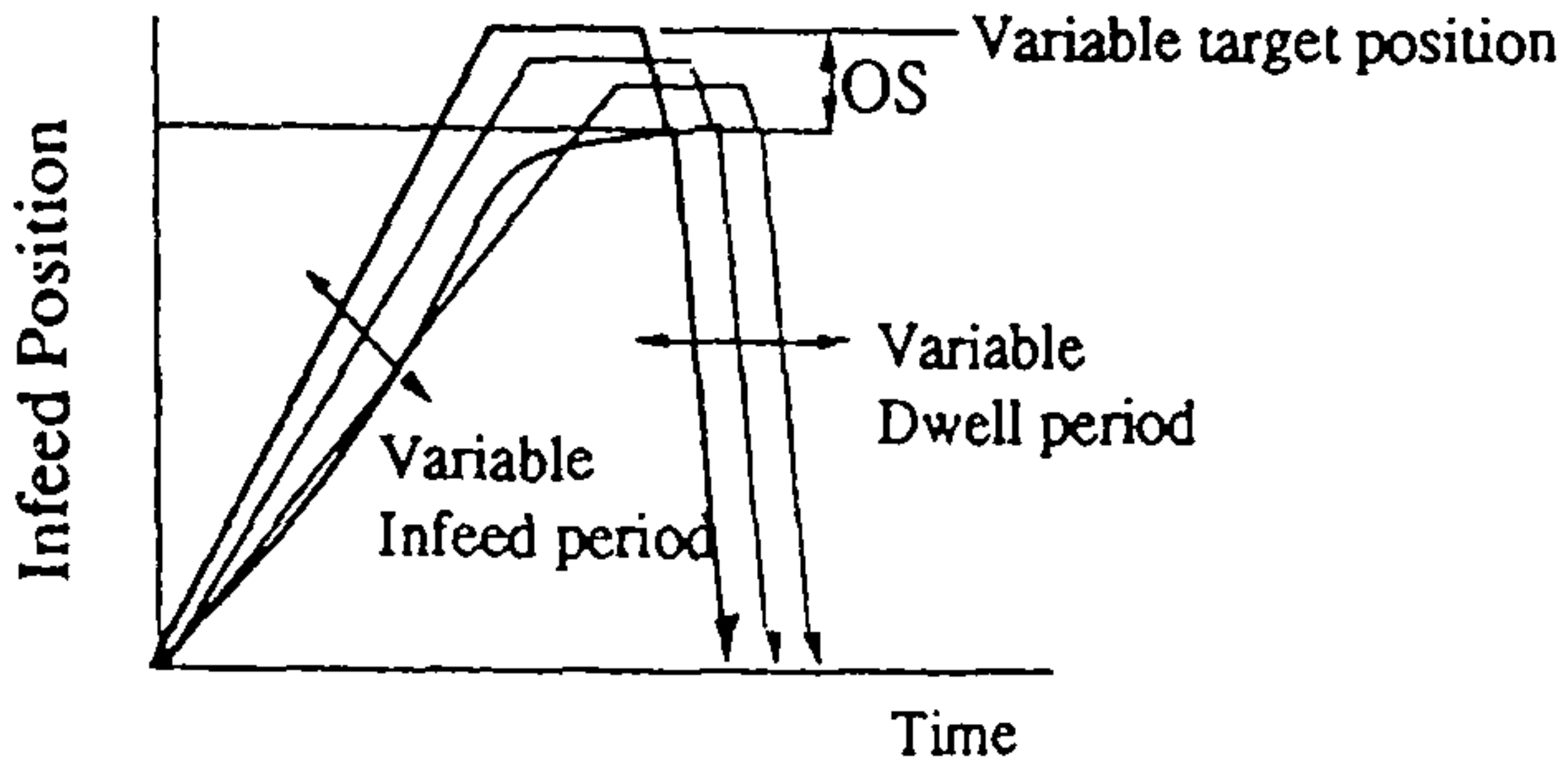
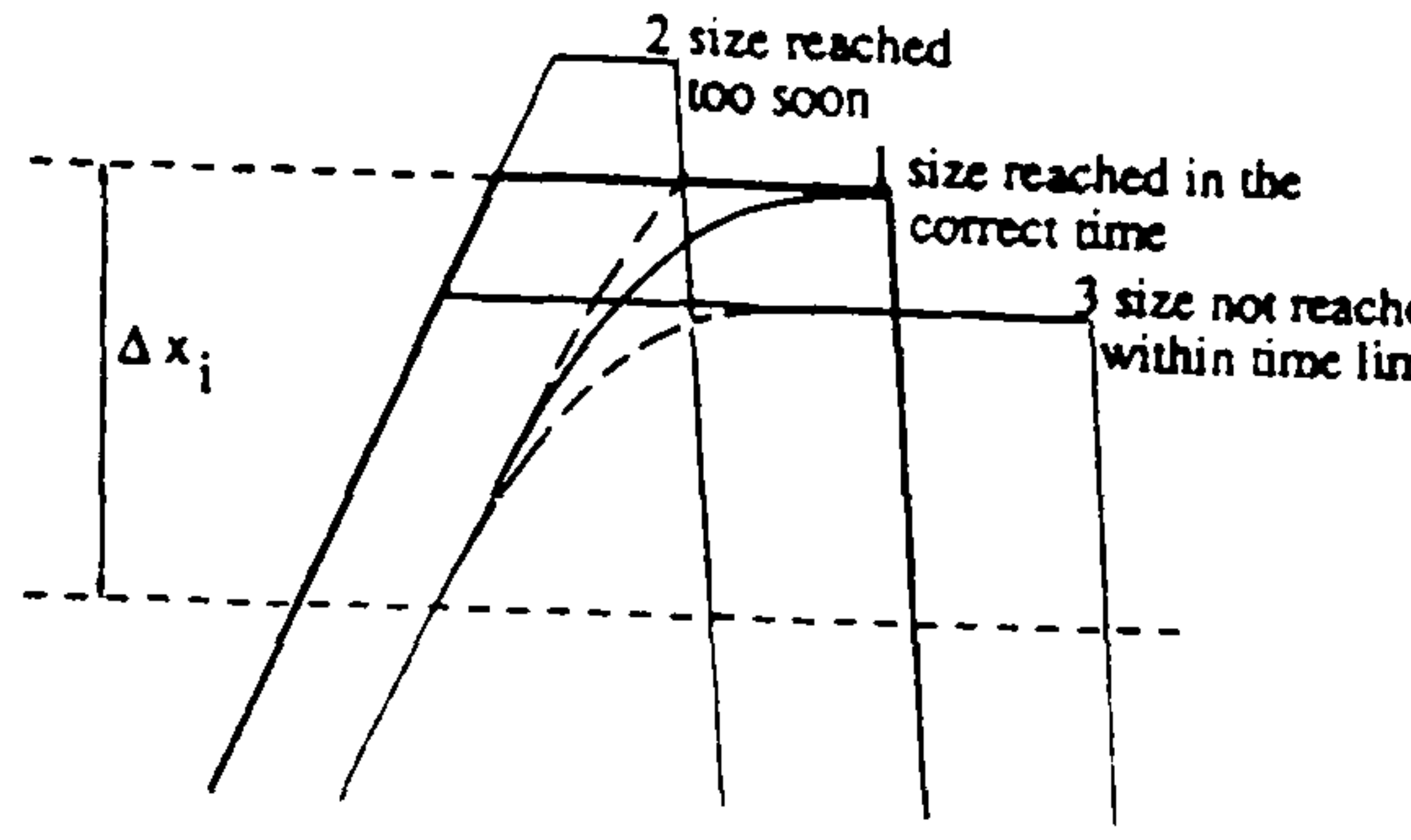


Fig. 8 Strategy for improved productivity in three stages

flection of the system is unknown the dwell period is set in a nonadaptive cycle to a value which is large enough to ensure that all the workpieces in a batch are finished to within the required size tolerance. This value is set in the part program and may be determined by a series of process trials prior to production. The dwell time is longer than required for many of the workpieces to allow for the variation of deflection experienced.

Adaptive Grinding Cycles. With the adaptive control strategy active, the time constant for the workpiece and machine system is determined from the power signal during the infeed section of the grinding cycle and a suitable value for the dwell time is calculated from Eq. (7). In this way the correct dwell time is used to bring the workpiece to size as shown in Fig. 8(*a*). If the infeed rate is updated from one grinding operation to another as part of an adaptive control strategy as shown in Fig. 8(*b*) the deflection changes, altering the required dwell time. In this situation the in-process measurement of time constant is essential to maintain accuracy and optimize cycle times.

Figure 8(c) shows an overshoot being applied to the infeed axis position [7, 10] in order to ensure that the size is reached within a given dwell time. If the axis was held at the target position, in principle, size would never be reached because of the exponential decay of the deflection of the system. In order



1 Stock allowance set correctly $x_i = \Delta X_i$
2 Stock allowance set too small $x_i > \Delta X_i$
3 Stock allowance set too large $x_i < \Delta X_i$

Fig. 9 A conventional gaging cycle—showing the effects of the setting of the stock allowance

to avoid this and to ensure that the required size is reached within an acceptable cycle time a small overshoot should be used for every grinding operation. It is important that the correct overshoot is used for the dwell time chosen as undersized workpieces would be produced by overshooting by too large an amount. The measured value of the system time constant can be used to calculate the overshoot correctly. From Eq. (7)

$$OS = x_i e^{-T_d/\tau} \tag{12}$$

Adaptive Gaging Cycle. The overshoot cycle may be used with diameter gaging to achieve high levels of accuracy and also to determine the error in the infeed position due to setup errors, wheel wear, dressing tool wear and thermal effects. With a given overshoot, the expected dwell time T_d is calculated. By comparing this value to the time T_d' taken for the gage to give an "at size" signal the infeed position error can be calculated using the following equation derived from Eq. (7)

$$Xe = x_i(e^{-T_d'/\tau} - e^{-T_d/\tau}) \tag{13}$$

However, for the nonadaptive gaging cycle shown in Fig. 9, the axis error is measured by comparing the axis position when target size is reached to the axis position corresponding to the programmed target diameter. The stock ΔX_i to be removed during the dwell period is set by the operator and should ideally be equal to the deflection x_i. The gage signals to the controller when this point is reached and the dwell period is commenced. The deflection is assumed to be the same for each grinding operation. However, if the deflection is greater than the stock allowance ΔX_i an overshoot which is greater than required to bring the workpiece to size is applied to the infeed axis. In this case the axis error calculated includes a component due to deflection, leading to size errors on subsequent workpieces, particularly on nongaged diameters. If the deflection is less than the stock allowance ΔX_i, the axis stops short and the target size is never reached. In this case the cycle is deemed to have failed, no axis error is calculated, and the workpiece must be reground to size.

It is evident that conventional methods of axis error measurement do not provide for any change in the deflection of the machining system. The offset generated may include a substantial component which is due to deflection. The new cycle is able to take into account the deflection because the value of the system time constant is known. The axis error calculation given by Eq. (13) can be used to generate a more accurate value of the axis error offset than can be achieved with conventional methods. In consequence better tolerances can be achieved at higher machining rates.

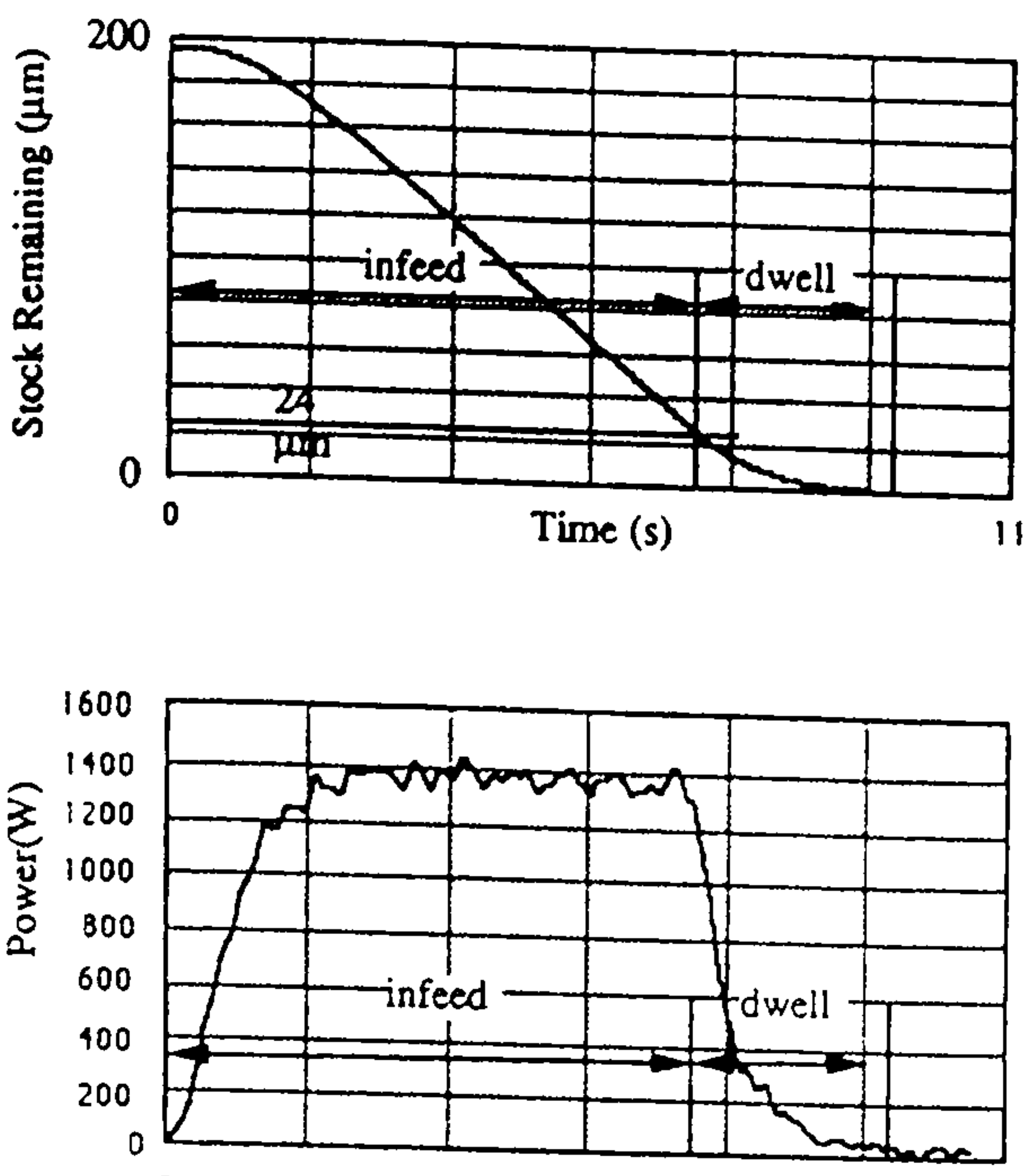


Fig. 10 Data logs of workpiece diameter and grinding power

Results

The System Time Constant. A grinding cycle consisting of a single infeed with dwell was used to evaluate the integral method of determining the system time constant. The data logs of grinding power and workpiece size are shown in Fig. 10. Data points an interval of one second apart on the integrated power curve were used to estimate a tangent which was then extrapolated to the time axis. The value of the intercept shown in Fig. 11 is seen to converge as steady state grinding conditions are approached, giving the value of the system time constant as 0.74 seconds.

The power signal and size signal confirm this value of time constant. Equation (9) predicts that when the time exceeds three time constants the power will have reached ninety five percent of the steady state value. The steady state power was reached after 2.2 seconds which agrees closely with the measured value of time constant.

The stock remaining at the start of the dwell was predicted from Eq. (6) by using the value of time constant calculated in real time. The predicted value of 22.2 μm agrees closely with the measured value of 24 μm. The value of the stock remaining after a dwell of three time constants was predicted to be 0.44 μm. Although measurement with confidence to this level of accuracy is difficult it can be seen from Fig. 10 that the majority of the material was removed after spark out for three time constants.

The values of time constant measured in-process by the control system were verified by curve fitting the power signal of the infeed section of the cycle. From the results shown in Fig. 12 it can be seen that this exercise confirmed the values measured by the control system. The change in the value of the time constant throughout the batch as the machining parameters were updated and the condition of the wheel changed shows the importance of measuring the time constant in-process in order to correctly control the grinding cycle.

As the cylindrical grinding process is a finishing operation the method of measuring the time constant must be able to cope with variations in workpiece geometry resulting from previous machining operations and heat treatment. Stock runout causes an intermittent cut while the workpiece is rounded up giving a power characteristic of the form shown in Fig. 13. Applying the integral method of calculating the time constant to this signal resulted in a smooth integrated power curve from which the time constant was successfully determined.

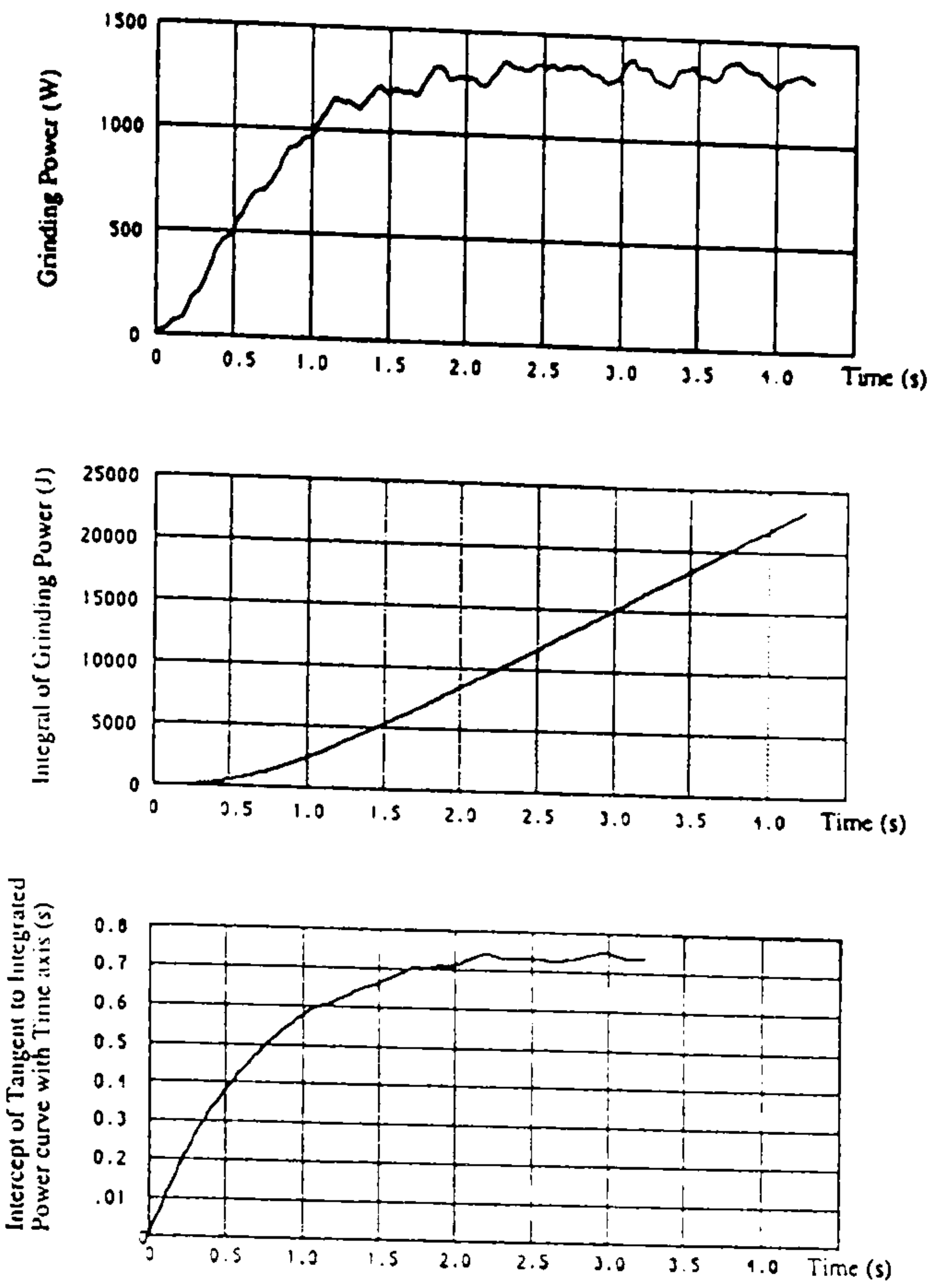


Fig. 11 Calculation of the system time constant from logged grinding power

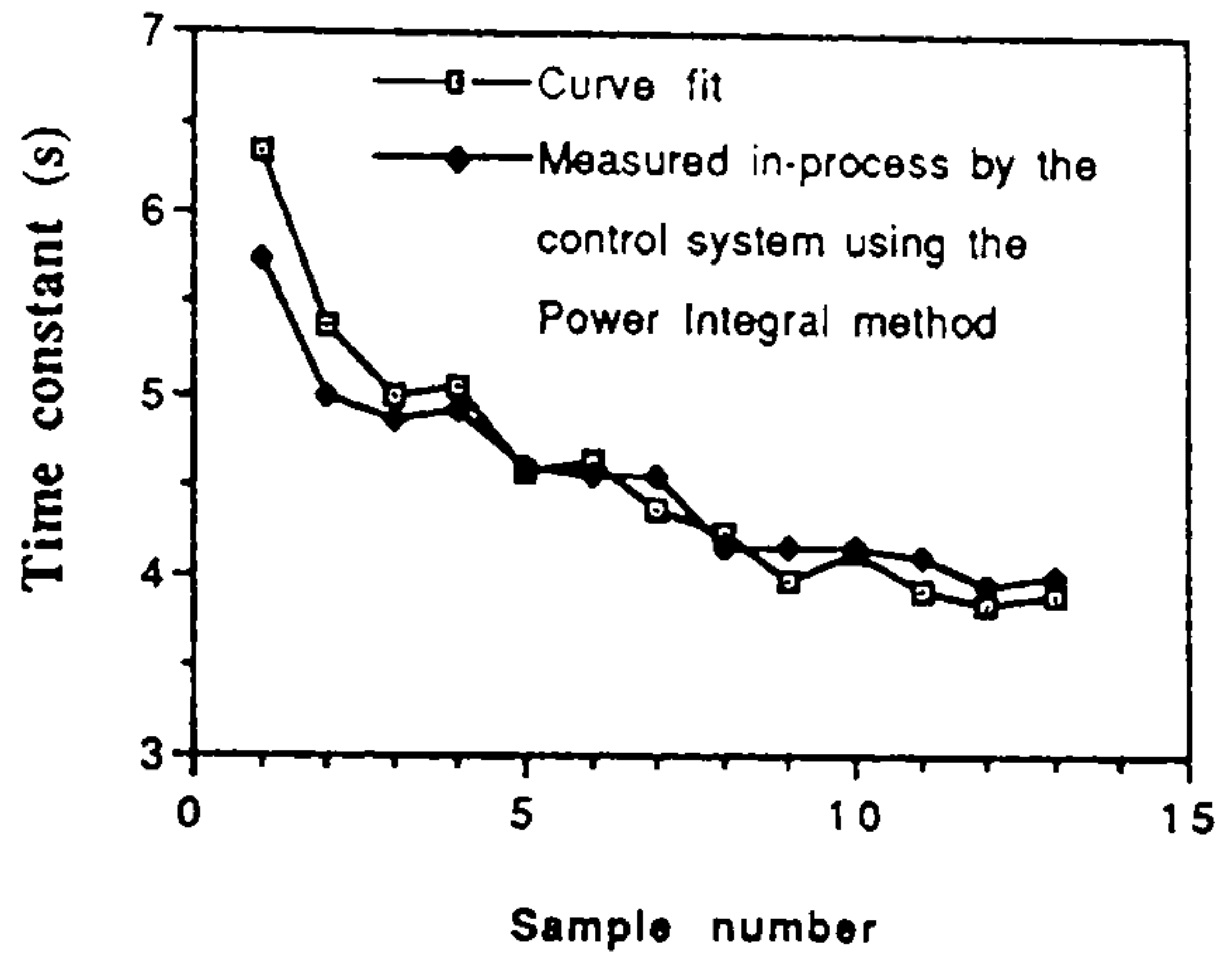


Fig. 12 The value of time constant measured in-process by the control system is confirmed by curve fitting the power signal

Grinding Cycles. Figure 14 shows the size results when grinding a batch of flexible workpieces using the standard control system. At low removal rates, excellent results are achieved, with sizes ranging from the target diameter to 1 μm under size. Inferior size results were obtained when using higher removal rates. The workpieces were under size by an average of 8 μm with a scatter of 2 μm. The deterioration in size holding results occurred because the control system had no knowledge of the magnitude of the deflection and the system applied an

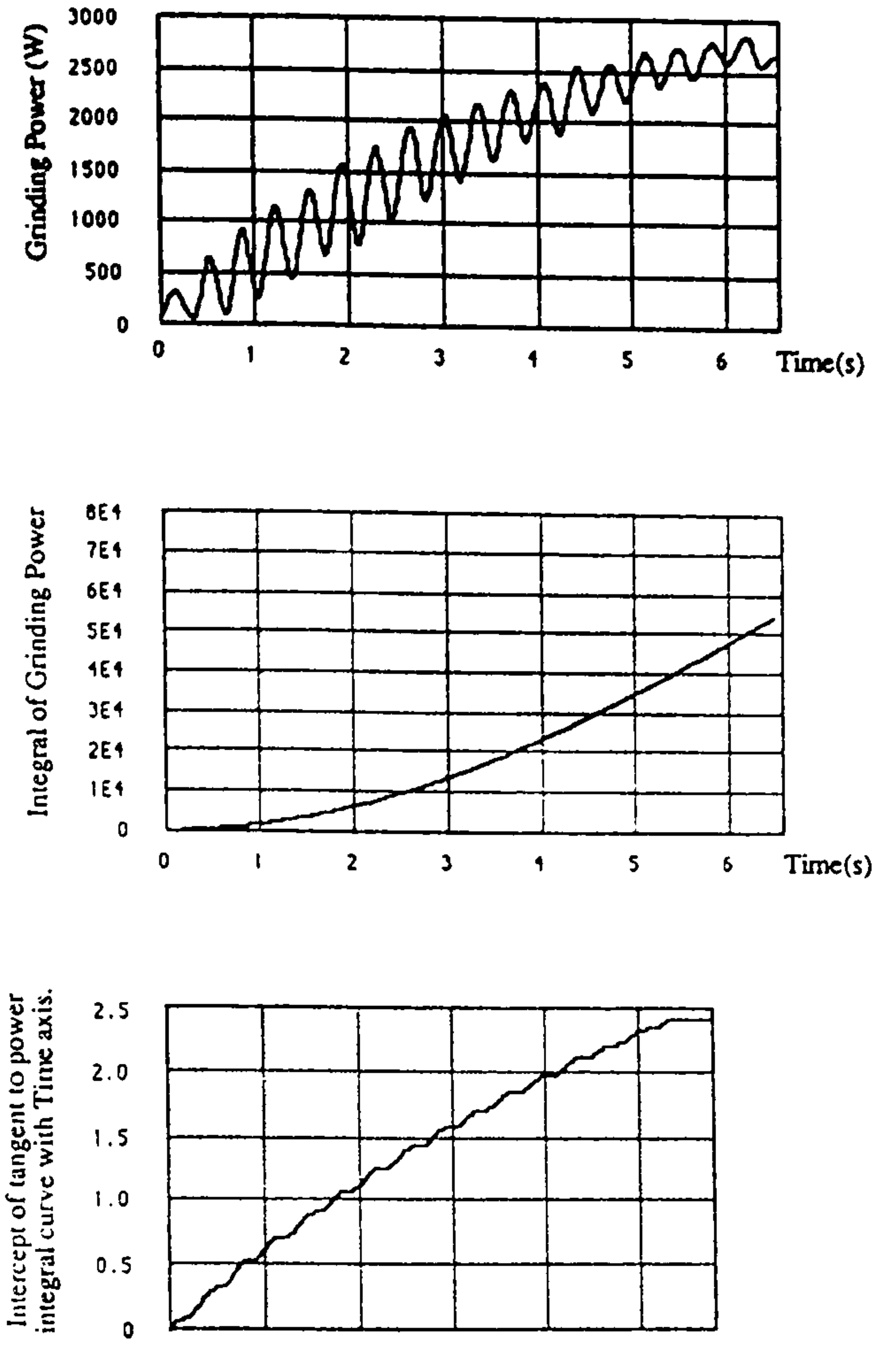


Fig. 13 Calculation of time constant for a workpiece with stock run out

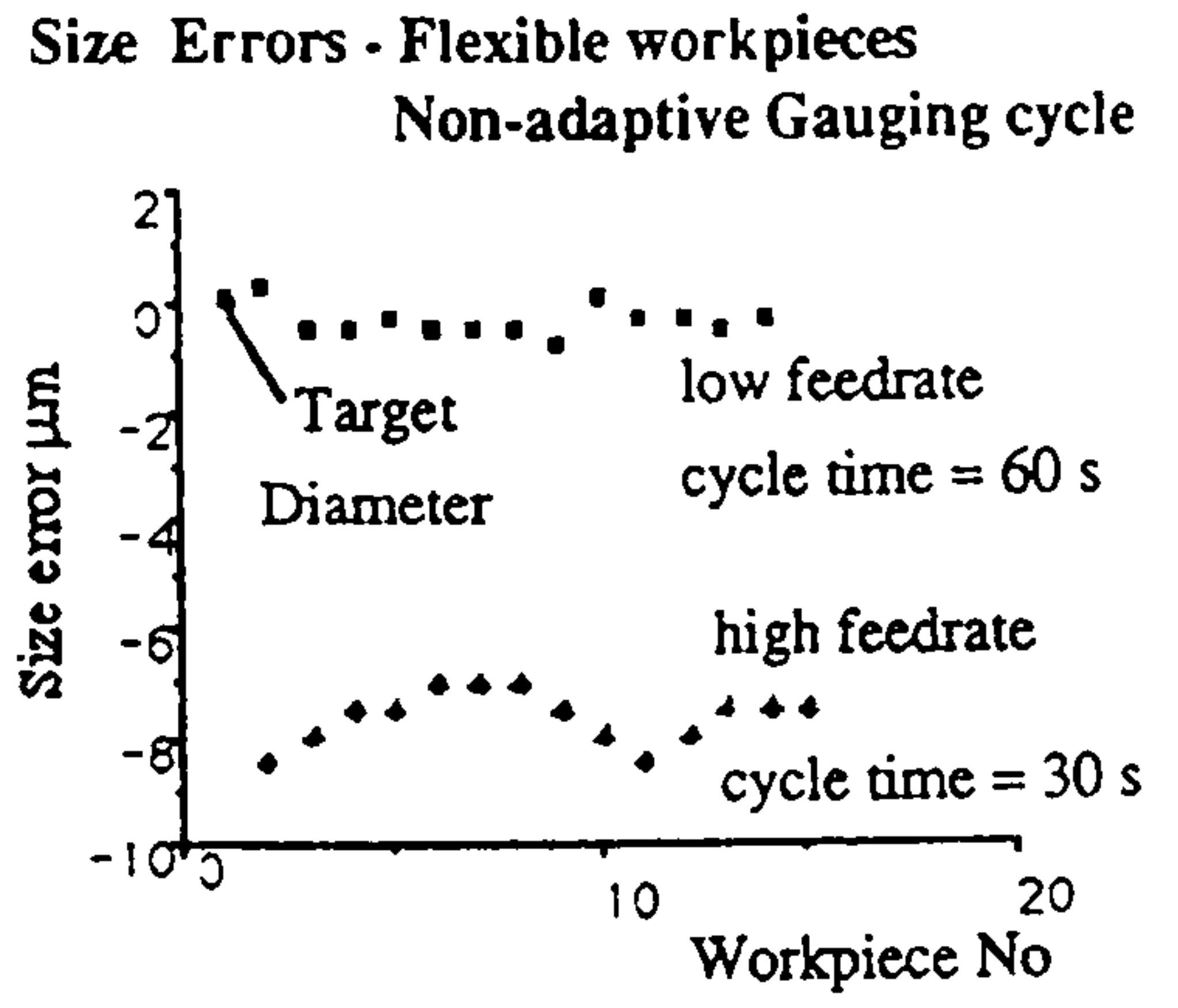


Fig. 14 Size results for nonadaptive cycle, where time constant = 3 s approx. Wheel A465K5V30W. Workpiece EN9, ds = 450 mm, dw = 46 mm, b = 50 mm, vw = 0.25 m/s, vs = 33 m/s, vf low = 5, 3, 1 µm/s, vf high = 9, 7, 5 µm/s

overshoot which was too large. As a result the final size was approached at a high removal rate and further material was removed after size had been signalled by the gage and before retraction could be effected.

Figure 15 shows the size results for grinding flexible workpieces using the adaptive control system. The feedrate was progressively updated to achieve a cycle time of between 26 and 32 s. It can be seen that the size control at this high removal rate was improved over the nonadaptive system with a mean error of 2 µm under target size compared with 8 µm under size for the nonadaptive cycle for a similar removal rate.

