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Comparison of high-intensity sound and mechanical vibration for cleaning porous titanium cylinders fabricated using selective laser melting

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ABSTRACT

Orthopedic components can be fabricated using porous metals and a process such as selective laser melting (SLM). This paper concerns how to remove the residual loose powder from the pores of porous metal components without damaging the component. We have compared acoustic cleaning using high-intensity sound inside acoustic horns with mechanical vibration, to remove residual titanium powder from SLM-fabricated cylinders. With acoustic cleaning, the amount of residual powder removed was not influenced by either the fundamental frequency of the horn used (75 Hz versus 230 Hz) or, for a given horn, the number of soundings (between 1 and 20). With mechanical vibration, the amount of residual powder removed was not influenced by the application time (10 s versus 20 s) but there is a higher risk of damaging an expensive medical implant. It is shown that acoustic cleaning is more reliable and effective in removal of residual powder than cleaning with mechanical vibration.

Keywords: acoustic cleaning, sonic cleaning, powder removal
I-INCE Classification of Subjects Number(s): 49.2.1, 49.2.2, 64.2

1. INTRODUCTION

High-performance, cementless orthopedic devices are currently used by the orthopedics industry. These implants rely on bone ingrowth to provide both primary and final fixation. Several techniques have been used to produce the porous structures required with the additive manufacturing process of Selective Laser Melting (SLM) providing a flexible and precise tool for their manufacture (1,2). SLM uses a fibre laser (200W, 1070nm, modulated CW) which is scanned over a powder bed to selectively melt the powder and form a consolidated layer in a cross-section that is defined by the required model geometry. Porous structures resembling both the pore structure and the porosity of real bone can be fabricated by developing specialist algorithms to control the position of the scanning beam. For a cross-section of a porous component where the laser scans a series of distributed points, rather than closely spaced hatch lines, it is possible to develop porosity between the point exposures. Furthermore, if these points are connected by the algorithm to the ones exposed in the previous and indeed subsequent layers than it is possible to develop a fully interconnected porous structure. The full process relies on the deposition of 50 micron thick powder layers, exposing and melting the layer according to their algorithmic positions and repeating the process in 50 micron steps until the full height of the component has been reached. Upon completion of all the layers, the object is removed from the build chamber.

The SLM process leaves a large amount of residual powder around and within the porous structure

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which is retrieved and reprocessed. However, with porous structures the powder that remains inside the pores of the structure may be problematic. For implants, any residual powder that post operatively leaves the implant and enters the tissue surrounding the implant could cause significant inflammatory response at the implantation site. This in turn causes osteoclastic bone resorption and fibrous tissue formation in the bone surrounding the implant which results in implant loosening and failure (3). Removal of the excess powder from the voids of the porous structure is therefore essential. Several methodologies are used by manufacturers including mechanical vibration, heat treatment and blasting with inert gas. The majority of these processes are followed by cleaning using a water-based ultrasonic process. This is a wet, relatively slow process and therefore it is advantageous to remove the majority of the residual powder beforehand in the dry state. One possibility is to use high levels of mechanical vibration to remove the loose powder; however high levels of vibration could damage the implant. This provides the motivation to identify an efficient non-contact process which could be used to remove the majority (or all) of the powder without using mechanical vibration. The challenge of removing micron size particles from the tortuous paths contained within a porous material is significant and this paper describes experimental work to demonstrate the feasibility of acoustic cleaning quantifying its efficacy in removing residual powder from internal voids of porous metal structures produced using SLM. To demonstrate its feasibility acoustic cleaning is also compared with high levels of acceleration induced by mechanical vibration.

Acoustic cleaning using high-intensity sound offers the potential to remove powder from within a porous implant, without causing any damage to the implant itself. This is because the forces produced by very high sound pressure levels are typically much smaller than those imparted by steady-state or transient mechanical vibration. High-intensity sound can be produced by air-driven horns and these are used in industry to promote flow in powders and to prevent the build-up of powder on surfaces. Previous work (4,5) has investigated the use of high-intensity, low-frequency sound required to de-bond powder layers from the collection plates of electrostatic precipitator air filters used in power stations. In such applications, the high-intensity sound overcomes the cohesive forces of the order 10-7N between powder particles. In contrast to these industrial applications where high-intensity sound is generated in large reverberant volumes, it is possible to place the medical implants inside the throat of a horn where there are extremely high sound pressure levels as well as turbulent airflow. This provides the novel aspect in this paper where high-intensity sound inside the horn is investigated to determine the effect of sound pressure level, duration and frequency content on the efficiency of powder removal from porous metals.