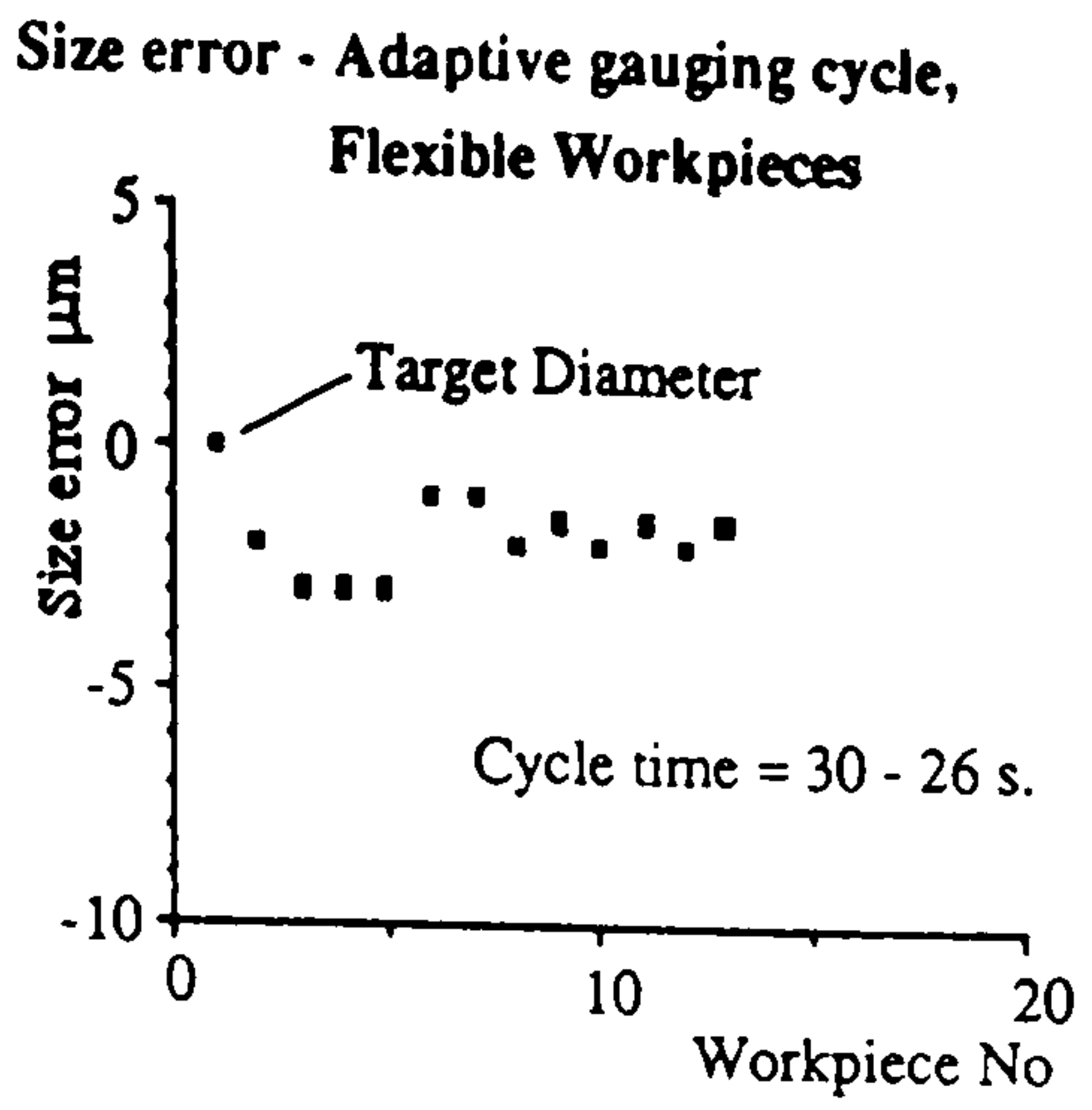


Fig. 15 Size results for adaptive cycle, where time constant = 3 s approx. Wheel A465K5V30W. Workpiece EN9, ds = 450 mm, dw = 46 mm, b = 50 mm, vw = 0.25 m/s, vs = 33 m/s, Power = 5 kW

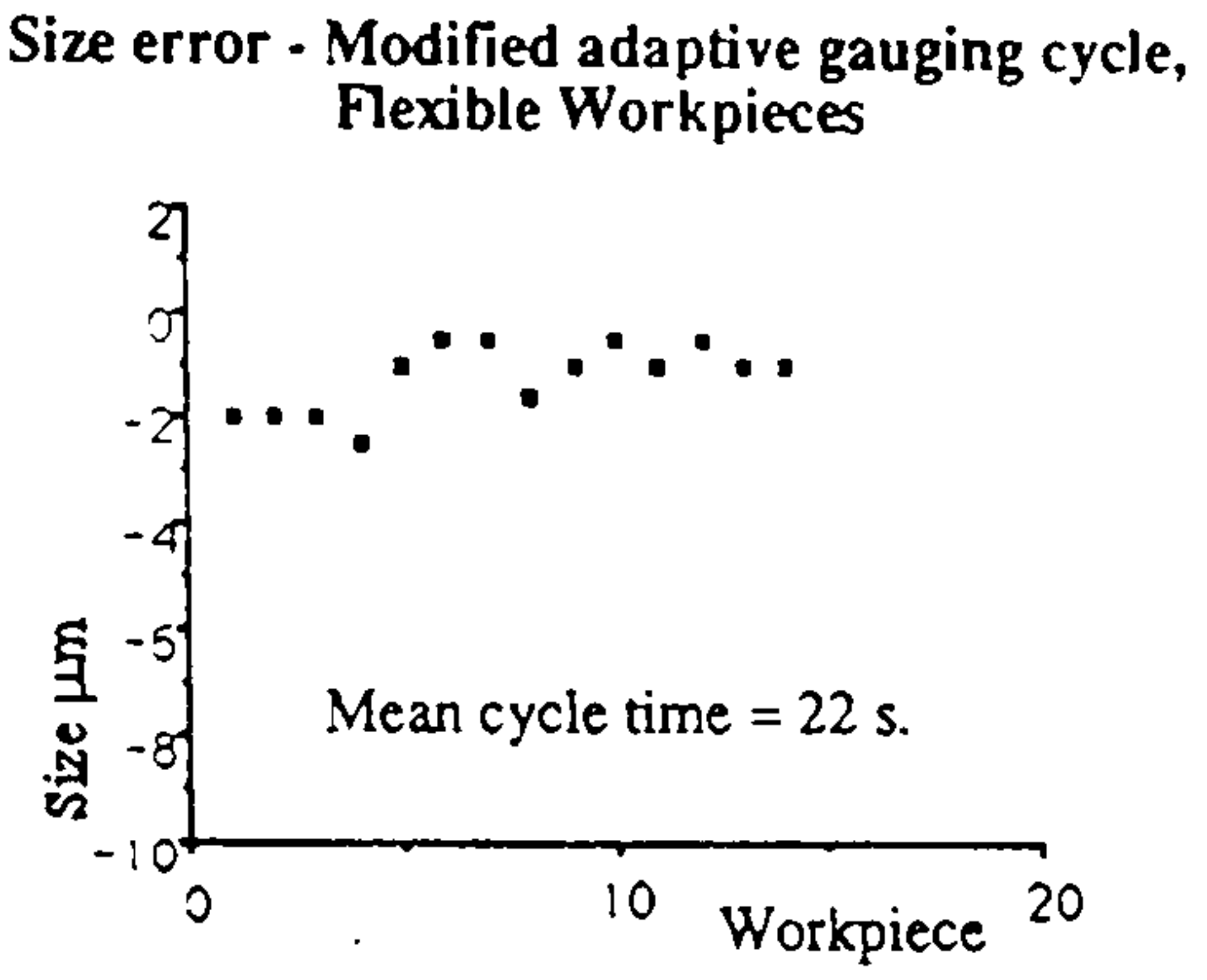


Fig. 16 Size results for modified adaptive cycle, where time constant = 3 s approx. Wheel A465K5V30W. Workpiece EN9, ds = 450 mm, dw = 46 mm, b = 50 mm, vw = 0.25 m/s, vs = 33 m/s, Power = 5 kW

In order to further improve the performance of the adaptive gaging cycle the length of the dwell period was increased from three to six time constants to allow more complete cooling of the workpiece [11] and to further reduce the removal rate as target size was approached. However, with a longer dwell period there is an increased possibility of a "time-out" situation where target size is not reached because of small infeed position errors. To avoid this situation the dwell was replaced by a very fine feed rate which ensured that the target size was always reached. Figure 16 shows that improved size holding was achieved with the modified adaptive gaging cycle.

From the dwell time required to achieve target size the adaptive gaging cycle was able to calculate an offset to compensate for errors in the infeed position. Figure 17 shows the offset generated by the modified adaptive gaging cycle. The initial offsets show "negative wheel wear" which indicates that the infeed axis was too advanced resulting in a shorter dwell time than expected. After the initial workpieces the system tracks the wheel wear, maintaining the "dwell time" and ensuring that the workpiece size is achieved in a controlled manner.

Conclusions

The time constant of the machining system can be calculated during the initial stages of an infeed cycle by integrating the process power. This method requires that the time at which grinding commences is known. This point can be accurately

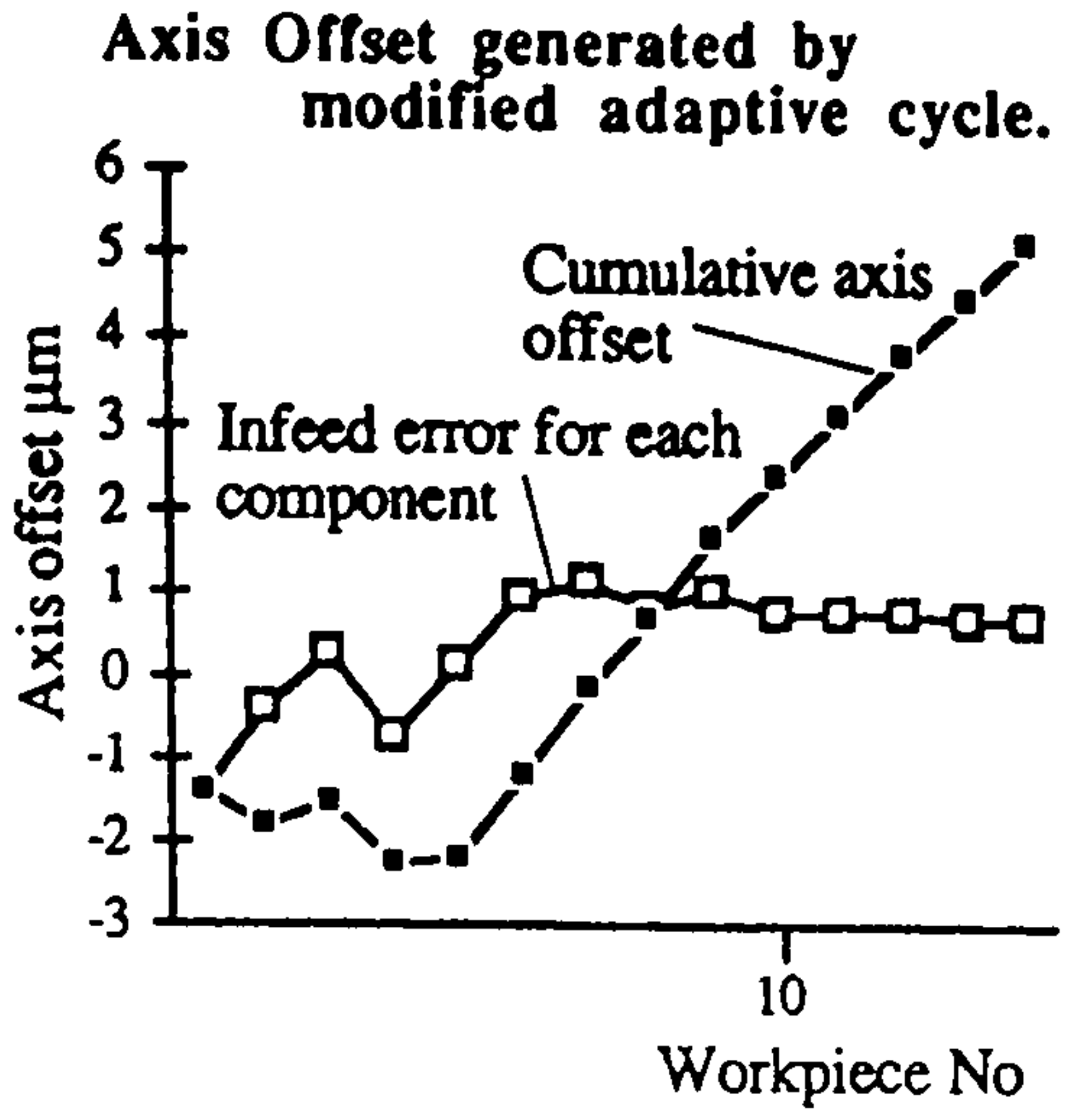


Fig. 17 Axis offset for modified adaptive cycle, where time constant = 3 s approx. Wheel A465K5V30W. Workpiece EN9, ds = 450 mm, dw = 45 mm, b = 50 mm, vw = 0.25 m/s, vs = 33 m/s, mean cycle time 22 s

detected from the variance of the grinding power. The use of these techniques is an advance in technology for grinding which provides better control of the process by adapting the target infeed position and the dwell time. It has been shown that the control system can cope with large variations in deflection due to changes in wheel sharpness or due to the updating of machining parameters as part of an adaptive strategy.

Because the time constant is measured from the grinding power, benefits are not restricted to machines that are fitted with diameter gaging systems. However, the best results are obtained when the new control system is used in conjunction with a diameter gage. When diameter gaging is used wheel wear can be accurately measured and compensated for by applying an offset to the infeed axis which does not include a proportion due to deflection. Replacing the dwell period with a very fine feed rate when using a diameter gage allows higher size accuracies to be achieved and ensures that the target size is always reached.

High levels of accuracy have been achieved at removal rates that are much greater than those normally used with a non-adaptive control system. Additionally, the adaptive gaging cycle has the advantage of decreased set-up times and reduced manual intervention as it is does not rely on the operator to manually adjust feedrate change points on the gaging system.

Acknowledgments

Acknowledgments are due to the SERC, Jones and Shipman plc, and Allen Bradley for supporting the work, and to P. Wright, P. Moran, and S. Ebbrell of Liverpool John Moores University for their technical support.

References

1 Allanson, D. R., Kelly, S., Terry, S., Moruzzi, J. L., and Rowe, W. B., 1989, "Coping with Compliance in the Control of Grinding Processes," *Annals of the CIRP*, Vol. 38, No. 1, pp. 311–314.

2 Malkin, S., and Koren, Y., 1984, "Optimal Infeed Control for Accelerated Sparkout in Plunge Grinding," ASME JOURNAL OF ENGINEERING FOR INDUSTRY, Vol. 106, February, pp. 70–74.

3 Kelly, S., Rowe, W. B., and Moruzzi, J. L., 1989, "Adaptive Grinding Control," *Journal of Advanced Manufacturing Engineering*, Vol. 1, October, pp. 287–295.

4 Kaliszer, H., 1980, "Adaptive Control in Grinding Processes," *Proceedings of the 4th International Conference on Production Engineering*, Tokyo, pp. 579–593.

5 Chen, X., Allanson, D., Thomas, A., Moruzzi, J. L., and Rowe, W. B., 1992, "Simulation of Plunge Grinding Cycles," *Proceedings of the International Advanced Manufacturing Technology Conference*, Sunderland, April 27–30.

6 Gao, Y., and Jones, B., 1992, "An Optimum Size and Roundness Adaptive Control Method for the Plunge Grinding Process," *Proc. Instn. Mech. Engrs.*, Vol. 206, pp. 107–116.

7 Malkin, S., 1981, "Grinding Cycle Optimisation," *Annals of the CIRP*, Vol. 30, No. 1, pp. 218–226.

8 Hahn, R. S., 1965, "Some Characteristics of Controlled Force Grinding," *Proc. 6th Int. Machine Tool Design and Research Conference*, Manchester, pp. 597–609.

9 Inasaki, I., 1991, "Monitoring and Optimisation of Internal Grinding Process," *Annals of the CIRP*, Vol. 40, No. 1, pp. 359–362.

10 Cai, C. G., Allanson, D., Rowe, W. B., and Morgan, M., 1991, "Accuracy in Plunge Grinding Cycles with Overshoot and Back-off," *CIRP Conference on Precision Engineering Held at Tianjin University*, June.

11 Peters, J., and Aerons, R., 1980, "Optimisation Procedure of Three Phase Grinding Cycles of a Series Without Intermediate Dressing," *Annals of the CIRP*, Vol. 29, No. 1, pp. 195–197.

A4.2 The paper published in the Int. J. Mach. Tools Manufact., Vol. 34, No. 5, 1994 pp 603-616.

Pergamon

Int. J. Mach. Tools Manufact. Vol. 34, No. 5, pp. 603-616, 1994
Printed in Great Britain.
0890-6955/94$7.00 + .00

SIMULATION OF FEED CYCLES FOR GRINDING BETWEEN CENTRES

XUN CHEN,† D. ALLANSON,† A. THOMAS,† J. L. MORUZZI† and W. BRIAN ROWE†

(*Received* 15 *October* 1992; *in final form* 7 *June* 1993)

Abstract—In order to grind workpieces accurately and effficiently, it is necessary to determine appropriate values of feed rate, target position and dwell time. The selection of optimum values depends on the deflection behaviour of the machine-workpiece system as represented by the system time constant. This paper describes the modelling and the simulation of feed cycles based on a standard simulation package. Simulated grinding cycles are compared with results from experimental measurements. The simulation technique has been employed to reduce the volume of experimentation required to develop and test feed cycles and control strategies. The paper highlights the advantages of simulation in developing a grinding process control strategy.

NOMENCLATURE

a	depth of cut
b	grinding width
d_e	equivalent diameter
d_s	wheel diameter
d_w	workpiece diameter
F_n	normal grinding force
F_t	tangential grinding force
G	grinding ratio
h_{eq}	equivalent chip thickness
k_a	contact stiffness of grinding zone
k_c	grinding force coefficient
k_e	overall effective stiffness of the grinding system
k_m	stiffness of the wheel and grinding machine
k_w	stiffness of the workpiece
n	the number of revolutions of the workpiece
n_w	workpiece rotational speed
P	grinding power
Q_w	grinding removal rate
$r(t)$	workpiece radius reduction
t	grinding time
T	period of one workpiece revolution
v_s	grinding wheel speed
v_w	workpiece speed
v_f	wheel axis infeed rate
$X(t)$	the position of the grinding wheel axis
δ	deflection of the grinding system
Δr	workpiece radius error
Δr_0	initial workpiece roundness error
ΔX_0	change of infeed rate according to the size control strategy
$\Delta \dot{X}_t$	change of infeed rate according to the power control strategy
τ	time constant.

INTRODUCTION

DEFLECTION occurs between the grinding wheel and the workpiece due to the interaction between the grinding force and the compliance of the machine and of the workpiece. The magnitude of the deflection is not always fully appreciated. Typically the deflection is of the same order of magnitude as the depth of cut in precision grinding. Sometimes the deflections measured are considerably larger than the depth of cut. The deflection causes a delay between the command signal for position and the system response, as

---

†School of Engineering and Technology Management, Liverpool John Moores University, Liverpool L3 5UX, U.K.

illustrated in Fig. 1. A consequence of the deflection are errors in the size and roundness of the workpiece. In-process measurement of size can help to ensure that final size errors are kept to a low level. In-process compensation for deflections and appropriate control strategies may also be employed [1–5]. In order to accelerate the grinding process, Hahn [6] introduced the grinding force as a control parameter to accelerate the initial feed-in process in the grinding cycle and maintain optimal removal rate. Malkin and Koren [7] introduced an over-shoot and retract strategy to accelerate the spark-out part of the grinding cycle.

This paper deals with simulation of the grinding process, a technique that was employed to assist in the development of appropriate control strategies to be utilized in an adaptive CNC system. The exercise was based on a simulation package SIMNON [8], which is easy to use assuming some familiarity with desk-top personal computers. Simulation can also be a useful technique where it is required to optimize for a fixed feed cycle operation. A limitation of the simulation technique is that the results are specific to the simulated grinding conditions. In real grinding operations, the time constant continually changes owing to the wear of the grinding wheel. In spite of this limitation, the simulation technique was found to be very useful for the insight that could be gained into the effect of changes in the values of feed rate, target position and cycle time employed for the feed cycle. Simulation can assist in determining the effects of feed cycle values on cycle time, size accuracy and roundness accuracy. Potential problems arising during grinding with different cycles can be observed and a cycle can be adjusted to eliminate any undesirable feature.

A MODEL OF THE PLUNGE GRINDING PROCESS

A basic plunge cycle consists of a feeding stage and a dwell period as illustrated in Fig. 1. Deflections are generated during the transient at the beginning of the feeding stage. The deflections have to be removed during the dwell period when the workpiece size approaches the value corresponding to the command position of the infeed. The roundness also improves during the dwell period. A mathematical model of the process should be broadly capable of describing these effects, so that the controller can predict the machine–workpiece deflection and apply the appropriate compensation in advance.

The cylindrical plunge grinding system is illustrated in Fig. 2. The machine structure supports the wheel with a linear spring of stiffness k_m and the workpiece with a linear spring of stiffness k_w. The stiffness of the grinding wheel at the point of contact with the workpiece is called k_a. An expression for the overall effective stiffness, k_e, can be obtained:

$$k_e^{-1} = k_a^{-1} + k_m^{-1} + k_w^{-1} \ . \tag{1}$$

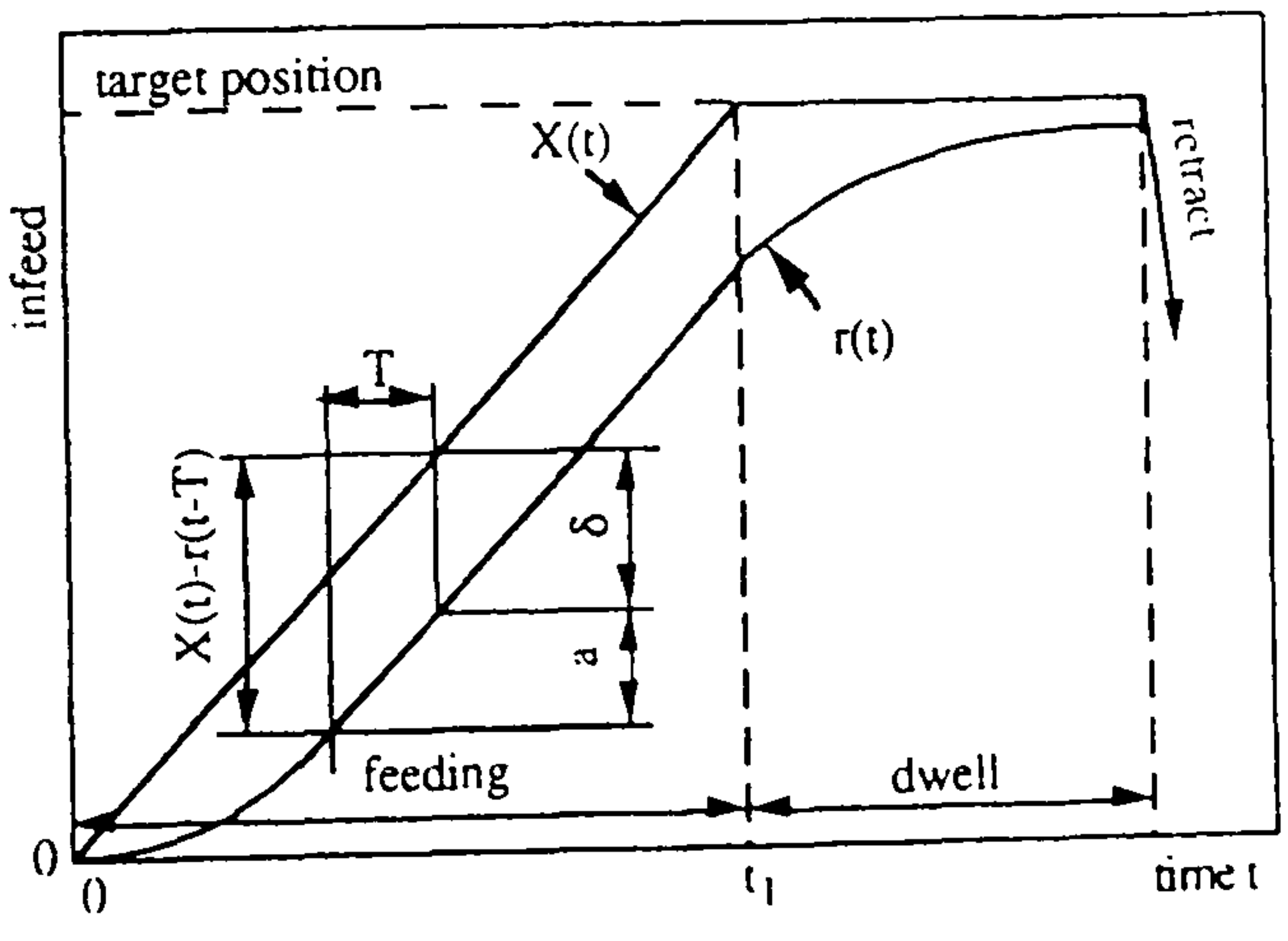


FIG. 1. Conventional plunge grinding cycle.

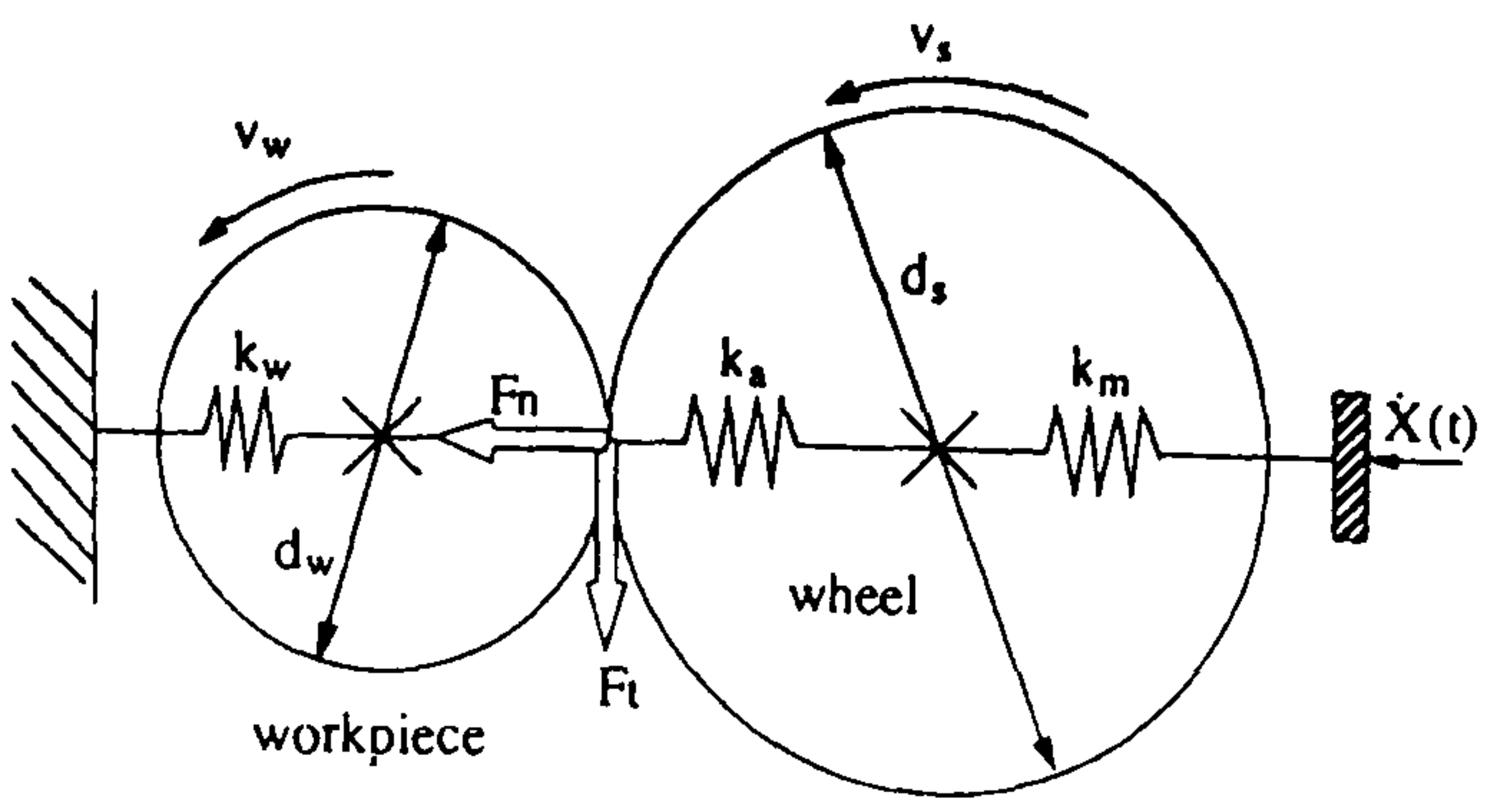


FIG. 2. Idealized model of cylindrical plunge grinding.

If grinding wheel wear is neglected, the difference between the command infeed velocity, $\dot{X}$, and the actual infeed velocity, $\dot{r}$, can be attributed to the changing radial elastic deflection, δ, in the grinding system [4]:

$$\dot{X} - \dot{r} = \dot{\delta} . \tag{2}$$

The parameter, r, is the reduction in radius of the workpiece and thus expresses the radial shape. The deflection is given by:

$$\delta = F_n / k_e \tag{3}$$

where F_n is the normal grinding force component. To facilitate the analysis, it can be assumed that the normal force component is proportional to the real depth of cut:

$$F_n = k_c \cdot a = k_c \cdot \dot{r} / n_w \tag{4}$$

where k_c is the grinding force coefficient, a is the real depth of cut and n_w is the workpiece rotational speed. Combining equations (2)–(4) leads to the controlling equation of the grinding system:

$$\dot{X} - \dot{r} = \frac{k_c}{k_e \cdot n_w} \cdot \ddot{r} \tag{5}$$

so that:

$$\ddot{r} = \frac{1}{\tau} [\dot{X} - \dot{r}] \tag{6}$$

where τ is the time constant of the system and is a measure of the relationship between stiffness and grinding force coefficient and also:

$$\tau = k_c / (k_e \cdot n_w) . \tag{7}$$

The time constant is affected by the wheel speed and workpiece speed through the rotational speed, n_w, and the factor k_c.

The simulation procedure is straightforward in its application. The most difficult aspect is to determine the appropriate value of the time constant from experiment to characterize the system. There are several ways of identifying the system time constant from experiment. Some possibilities are:

(i) the time constant can be derived from the size error in a test where the workpiece is ground without dwell. This is a relatively simple techique and is described in more detail in Appendix 1;

(ii) the time constant can be derived from measurements of the system stiffness and the grinding force coefficient according to equation (7). This is more complicated and is less reliable; and

(iii) the time constant can be derived from a data log of either size or power level during the dwell period. This technique is relatively straightforward if the size or power level is monitored as a part of the control strategy. Analysing the shape of the power curve enables the time constant to be determined during the grinding process. The required information for this technique was available since the purpose of the exercise was to simulate a process where power is sensed as the main feedback in the system. More detail is given in Appendix 2.

So far, the effect of wheel wear has been neglected. The grinding model can be readily modified to include the effect of wheel wear if a grinding ratio, G, is defined as the volumetric ratio of material removal rate to the wheel wear rate:

$$G = \frac{\pi d_w \cdot b \cdot \dot{r}(t)}{\pi d_s \cdot b \cdot \dot{w}(t)} = \frac{d_w \cdot \dot{r}(t)}{d_s \cdot \dot{w}(t)} \tag{8}$$

where $\dot{w}(t)$ is the radial wear rate of the grinding wheel. If wheel wear is taken into account, the continuity condition, given by equation (2), is modified to:

$$\dot{X} - \dot{r} - \dot{w} = \dot{\delta} \tag{9}$$

and thus:

$$\ddot{r}(t) = \frac{1}{\tau'}[\dot{X}'(t) - \dot{r}(t)] \tag{10}$$

where

$$\tau' = \frac{\tau}{1 + \dfrac{d_w}{d_s \cdot G}} \tag{11}$$

and

$$\dot{X}'(t) = \frac{\dot{X}(t)}{1 + \dfrac{d_w}{d_s \cdot G}}\,. \tag{12}$$

Where the amount of wheel wear during one grinding cycle is small in comparison to the radial penetration rate, the wheel wear can be neglected, enabling equation (6) to be used. Because the time constant is taken from experiment by data logging, wheel wear does not affect the time constant evaluation.

Roundness errors mainly result from machine vibration and from geometrically generated errors. The geometrically generated errors are primarily due to variations in the differences between $r(t)$ and $r(t - T)$, where T is the period of one workpiece revolution. In the absence of significant vibrations and at high feed rates, roundness errors are mainly caused by variations in the differences between $r(t)$ and $r(t - T)$. Roundness errors also occur due to the residual effects of the initial workpiece roundness errors Δr_0. The effect of the initial workpiece roundness errors is only $\Delta r_0 \cdot (k_c/(k_c + k_c)^n$ for low frequency Fourier shape harmonics and can be neglected. Here, n is the number of revolutions of the workpiece during grinding. More details are given in Appendix 3. Therefore, considering only the effects of feed rate and static compliance, the roundness error of the workpiece at any time in the grinding process can be assumed to be $r(t) - r(t-T)$.

Grinding power and grinding force are important parameters of the grinding process that can be directly controlled if the technology is available. Because the grinding power is easier to monitor in grinding operations, the grinding power was chosen as an analysis parameter. A power model was used to express the variation of grinding power and specific energy during grinding for the purposes of simulation. The theoretical expression used for the grinding power [9, 10] was:

$$P = u_0\, b\, v_w\, a + B\, b\, d_e^{1/4}\, a^{1/4}\, v_w^{1/2} \tag{13}$$

where u_0 and B are constants, b is the grinding width, and $d_e = d_s \cdot d_w / d_s + d_w$ is the equivalent diameter. For the purpose of this exercise, the empirical grinding power model was approximated as [11]:

$$P = F_t \cdot v_s = b \cdot F_1 \cdot h_{eq}^f \cdot v_s = b \cdot F_1\, (\pi \cdot d_w)^f\, v_f^f \cdot v_s^{1-f} \tag{14}$$

where F_1 is a constant, f is an exponent and h_{eq} is equivalent chip thickness. Equation (14) can be expressed as a relationship between power and the rate of reduction in radius, $\dot{r}$, that is:

$$P = k\, \dot{r}^f. \tag{15}$$

THE SIMULATION PACKAGE

Simulation of the grinding cycle can be usefully undertaken to illustrate the effects of the various cycle parameters. Figure 3 illustrates the structure of the simulation package. This grinding simulation package consists of an executor simulation program and a data base. The executor mimics a CNC controller and is used to simulate various grinding cycles with any combination of values of grinding cycle parameters using information stored in the data base. Thus the simulation is able to predict the final workpiece size and cycle time that the selected cycle will achieve.

The elements of the simulation package in control terms are listed below.

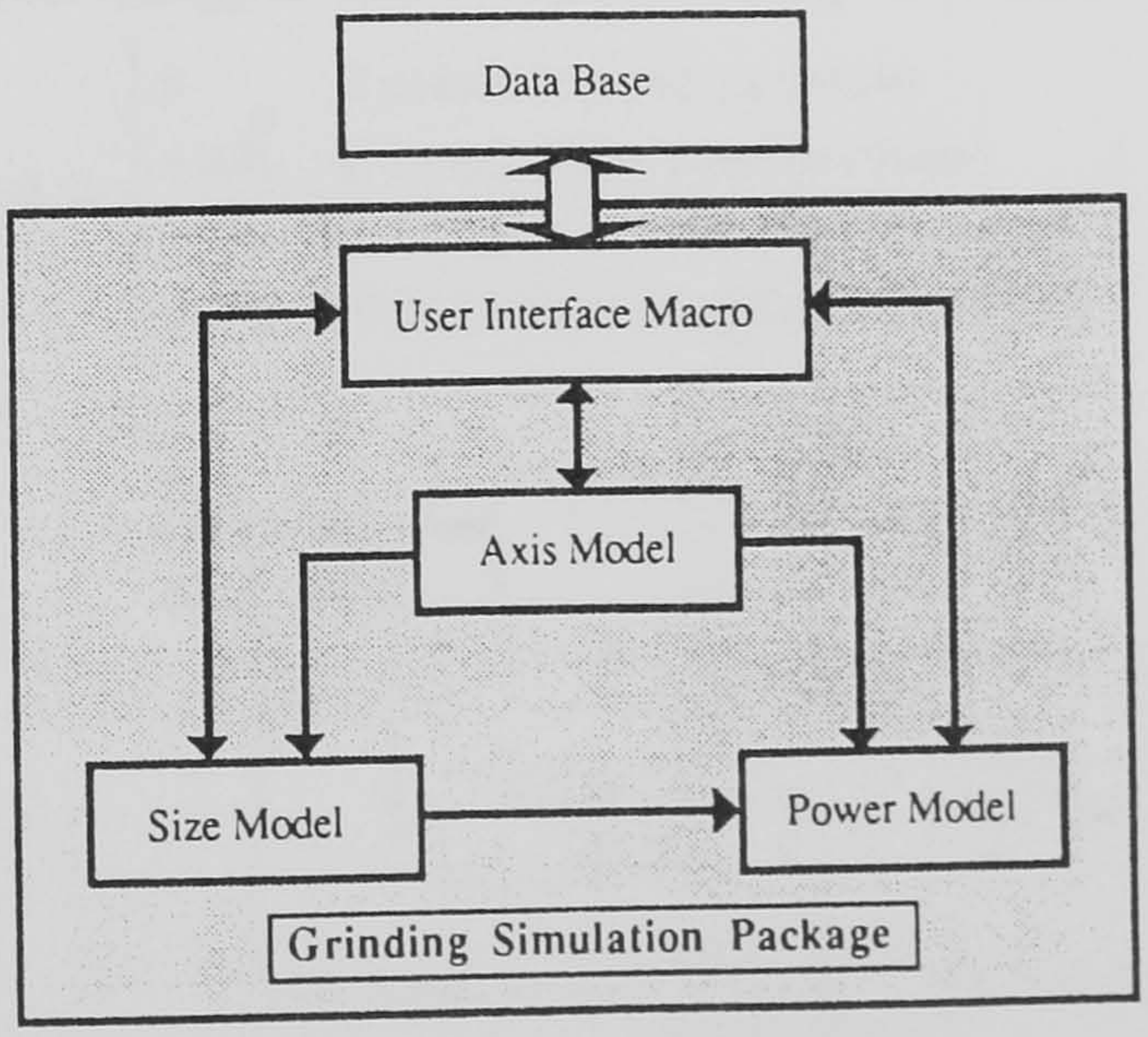


FIG. 3. The structure of the simulation package.

(i) The wheel axis model, which gives the axis position, is:

$$\frac{X(s)}{\dot{X}(s)} = \frac{1}{s}. \tag{16}$$

(ii) The workpiece size model, which gives the radius of the workpiece, derived from equation (6), is:

$$\frac{r(s)}{\dot{X}(s)} = \frac{1}{s(s \cdot \tau + 1)} \tag{17}$$

where $X(s)$, $\dot{X}(s)$ and $r(s)$ are the Laplace transforms of the wheel axis position, wheel axis infeed rate and workpiece size. When the wheel wear rate is large, the G ratio should be used in the size model as in equations (10)–(12).

(iii) The power model is $P/\dot{r}^f = k$. This relationship is shown as $T(P(t))$ in Fig. 4. The exponent f can easily be updated according to the grinding condition. From the power model, the variation of grinding power during grinding can be clearly predicted. In addition, if the information is entered to allow burn to be predicted for the materials being used [12, 13], the system will give a warning when damage is likely to occur.

(iv) Simulation control program. The simulation control program supervises the simulation and contains the simulation algorithm. Various grinding cycles were simulated by varying the algorithm. How this simulation package simulates the grinding cycle is shown as a block diagram in Fig. 4, where $T(P(t))$ is the transfer function of the grinding power model. Either a constant feed rate control strategy may be employed or a power control strategy depending on the type of cycle to be simulated. The constant feed rate control strategy is described by the following set of conditional statements:

$$\Delta\dot{X}_0 = \left\{\begin{array}{ll} 0 & \text{If size threshold not crossed} \\ \Delta\dot{X}_c & \text{If within coarse infeed stage} \\ \Delta\dot{X}_m & \text{If within the medium infeed stage} \\ \Delta\dot{X}_f & \text{If within the fine infeed stage} \\ \dot{X}_0 & \text{If the command size is achieved} \end{array}\right\}. \tag{18}$$

The power strategy is described by the following set of conditional statements:

$$\Delta\dot{X}_1 = \left|\begin{array}{ll} 0 & \text{If power threshold not crossed} \\ -\Delta\dot{X}_i & \text{If the initial action level is crossed} \\ -\Delta\dot{X}_h & \text{If the higher power threshold is crossed} \\ +\Delta\dot{X}_l & \text{If the lower power threshold is crossed} \end{array}\right|. \tag{19}$$

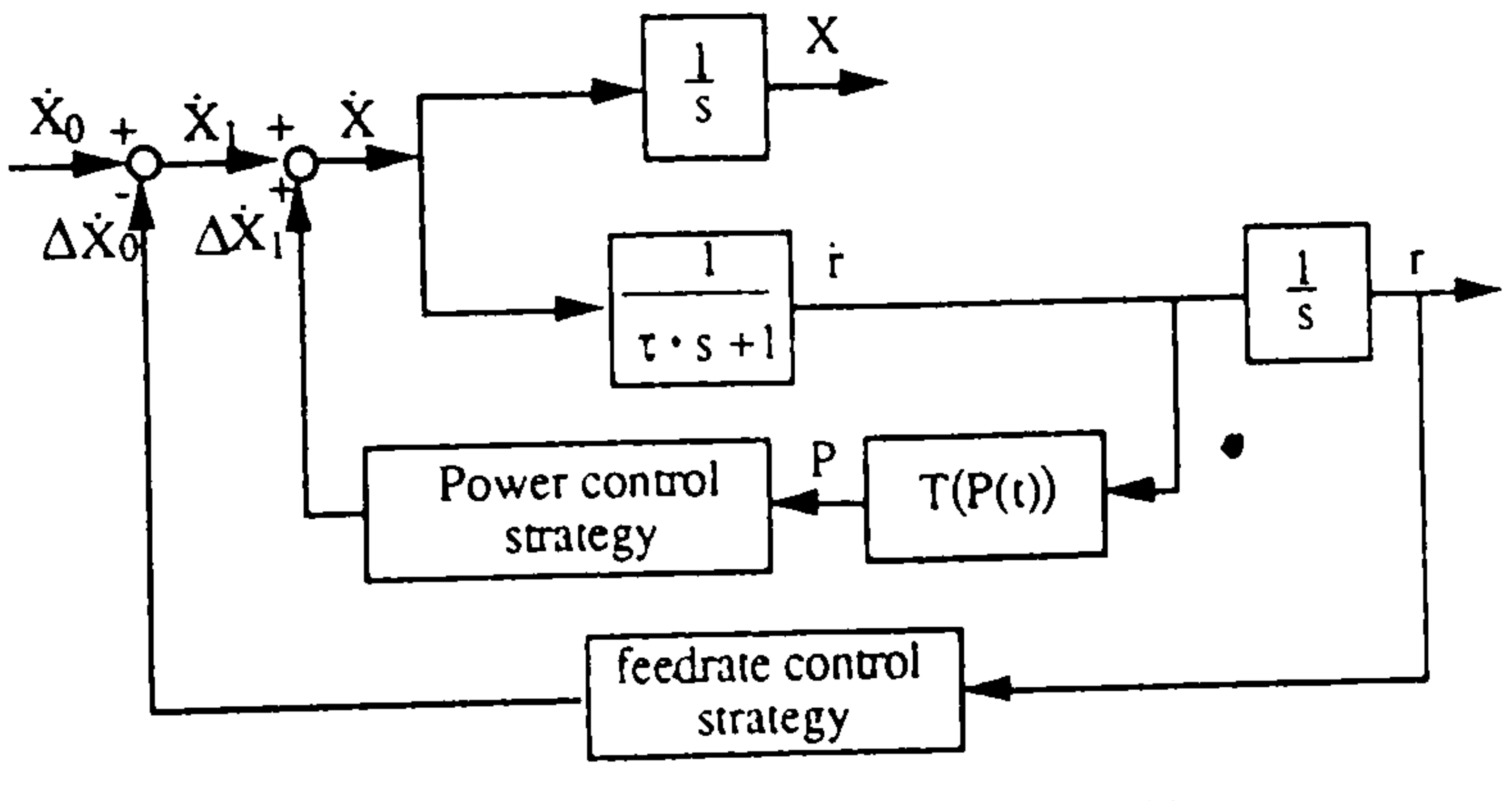


Fig. 4. Block diagram of the simulation relationships.

The above strategies are further discussed and explained in relation to simulated and experimental results for particular grinding cycles under the Results.

(v) The data base. Values required for the simulation are stored in a data base. This information has been established from previous grinding experiments.

For a single or multi-feed rate plunge grinding cycle, the following parameters have to be specified:

1. infeed rates and durations;
2. dwell period;
3. workpiece speed; and
4. wheel speed.

For a controlled power cycle the parameter to be specified is the maximum power level.

In order to fully utilize the capabilities of the simulation package, the following data have to be available:

1. the time constant of the grinding system;
2. the maximum power to be employed; and
3. the thermal properties of the workpiece and the grinding wheel. Where these cannot be supplied, the nearest known equivalents can be used for common material types.

Briefly, the method of using the simulation package was as follows. After the grinding cycle had been simulated, the results were evaluated and a decision taken as to the nature of the best grinding cycle to be employed. Adjustment of the values of the grinding parameters was made and further simulations carried out within a matter of minutes. The grinding system characteristics were monitored on a real machine and the simulation package used to assist in decision making as grinding trials proceeded.

The data base played an important part in the grinding simulation package. It was therefore necessary that the structure of the data base was readily accessible. In this respect, the data base needs to be flexible enough to allow simulation of a wide range of grinding conditions. The data base was designed to give access to relevant process information such as the workpiece, wheel types and their properties. The data base contains the physical constants such as the thermal/mechanical properties of the grinding wheel and workpiece. The data base also forms the "memory" of the simulated control system and allows the system to store adaptively generated optimum values of kinematic parameters for future use. The system was designed to learn about the process and allow safe starting conditions to be predicted. The process models are independent of the data base and can be updated easily depending on different types of grinding situation.

EXPERIMENTAL CONDITIONS

The experiments were undertaken on a Jones & Shipman Series 10 grinding machine and the results simulated using the simulation package. The grinding wheel specification was A465-K5-V30W. The workpiece material was oil-hardened cast steel. Arrow Synthetic Cutting Fluid was used, which is a soluble-oil-based coolant. The dilution rate was 1:16. The dressing procedure consisted of two dressing passes taken with a dressing lead of 100 μm rev^{-1} and a dressing increment of 10 μm. The values of grinding parameters were selected from the results of the simulation experiments.

RESULTS

Single infeed and dwell cycle

A simple plunge grinding operation consisting of a single infeed and dwell was used to demonstrate correspondence between experimental results and simulated results. This cycle was used to provide high initial removal rate. The removal rate reduces during the dwell period as size is approached. Longer dwell periods tend to improve

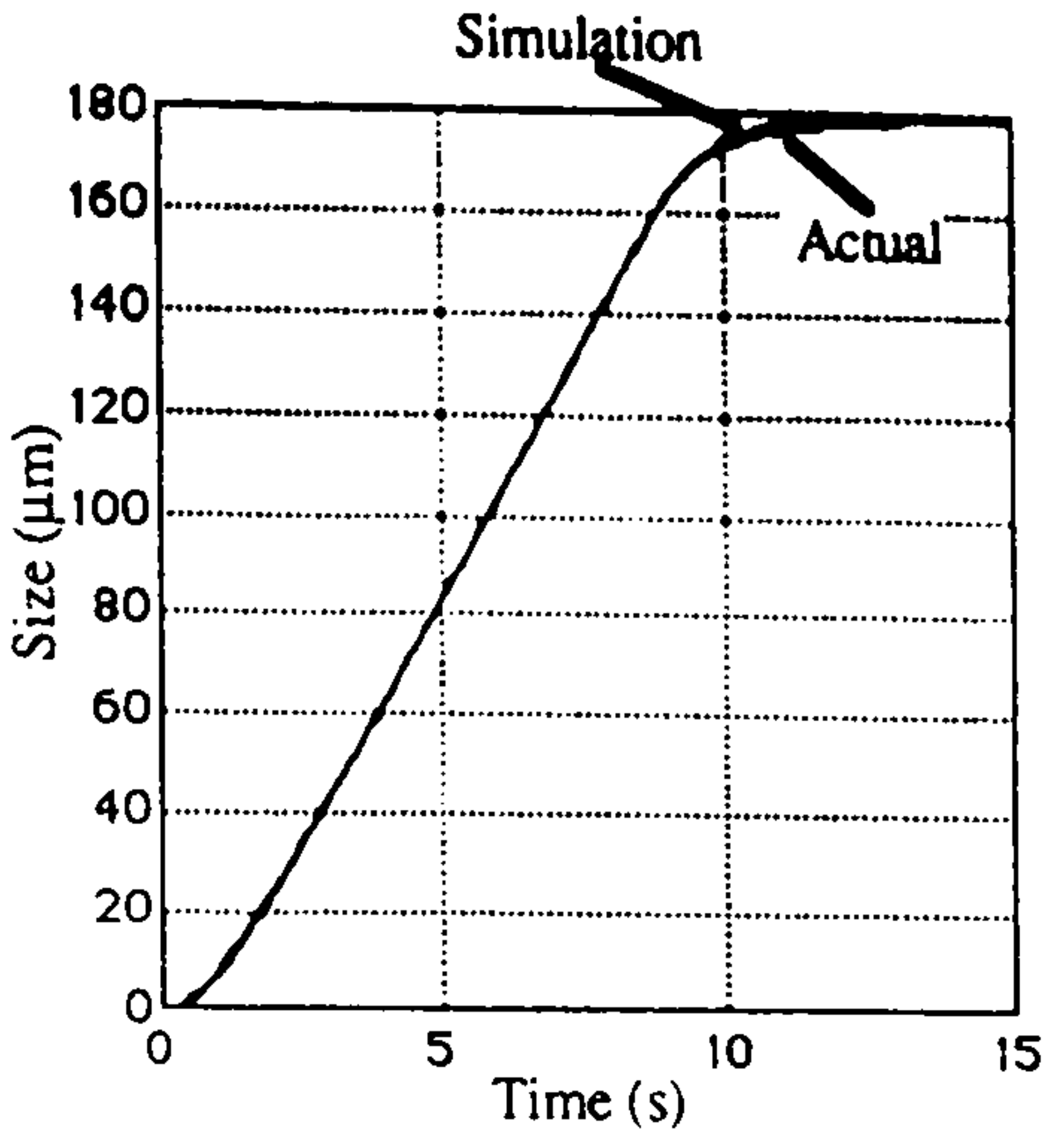


Fig. 5. Comparison between actual and simulated size reduction curves.

size control and roundness at the expense of increased cycle time. Figure 5 shows the difference between a real grinding cycle and the simulated result for a plunge grinding cycle. The values of the grinding parameters in the experiments were as follows: the wheel speed was 33 m s^{-1}, the workpiece speed was 0.167 m s^{-1}, and the wheel axis infeed rate was 10 µm s^{-1}. It can be seen that the simulated values and the real values are in close agreement. The largest size error observed in this simulation was only 1.7 µm, which was judged to be satisfactory for the purpose of cycle optimization.

Multi-infeed and dwell cycle

Figure 6 illustrates a standard grinding cycle consisting of coarse infeed, medium infeed, fine infeed and dwell stages. The response of the system in bringing the workpiece to size was simulated and the overall cycle time, the final size errors and the final roundness were predicted. The grinding cycle was optimized to control errors within the required tolerances for size and roundness by adjusting the infeed rate, infeed period, overshoot and dwell period. All changes caused by adjusting parameters were clearly evident in graphical representations of the grinding cycle.

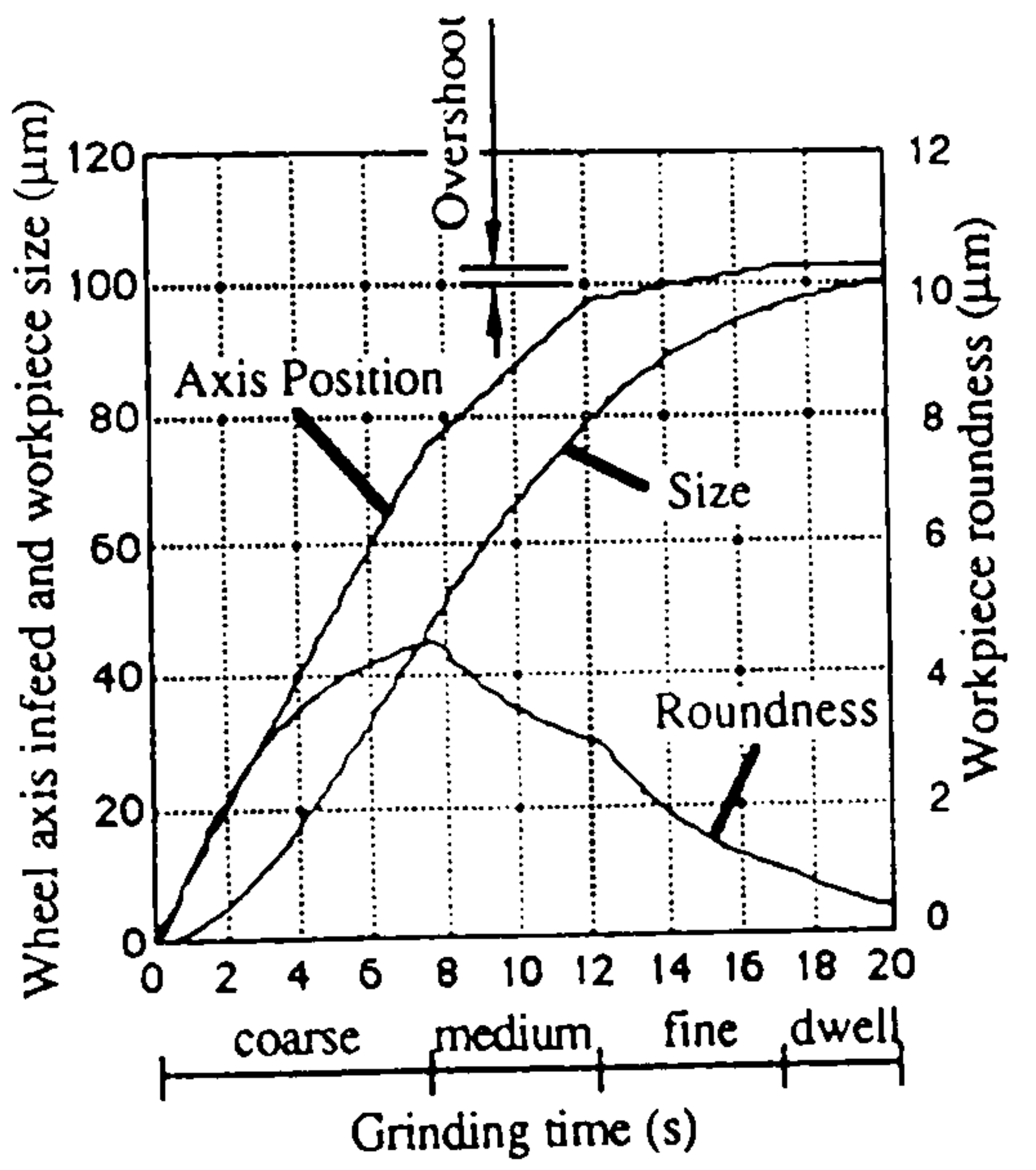


Fig. 6. Multi-infeed and dwell cycle simulation.

In-process power control

In principle, the best strategy is to control the power level rather than the infeed rate in order to achieve a minimum cycle time consistent with specified quality requirements. This strategy requires that the power is increased to the set power limit as quickly as possible and the controller adjusts the infeed rate adaptively to maintain the power setting [6, 10, 14]. However the implementation of in-process power control presents a difficulty, because of deflections in the system. It is difficult to know when and how the infeed rate should be reduced to prevent the grinding power overshooting the power setting. This problem is illustrated in Fig. 7, which indicates that the grinding power, which should approach the power limit, takes an appreciable time to react to decreases in infeed rate and a power "overshoot" occurs. This situation could be unacceptable if the power limit setting has been set to avoid poor size accuracy and possible burn. To avoid the occurrence of this phenomenon, the infeed rate needs to be reduced at appropriate times before the power limit is reached. This was achieved by setting an initial action level that was lower than the lower power threshold. When the grinding power was higher than the power initial action level, the infeed rate was decreased. In this way, the shape of the grinding power curve was adjusted to prevent power overshoot.

Figure 8 illustrates the procedure employed for simulating and developing an in-process power control cycle. In this grinding cycle control strategy, the grinding process begins with the fastest infeed rate. When the grinding power is higher than the initial action level, the infeed rate decreases with set change steps. When the grinding power is between the required power control limits, the infeed rate is varied to constrain the power within this power control band. This is achieved by decreasing infeed rate when power is higher than the upper power threshold and increasing infeed rate when the power is lower than the lower power threshold.

The grinding cycle was optimized by adjusting the upper power threshold, the lower power threshold, and the initial action level together with infeed rate change steps. Figure 9 illustrates a simulation of a grinding cycle developed using the above procedure. The grinding power was controlled to remain under the set limit of 1.5 kW. It was found that the power reached its limit in about 1 s with no overshoot. Providing the

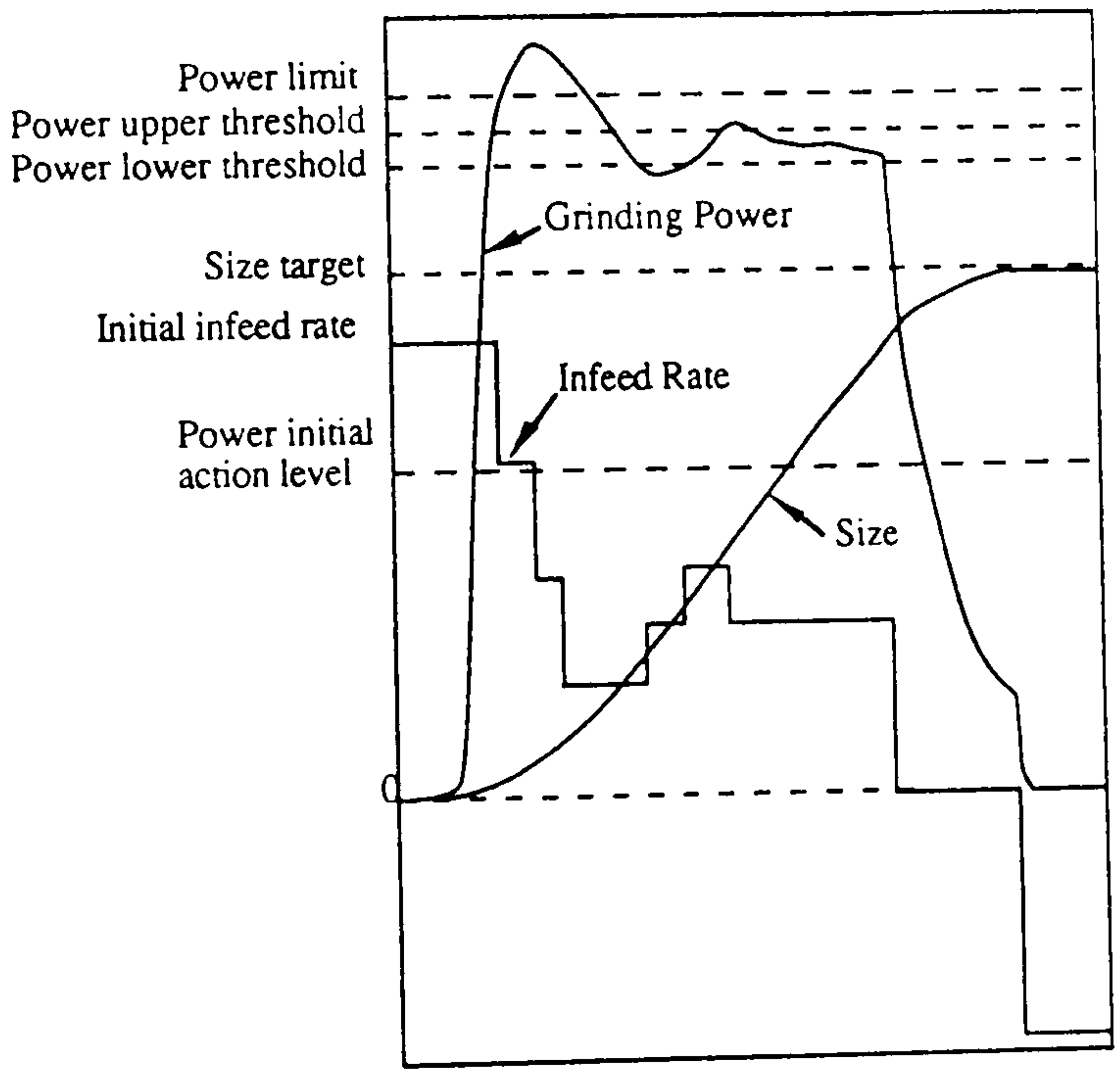


FIG. 7. A simulated power control grinding cycle using a non-optimal in-process power control strategy.

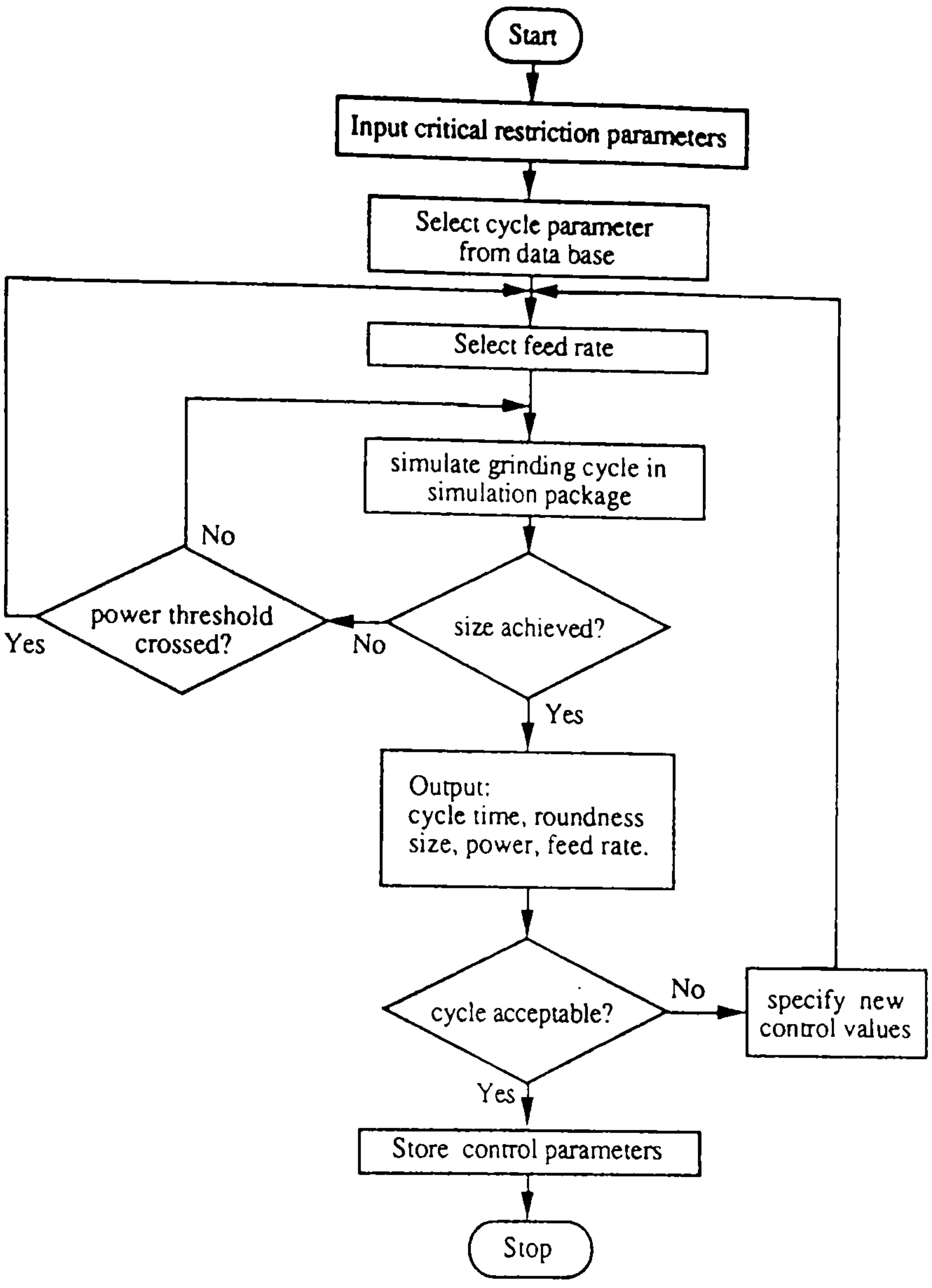


FIG. 8. The flow chart for simulation of in-process power control.

data base values are appropriate, the simulation indicated that burn will not occur and the cycle time will be close to the shortest possible. In principle, the dwell time can also be minimized, if the system time constant is known. The effectiveness of the control strategy developed by the simulation technique was evaluated by using the parameters determined by these means on a real machine fitted with an appropriate adaptive control system.

Figure 10 illustrates the grinding process control achieved in a real grinding experiment using the values developed by simulation. Power overshoot was avoided and maximum power was reached in the shortest time possible for the particular system. In this trial the wheel speed was 33 m s^{-1} and the workpiece speed was 0.25 m s^{-1}. Because the infeed rate was frequently varied during the power control cycle, the control of size accuracy and roundness was worse than that of the cycle using a constant infeed rate. This means a longer dwell period was required to achieve the same accuracy. This problem could also be solved by using an overshoot and retract strategy [7, 15]. However, further research is required on this subject to determine the practical problems and benefits of attempting to achieve a controlled retraction.

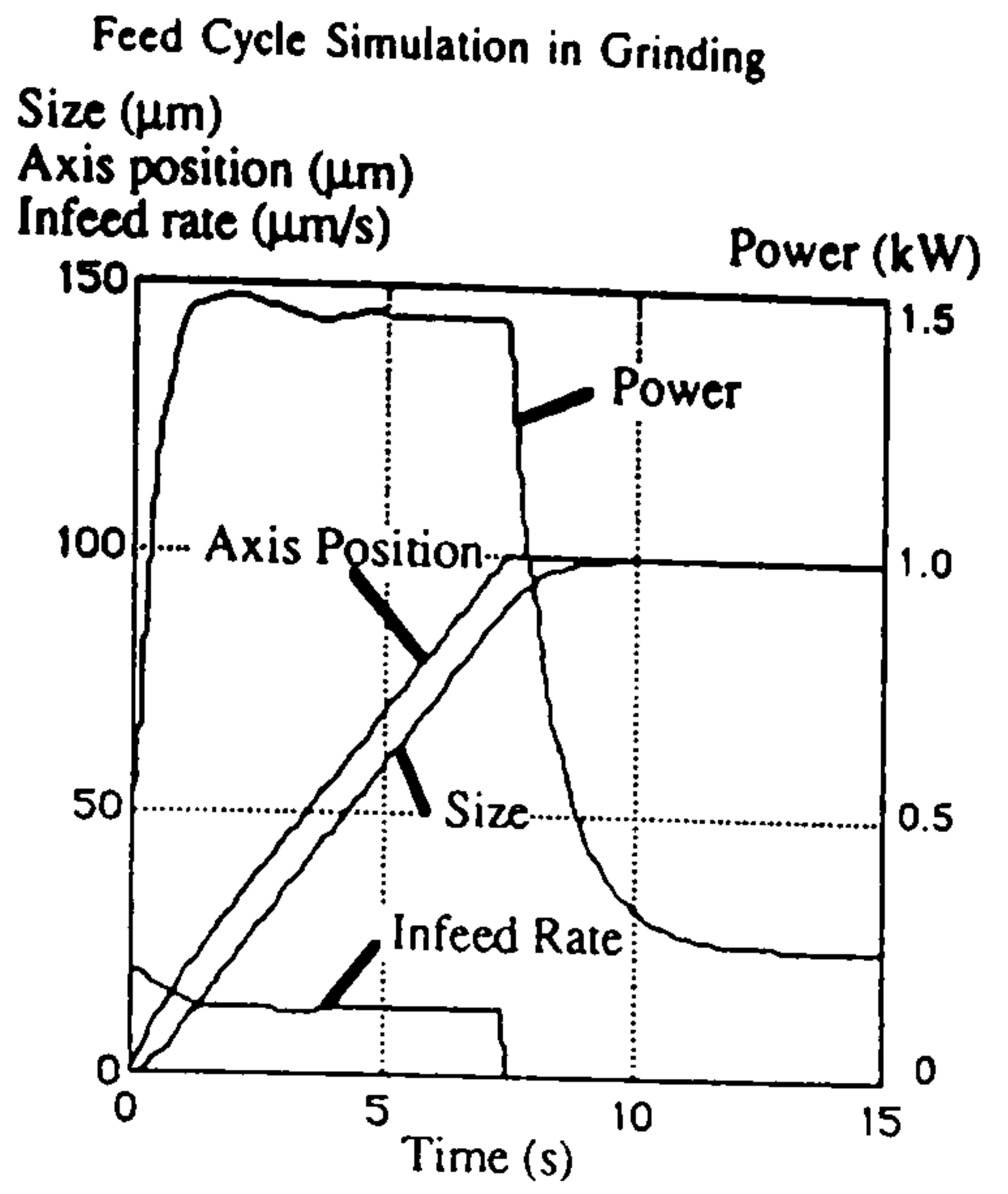


FIG. 9. The simulated grinding cycle after optimization.