An experimental rather than theoretical approach is used to demonstrate the efficacy of acoustic cleaning because the theoretical predictions that were considered in previous work (5) are better suited to the removal of powder from large plane surfaces rather than complex porous solids. In addition, the Hamaker constants required to undertake theoretical analysis are not known for the Titanium powder used in the manufacturing process.

This paper gives an overview of recently published research (open-access) by the authors (6) which concerns the removal of residual powder from commercially-pure titanium cylinders that were manufactured using SLM.

2. MATERIALS AND METHODS

This section describes the experimental procedures and equipment used to carry out the removal of powder from the porous metal samples.

2.1 Porous metal samples

Cylindrical porous metal samples were produced from commercially pure titanium (CpTi) built off a substrate using an SLM100 machine (Realizer, De). The porous material was 30% randomised based on a tessellated octahedral matrix. Randomisation is applied by shifting the nodal coordinate of a regular octahedral lattice by ±30% of the unit cell dimension as described in Mullen *et al* (7). Each sample was a 30mm high cylinder with an outer diameter of 15mm which had a porosity of ≈60% and average pore size 450 microns. Figure 1 shows the 16 samples in the sample holder immediately after manufacture which are embedded in the surplus titanium powder, and a single sample.

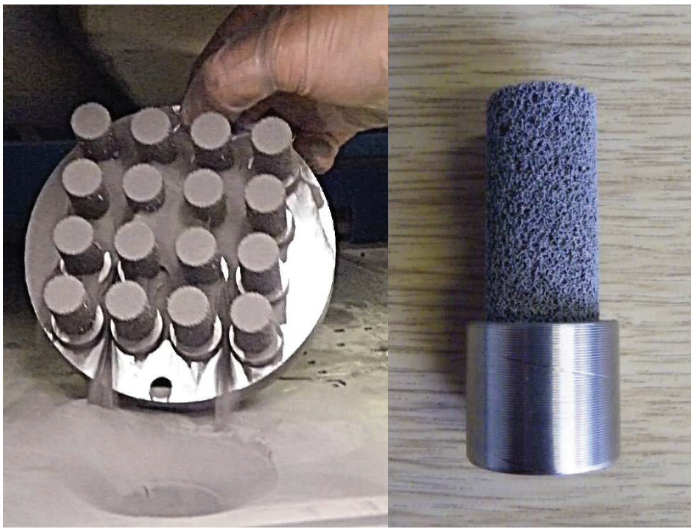

Figure 1. (Left) Sixteen cylindrical samples on a substrate holder showing the large quantity of surplus titanium powder being poured off at the end of the manufacturing process. (Right) Close-up of single cylindrical sample on a mini-substrate.

2.2 Air-driven horns

Air-driven horns are capable of generating high sound pressure levels which cannot be created and/or sustained by standard loudspeakers. Two horns are used in this investigation. These were the PAS 75 and PAS 230 industrial cleaning horns (Primasonics International Ltd, UK) which are named according to their fundamental frequencies which are 75Hz and 230Hz respectively. The PAS 75 horn is 3m long with a bell diameter of 400mm (i.e. at the mouth of the horn) and is comprised of three fibre-glass sections that are bolted together. The PAS 230 is a spun aluminium horn, 0.62m long with a 208mm bell diameter. The reasons for assessing two different horns were that (a) horns with lower fundamental frequencies need to be longer and this might not be always be practical to implement in an manufacturing process and (b) it is not known whether the efficacy of acoustic cleaning depends on frequency. Compressed air is used to drive the horn which was delivered from a large compressor. For both horns the air pressure is set to 1034kPa (150 psi) for all soundings for which the air reservoir volume gave a 12s sounding.

2.3 Equipment to measure high sound pressure levels

Conventional measurement microphones with thin metal diaphragms cannot be used to measure the sound pressure level inside the horn or near the mouth of the horn because the high-intensity sound and turbulent nature of the field would destroy the microphone diaphragm. For this reason a piezoelectric hydrophone was used because this sealed transducer is sufficiently robust to be used in high sound pressure fields with turbulent flow. A hydrophone (Brüel & Kjær Type 8103, UK) is connected to a signal conditioning amplifier (Brüel & Kjær Nexus Type 2692, UK) to measure narrow band spectra and maximum sound pressure levels. Hydrophones are designed for use in water; hence the sensitivity in air was established by comparison against calibrated measurement microphones in the reverberation chamber (volume 122m^3) with a broadband white noise source, power amplifier and loudspeaker (100Hz to 10kHz). This demonstrated that the hydrophone is accurate within 1dB which was sufficient to enable precise and repeatable measurements in air. The horn was sounded for 12s but the equivalent continuous sound pressure level, $L_{\mathrm{eq,10s}}$, was measured over a 10s time period to avoid the initial rise and decay of the sounding.