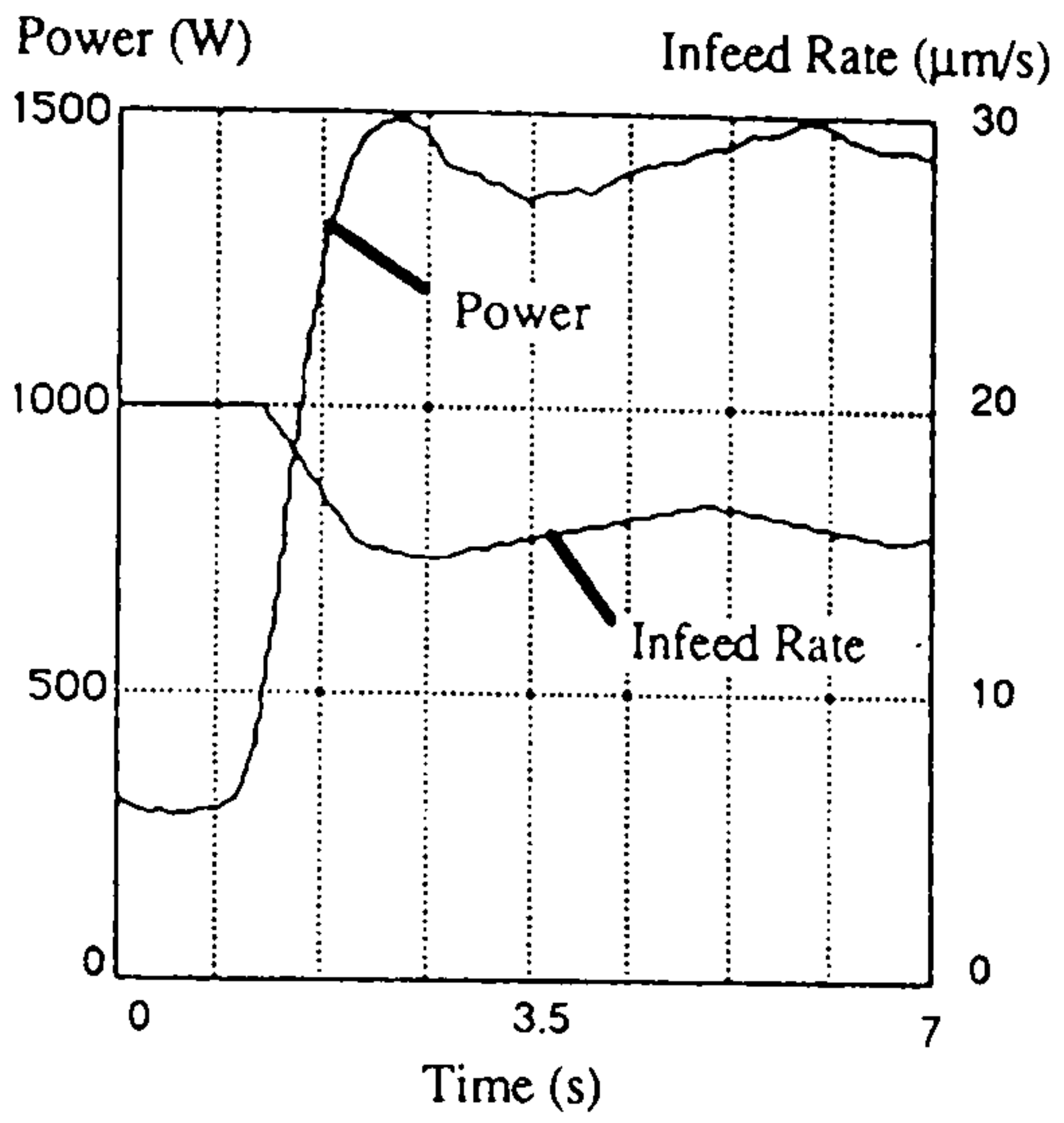


FIG. 10. Experimental power control trial using the cycle determined by simulation.

DISCUSSION

The grinding process is one that is particularly suitable for simulation owing to the broad range of operating parameters and the complexity of the process. It is expensive in machine time, materials and manpower to evaluate the effect of changes in values of grinding cycle parameters on the resulting quality and accuracy of the workpiece purely by experiment. The simulation technique allowed algorithms for real time control to be developed and tested prior to implementation on a grinding machine. This greatly reduced the number of grinding trials required, and as such, simulation was found to be a valuable tool for decision making in selecting the most suitable grinding cycle.

Most aspects of grinding can be simulated and the following list is a summary of the areas in which the technique has been successfully used to study grinding cycle performance:

(a) observing the effects of variability in the system time constant;
(b) predicting the overall cycle duration;
(c) predicting final size errors;
(d) predicting roundness errors for a given dwell period;

(e) observing the effects of changing infeed rates after various time durations;
(f) designing the grinding cycle for optimal results under particular constraints;
(g) communicating and illustrating ideas for the purposes of training; and
(h) presenting graphical representations of improvement in the grinding cycle.

CONCLUSIONS

It hs been shown that a variety of grinding cycles can be simulated using simple process and system models. Comparisons between simulated grinding cycles and real grinding trials have been presented in this paper and indicate that a significant degree of accuracy in the simulation can be achieved. It has also been demonstrated that grinding cycles can be optimized by simulation with the benefits of considerable economy compared to experimental grinding trials, and achievement of improved insight into grinding behaviour. Simulation was found to be particularly useful in developing adaptive control strategies.

Acknowledgements—Thanks are due to the SERC, the Royal Society, Jones & Shipman Ltd., and OSAI A-B Ltd, for their support of this work.

REFERENCES

[1] S. Kelly, W. B. Rowe and J. L. Moruzzi, Adaptive grinding control, *Adv. Mfg Engng* **1**, 287–295 (1989).
[2] W. B. Rowe, J. L. Moruzzi, D. R. Allanson, S. Kelly and S. Terry, Coping with compliance in the control of grinding processes, *Ann. CIRP* **38**, 311–314 (1989).
[3] H. Kaliszer, Adaptive control in grinding processes, *Proc. 4th Int. Conf. Prod. Engng*, pp. 579–593, Tokyo (1980).
[4] G. J. Trmal, In-process control of size of a ground component, *Proc. 20th MTDR Conf.*, pp. 405–411, Manchester (1979).
[5] J. Webster and Y. W. Zhao, Time-optimum adaptive control of plunge grinding, *Int. J. Mach. Tools Manufact.* **30**, 413–421 (1990).
[6] R. S. Hahn, Controlled force grinding—A new technique for precision internal grinding, *Trans. ASME, J. Engng Ind.* **86**, 287–293 (1964).
[7] S. Malkin and Y. Koren, Optimal infeed control for accelerated spark-out in plunge grinding, *Trans. ASME, J. Engng Ind.* **106**, 70–74 (1984).
[8] H. Elmqvist, K. J. Åström, T. Schönthal and B. Wittenmark, *Simnon User's Guide for MS-DOS Computers*. SSPA Systems, Sweden (1990).
[9] S. Malkin, *Grinding Technology, Theory and Applications of Machining with Abrasives*. Ellis Horwood, Chichester, U.K. (1989).
[10] G. Amitay, S. Malkin and Y. Koren, Adaptive control optimization of grinding, *Trans. ASME. J. Engng Ind.* **103**, 103–108 (1981).
[11] R. Snoeys, J. Peters and A. Decneut, The significance of chip thickness in grinding, *Ann. CIRP* **23**, 227–237 (1974).
[12] W. B. Rowe, W. F. Bell and D. Brough, Limit charts for high removal rate centreless grinding, *Int. J. Mach. Tools Manufact.* **27**, 15–25 (1987).
[13] W. B. Rowe, J. A. Pettit, A. Boyle and J. L. Moruzzi, Avoidance of thermal damage in grinding and prediction of the damage threshold, *Ann. CIRP* **37**, 327–330 (1988).
[14] S. Malkin, Thermal aspects of grinding, *Trans. ASME, J. Engng Ind.* **96**, 1184–1191 (1974).
[15] G. Q. Cai, D. Allanson, W. B. Rowe and M. Morgan, Accuracy in plunge grinding cycles with overshoot and back-off, *CIRP Conf. Prec. Engng*, Tianjin University, P.R. China (1991).
[16] W. B. Rowe, J. I. Willmore and L. J. Hulton, A technique for simulation of cylindrical grinding processes by hybrid computation, *Int. J. Mach. Tool Des. Res.* **13**, 111–121 (1973).

APPENDIX A

Derivation of the time constant from size measurements

When the wheel infeed rate, $\dot{X}$, is selected as a constant v_f, the solution of equation (6) is:

$$r(t) = v_f \cdot (t - \tau + \tau \cdot e^{-t/\tau}) \,. \tag{A.1}$$

From Fig. 1, the deflection, δ, can be expressed as:

$$\Delta = X(t) - r(t) = v_f \cdot \tau \cdot (1 - e^{-t/\tau}) \,. \tag{A.2}$$

If the grinding time is long enough, $e^{-t/\tau}$ is much smaller than 1, so:

$$\delta \approx v_f \cdot \tau \,. \tag{A.3}$$

Where the workpiece is ground without dwell, the size error is mainly due to the grinding deflection.

Therefore the grinding system time constant can be calculated by means of measuring the workpiece size error, that is:

$$\tau = \Delta size/(2 \cdot v_f) \,. \tag{A.4}$$

APPENDIX B

Derivation of the time constant from power measurements

The time constant can be derived from a data log of either size or power level during the dwell period by using a curve fitting technique. If the grinding cycle is selected, as in Fig. 1, the solution of equation (6) during the dwell period ($t > t_1$) is:

$$r(t) = v_f \cdot (t_1 - \tau \cdot e^{-\frac{t-t_1}{\tau}}) \tag{B.1}$$

$$\dot{r}(t) = v_f \cdot e^{-\frac{t-t_1}{\tau}} \,. \tag{B.2}$$

Equation (4) leads to :

$$P(t) = P(t_1) \cdot e^{-\frac{t-t_1}{\tau}} \tag{B.3}$$

so that at any time t_2 on the decay curve in the dwell period:

$$\frac{P(t_2)}{P(t_1)} = e^{-\frac{t_2-t_1}{\tau}} \tag{B.4}$$

$$\tau = \frac{\log P(t_2) - \log P(t_1)}{t_2 - t_1} \,. \tag{B.5}$$

An alternative method, which is convenient when used with data logging on a computer, involves integration of the power signal. This refinement automatically filters noise. Integrating equation (B.3) leads to:

$$\int_{t_1}^{t} P(t) = \tau\, P(t_1)\,(1 - e^{-\frac{t-t_1}{\tau}}) \,. \tag{B.6}$$

When t is big enough, $e^{-\frac{t-t_1}{\tau}}$ is much smaller than 1, so that the time constant can be expressed as:

$$\tau = \frac{\int_{t_1}^{t} P(t)}{P(t_1)} \,. \tag{B.7}$$

The equations (B.1) and (B.3) can also be used for the time constant evaluation by means of data regression.

APPENDIX C

A simplified analysis of the rounding process

A simplified analysis of the rounding process relates roundness errors after n workpiece revolutions to the initial roundness error. This analysis is very much over-simplified and is only applicable if the frequencies represented by the combined effects of the roundness errors and the workpiece speed are much lower than the first resonant frequency of the grinding system. However, the process broadly reflects the rounding process for large low frequency errors [16]. Here, Δr_0 is denoted as an initial radius error of the workpiece. After the first revolution of grinding, Δr_0 will be reduced by a_1. The remaining error is equal to the deflection caused by Δr_0. Therefore:

$$\Delta r_0 = a_1 + \delta_1 = \delta_1 \cdot (k_c + k_c)/k_c \tag{C.1}$$

where $k_c = F_n/\delta$, and $k_c = F_n/a$. So:

$$\Delta r_1 = \delta_1 = \Delta r_0 \cdot \left(\frac{k_c}{k_c + k_c}\right) \,. \tag{C.2}$$

Similarly:

$$\Delta r_1 = a_2 + \delta_2 = \delta_2 \cdot \left(\frac{k_c + k_c}{k_c}\right) \tag{C.3}$$

$$\Delta r_2 = \delta_2 = \Delta r_1 \cdot \left(\frac{k_c}{k_c + k_c}\right) = \Delta r_0 \cdot \left(\frac{k_c}{k_c + k_c}\right)^2 \,. \tag{C.4}$$

Continuing the same procedure, the roundness error of the nth revolution is obtained as:

$$\Delta r_n = \Delta r_0 \cdot \left(\frac{k_a}{k_e + k_a} \right)^n . \tag{C.5}$$

Combining Equations (7) and (C.5) gives

$$\Delta r_n = \Delta r_0 \cdot \left(\frac{1}{1 + \frac{1}{\tau n_w}} \right)^n . \tag{C.6}$$

A4.3 The SME Technical Paper MR93-370, presented at the 5th International Grinding Conference, 1993.

TECHNICAL PAPER

MR93-370

Adaptive Control of Cylindrical Grinding—From Development to Commercialization

authors

JOHN LIVERTON
Director of Engineering
Jones & Shipman plc
Leicester, England

W. BRIAN ROWE
Professor
Liverpool John Moores University
Liverpool, England

J.L. MORUZZI
Professor
Liverpool John Moores University
Liverpool, England

ANDREW THOMAS
Liverpool John Moores University

D.R. ALLANSON
Liverpool John Moores University

abstract

The paper describes the development of an adaptive control system for a CNC cylindrical grinding machine, from initial investigations at a university based grinding research group to forthcoming availability as a feature for commercial machines. The system optimized the performance of infeed cycles by maintaining a desired grinding power level and by compensating for deflections. Provision was made for the optimum grinding conditions to be stored in an economic data base. Also, the set-up procedure for in-process gauging was simplified. Grinding results are presented illustrating the major improvements in productivity that can be achieved without sacrificing part quality.

conference

5th INTERNATIONAL GRINDING CONFERENCE
October 26-28, 1993
Cincinnati, Ohio

index terms

CNC
Grinding
Machine Tools
Adaptive Control

Society of
Manufacturing
Engineers
1993

Society of Manufacturing Engineers
One SME Drive • P.O. Box 930 • Dearborn, Michigan 48121
Phone (313) 271-1500

Nomenclature

Xi	*programmed infeed position of the grinding wheel - workpiece interface*	b	*width of contact between the grinding wheel and workpiece*
Xp	*actual infeed position of the grinding wheel - workpiece interface*	Vw	*workpiece speed*
		Vs	*grinding wheel speed*
t	*time since the start of grinding*	Vf	*infeed rate*
τ	*time constant of the machining system*	x_1	*deflection at start of dwell*
P	*grinding power*	X_1	*actual infeed position of grinding wheel-workpiece interface at start of dwell.*
ds	*grinding wheel diameter*		
dw	*workpiece diameter*	T_1	*time at start of dwell*
		T_2	*time at end of dwell*

1 Introduction

The cylindrical grinding process is widely used for the finishing of precision component parts because of the fine tolerances and surface finishes that can be achieved. However, the process is complex in nature because wear and dressing cause variations in the topography of the grinding wheel. The grinding forces change and consequently the optimum machining conditions do not remain constant. Therefore it is not a trivial matter to optimise the design of infeed cycles which produce accurately finished parts while maintaining short cycle times and set-up times. Pre-production trials are normally carried out in order to determine the optimum grinding conditions, but in practice the process is often operated conservatively in order to allow for its variability and ensure the quality of all the finished parts.

Adaptive control systems for grinding monitor the process by measuring the output of sensors

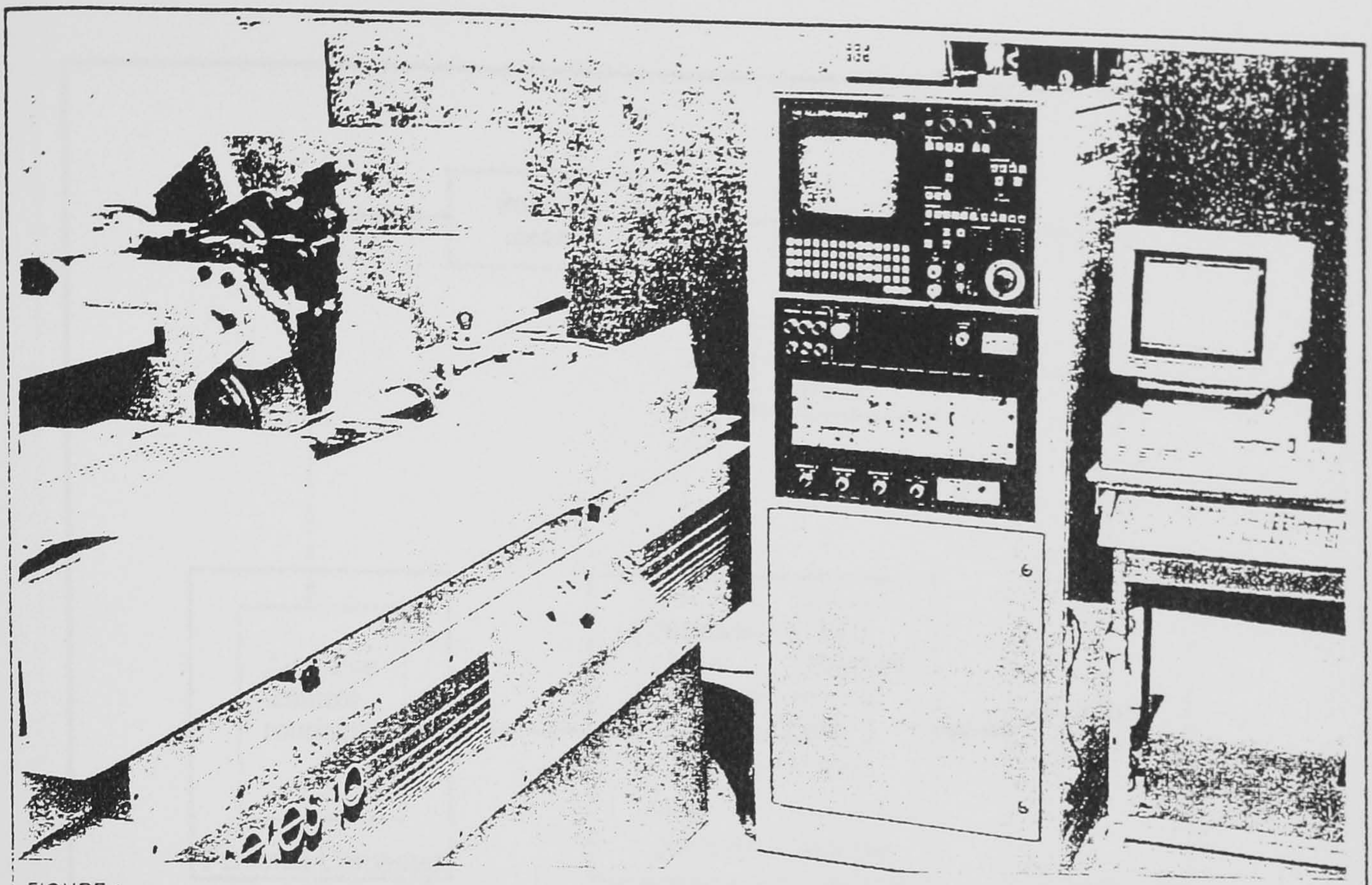


FIGURE 1

Equipment used for developing adaptive control techniques for cylindrical grinding

installed on the grinding machine. The information from the sensors is analysed and the machining parameters modified in order to maintain the desired grinding conditions.

This paper describes the adaptive techniques developed during a government funded project to develop adaptive and learning strategies for CNC grinding, and the subsequent work to make the new technology commercially available. The work was carried out by the AMT Research Laboratory at Liverpool John Moores University in collaboration with Jones & Shipman plc and Allen-Bradley. The research indicated that major improvements in the performance of CNC grinding could be achieved using techniques that could be incorporated into a conventional CNC system. On the successful completion of the project it was agreed that the work should continue with a three year Teaching Company Programme to apply adaptive techniques to a range of Jones & Shipman products. University staff employed on the project are based at the company in order to carry out the technology transfer required to bring the new systems to market.

2 System development

The techniques described in the paper were developed on a personal computer which was interfaced to a standard Jones & Shipman Series 10 CNC cylindrical grinding machine with Allen Bradley 8200 control system. The development system is shown in figure 1 (photograph) and figure 2 (diagram). The infeed and table axes of the machine were driven by d.c. servo motors with linear scale feedback giving 0.2 micron on diameter and 1 micron minimum programmable increment respectively. The grinding wheel was powered by a 7.5 kW a.c. motor driven by a frequency inverter to give a constant grinding wheel surface speed.

An in-process diameter gauge which was advanced hydraulically onto the workpiece during

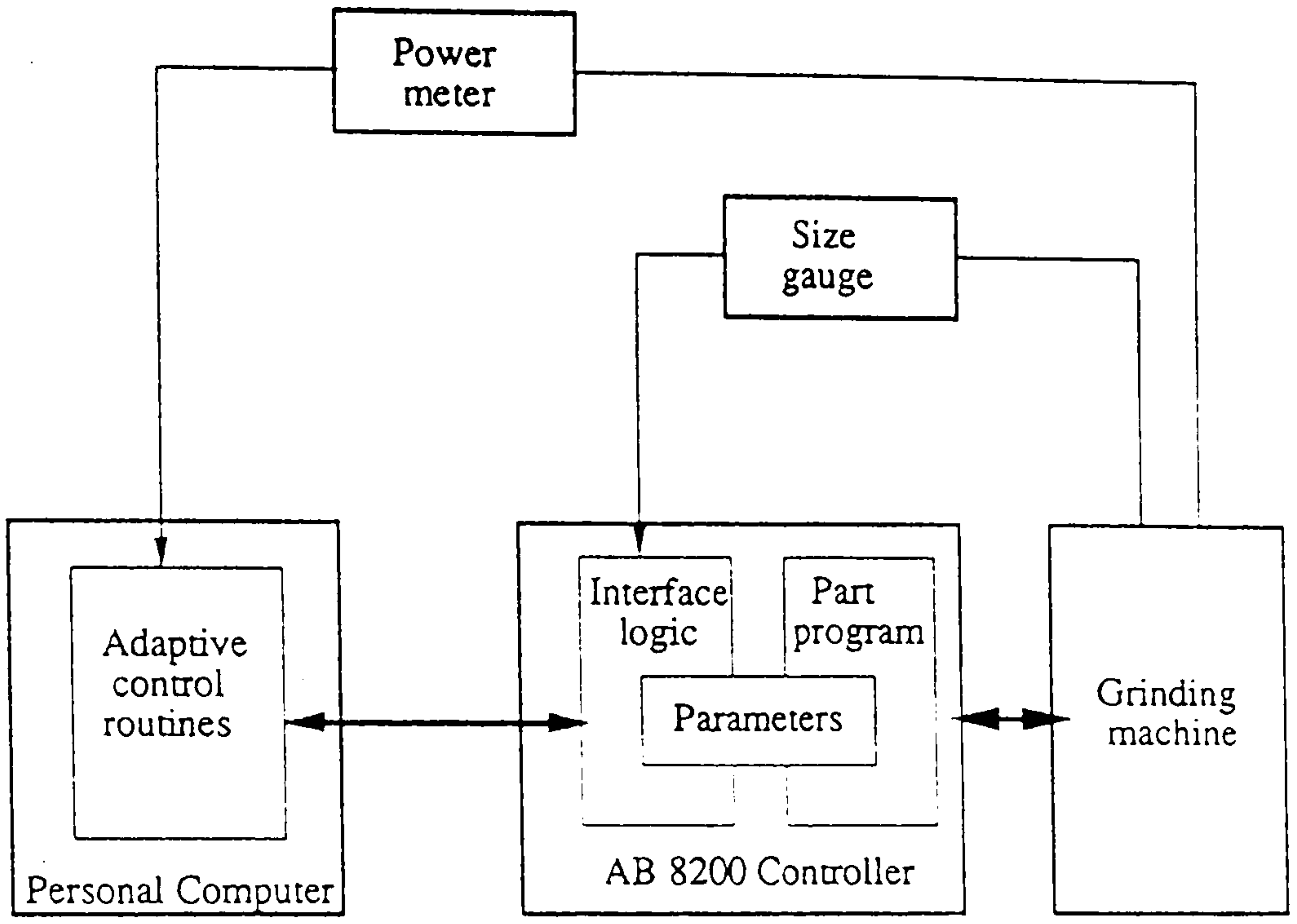


FIGURE 2
The modified control system used for developing adaptive techniques.

the infeed cycle was also fitted to the machine. A commercially available power transducer was installed on the grinding wheel drive. A third order Butterworth filter with cut-off frequency of 6 Hz was implemented in hardware and used to attenuate much of the noise on the 0-1 v analogue output of the transducer. Software running on the personal computer sampled the filtered output of the power transducer at 20 Hz via a twelve bit analogue to digital converter. The data was input to the adaptive routines also running on the personal computer. New values of machining parameters were calculated and downloaded to the machine tool controller via an interface which allowed machining parameters to be modified while an infeed cycle was in progress.

To implement the adaptive infeed cycles specialist part program macros were written for the machine tool controller. The software for the personal computer was written in the C programming language.

3 The adaptive strategy

The strategy that was used to maintain the desired grinding conditions is shown by the flow chart in figure 3. If information for the grinding operation had already been stored in the data base the initial grinding parameters were selected automatically. Otherwise the initial values were selected by the user. Workpieces could be ground with or without dimeter gauuging as infeed cycles were provided for both cases. The grinding power for the first workpiece to be ground was recorded. The infeed rate required to give the target grinding power level was calculated and this value was used when grinding the next workpiece. By updating the infeed rate throughout a batch of workpieces in this way, the target power level was maintained as shown in figure 4.

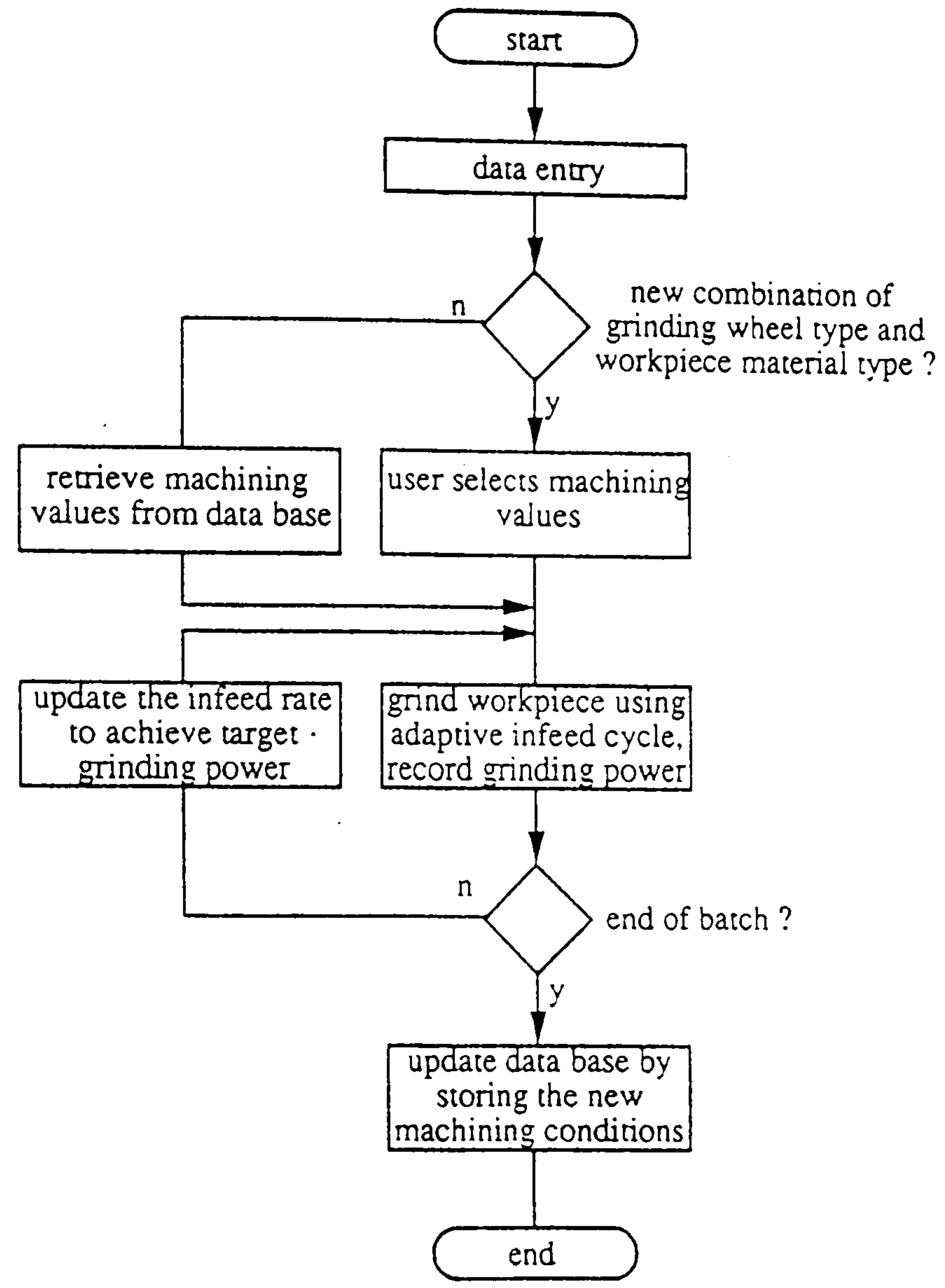
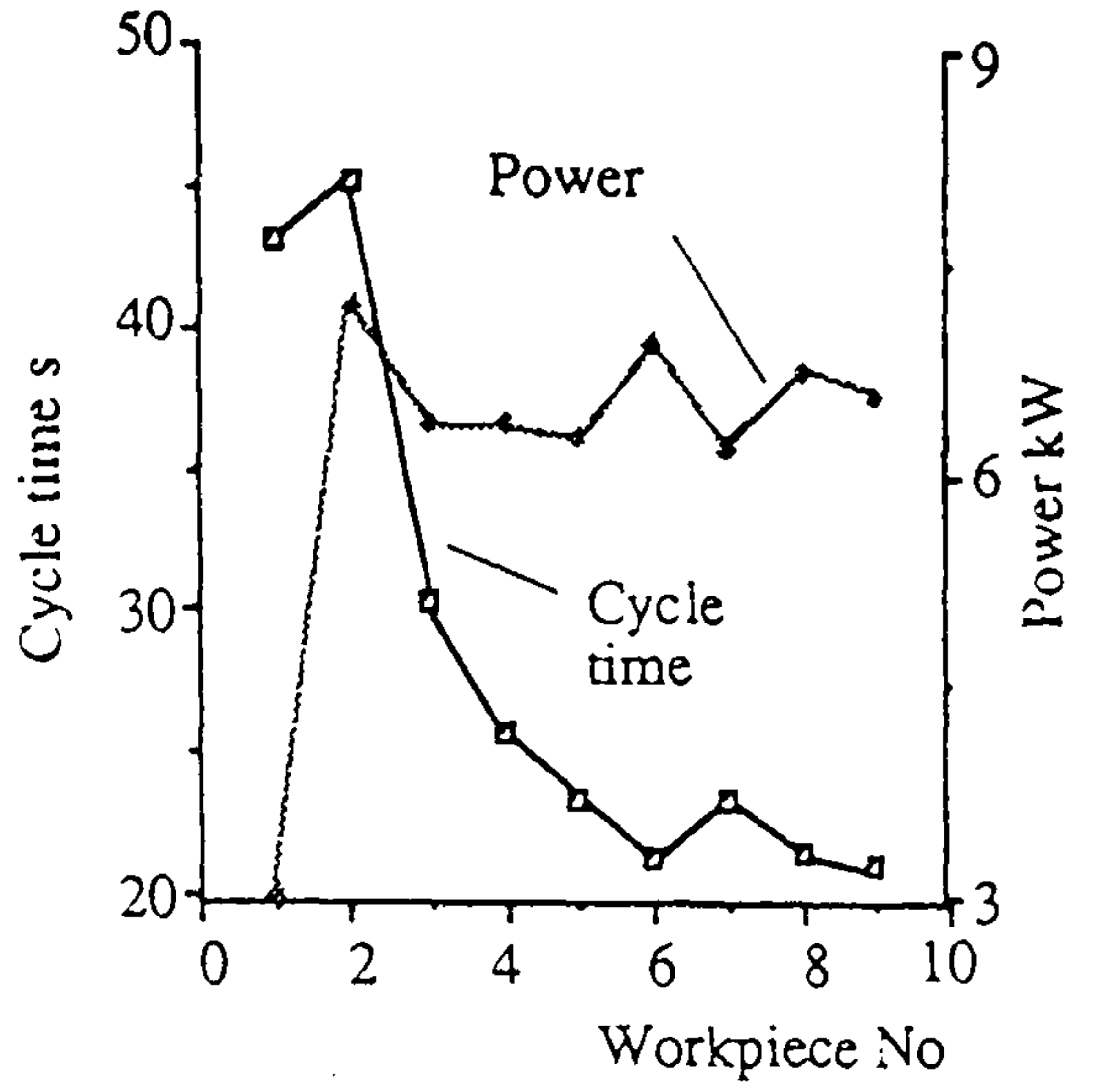


FIGURE 3
The adaptive stategy

At the end of the batch the data base was updated by storing the new grinding conditions in the form of the kinematic parameters mean chip length and chip shape ratio and the grinding wheel speed, as suggested by Rowe et al [1,2]. The information could be retrieved and converted back to machining parameter values. This principle is illustrated in figure 5 which shows the infeed rate and workpiece speed required to give the same kinematic parameters for a number of different workpiece diameters.