2.4 Sound pressure level measurements inside horns

The horns are installed in a reverberation chamber to reduce sound transmission to areas outside the laboratory. To measure the sound field inside the horn, the PAS 75 horn is mounted horizontally as shown in Figure 2 and the hydrophone is located at the mouth of the horn (i.e. at the bell). The hydrophone is then moved a distance of 100mm inside the horn and the measurement repeated. This process is repeated by moving the hydrophone in 100mm steps inside the horn until it is 1.5m from the mouth. The smaller PAS 230 horn was mounted vertically as shown in Figure 2 and the hydrophone was used to measure up to a distance of 500mm inside the horn. Beyond a distance of 500mm the diameter of the horn reduces to less than 60mm which, for cleaning purposes, is too small a space to easily position and fix samples.

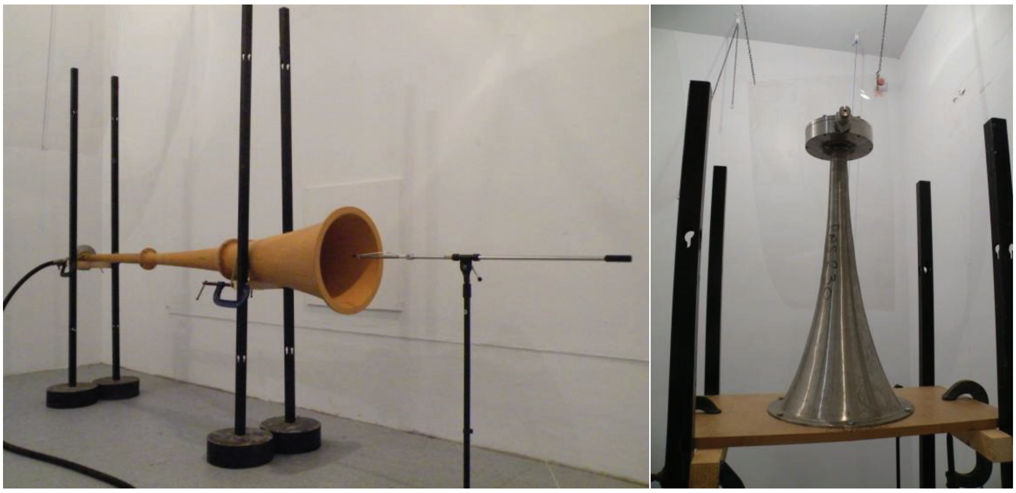

Figure 2. Horns installed in the reverberation chamber. (Left) The PAS 75 horn with the hydrophone fixed to a boom allowing sampling at different positions inside the horn. (Right) The PAS 230 horn supported by a wooden plate (NB A circular aperture exists underneath the horn to allow normal operation).

2.5 Acoustic cleaning

This section describes the procedure for installing and acoustically cleaning the porous metal samples inside the horns.

Three porous metal samples are weighed to ±0.01g using a precision balance immediately before insertion inside the cleaning chamber. Each sample is then rotated at 12 rpm. The horn is sounded for 12 seconds after which the sample is removed from the chamber and re-weighed. This process is repeated 5 times for each of the three samples. However, for one of these three samples the process was repeated 20 times to check if there was any advantage in increasing the exposure.

2.6 PAS 75 horn

Due to the length of the PAS 75 horn it is possible to access the high-intensity sound field inside the horn. Therefore, a cleaning chamber was designed and constructed to fit into the mid-section of the horn as shown in Figure 3. This allows the sample to be exposed to higher sound pressure levels inside the horn than occur at the mouth. There are practical limitations on the position for the cleaning chamber along the horn. The position that was chosen allowed insertion of an appropriate size chamber before the throat narrowed towards the driver; the distance from the mid-point of the chamber to the mouth of the horn being 870mm. The chamber is transparent to enable visual inspection of the porous metal sample. The sample is rotated in the sound field whilst the horn is sounding to try and ensure maximum removal of powder by exposing all sides of the sample to the incident sound and allowing the powder to exit from all surfaces.