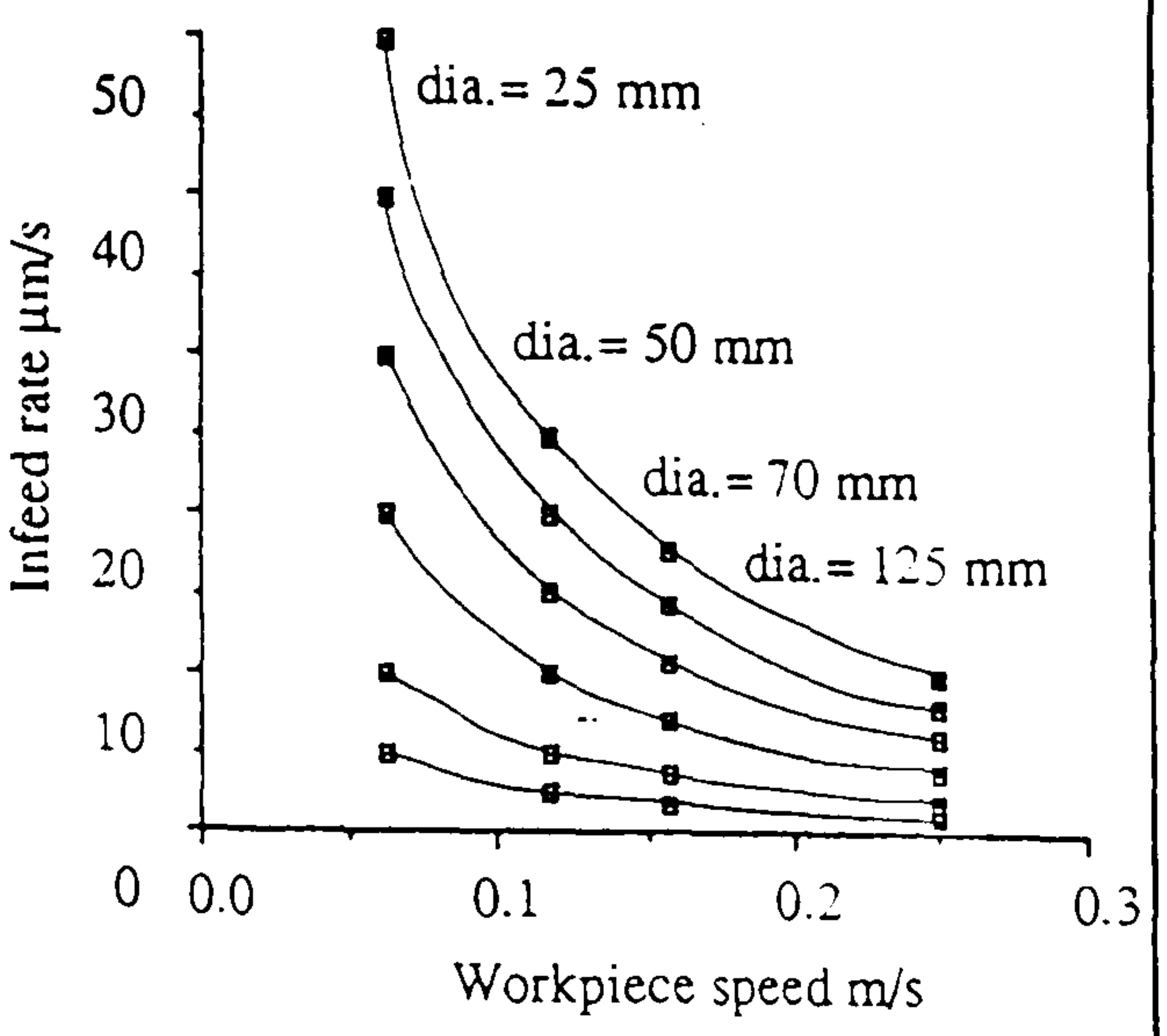
The advantage of this approach was that the stored data from one grinding operation could be used to generate the values of machining parameters to be used for another operation which used the same grinding wheel type and workpiece material combination, regardless of the



Time constant = 3 s. Workpiece En9. Wheel A465K5V30W. ds = 450 mm, dw = 46 mm, b = 50 mm, vw = 0.25 m/s, vs = 33 m/s.

FIGURE 4

The effect of updating infeed rate on power and cycle times



Workpiece K9. Wheel A465K5V30W. ds = 450 mm, b = 50 mm, vs = 33 m/s.

FIGURE 5

The infeed and workpiece speed required to achieve similar kinematic conditions for a range of workpiece diameters

diameter of the workpiece and grinding wheel.

The structure of the data base is shown in figure 6. Grinding wheel data, workpiece data and machining data were required by the data base routines. Grinding wheel and workpiece data were read from files by the front end / user interface. Machining data were read from the part program and the CNC system. This information was loaded into data structures and passed to the data base routines which were able to store and retrieve kinematic parameters from the learned data file. The data base routines also performed the conversion of kinematic parameters to machining parameter values. Once the machining parameter values had been calculated they were loaded into the machining data structure and passed to the part program via the front end / user interface.

4 Avoiding thermal damage of the workpiece

Residual tensile stresses and cracking of the workpiece associated with thermal damage in abusive grinding are significant limitations when selecting values of grinding parameters. A thermal model has been developed [3] which partitions the grinding energy into heating of the workpiece, heating of the grinding wheel, heat carried away by the grinding chips and heat dissipated into the coolant as shown in figure 7. The model predicts the critical specific energy, above which workpiece burn would occur if the infeed rate is too high or the workpiece speed is too low.

The specific energy of the grinding process can be measured by dividing the grinding power by the material removal rate. By modifying the machining parameters the specific energy can

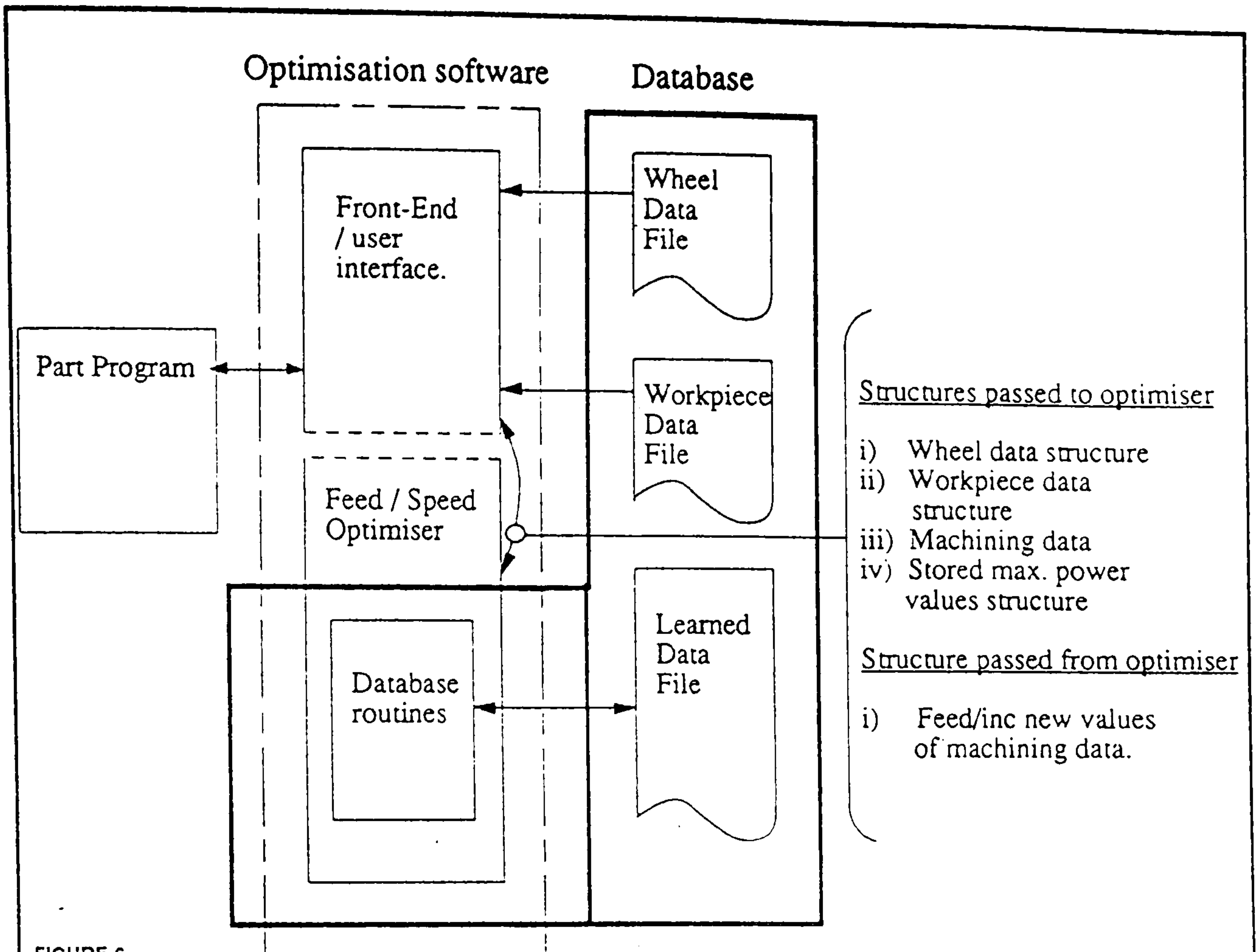


FIGURE 6
Structure of the data base

be maintained at a lower level than the critical specific energy, thus avoiding thermal damage of the workpiece.

5 Controlling workpiece size

The factors affecting workpiece size were found to be:

Deflection of the machining system.

Wear of the grinding wheel.

Wear of the dressing tool.

Thermal deformation of the machine tool due to changes in ambient temperature.

Thermal expansion of the workpiece during grinding.

5.1 Compensating for deflection of the machining system

Forces generated by the grinding process cause the machine - grinding wheel - workpiece system to deflect. As a result the actual material removal lags behind that programmed as shown in figure 8. A dwell period at the end of the infeed period allows the deflection to relax and the workpiece diameter to approach the target size. The steady state deflection is directly proportional to the lag, which can be expressed as the time constant τ of a first order system [4]. With knowledge of the system time constant the size of the workpiece during the dwell period

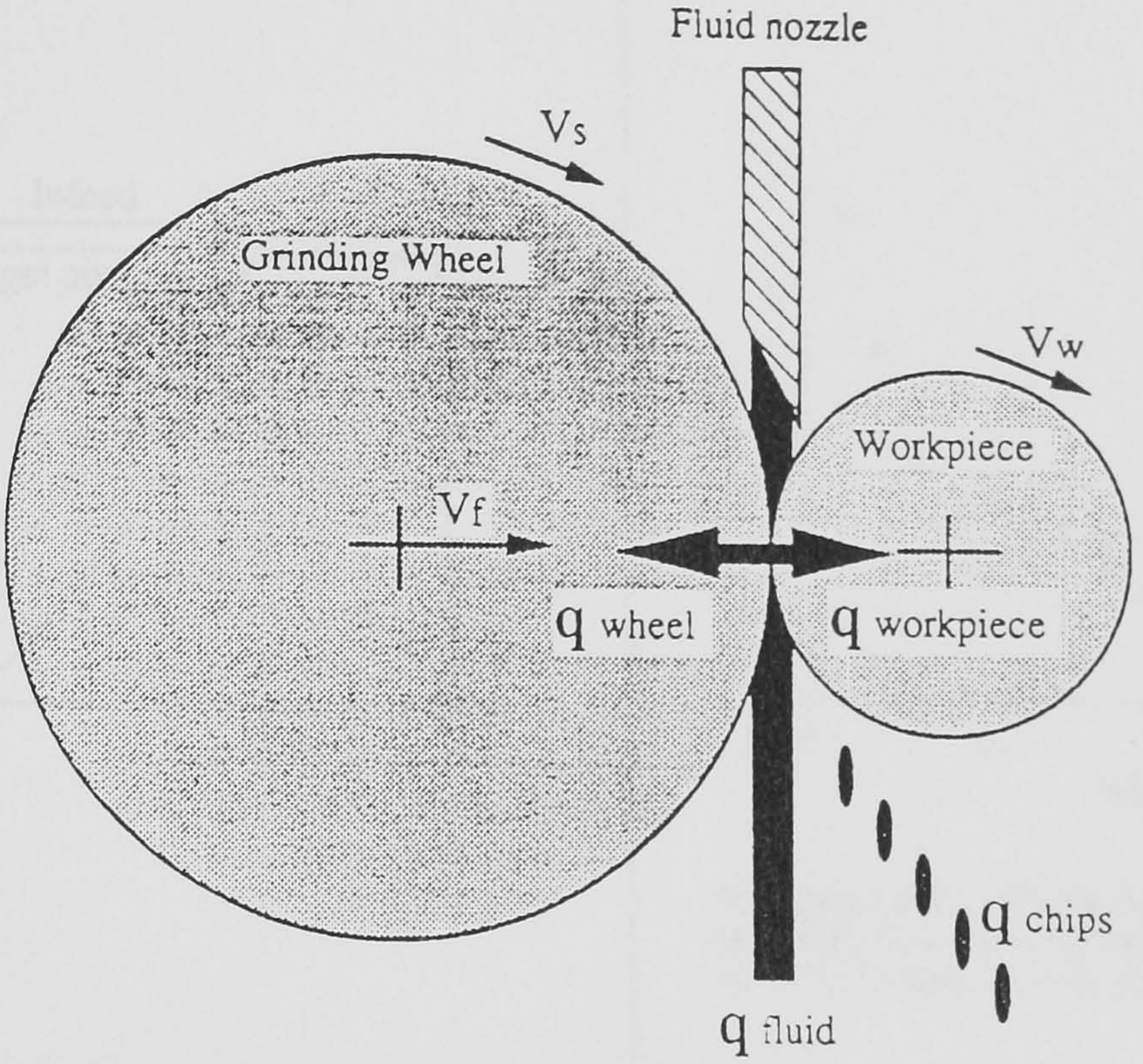


FIGURE 7
Partioning the grinding energy

can be determined from equation 1.

EQUATION 1

$$X_i = X_1 + x_1 (1 - e^{-(t-T1)/\tau}) \quad T1 < t < T2$$

The deflection and the time constant depend on a number of factors, including grinding wheel type, grinding wheel sharpness, machine stiffness, workpiece geometry, workpiece material properties, and machining parameter values. Good design has resulted in stiff grinding machine structures, but the stiffness of the workpiece and the sharpness of the grinding wheel are difficult to predict. The value of the system time constant can range from less than one second for a very stiff workpiece to more than ten seconds for a very compliant workpiece, and can also vary by more than 100 per cent because of changes in grinding wheel sharpness as shown in figure 9.

To accommodate this variability the adaptive control system was provided with the capability to characterise the deflections and automatically adjust the infeed cycle to produce workpieces of the required size without incurring excessive cycle times. This was accomplished by identifying the time constant during the infeed and using this value to determine the required dwell period. The time constant was derived from the grinding power characteristic, which exhibits the same lag as the material removal [4]. The power signal was first filtered and then integrated to reduce the effects of noise as shown in figure 10. The start of grinding was detected from the variance

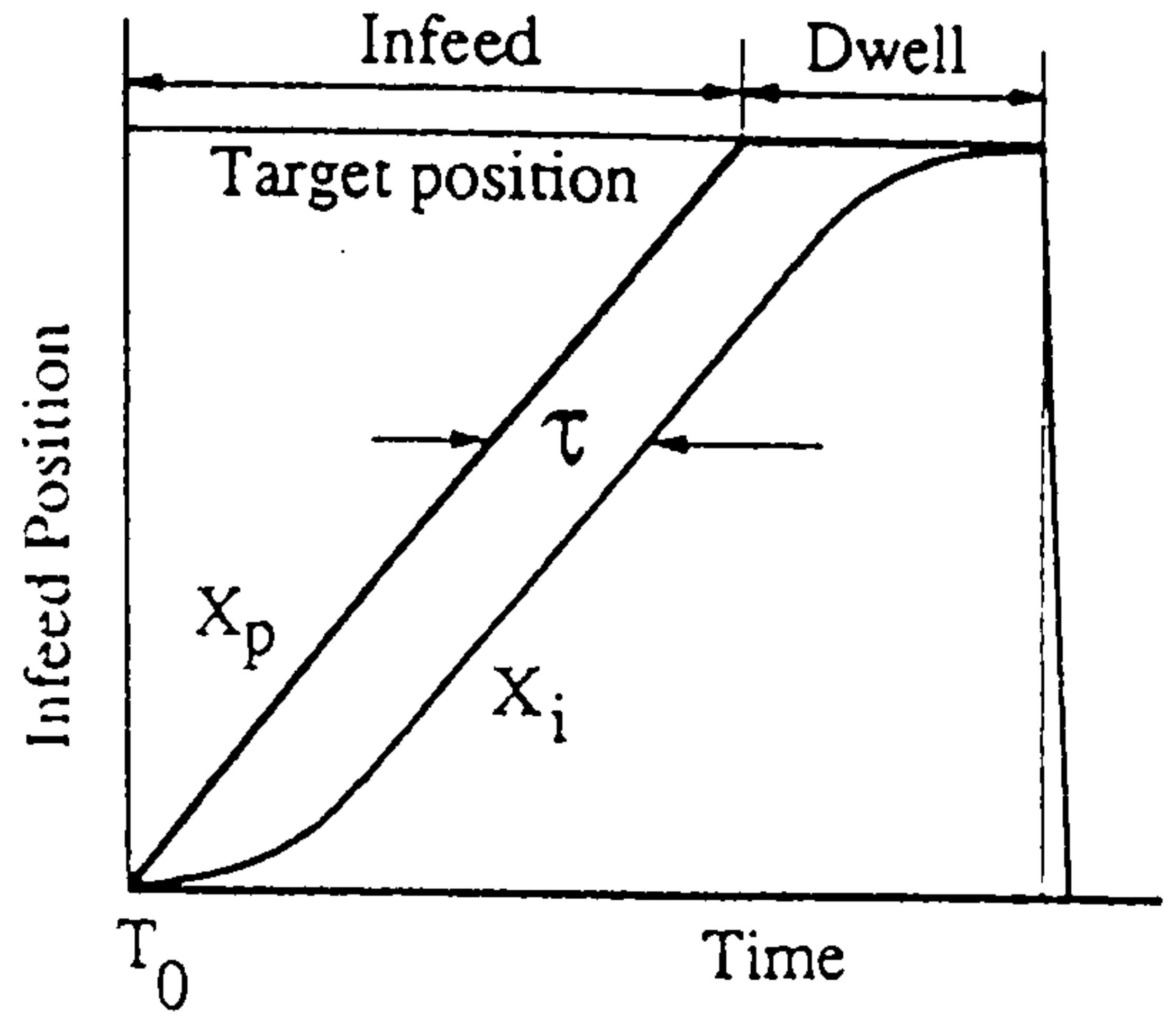
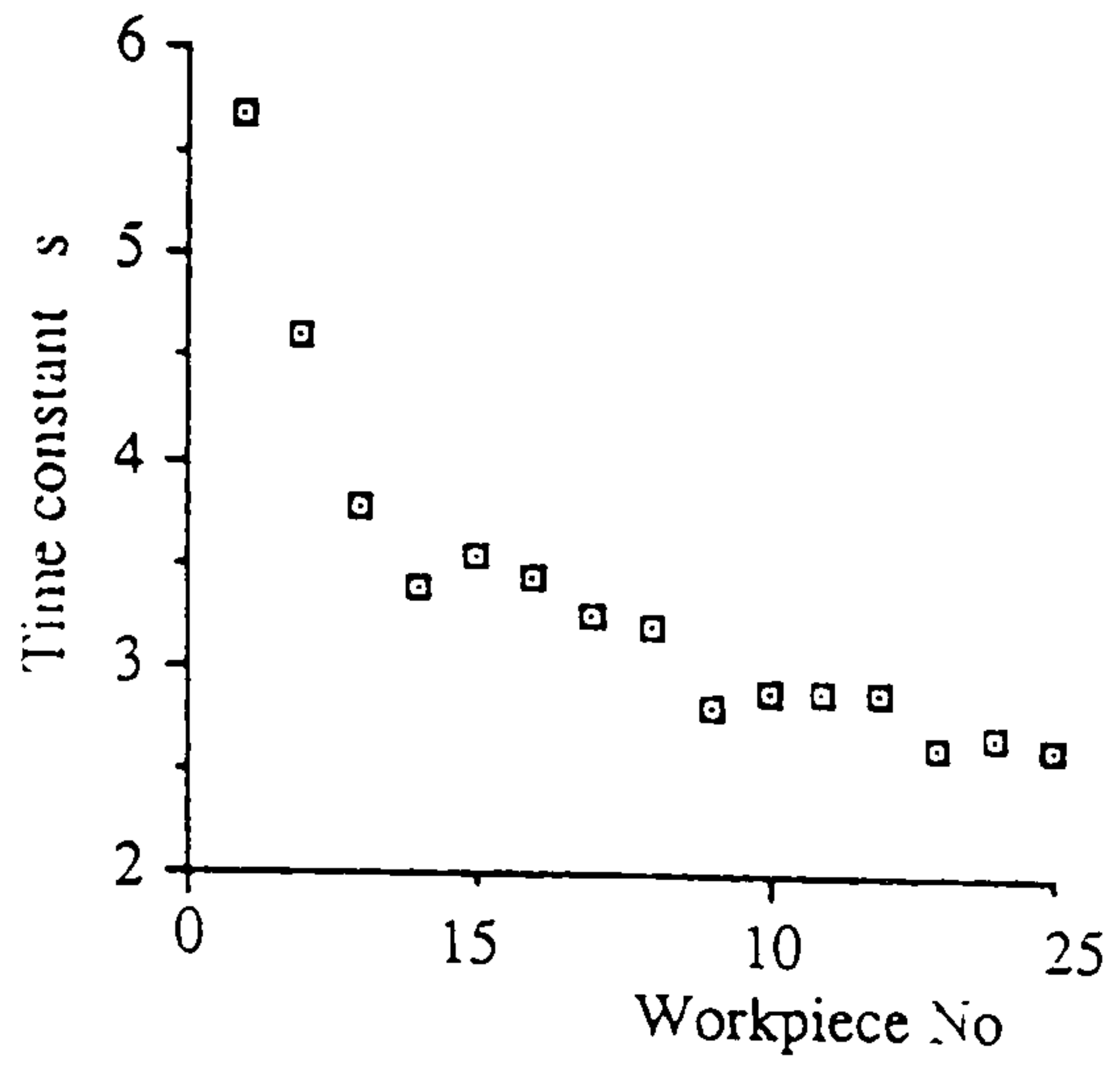


FIGURE 8

A basic infeed cycle showing the programmed position (Xp) and the actual position (XI) of the grinding wheel/workpiece interface.



Workpiece En9. Wheel A465K5V30W.
ds = 450 mm, dw = 46 mm, b = 50 mm,
vw = 0.25 m/s, vs = 33 m/s.

FIGURE 9

Change in the system time constant value with varation of the topography of the grinding wheel surface.

of the grinding power [5] and the time constant was calculated using equation 2, which gives the intercept of the power integral with the time axis.

EQUATION 2

$$t = \frac{t1 \int_0^{t1} Pdt \ - \ t2 \int_0^{t2} Pdt}{\int_0^{t2} Pdt \ - \ \int_0^{t1} Pdt}$$

5.2 Compensating for errors due to wear of the grinding wheel, wear of the dressing tool, and thermal deformation of the machine tool

The best performance of the standard CNC system was achieved when using in-process diameter gauging. The gauge signalled the retraction of the grinding wheel when the target size was attained during sparkout. In addition an offset was applied to the infeed axis to compensate for any errors due to wear of the grinding wheel, wear of the dressing tool, or thermal deformation of the machine tool. Using this technique size errors of less than one micron were consistently achieved.

To ensure the correct operation of the standard system with gauging, the infeed cycle was set up so that all the deflection was relieved when target size was reached. If this condition was not satisfied further material was removed before the grinding wheel could be retracted, causing size errors. Often, a number of workpieces were required to set up the infeed cycle. Also, conservative grinding conditions were used to minimise deflections. In this way, changes in deflection due to conditioning of the grinding wheel were relatively small and did not greatly effect

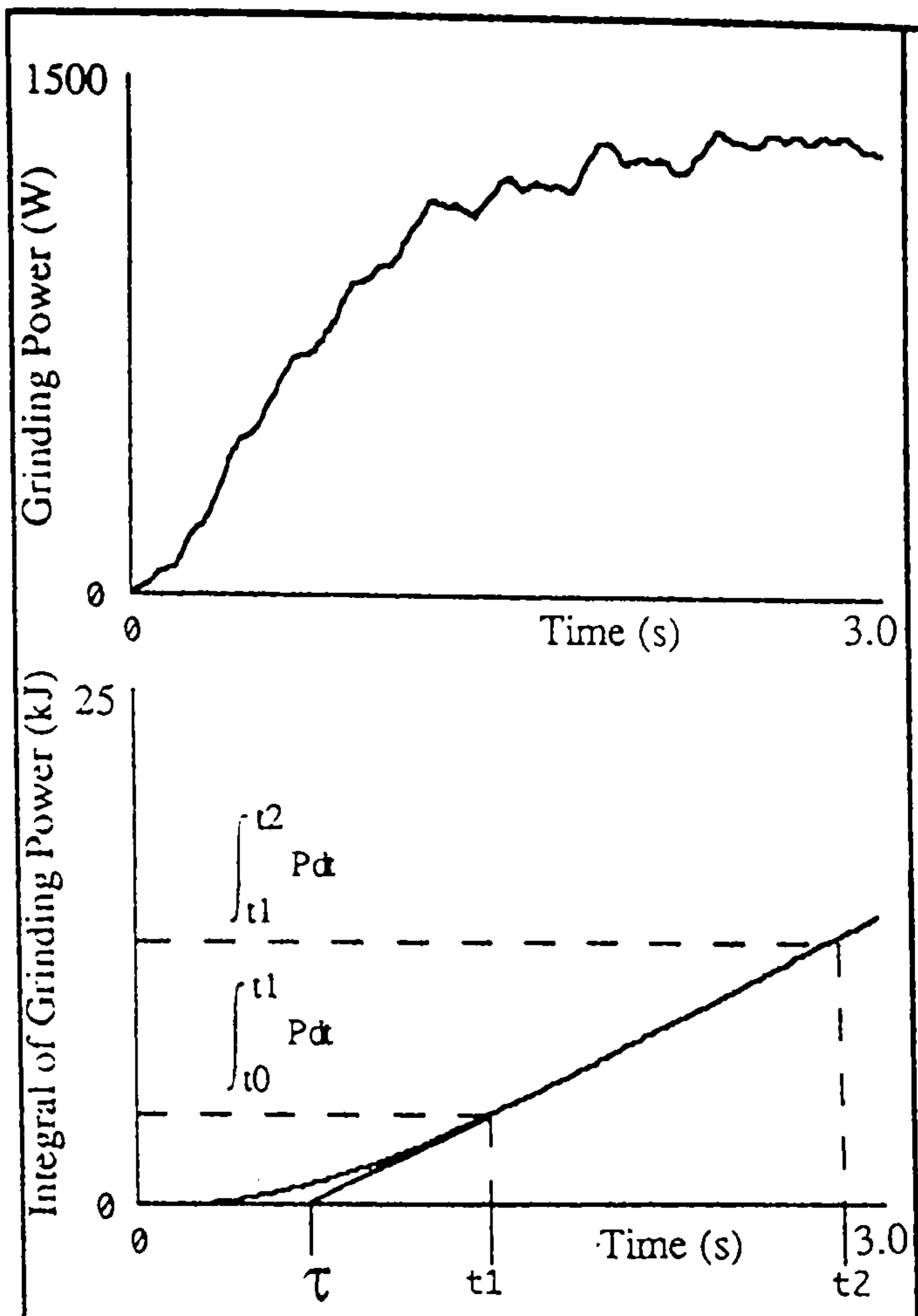


FIGURE 10.

Calculation of the system time constant from the grinding power characteristics

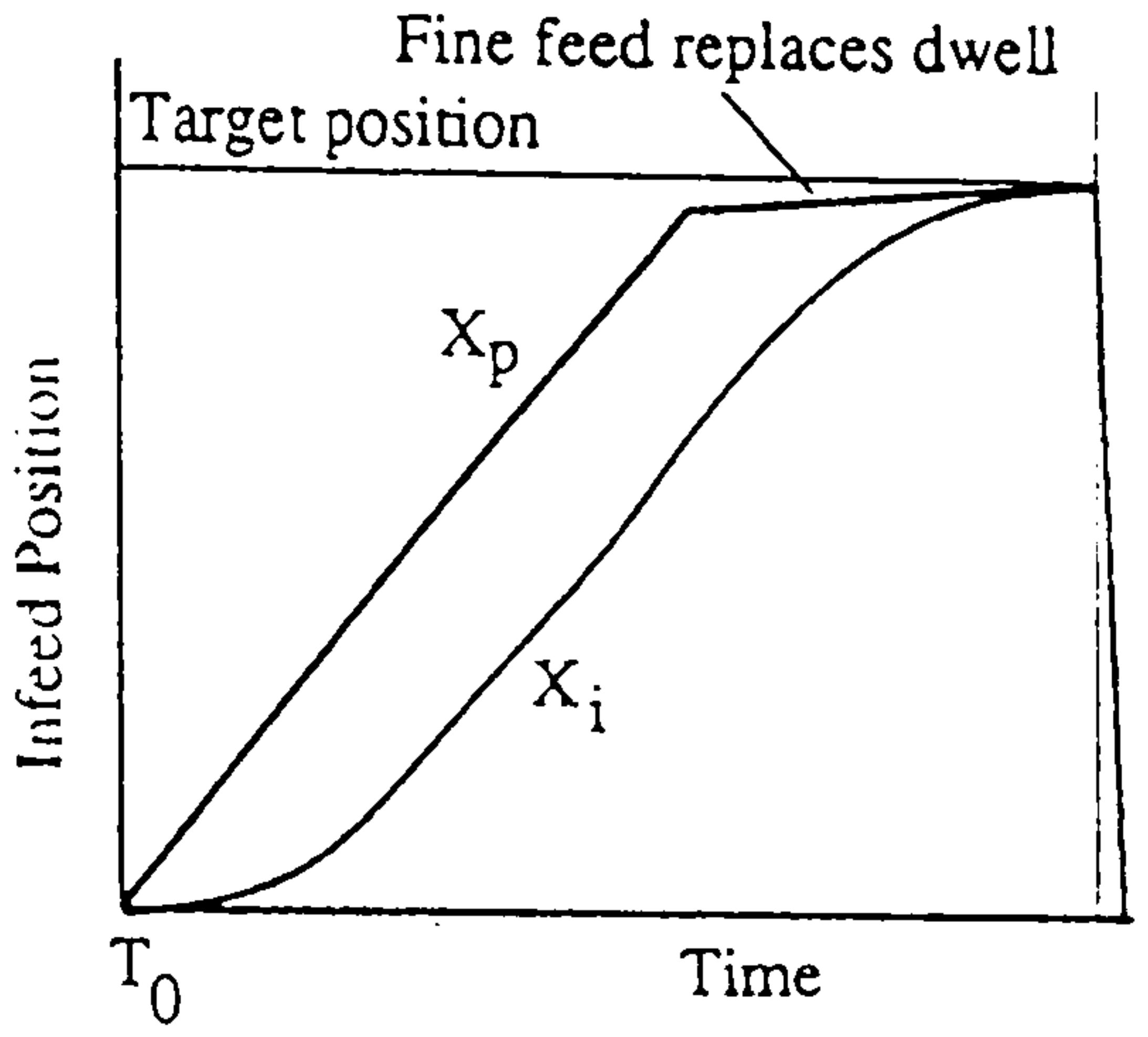


FIGURE 11

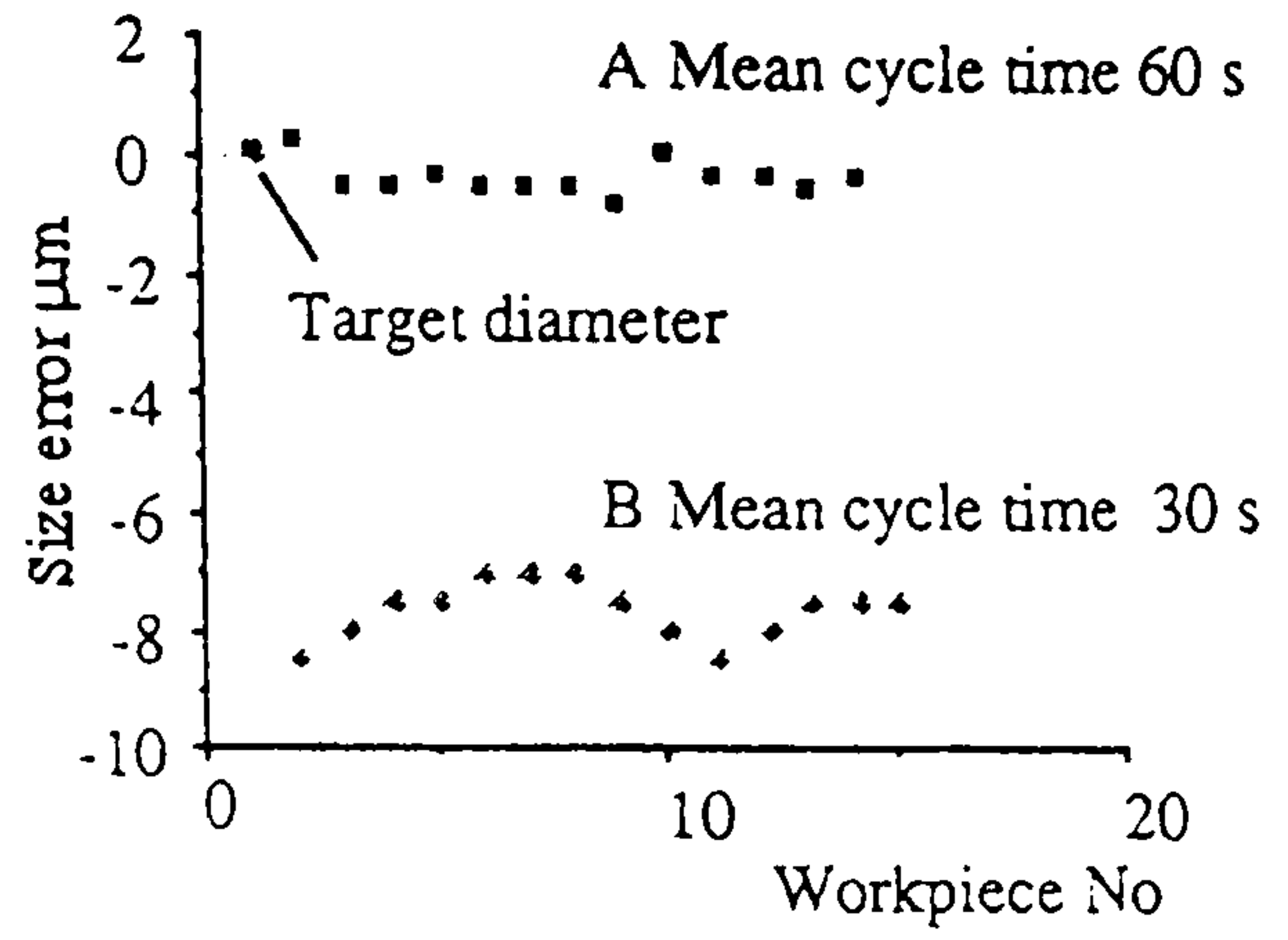
The adaptive gauging cycle with the dwell period replaced by a fine infeed rate.

size holding.

The adaptive system automatically adjusted the dwell period according to the magnitude of the deflection. This eliminated the need for the user to experiment to determine the correct set-up of the gauging infeed cycle. Additionally, variations in the magnitude of the deflection due to conditioning of the grinding wheel were automatically compensated for. Thus performance was not significantly effected when higher removal rates were used and relatively large changes in deflection occurred from one grinding operation to another. The need to use conservative machining conditions to keep deflections small was reduced. This allowed higher removal rates to be used and shorter cycle times to be achieved. In addition, the automatic adjustment of the infeed cycle greatly reduced the set-up procedure.

5.3 Thermal expansion of the workpiece during grinding

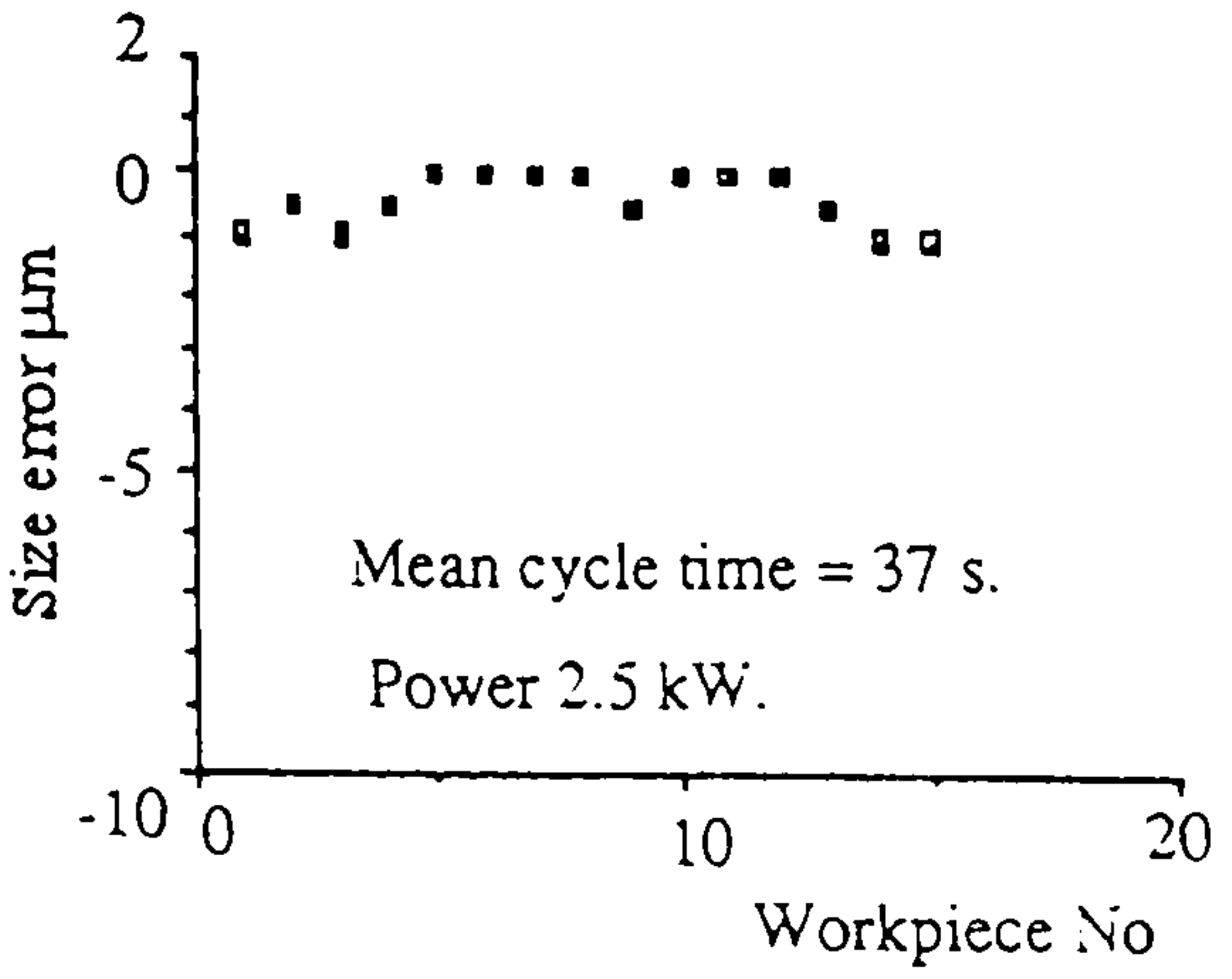
Higher removal rates resulted in higher grinding power levels, and heating of the workpiece as described by Peters and Aerens [6] became a significant factor in the capability to hold size. It was discovered that if the workpiece did not cool completely before the end of the dwell period and retraction of the grinding wheel, subsequent cooling of the workpiece resulted in undersize components. The problem was overcome by introducing a very fine feed rate of 0.2 micron / second on diameter as shown in figure 11. This lengthened the "dwell" period and allowed the workpiece to cool sufficiently before target size was reached.



Time constant = 3 s approx.
Wheel A465K5V30W. Workpiece EN9.
ds = 450 mm, dw = 46 mm, b = 50 mm,
vw = 0.25 m/s, vs = 33 m/s, vf low = 5, 3, 1 µm/s, vf high = 9, 7, 5 µm/s

FIGURE 12

Size error when using the gauging infeed cycle of the standard CNC to grind flexible workpieces at high and low removal rates.



Time constant = 3s approx.
Wheel A465K5V30W. Workpiece EN9.
ds = 450 mm, dw = 46 mm, b = 50 mm,
vw = 0.25 m/s, vs = 33 m/s, Power = 5 kW and 2.5 kW.

FIGURE 13

Size error when using the gauging infeed cycle of the adaptive system to grind flexible workpieces.

5.4 Size results

Figure 12 shows the size results achieved with the standard CNC machine when grinding flexible workpieces ($\tau \simeq 3s$) and using diameter gauging. Line A shows the best performance with all the workpieces within one micron of size. Line B shows the size results when the removal rate was increased. The large size error was attributed to a combination of workpiece heating, and deflection which caused further material removal after target size had been achieved and before retraction of the grinding wheel. Figure 13 shows the size results achieved when grinding similar workpieces using the adaptive infeed cycle with diameter gauging and with the dwell substituted by a very fine feed rate. Good size results were achieved with faster cycle times than were achieved with the conventional infeed cycle. With the adaptive infeed cycle size was held to within one micron throughout the batch of workpieces with an average cycle time of 32 seconds. This compares with a mean cycle time of 60 seconds which was required to achieve similar size holding capability with the standard infeed cycle.

6 Commercialisation issues

Adaptive techniques for cylindrical grinding have been developed on a prototype system and tested in laboratory conditions. Initial results promise improved performance in terms of workpiece quality and productivity. However, interfacing a personal computer to a conventional CNC is not seen as a practical solution for industrial environments. Rather, the adaptive routines should be implemented within the machine tool controller. In order to implement adaptive control the machine tool controller must have the ability to:

sample and store data from transducers.

perform typical high level language operations (including mathematical operations).

modify machining parameters while a machining cycle is in progress.

save and retrieve data base records in bulk storage.

Multi-tasking operating systems of modern controllers allow the machine tool builder to write real-time applications which have access to analogue and digital inputs, can modify part program parameters, and read and write data to devices such as hard disk, floppy disk, or RAM drive. It is therefore possible to implement adaptive routines on these controllers.

A project to implement some of the adaptive features described in this paper has commenced with the aim of introducing the techniques on commercially available CNC grinding machines. Emphasis is being placed on producing a system which is reliable and robust. To ensure that this is achieved the system will be evaluated by testing on a wide range of components. In order for the system to be readily accepted, attention is being paid to developing a human interface which is user friendly to allow ease of operation.

7 Conclusions

The facility to maintain a desired grinding power level and to store grinding conditions in a data base gave the ability to "learn" optimum machining conditions. The information obtained from one grinding operation was subsequently used for the automatic selection of machining parameter values for other grinding operations on the same workpiece material type with the same grinding wheel type.

Deflection of the machine - grinding wheel - workpiece system was characterised during the initial stages of grinding by identifying the time constant (or lag) of the system. The infeed cycle was modified in order to achieve workpiece size in a controlled manner without incurring excessive cycle times. Because the time constant was determined from the grinding power characteristics advantages were demonstrated both with and without diameter gauging.

The best size results were obtained when using in-process diameter gauging. When used in conjunction with a very fine feedrate replacing the dwell period, the adaptive infeed cycle greatly simplified the set-up procedure for the diameter gauging system. The very fine feed rate also compensated for workpiece heating and allowed better accuracies to be achieved at high removal rates.

The adaptive features were tested on a development system and preliminary results when grinding testpieces in the laboratory promise to improve the accuracies that can be achieved, simplify set-up procedures and reduce cycle times, and reduce the need for pre-production trials.

Work is currently under way to integrate the adaptive features into the machine tool controller so that adaptive features may be provided alongside conventional infeed cycles in the next generation of CNC grinding machine software packages.

8 Acknowledgements

Acknowledgements are due to the SERC and DTI for supporting the research work.

9 References

1 Rowe W.B., Bell W.F., Brough D., "Limit Charts for High Removal Rate Centreless Grinding",

Int. J. Mech. Tools Manufact., vol.27, No.1, p.15-25, 1987.

2 Rowe W.B., Allanson D.R., Pettit J.A., Moruzzi J.L., Kelly S., "Intelligent CNC for Grinding", Proc. Instn. Mech. Engrs., vol.205, p.233-239.

3 Rowe W.B., Pettit J.A., Boyle A. and Moruzzi J.L., "Avoidance of Thermal Damage in Grinding and the Prediction of the Damage Threshold", Annals of the CIRP, vol. 37/1/1988, p.327-330.

4 Allanson D.R., Kelly S., Terry S., Moruzzi J.L., Rowe W.B., "Coping with Compliance in the Control of Grinding Processes", Annals of the CIRP vol. 38/1/1989, p.311 - 314.

5 Allanson D.R., Thomas D.A., Moruzzi J.L., Rowe W.B., "Adaptive and Learning Strategies for CNC Grinding", Proceedings of the SERC / ACME Conference on AMT held at Brunel University, 1-4th Sept. 1992.

6 Peters J., Aerens R., " Optimisation Procedure of Three Phase Grinding Cycles of a Series without Intermediate Dressing", Annals of the CIRP, vol. 29/1/1980, p.195-197.

A4.4 The paper published in the Manufacturing Engineer, October 193, pp 238-241.

GRINDING

Intelligent CNC grinding

Brian Rowe, Andrew Thomas, Jim Moruzzi and David Allanson consider the effect of adaptive and learning strategies, with and without in-process gauging, on productivity and quality in typical CNC grinding operations.

Computers are increasingly being employed to achieve in-process optimisation in machining operations. Examples can be found in many fields including electric discharge machining (EDM), turning, plastic moulding and drop forging. Using computers it is possible to incorporate a range of features into a manufacturing system which maintain quality, assist set-up, minimise machining time and improve accuracy.

Here, we describe a system developed for precision cylindrical grinding between centres. A particular feature of the system is that the control strategies are based on a model of the grinding process. A compliance model allows workpiece and machine deflections to be predicted, and compensation can therefore be applied to minimise size variations. A model of heat transfer within the grinding process is used to predict thermal damage of the workpiece. Thermal damage may thus be avoided by limiting feedrate or increasing workpiece speed.

A number of workers have developed adaptive control systems for grinding including Hahn,[1] Malkin,[2,3] Kaliszer,[4] Koenig,[5] Toenshoff,[6] Inasaki,[7] and Webster.[8] Most of these systems adjust feedrate to maximise removal rate. Early systems demonstrated the advantages and feasibility of adaptive control, but industrial take up of such systems has been slow because of the requirement for special instrumentation and the lack of integration with existing CNC systems. The system about to be described avoids introducing force and temperature sensors and is therefore expected to be more robust and attractive to users. It has been designed to be integrated with standard CNC systems.

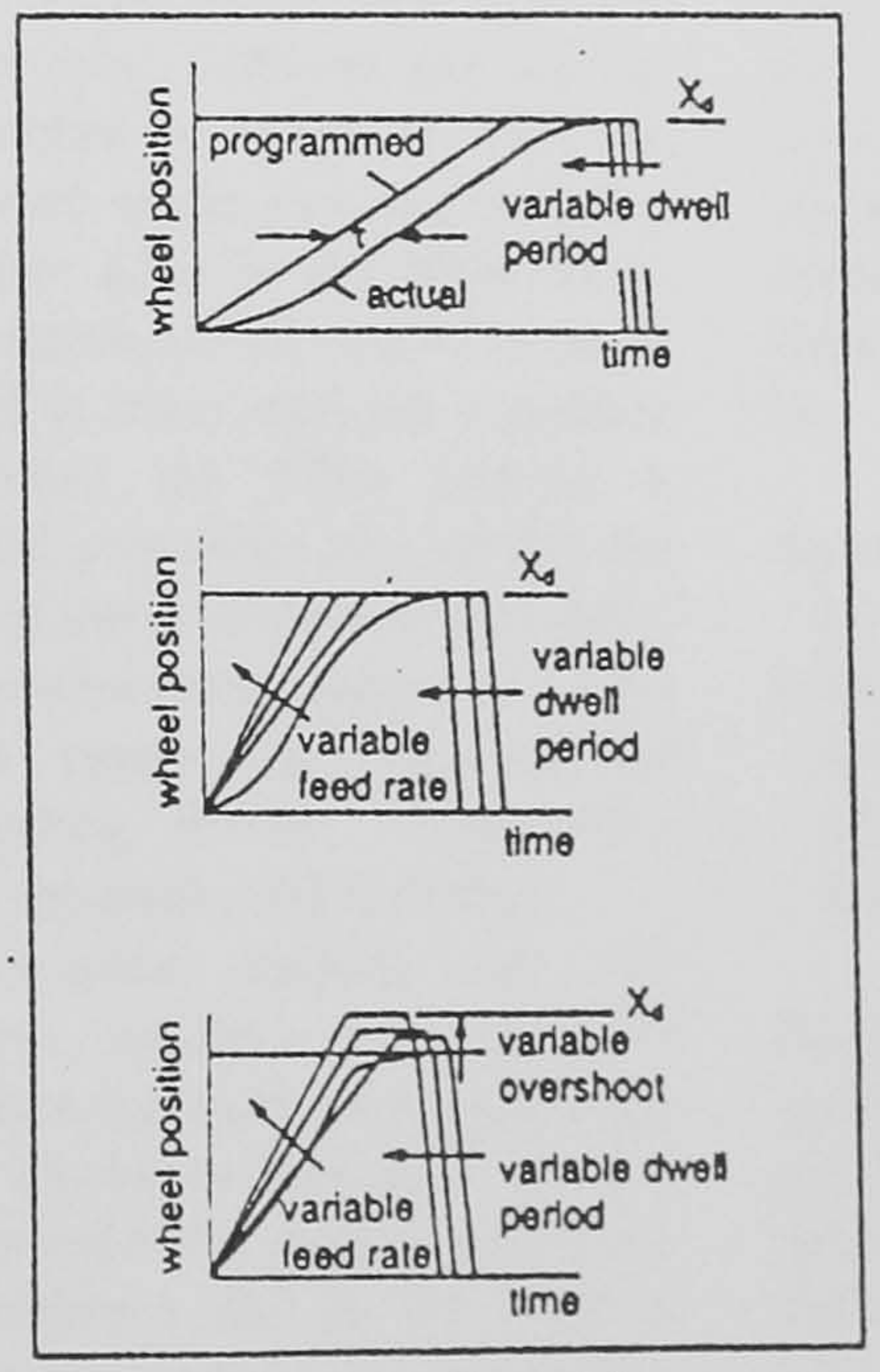


Figure 1. Strategy for achievement of improved productivity in three stages

Such an adaptive control system was first applied to centreless grinding in 1989 by Rowe, Allanson, Pettit, Moruzzi and Kelly.[9] The system was used for the production of engine cylinder liners and demonstrated the ability to automate the process and maintain size tolerances with highly compliant workpieces of variable wall thickness.

Subsequently, a new system was developed for precision centre grinding with real time in-process control. This is a significant advance which makes it possible to maintain closer limits on size accuracy and further reductions in cycle time, in addition to improved productivity through reduced set-up time.

The new system was developed and implemented on the Jones and Shipman Series 10 cylindrical grinding machine with an Allen Bradley 8200 CNC. The adaptive features were initially based on a PC interfaced to the CNC. Further work is now in hand to integrate the adaptive features within the CNC.

Organisation

Accuracy and production rate in grinding are limited by the deflection of the workpiece and the machine. Th separating force between the grindin wheel and the workpiece is relativel high so that the deflections, even wit very stiff machines, are of the same orde of magnitude as the depth of cut.

The separating force depends on th cutting sharpness of the grinding whee groups together materials having similar grinding characteristics. For a particular grinding wheel and material combination a set of values required to control the process is stored. The information stored includes part programs and kinematic parameters which define starting values for feed rate and workpiece speed in relation to workpiece diameter and wheel width. Physical parameters and dressing values are also stored in the database.

The system has the capability to learn optimal conditions for different workpiece speeds by comparing the specific energy measured during the cycle with previously stored values over a series of batches.

Modular framework

Strategies for improved productivity and quality were incorporated into a modular CNC system; the intelligent modules are illustrated in figure 2.

The system contains mathematical models of the physical process which provide an efficient basis for process optimisation subject to process constraints. The constraints prevent thermal damage, excessive roughness, roundness and size errors. A selection strategy for dressing conditions is still under development.

Identification of time constant

The time constant depends on the magnitude of the grinding forces, the stiffness of the workpiece and the stiffness of the machine. High grinding forces and low workpiece stiffness lead to a long time constant. The time constant varies with many parameters, including the dressing procedure, wheel wear, width of the grinding wheel, workpiece material properties, coolant, workpiece diameter, feed rate and workpiece speed. Typically, the time constant lies in the range from one to ten seconds.

A general method was required for the identification of the time constant which did not depend on the use of in-process gauging or the measurement of forces. The decision was therefore taken to employ power measurement.

The conventional way to extract the time constant in real time is by taking the derivative of the power. Unfortunately, the time constant extracted by this method is extremely sensitive to noise. It was therefore necessary to investigate alternative techniques.

Several methods were developed based on integration of the power signal in order to overcome this problem. The method finally chosen was based on integrating the process power signal as follows:

$$\tau = \frac{t_1 \int_0^{t_1} P\,dt - t_2 \int_0^{t_2} P\,dt}{\int_0^{t_2} P\,dt - \int_0^{t_1} P\,dt}$$

This method requires the start of grinding to be detected which was achieved by monitoring the change in variance of the power signal. The integration technique copes both with noise and runout problems. Checks and rules are incorporated into the system to ensure that false values of time constant are not generated.

Wheel wear and dressing

A feature of non-adaptive cycles when used with in-process diameter gauging is the ability to compensate for grinding wheel wear and for reductions in wheel diameter due to dressing. The position of the in-feed axis when the diameter gauge indicates size has just been reached is compared with the value stored in the part program. The axis is then offset by the difference to compensate for wheel wear. This works very well in many cases but a problem arises when the offset includes a substantial proportion due to thermal expansion and deflections in the wheel/workpiece/machine system. A non-adaptive system has no way of distinguishing betwen wheel wear, thermal expansion and deflection.

Non-adaptive systems may also experience problems when grinding multi-diameter shafts where gauging is usually limited to application on one diameter only. The gauged diameter is often undersize due to the effect of compliance and error in the wheel offset from the first diameter is carried over to the second ungauged diameter which is even more undersize. The wheel wear compensation includes a substantial element due to system deflection particularly at high removal rates. The result is an axis overshoot so that size is approached too rapidly. When the gauge signals the need to retract, too much material has been removed. The result in the example shown in figure 3 is that workpieces are undersized by approximately 8 µm.

The adaptive system overcomes these problems by computing the deflection and adjusting the offset accordingly. The dwell time to reach size is used to compute the actual overshoot present. This value is then compared with the programmed value and the difference which is due to wear is applied as an axis offset.

Problems of wheel wear and diamond wear can be directly avoided by employing in-process gauging. For best results gauging should be employed on all diameters and faces although this approach is expensive., lengthens the set-up operation and is used infrequently.

Accuracy and cycle time

Figure 3 compares accuracy and productivity results obtained using the adaptive system with results using the non-adaptive system.

Flexible workpieces were ground to provide a challenging test condition. At low removal rates, the non-adaptive cycle gave good results that lie within a maximum range of 1 µm, but at high removal rate the mean size was 8 µm below target. This inaccuracy was due to:

- a relatively high removal rate when final size is reached;
- incomplete cooling of the workpiece during the grinding operation leading to thermal contraction after the end of the grinding cycle.

Both these problems could have been overcome by extending the dwell period. However, lengthening the dwell period gave rise to a further problem. If size was achieved in a shorter time than expected the system calculated the error in axis position and compensated accordingly. If the dwell and is variable depending on the grinding wheel dressing operation and the extent of grinding wheel wear. A dwell period in a grinding cycle allows the grinding forces and the associated deflections in the mechanical system to reduce to a very small level.

To allow for the maximum grinding force, whilst achieving the required accuracy and programmed removal rate, a non-adaptive cycle must be longer than would otherwise be necessary. Maximum grinding forces are achieved immediately after dressing the grinding wheel and again after grinding a number of workpieces. An adaptive system speeds up the cycle and as a result the grinding wheel is found to grind more efficiently throughout its life between dressing operations.

The basic strategy to improve productivity of the feed cycle, illustrated in figure 1, was implemented in three phases.

In the first stage illustrated the system time constant, τ, is measured in real time and this value is used to adjust the dwell time so that the size will be within tolerance. This requires the time constant to be identified in real time within the feed period. The feature of variable dwell period makes it possible to achieve the best accuracy of size and roundness. The dwell time must be at least three time constants to reduce the deflection by 95 %, and for high accuracy grinding it may be set to six time constants or more. The longer dwell allows extra time for workpiece cooling after the high removal rate in the feed period.

The second stage enhances the cycle by adapting the feed rate after each diameter has been ground to ensure that the maximum feed rate is consistent with the specified power level. The feed rate is updated based on the measured power level. A clear advantage is found in adapting feed rate in that the grinding wheel cuts more efficiently and is less susceptible to glazing.

In the third stage, an overshoot is incorporated. The command position, X_u, is calculated to give an overshoot which will bring the workpiece to the required size and roundness after the required dwell. In practice, all grinding operations are required to employ a small overshoot, otherwise size can never be reached. The difference in adaptive overshoot is that the degree of overshoot is varied depending on the time constant to achieve improved size control.

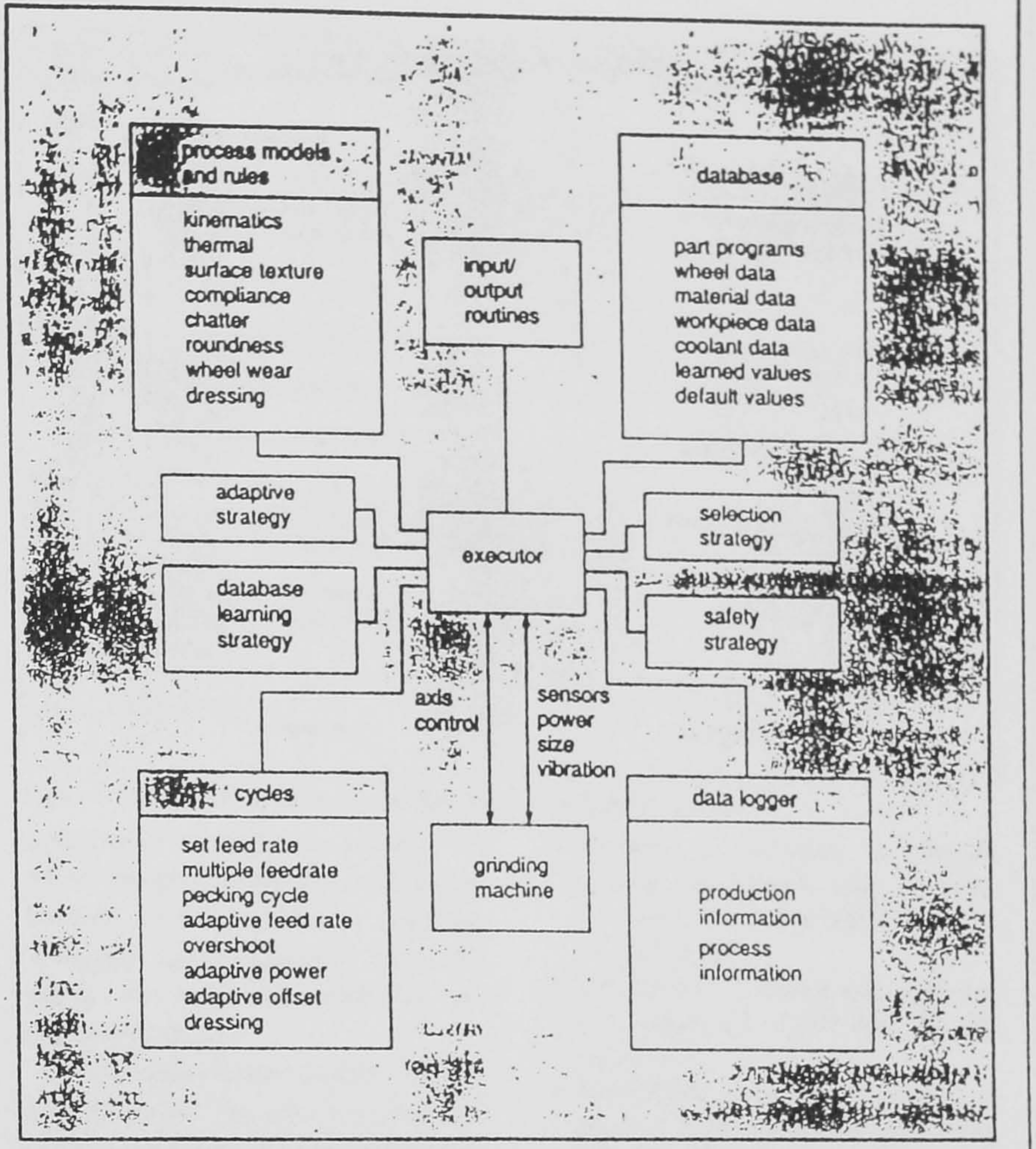


Figure 2. Modular framework for the adaptive CNC system

Improved quality

Initially, a set of trials was undertaken to determine the accuracy levels achievable with standard test pieces under gentle grinding conditions. These trials identified the critical control features required to achieve consistently high accuracy with batches of thirty workpieces as:

- identification and compensation for deflection;
- control of dwell period to control size and roundness;
- identification and compensation for wheel wear;
- identification and compensation for dressing tool deflection and wear;
- control of feed rate to achieve a specified power level.

Applying the strategy already described for maximum removal rate, quality levels can be adjusted by rules which provide constraints on minimum dwell period and maximum power level. Thermal damage is avoided by reference to a thermal model, and if damage is predicted the maximum feed rate is constrained. Workpiece speed may be increased for the next workpiece to allow power level to be restored to the required level.

Learning strategies

The learning strategy provides for optimised values of grinding parameters to be stored in a database for future use. The particular benefit of a learning strategy is that an operator does not need to revert to over conservative grinding conditions at the commencement of each batch. There is also the potential to use the system as an experimental facility to create a database for new materials by data logging the production and process information.

A database has been designed which

time taken to achieve size was greater than expected the system tracked the axis error provided that the magnitude of the error was smaller than the overshoot applied. With a lengthy dwell period the required overshoot was typically smaller than the wheel wear and the system failed. The machine could never achieve size under such conditions with a conventional cycle.

A new cycle was introduced to overcome this problem by replacing the programmed dwell period with a fine feed rate of the order of 0·1 μm/s. This ensured that the workpiece achieved size and allowed the use of a longer dwell period.

The size holding results for the adaptive system under high removal rate conditions are shown in figure 3 (c). The improved accuracy is due to fine feeding for a period of six time constants which ensured a slow approach to size and the cooling of the workpiece. The size holding results with a lower removal rate are shown in figure 3 (d). Size holding is similar to that achieved with the non-adaptive cycle at the same maximum removal rate, but the cycle time is greatly reduced.

Table 1. Comparison of average cycle times for Figure 3

maximum power level (kW)	adaptive cycle time (seconds)	non-adaptive cycle time (seconds)
2·5	37	60
5·0	22	30

Set-up

Conventional non-adaptive cycles require the operator to exercise judgement in the setting of the stock removal at the commencement of the dwell period. If the stock to be removed during the dwell period is too small the dwell period will be too short and the workpiece will be undersize and out of round. If the stock to be removed is greater than the system deflection, the target size will never be reached.

In practice, the operator may have to grind a number of workpieces until the correct setting is achieved. In multi feed rate cycles the process is further complicated by the need to determine appropriate settings for the feed rate change points. For the most accurate work the operator also has to make adjustments when the sharpness of the wheel changes beyond acceptable limits. Because of these problems operators invariably use conservative feed rate values in order to minimise the machining errors.

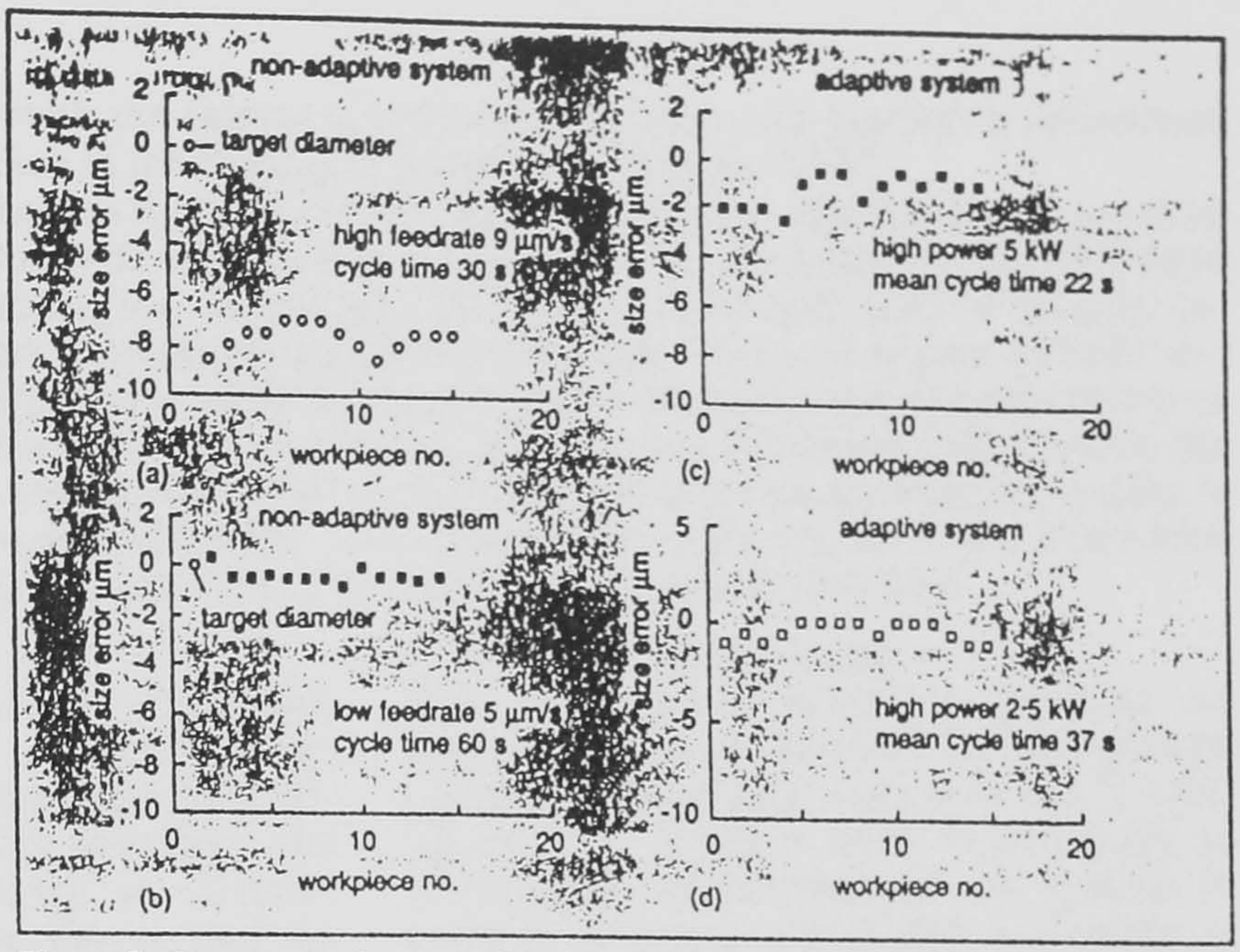


Figure 3. Size results for non-adaptive and adaptive cycles

The adaptive cycle simplifies the set-up procedure. The commencement of dwell is programmed to take effect early on the first workpiece. Size is always achieved because of the fine feed rate which is used instead of a dwell. The first workpiece takes longer to grind than subsequent workpieces but the savings in set-up time are substantial. Thereafter the system adjusts the offset automatically to yield the dwell time required to achieve the specified size tolerance.