The PAS 75 horn is mounted above a circular aperture in order not to impede air flow through the horn – see Figure 3. This allows the powder that is dislodged from the sample to fall under gravity away from the sample. The cleaning chamber with the sample installed close to the hydrophone is also shown in Figure 3.

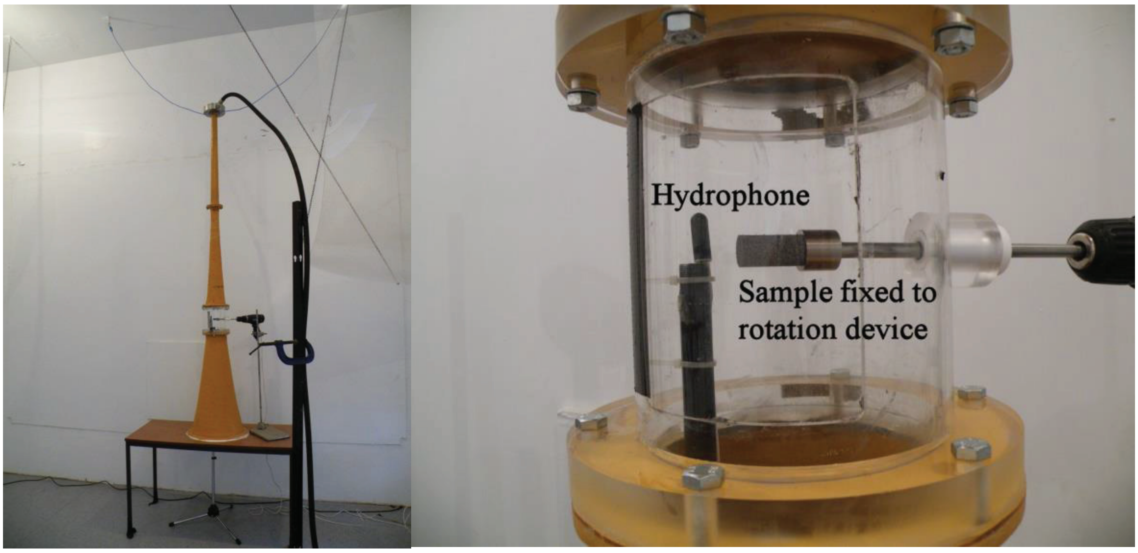

Figure 3. Modified PAS 75 horn with the cleaning chamber fitted (Left). Experimental set-up. (Right) Porous metal sample installed in the cleaning chamber close to the hydrophone.

2.7 PAS 230 horn

The PAS 230 horn is smaller than the PAS 75; hence it is not practical to install a cleaning chamber with this unit. As with the PAS 75, it is mounted above a circular aperture as shown in Figure 2.

2.8 Cleaning using mechanical vibration

Previous work (4,5) used sinusoidal signals to identify the vibration level required to de-bond powdered material that had been electrostatically deposited onto a metal surface. This required acceleration levels between 153 to 164dB re 10^{-6}m/s^2 which corresponds to peak acceleration values in the range of 63 to 224m/s^2. To remove metal powders from the implant it was assumed that the required levels were likely to be higher than this and that mechanical rapping (rather than sinusoidal excitation) would be beneficial in shaking/removing loose powder from the voids within the porous material. For comparison with acoustic cleaning, a hammer drill was used to vibrate the underside of the metal sample holder (shown in Figure 1a). Into this holder an inverted sample was fixed by a screw in its substrate. As vibration was applied the powder fell under gravity into a collection beaker. An accelerometer (Brüel & Kjær Type 4374, UK) was fixed to the base of each sample. This measured an overall acceleration level of 170dB re 10^{-6}m/s^2 which corresponds to a peak acceleration of 449m/s^2. The vibration was applied for 10s (i.e. similar to the time used for the acoustic cleaning). The setup for cleaning using mechanical vibration is shown in Figure 4.

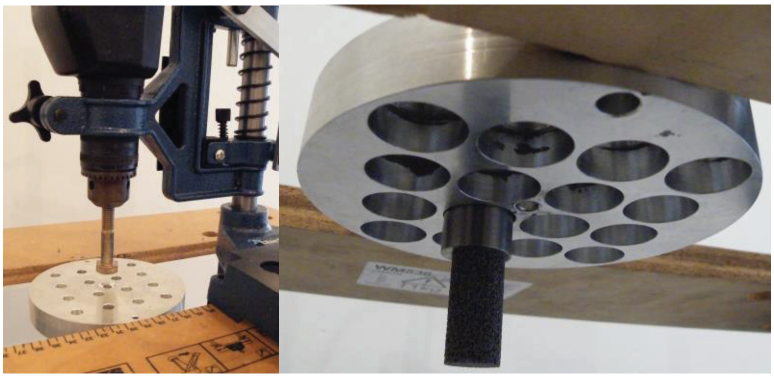

Figure 4. Mechanical vibration. (Left) Hammer drill used to apply vibration to the upper surface of the sample holder. (Right) A single sample fixed to the underside of the sample holder.