Conclusions

In-process adaptive control allows cycle times to be reduced significantly. Size and roundness accuracies are maintained or improved. Operator intervention and set-up time are reduced.

Acknowledgments are due to the Science and Engineering Research Council, Jones and Shipman plc and Allen Bradley Ltd who provided financial support.

References

1 HAHN, R. S., and GRAHAM, G.: 'An application of force-adaptive grinding'. Society of Manufacturing Engineers Paper MR84-530, 1984, Michigan

2 MALKIN, S., KOREN, Y.: 'Off-line grinding optimisation with a micro-computer', *Annals of the CIRP*, 1980, **29**, (1), pp.213–215

3 MALKIN, S.: 'Grinding cycle optimisation', *Annals of the CIRP*, 1981, **30**, **(1)**, pp.213–217

4 KALISZER, H.: 'Adaptive control in grinding processes'. Proc. 4th International Conference on Production Engineering, 1980, Tokyo, p.579

5 KOENIG, W., BIERLIC, R., KLEENSAUG, R.: 'Development of an adaptive control system in cylindrical plunge grinding', Society of Manufacturing Engineers, 1976

6 TOENSHOFF, H. K., ZINNGREBE, M., and KEMMERLING: 'Optimization of internal grinding by micro-computer-based force control', *Annals of the CIRP*, 35, (1), pp.293–296

7 INASAKI, L.: 'Monitoring and optimisation of internal grinding processes', *Annals of the CIRP*, 1980, **40**, **(1)**, pp.359–362

8 WEBSTER, J., and ZHAO, Y. W.: 'Time-optimum adaptive control of plunge grinding', *Int. J of Machine Tools and Manufacture*, 1990, **30**, **(3)**, pp.413–421

9 ROWE, W. B., ALLANSON, D. R., PETTIT, J. A., MORUZZI, J. L., and KELLY, S.: 'Intelligent CNC for grinding'. *Proc. Inst. of Mech. Eng., Journal of Engineering Manufacture*, 1991, **205**, pp.233–239

The authors are with Liverpool John Moores University.

A4.5 The paper published in the Proceedings of the SERC ACME Conference, pp84-89.

ADAPTIVE AND LEARNING STRATEGIES FOR CNC GRINDING

D. R. Allanson, D. A. Thomas, J. L. Moruzzi, W. Brian Rowe.
Liverpool John Moores University.

Summary

The project was concerned with the improvement of productivity and quality in cylindrical grinding through the application of the intelligent capability within the CNC.
Initial trials with the CNC showed that size control was affected by a combination of grinding wheel wear, system deflections and variations in wheel size after dressing. The development of adaptive and learning strategies within the CNC system to be used with or without in-process gauging allowed these problems to be largely overcome. The new system reduces set-up time and avoids the requirement to grind test-pieces before the batch run. Improvements in productivity have been further achieved by adapting the feed-rate and dwell period within the feed-cycle to minimise the length of the feed-cycle while ensuring an appropriate quality is achieved. This is seen as a major advantage. A further benefit of the system is that it provides for learned conditions for optimal grinding to be stored in an economic data base.

1. Introduction

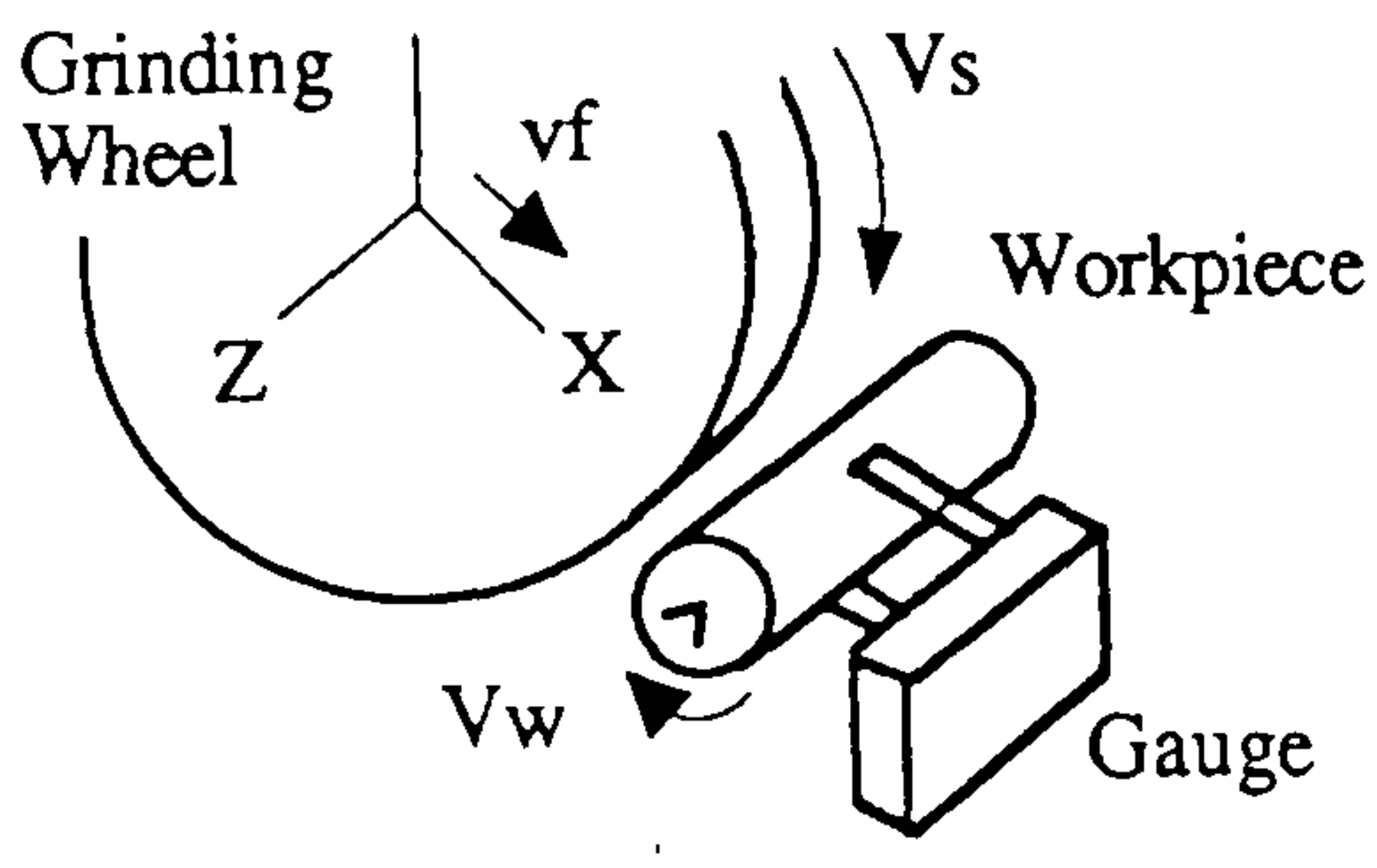
Previous work on adaptively controlled centreless grinding of cylinder liners demonstrated a modular approach to CNC grinding. Process models provided the system equations necessary to control deflection, burn, roundness, chatter and the storage of kinematic relationships. Other modules provided input and output screens, the data base design, safety strategy, learning strategy, in-process gauging, adaptive control strategy and machine tool interfacing. The system demonstrated the ability to automate the process and maintain size tolerances with highly compliant components of variable wall thickness. Adaptive control was essential to cope with large variations in grinding forces as grinding proceeded. Without adaptive control it would have been impossible to achieve high removal rates and consistent size control. The adaption of feed-rate and in-feed position was implemented after each workpiece.

The current project aimed to demonstrate that the same principles could be applied to precision grinding between centres. A particular aim, however, was to achieve real time in-process control. This is a significant development which makes it possible to maintain closer limits on size accuracy, in addition to improved productivity through reduced set-up time and shorter cycle times.

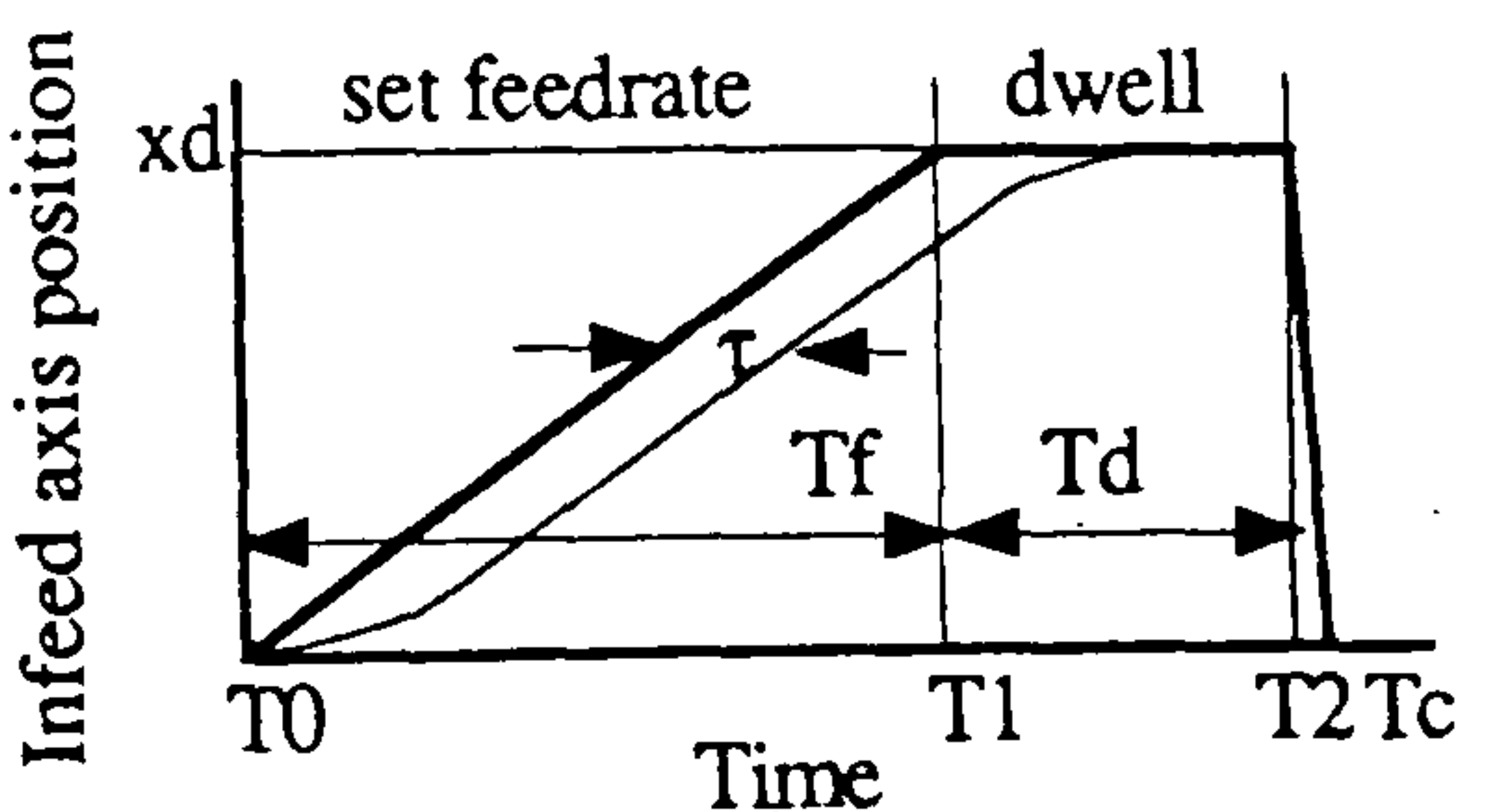
The scope of the project covered an initial investigation of the critical features to be controlled in grinding between centres, the development and testing of improved strategies for control and the implementation and evaluation of the software solutions within the CNC system.

2. Process Description

The cylindrical grinding process as investigated was limited to the plunge operation where feed occurs in the X axis, figure 1(a). Further work is necessary to investigate performance of the system in traverse grinding where the workpiece is moved along the Z axis. The process may be operated with or without an in-process diameter size gauge which is interfaced to the CNC to control final size. The form and condition of the grinding wheel is controlled by a dressing operation where a single point diamond or other dressing tool is traversed



(a) Schematic layout of grinding between centres



(b) A basic feed cycle

Figure 1. The basic process, the feed cycle and the effect of the time constant τ.

across the face of the grinding wheel. A dressing operation is either performed once before grinding a batch of workpieces or may also be performed with re-dressing before grinding each workpiece.

A variety of feed cycles may be employed. The most basic cycle is an infeed at constant rate to the target position and a fixed dwell period to reduce system deflection and bring workpiece diameter to the required size as illustrated in figure 1(b). The time constant is a measure of the deflection as illustrated.

3.Strategy for Improved Productivity

The requirement for a dwell period in grinding is a direct result of the deflections of the machine, workpiece and grinding wheel system. The separating force between the grinding wheel and the workpiece is relatively high in grinding so that the deflections are of the same order of magnitude as the depth of cut. The forces depend on the cutting sharpness of the grinding wheel and are variable depending on the grinding wheel dressing operation and the extent of grinding wheel wear.

A standard cycle has to be longer than necessary for the required accuracy and programmed removal rate, to allow for the maximum system deflection likely to be experienced.

The basic strategy to improve productivity in three phases is illustrated in figure 2.

The first stage Figure 2(a) requires the system to predict the time at which size will be within tolerance. This requires the system time constant to be determined within the infeed period. This stage is an important element to ensure accuracy of size and roundness

The second stage Figure 2(b) enhances the cycle by adapting the feed-rate after each diameter has been ground to ensure that the maximum feed-rate is employed consistent with the set power level. The feed-rate is updated based on the measured power level.

In the third stage, Figure 2(c) an overshoot is incorporated. The command position Xd is predicted to give an overshoot which will bring the workpiece to the required size and roundness after the required dwell.

All three elements of the adaptive strategy for improved productivity can be employed with little modification with or without gauging.

The are four basic modes of operation as indicated in table 1. Each mode has its own particular advantages and disadvantages and is used under different circumstances.

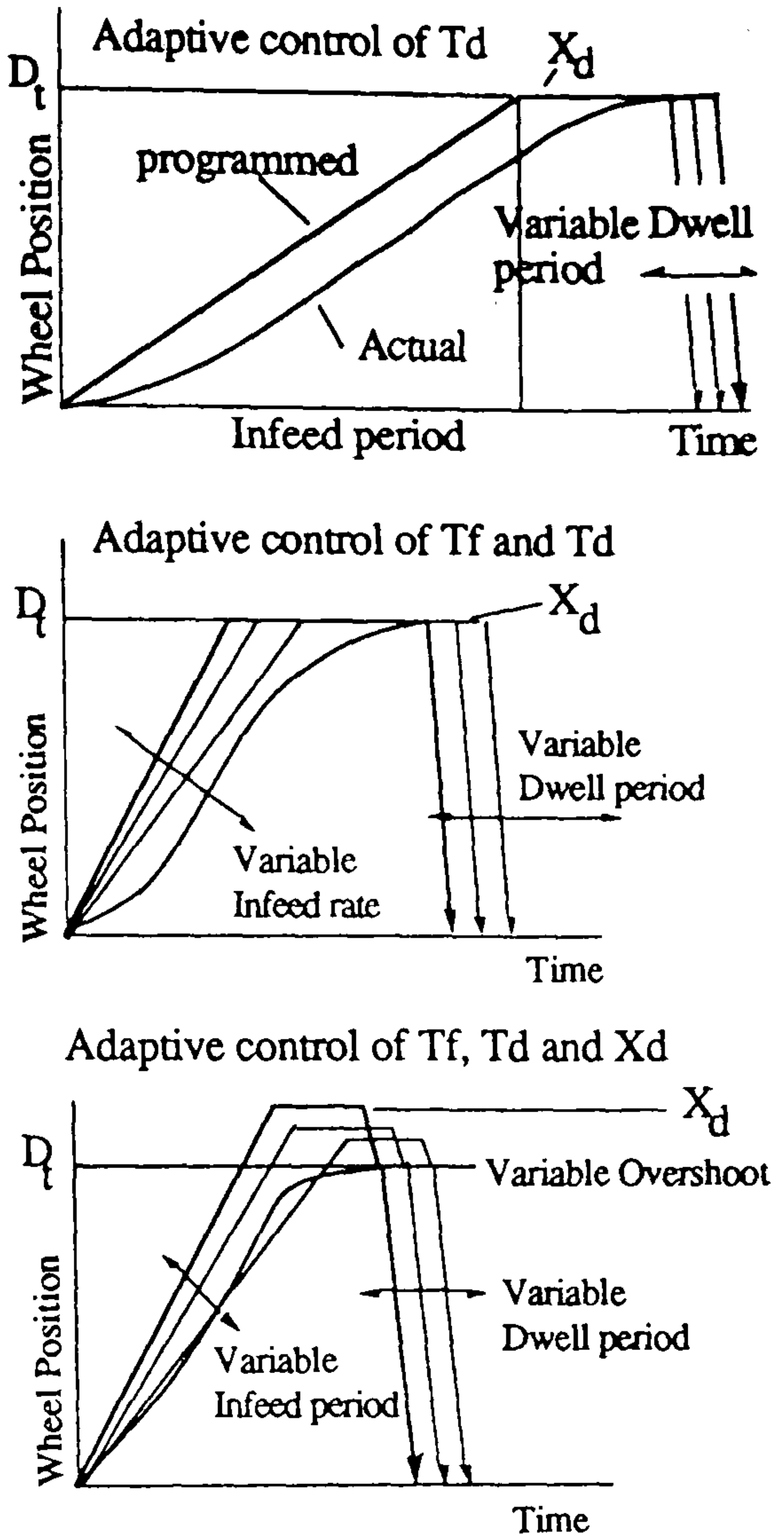


Figure 2. Strategy for improved productivity in three stages.

4. Strategy for improved quality

Initially a set of trials were undertaken to determine the accuracy levels achievable with standard testpieces under gentle grinding conditions. These trials identified the critical control features required to achieve consistently high accuracy with batches of

Table 1. Four modes of operation

Mode 1 **No gauging** **No re-dressing**	**Mode 3** **No gauging** **Re-dressing**
Mode 2 **Gauging** **No re-dressing**	**Mode 4** **Gauging** **Re-dressing**

thirty workpieces.

The critical features were;

- identification and compensation for deflection
- control of dwell period to control size and roundness
- identification and compensation for wheel wear
- identification and compensation for dressing tool deflection and wear.

5. Learning strategy for new materials and grinding wheels

A database was designed which grouped materials having similar grinding characteristics. For a particular grinding wheel and material combination a set of values required to control the process are stored. The information stored includes part programs and kinematic parameters which define starting values for feed-rate and workpiece speed in relation to workpiece diameter and wheel width. Physical parameters and dressing values are also stored in the database.

New groups can be generated under the control of the operator in order to store specific optimal conditions. The system learns optimal conditions for different workpiece speeds by comparing the specific energy measured during the cycle with previously stored values over a series of batches.

The particular benefit of a learning strategy is that an operator does not need to revert to over-conservative grinding conditions at the commencement of each batch. However there is the potential to use the system as an experimental facility for new materials by data logging the production and process information.

6. The modular conceptual framework

The strategies for improved productivity and quality were incorporated into a modular CNC system. The modules developed and applied to grinding between centres are illustrated in Figure 3. The principal new features were:

- in-process measurement of time constant
- in-process control of command position for dwell and dwell period
- compensation for setup error

7. Identification of time constant

The time constant varies with many parameters, including the dressing procedure, wheel wear, width of the grinding wheel, workpiece material properties, coolant, workpiece diameter, feed-rate and workpiece speed.

A general method was desired for the identification of time constant which did not depend on the use of in-process gauging or the measurement of forces. The decision was therefore taken to employ power measurement.

There are two basic methods of measuring time constant during the transient phases of the grinding:

i) Measure time constant within the dwell period

ii) Measure time constant while making the infeed.

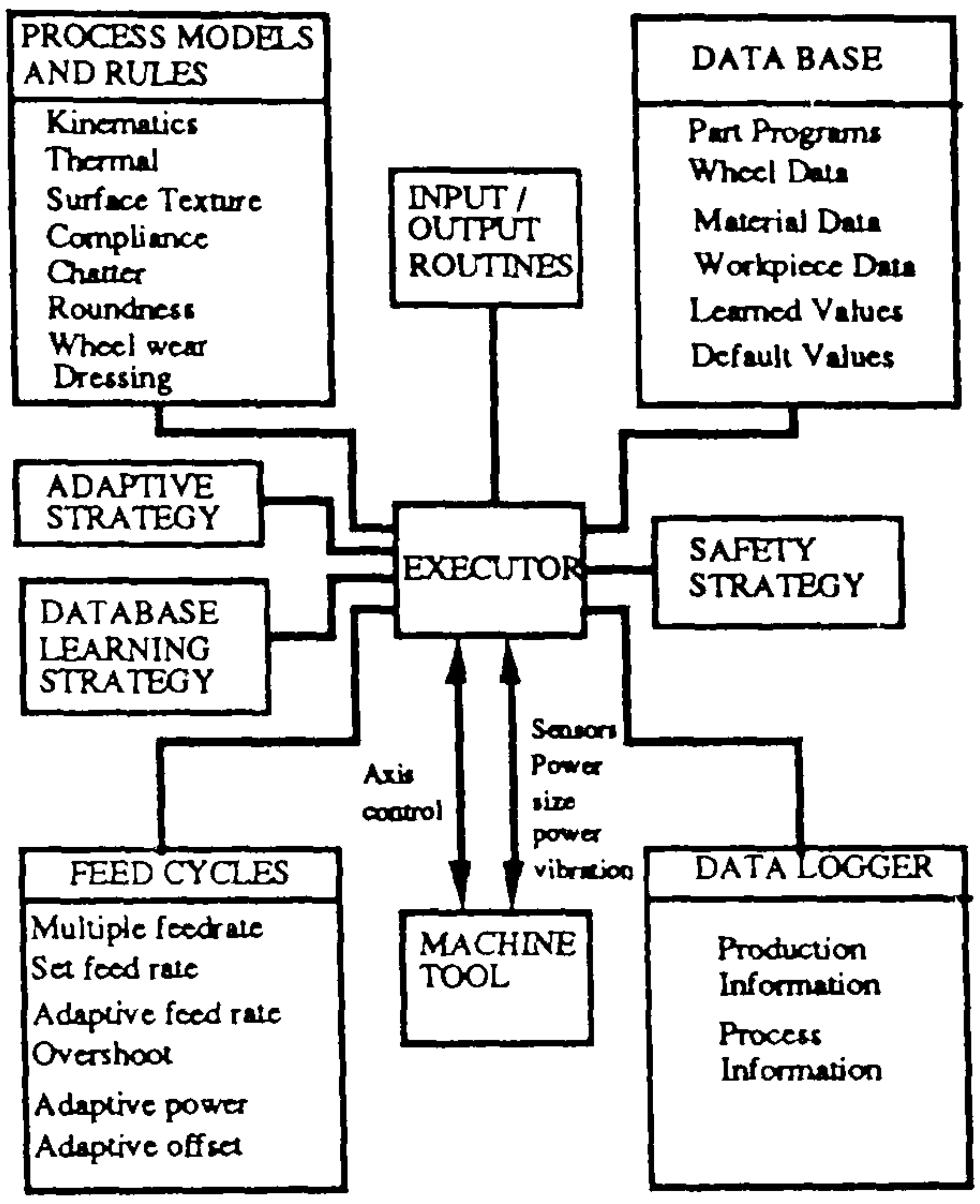


Figure 3. Modular framework for the adaptive CNC system.

A dwell period measurement is more direct since in principle only two data points are required, see figure 4.

However, in-process control of the cycle requires the time constant to be measured while in-feeding in order to determine the appropriate feed and dwell periods.

The conventional way to extract the time constant is by taking the derivative of the power, when the time constant is given by the expression shown in figure 5.

Unfortunately, the time constant extracted by this method is extremely sensitive to noise. It was therefore necessary to investigate alternative techniques. Several methods were developed based on integration of the power signal in order to overcome this problem. The method finally chosen was based on the expression illustrated in figure 6

$$\tau = \frac{t_2 - t_1}{\log_e (P_1/P_2)}$$

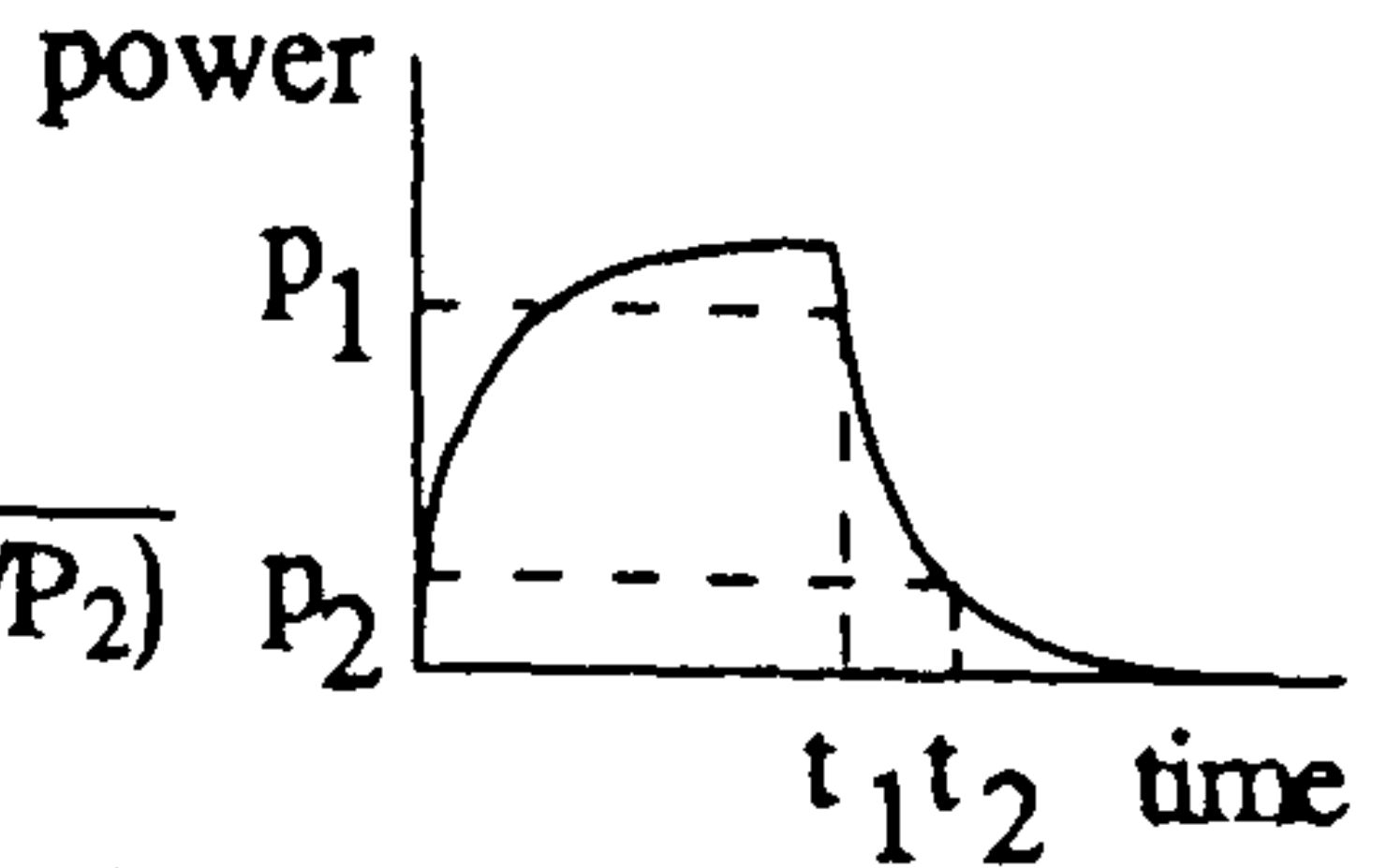


Figure 4. Calculation of the time constant during the dwell period.

This method requires the start of grinding to be detected. A problem experienced in this connection was the false start indicated when the coolant was dragged into the grinding gap just before grinding commenced as in Figure 7(a). A method was found to reliably detect the onset of grinding by monitoring the change in variance of the power signal. This change is indicated in Figure 7(b) where the second large increase in variance corresponds to the commencement of grinding.

$$\tau = \frac{t_2 - t_1}{\log_e (\dot{P}_1/\dot{P}_2)}$$

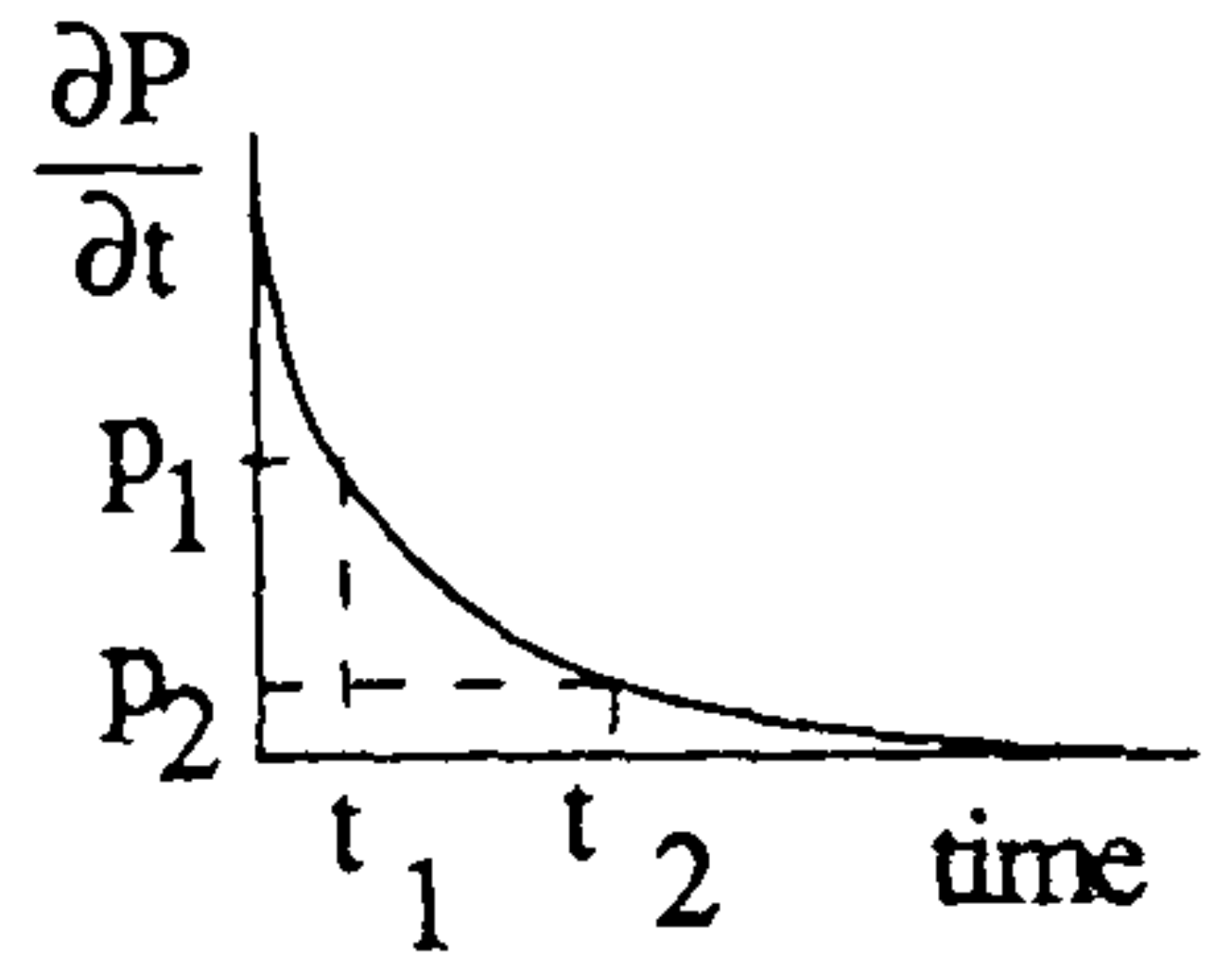
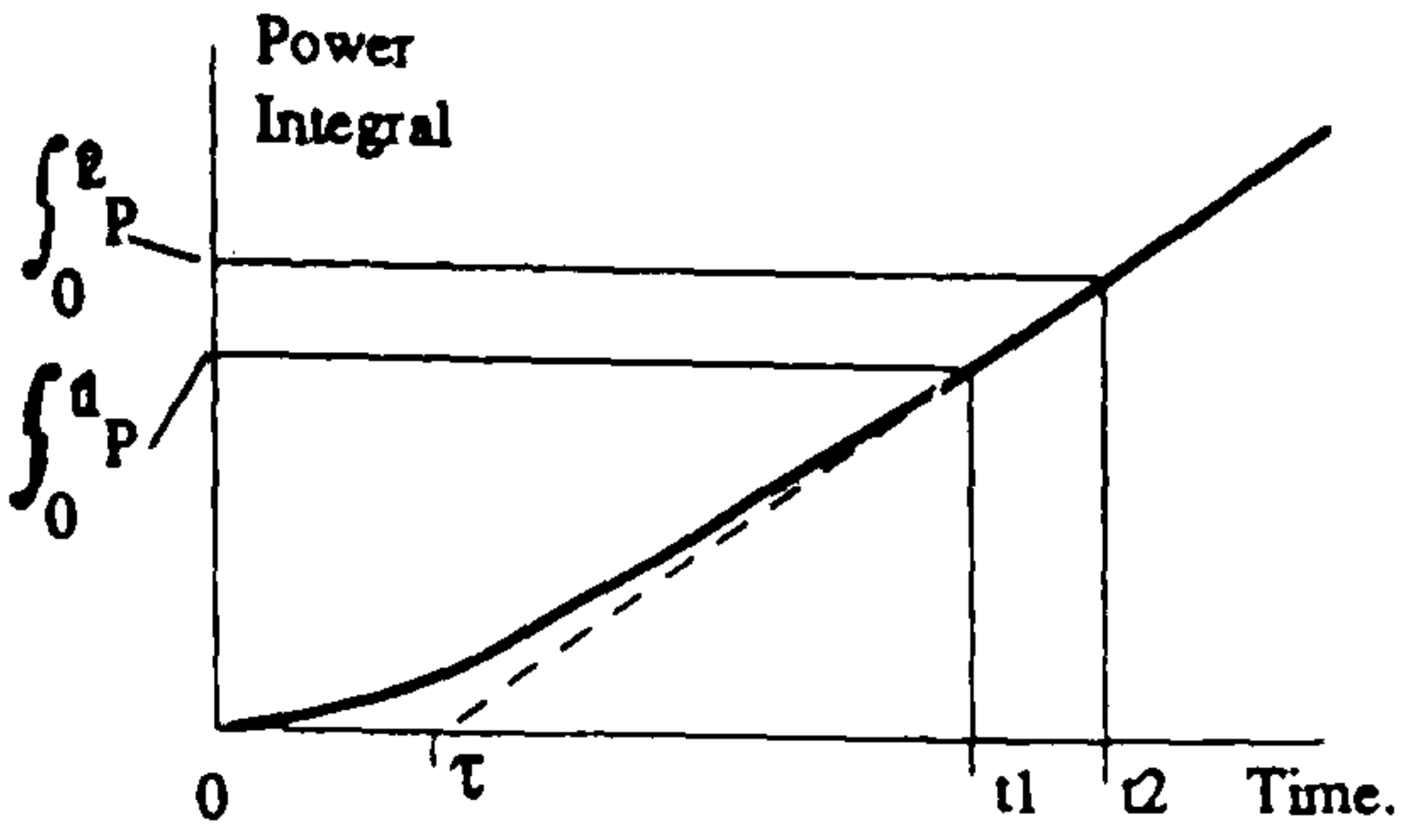


Figure 5. Calculation of the time constant during the infeed period.