3. RESULTS

This section presents the experimental results and analysis on the sound field inside the horn and the removal of powder using acoustic cleaning and mechanical vibration.

3.1 Quantifying the sound field inside the horn

The narrow band sound pressure level spectra in terms of $L_{\mathrm{eq,10s}}$ at the mouth of the horn as well as at positions inside the horn are shown in Figure 5 for the PAS 75 horn and PAS 230 horn.

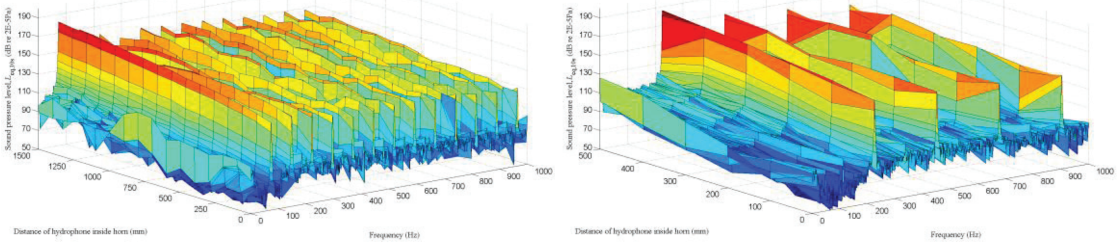

Figure 5. Sound pressure level measured at distances up to 1500mm inside the PAS 75 horn (Left) and up to 500mm inside the PAS 230 horn (Right).

For the PAS 75 the first peak in the spectrum occurs at the fundamental frequency of the horn which is 75Hz, with subsequent peaks occurring at the harmonics. At a distance of 1500mm inside the horn the overall sound pressure level is dominated by the level at the fundamental frequency because the levels at the harmonics are at least 10dB lower. At the mouth of the horn (i.e. a distance of 0mm on the graph) the first two harmonics are at a higher level than the fundamental. This is in contrast to the PAS 230 for which the harmonics all have lower levels than the fundamental. Hence it is more instructive to refer to the overall sound pressure level (also in terms of $L_{\mathrm{eq,10s}}$), rather than quote the levels at individual frequencies.

For both horns the sound pressure level increases with increasing distance inside the horn. The PAS 230 has higher sound pressure levels than the PAS 75; this is partly due to the rigidity of the PAS 230 which is made of metal rather than fibre glass. For the PAS 75 the overall level at the mouth is 154dB but this increases to 185dB at a position 1500mm inside the horn; an increase of 31dB. For the PAS 230 the overall level is 162dB at the mouth which increases to 186dB at a position 500mm inside the horn; an increase of 24dB.

To put these high sound pressure levels inside the horns in context, it is noted that for the PAS 230 and the PAS 75 the average levels in the reverberant chamber at 140dB and 144dB respectively; i.e. the levels were significantly lower outside the horn. For the acoustic cleaning of small samples it is possible to position them within the horn or close to the mouth of the horn to take advantage of the highest sound pressure levels.

3.2 Acoustic cleaning of porous metal samples

Each porous metal sample had a porosity of 60%. As the titanium powder has a tap density that is approximately 60% of the solid titanium, it was estimated that each sample could hold 5.7g of powder.

Table 1 shows the change in weight of samples A, B and C when exposed to 170dB inside the cleaning chamber of the PAS 75 horn. On average, 5.8g of loose powder was removed from the samples for five 12s soundings of the horn. This closely corresponds to the estimated weight of powder inside the pores of 5.7g. However, it could be questioned whether the process of merely installing it in the cleaning chamber and rotating it could dislodge some loose powder. To check this, sample C was weighed, installed in the cleaning chamber and rotated for 12 seconds without the horn sounding, removed and re-weighed. This sample only changed in weight by 0.17g which is negligible compared to the amount removed by sounding the horn once. One sample was exposed to 20 soundings of the horn, but the weight of the sample did not change from that measured after five soundings.