The oscillations in the power signal reflect the initial runout of the workpiece. The integration technique copes both with noise and runout problems.

8. Offsets for wheel wear and wheel dressing

A feature of the standard cycle when used with in-process diameter gauging is the ability to compensate for grinding wheel wear and for reductions in wheel diameter due to dressing. The position of the infeed axis when the diameter gauge indicates size has just been reached is compared with the value stored in the part program. The axis is then offset by the difference to compensate for wheel wear as indicated in Figure 8. This works very well in many cases but a problem arises when the offset includes a substantial proportion due to deflections in the wheel-workpiece-machine system. The system has no way of distinguishing between wheel size error x_w and deflection error x_c. Problems are also experienced when using standard cycles with multi-diameters where gauging is often limited to application on one diameter only. The new cycles largely overcome these problems by computing the deflection x_c and adjusting the offset accordingly.



$$\tau = \frac{\left(t_1 \int_0^{t_1} Pdt - t_2 \int_0^{t_2} Pdt \right)}{\int_0^{t_2} Pdt - \int_0^{t_1} Pdt}$$

Figure 6. The calculation of time constant by integrating the process power signal.

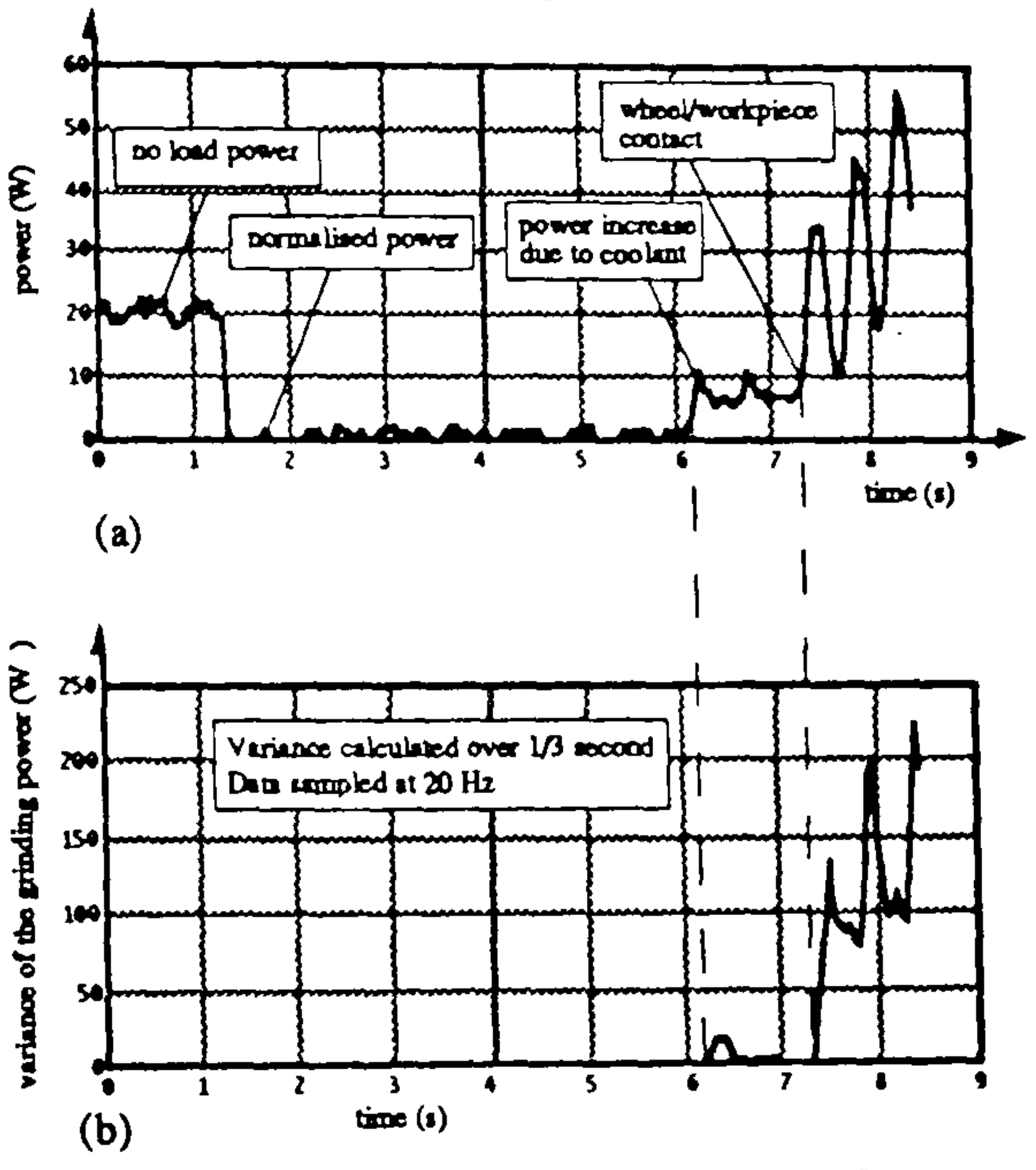


Figure 7. The detection of the start of grinding. a) The typical power curve. b) the variance of the power signal.

The dwell time to reach size is used with the system time constant to compute the actual

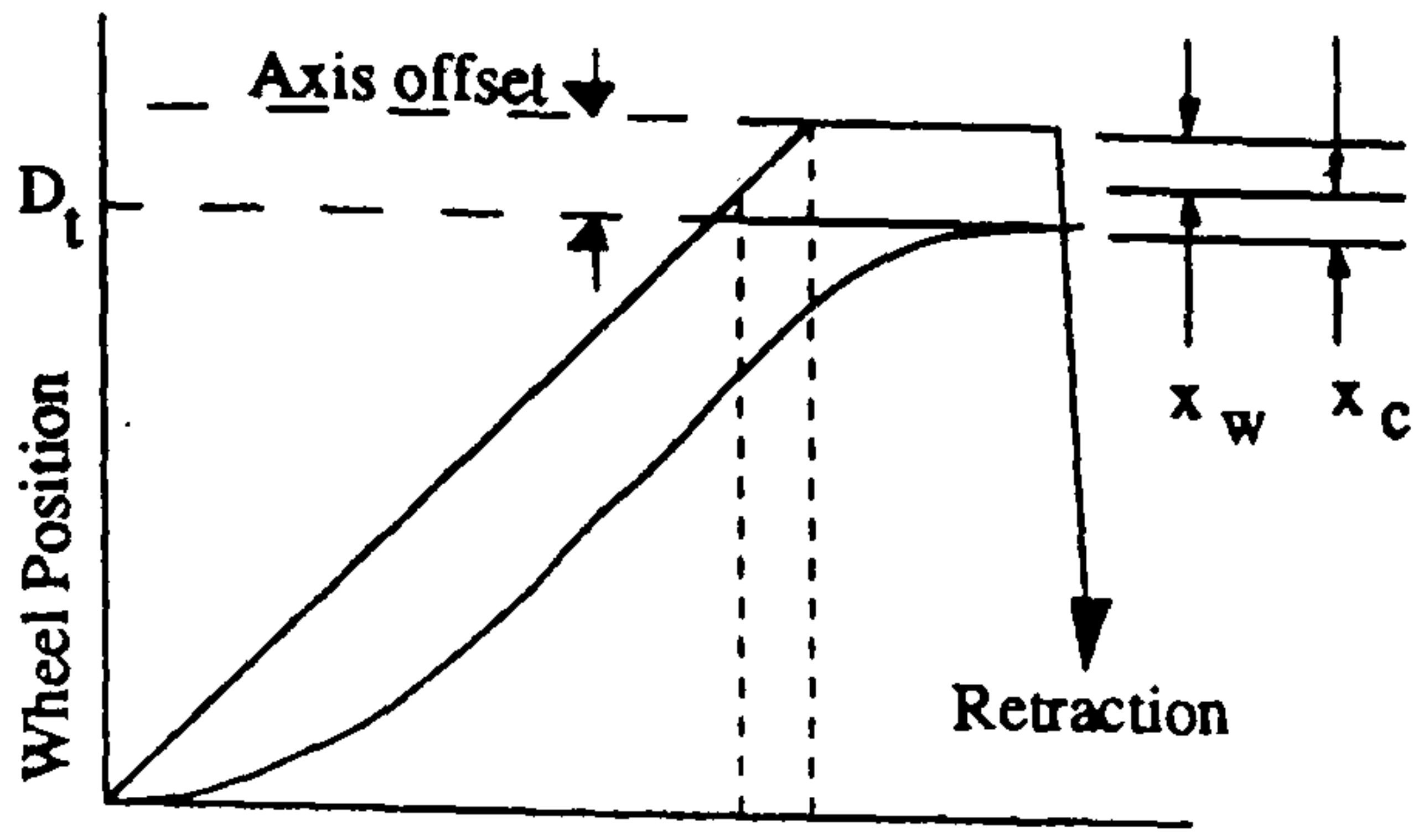


Figure 8. The axis offset includes components for wheel wear and deflection.

overshoot present. This value is then compared with the programmed value and the difference which is due to wear is applied as an axis offset.

9. Size results.

Figure 9 illustrates typical size variations for the four modes of plunge grinding of stiff workpieces for the standard cycles. The non gauging cycle shows the cumulative effect of grinding wheel wear. A learning strategy allows a compensation to be programmed for wheel wear.

Re-dressing the wheel after each cycle increases the size variations due to diamond wear and deflections in the dressing operation. A learning strategy allows a compensation to be programmed for diamond wear and deflection. The selection of dressing parameters and control of the dressing process was found to be very important for the achievement of high accuracy and productivity.

The problems of wheel wear and diamond wear may be directly avoided by employing in-process gauging. For best results gauging should be employed on all diameters and faces although this approach is expensive, lengthens the set-up operation and is rarely used.

Figure 10 illustrates the problem experienced when trying to increase removal rates particularly with flexible workpieces. The problem occurs when employing in-process gauging due to the automatic compensation for wheel wear. The compensation includes a substantial element due to system deflection. The result is a large axis overshoot so that size is approached too rapidly. After the gauge signals the need to retract, further material is removed before the retraction can be effected. The result, figure 10, is that workpieces are undersized in this case by approx. 8 µm.

Figure 11 shows the size errors when grinding flexible workpieces employing diameter gauging with the adaptive cycle. The feedrate was progressively updated to maintain a power level of 5.0 kw. It can be seen that the size control at this high removal rate was improved over the non-adaptive cycle. The scatter around the mean size for both the adaptive and non-adaptive cycles when using high removal rate is approximately 2µm. The mean size error is 2µm below target for the adaptive cycle as compared with 8µm below target for the non-adaptive high removal rate cycle.

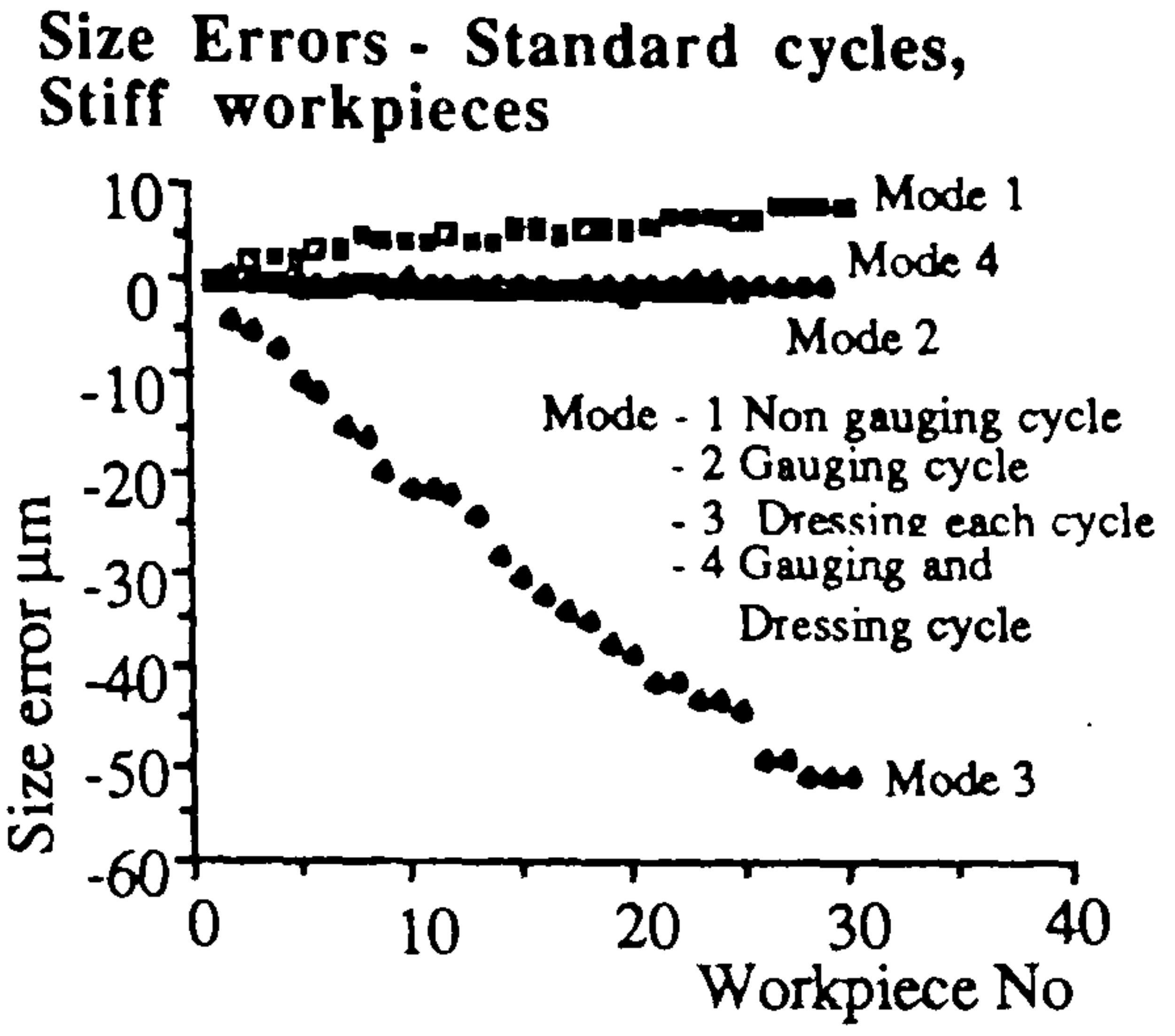


Figure 9. Size results for non- adaptive cycles, where, time constant = 1s approx. Workpiece, oil hardened cast steel, ds=450mm, dw=19mm, b=50mm, vw=0.25 m/s, vf=10, 5, 1µ/s, vs=33m/s. Wheel, A465K5V30W.

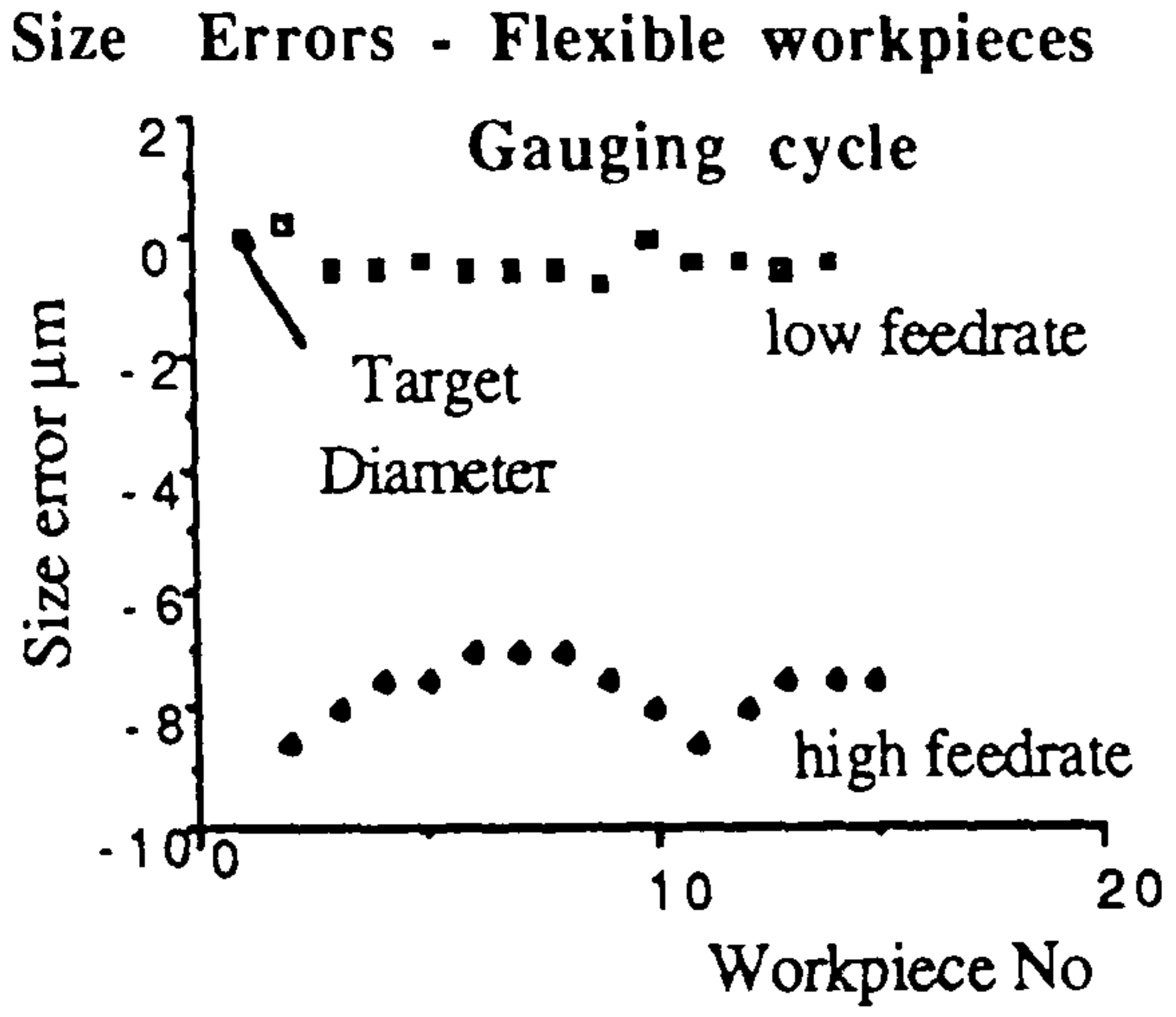


Figure 10. Size results for non - adaptive cycle, where, time constant=3s approx. Wheel, A465K5V30W. Workpiece EN9, ds=450mm, dw=46mm, b=50mm, vw=0.25m/s, vs=33m/s, vf low=5, 3, 1µm/s, vf high=9, 7, 5 µm/s

Figure 12 illustrates the roundness achievable when grinding flexible workpieces

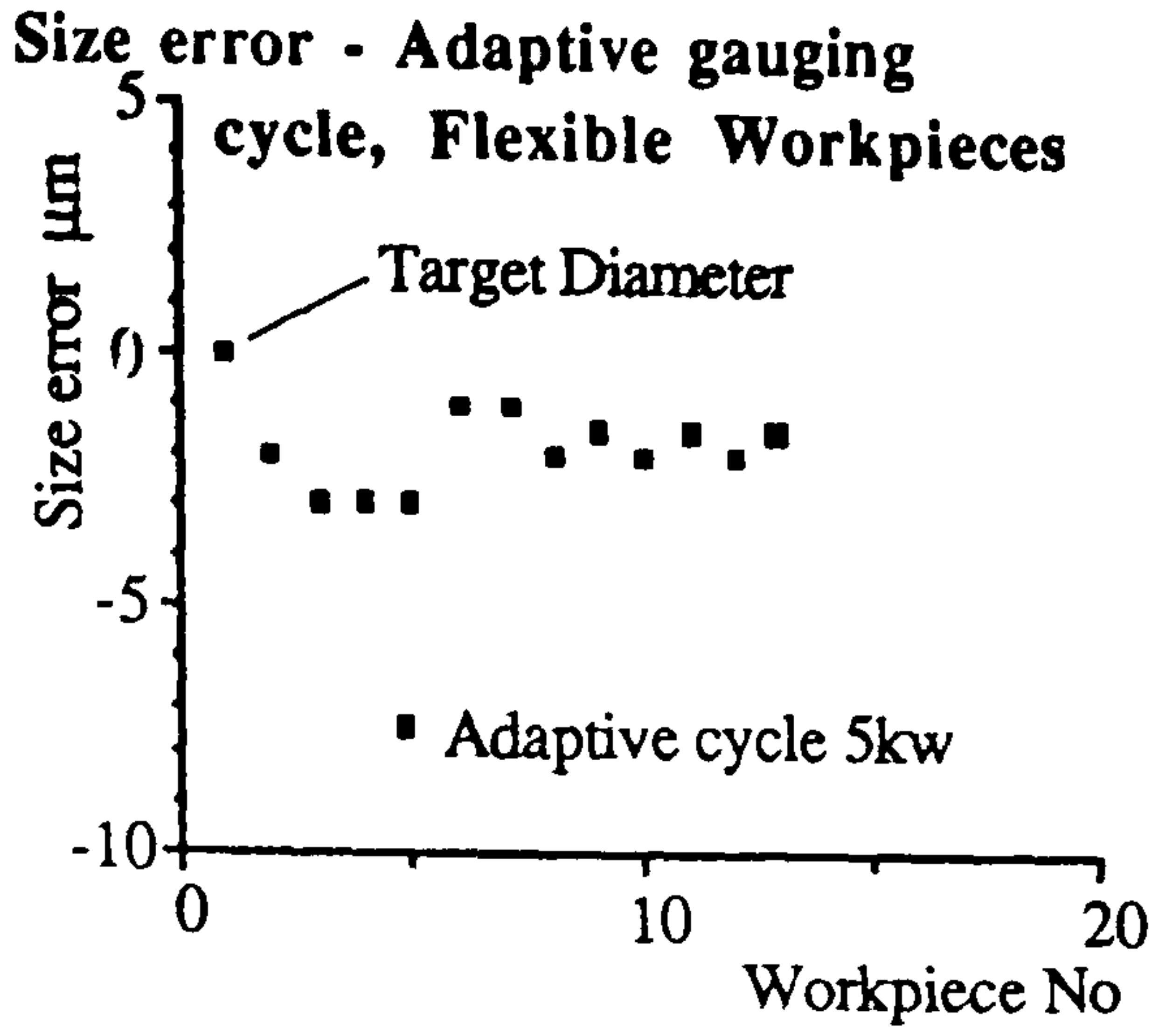


Figure 11. Size results for adaptive cycle, where, time constant=3s approx. Wheel, A465K5V30W. Workpiece EN9, ds=450mm, dw=46mm, b=50mm, vw=0.25m/s, vs=33m/s, Power=5kW.

using standard cycles compared with adaptive cycles. It can be seen that the adaptive cycles give improved roundness at high removal rates.

10. Adaptive control and learning

The adaption of the feedrate between workpieces allows fast learning of the optimum feed cycle. Figure 13 illustrates the achievement of the target power (7 kW) on the second workpiece. The cycle time reduces over a number of workpieces as the wheel condition changes. The cycle times achieved in this instance (20-24 s) compare favourably with those achieved with the standard high feedrate cycle (26 s).

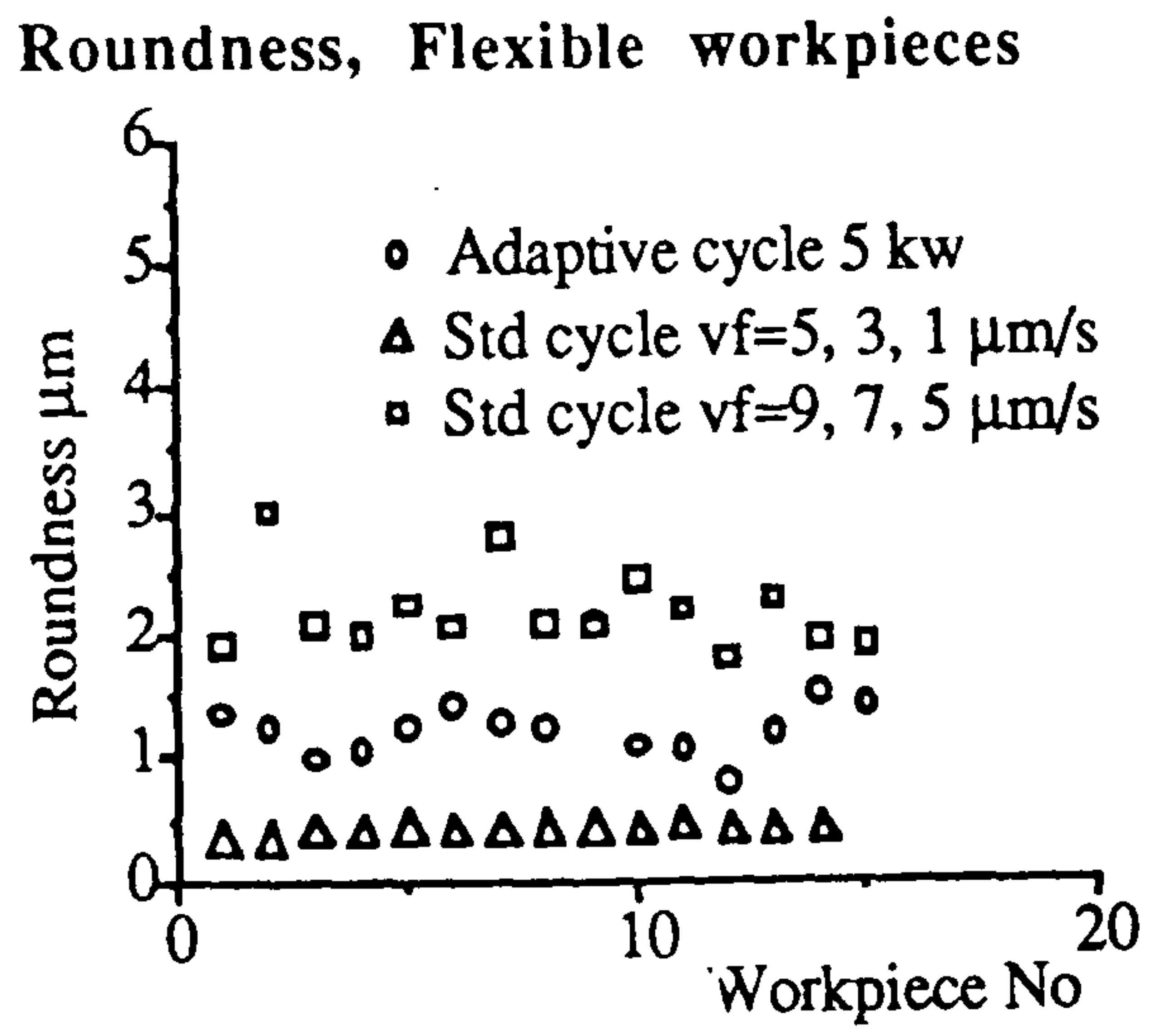


Figure 12. Time constant=3s. Workpiece En9. Wheel A465K5V30W. ds=450 mm,dw=46 mm, b=50 mm, vw=0.25m/s, vs=33m/s.

11. Conclusions

(i) It has been shown that in-process adaptive cycles allow accuracy to be maintained or improved with reduced operator intervention and improved productivity.

(ii) The adaptive and learning strategies developed in this project has the potential to assist the operator in several ways:

- It avoids the need to guess the position for the commencement of dwell. Getting this wrong causes the cycle to fail and costs time and materials.
- Compensation can be provided for wheel wear and diamond wear.

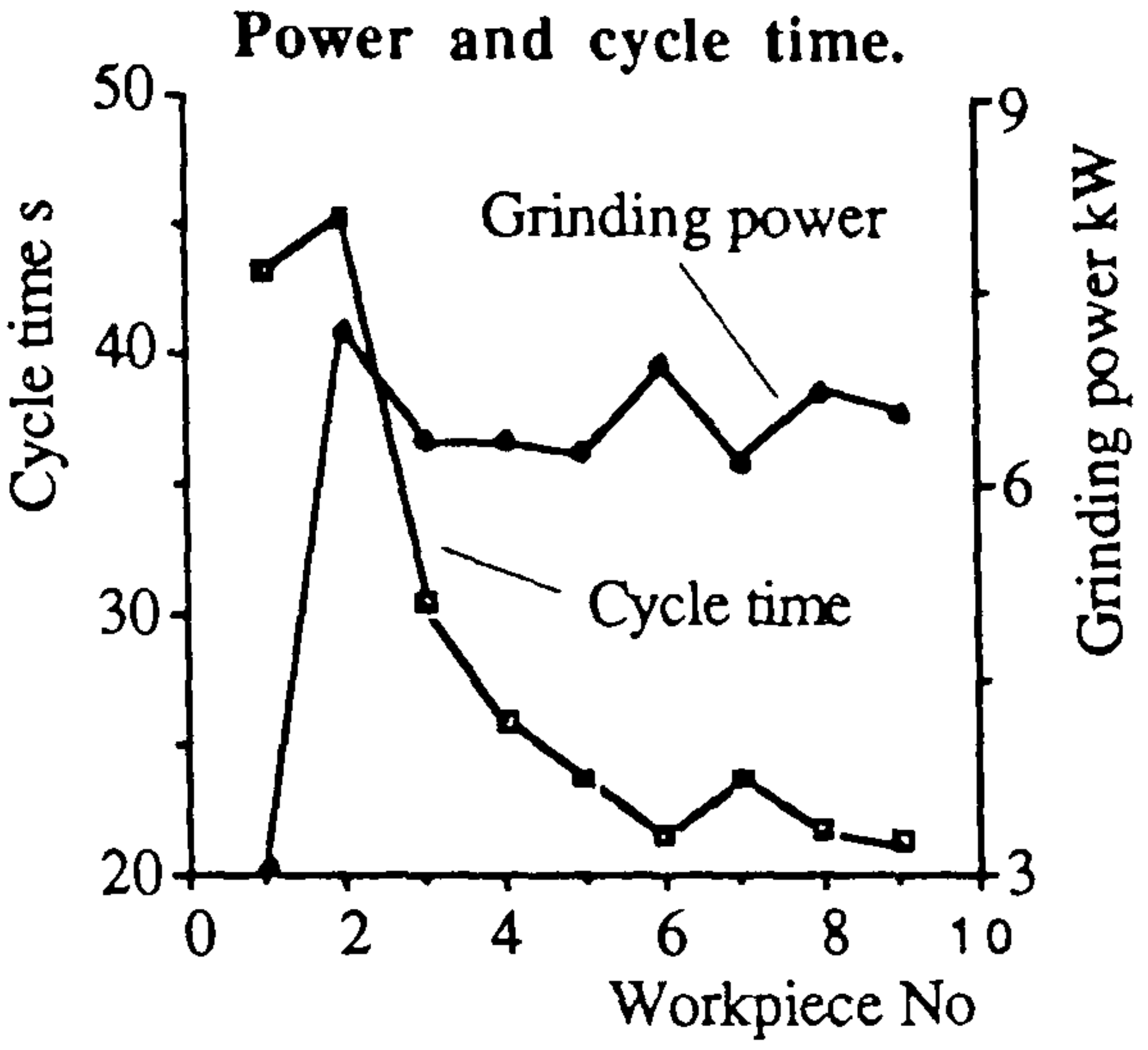


Figure 13. Effects of Adaptive Control on Power and Cycle time. Time constant=3s. Workpiece En9. Wheel A465K5V30W. ds=450 mm,dw=46 mm, b=50 mm, vw=0.25m/s, vs=33m/s.

- Greater accuracy is potentially achieved in multi-diameter grinding due to elimination of deflection from the automatic offset adjustment. Greater accuracy can also be achieved when grinding flexible workpieces for the same reason.

(iii) The selection of dressing parameters and the control of the dressing process was found to be very important for the achievement of high accuracy and productivity. There is the potential to monitor the dressing performance using the intelligence capability of the CNC and to control the process more effectively.

11. Acknowledgements

Acknowledgements are due to SERC, Jones and Shipman and Allen Bradley for their support for this project, also to Paul Wright and Peter Moran for technical support.