Table 2 shows the change in weight for samples D, E and F when exposed to 165dB at the mouth of a PAS 230 horn. An average of 5.9g of loose powder was removed from the samples after five 12s soundings of the horn. This is also close to the estimated weight of powder inside the pores of 5.7g. However, the fact that it is slightly larger indicates that there may have been additional powder on the outer surface of the sample. One sample was exposed to twenty soundings of the horn but the weight of the sample did not change from that measured after five soundings.

The results in Tables 1 and 2 indicate that the frequency of sound (75Hz for PAS 75 and 230Hz for PAS 230) is not critical provided that the sound pressure level is high enough. For the future design of acoustic cleaning systems this is useful information because it is simpler and more cost-effective to attenuate high frequency sound rather than low frequency sound.

Specimen	Initial mass (g)	Mass after sounding No.1	Mass after sounding No.2	Mass after sounding No.3	Mass after sounding No.4	Mass after sounding No.5	Mass of powder removed after 5 soundings (g)
A	38.62	32.81	32.78	32.76	32.75	32.75	5.87
B	37.39	31.94	31.93	31.92	31.91	31.91	5.48
C	38.29	32.32	32.28	32.27	32.27	32.27	6.02

Table 1 – Summary of test results from acoustic cleaning after exposure to 170 dB inside the PAS 75 horn. Note that the mass corresponds to the cylinder and substrate.

Specimen	Initial mass (g)	Mass after sounding No.1	Mass after sounding No.2	Mass after sounding No.3	Mass after sounding No.4	Mass after sounding No.5	Mass of powder removed after 5 soundings (g)
D	38.53	32.66	32.4	32.38	32.38	32.38	6.15
E	38.01	32.2	32.19	32.18	32.16	32.16	5.85
F	38.44	32.76	32.76	32.74	32.73	32.73	5.71

Table 2 – Summary of test results from acoustic cleaning after exposure to 165 dB at the mouth of the PAS 230 horn. Note that the mass corresponds to the cylinder and substrate.

3.3 Mechanical vibration used to clean porous metal samples

Table 3 shows the initial weight and the change in weight of samples G, H and I after exposure to 10s of mechanical vibration, followed by another 10s of mechanical vibration, followed by exposure to 170dB inside the cleaning chamber of the PAS 75 horn for five 12 second soundings of the horn. Note that the initial weight of samples G and H was slightly lower than samples A to F because some of the loose powder near the surface of the sample fell off naturally during handling. Between the first and second 10s exposure to vibration there was only a further decrease of between 0.01 to 0.03g. However, the subsequent use of acoustic cleaning was able to remove additional powder between 0.18 and 0.23g. These results indicate that acoustic cleaning is potentially more efficient than mechanical vibration as well as avoiding the risk of damage due to high vibration levels.

Specimen	Initial mass (g)	Mass after vibration for 10 s (g)	Mass after vibration for 20 s (g)	Mass of powder removed after vibration for 20 s (g)
G	36.04	32.20	32.18	3.86
H	36.95	32.82	32.79	4.16
I	37.97	32.87	32.86	5.11

Table 3 – Summary of test results from cleaning using mechanical vibration. Note that the mass corresponds to the cylinder and substrate.

4. CONCLUSIONS

This study demonstrates that acoustic cleaning with high-intensity sound is highly effective at removing powder from inside porous metals. To quantify sound pressure levels inside and at the mouth of the horn, a novel measurement approach was implemented using hydrophones. This allowed measurement of high-intensity sound fields with turbulent flow inside a horn using conventional measurement microphones. Inside two different horns the sound pressure level increased with increasing distance from the mouth to levels as high as 186dB. These two horns had fundamental frequencies of 75Hz and 230Hz but there was no evidence that frequency had a significant effect on the efficacy of the acoustic cleaning. The weight of powder removed confirmed that the powder was removed by acoustic cleaning. These results indicated that acoustic cleaning can remove more trapped powder from the pores than mechanical vibration. This is advantageous because sound avoids the risk of damaging the object with high levels of mechanical vibration.

Nowadays, many different objects are manufactured using rapid prototyping which often leaves the objects covered with powder; hence acoustic cleaning could be considered as an alternative to high levels of mechanical vibration which can potentially damage them. Although acoustic cleaning is quick, dry and non-destructive there are limitations on the sample size that can enter inside a horn or at the mouth of a horn. In addition, any manufacturing implementation of acoustic cleaning would need careful design to avoid exposure of operators to damaging levels of sound.

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