An investigation of stick-slip oscillation of Mn-Cu damping alloy as a friction material

X.C. Wang1, J.L. Mo1, \*, H. Ouyang2, B. Huang1, X.D. Lu1, Z.R. Zhou1

1) Tribology Research Institute, School of Mechanical Engineering, Southwest Jiaotong University, Chengdu, 610031, China

2) School of Engineering, University of Liverpool, Liverpool L69 3GH, UK

\* Corresponding author: jlmo@swjtu.cn (J.L. Mo)

ABSTRACT

The capability of Mn-Cu damping alloy in suppressing stick-slip oscillation when used as the friction pair material is investigated through the experimental method and the forged steel, cast iron, Al alloy and Mn-Cu alloy are chosen for the comparative study. The results show that the Mn-Cu damping alloy and Al alloy have a great potential in suppressing stick-slip oscillation as compared with others. The results also reveal the varying wear behaviours and the relationship between the wear state and the stick-slip oscillation. They indicate that the wear debris on the contact interface make a noticeable contribution to reduce stick-slip oscillation. In addition, the high damping capacity of the Mn-Cu damping alloy may also help to suppress the stick-slip oscillation.

**Keywords**: Stick-slip; Mn-Cu damping alloy; friction; wear

1. INTRDUCTION

As a typical kind of friction-induced vibration, stick-slip oscillation is very common in engineering and life. There are two distinct motion regimes: in the stick regime one part of the friction pair moves or stays together with the other part and the friction force balances the external force, while in the slip regime the two parts of the pair move relatively to each other and the friction force is ‘controlled’ by the friction law [1-4]. Normally stick-slip oscillation is unwanted, and in most cases, it can cause serious problems, including noisy brakes, tire squeal, squeaky hinges, earthquakes and so on. Therefore, suppression of stick-slip oscillation is very useful [5-7].

As a kind of non-smooth vibration, stick-slip oscillation is a complex nonlinear problem, and it has attracted many scholars to study its mechanism and discover the possible methods to suppress stick-slip oscillation using both numerical and/or experimental methods [5, 8-18]. Li et al. [5] studied the in-plane stick-slip oscillation of a damped oscillator dragged around an annular elastic plate and found that ignoring separation of the slider from the plate often led to very different dynamic behaviour and possibly misleading results. Popp et al. [8, 9] studied the bifurcation and chaotic behaviour caused by stick-slip oscillation through experimental and numerical methods. Fulleringer and Bloch [10] proposed a method for characterizing the stick-slip oscillation and removing its adverse effect on the friction force measurement. Gao and Cao [11] studied the periodic motion, bifurcation and chatter of a two-degree-freedom vibro-impact system and found that it possessed rich dynamics characterized by periodic motion, stick-slip-impact motion, quasi-periodic motion and chaotic attractors. Thomsen and Fidlin [12] investigated the critical speed for stick-slip, pure-stick, and pure-slip oscillations. Denny [13] reviewed the main characteristics of stick-slip vibration and also found that there was a critical speed which depends on some system parameters. Dankowicz and Nordmark [14] proposed a macroscopic dynamic friction model and investigated the bifurcation associated with stick-slip oscillation using a numerical method. Lee et al. [15, 18] and Dong et al. [16, 17] all reported that the friction materials had a significant effect on the stick-slip behaviour from an experimental study.

In recent years, a new kind of material, damping alloys has shown a good ability to reduce common friction-induced vibration and noise in industry [19-23]. Huang et al. [22] studied capability of a Cu-Al-Mn SMA (shape memory alloy) in reducing excessive vibration and found that the SMA could reduce the vibration response significantly. Baik et al. [23] developed a high-damping Fe-Mn alloy and investigated its characterization. They found that the Fe-Mn alloy was able to reduce noise and vibration.

Among the various kinds of damping alloys, it has been reported that Mn-Cu damping alloy shows great capability in suppressing vibration as a damping material in various structures [24-26]. Whether it is effective in suppressing stick-slip oscillation when working as part of a friction pair material remains to be investigated. The aim of this study is to explore this potential under low speeds, heavy loads and dry friction conditions through the experimental method. A comparative study of the stick-slip oscillation is conducted with disc specimens made in five kinds of materials, i.e., Mn-Cu damping alloy (Mn-20Cu-5Ni-2Fe), Mn-Cu alloy (Mn-20Cu-5Ni-2Fe without heat treatment), Al alloy (7075), forged steel and cast iron. The reason why these four kinds of materials are selected is that the forged steel, cast iron and Al alloy are common friction pair materials used in engineering. Additionally, they are prone to sustained vibration when excited due to their low damping. For a fair comparison, both Mn-Cu damping alloy and conventional Mn-Cu alloy (Right heat treatment can improve damping capacity of Mn-Cu alloy and may in turn affect the stick-slip vibration of the pad and wear of both the pad and the disc.) are selected in the comparison so that the role of damping would be clear. The vibration acceleration signals, friction forces and wear states for five kinds of discs are performed to determine whether the Mn-Cu damping alloy can reduce stick-slip oscillation.

2. EXPERIMENTAL PROCEDURE

## **2.1 Experimental setup**

Friction characteristics of stick-slip phenomena are studied in this investigation by performing tribological tests on a self-designed setup in a pad-on-disc configuration. Its schematic can be seen in Figure 1. This setup has the advantage of a well-defined contact area and a simple friction pair, which creates a rather simple structure and thus helps understanding of the characteristic of stick-slip phenomena. The fixture system was used to hold the specimens: the pad was held in the upper holder which was connected with the connection part by the screw thread. A strong glue was used to fix the disc onto the metal base which will rotate with the rotational motion device. During the tests, the moving stage which was controlled by the computer would move downwards and push the pad into contact with the disc under a given normal load. Then the disc would rotate with the rotational motion device which was also controlled by the computer. To protect the force sensor, the spring suspension was fixed between the connection part and the force sensor.

In the test, the 2-D force sensor (sensitivity: 0.025 N; measuring range: 5-500 N) was installed to record the normal and friction forces during the whole tests. To protect the force sensor, the suspension was fixed between the connection part and the force sensor. The signals of the forces were recorded by the computer. In order to record the vibration features, the uniaxial accelerometer (sensitivity: 106.3 mV/g; measuring range: 50 g; frequency range: 0.5–10 kHz) was fixed on the upper holder to get the signal of tangential vibration acceleration and the data acquisition and analysis system was used to the record and process the signals.

## **2.2 Details of specimen samples**

In this work, five kinds of discs, which were made from the materials of: Mn-Cu damping alloy (Mn-20Cu-5Ni-2Fe), Mn-Cu alloy (Mn-20Cu-5Ni-2Fe without heat treatment), Al alloy (7075), forged steel and cast iron, respectively, were chosen. Among the five discs, the forged steel disc was cut from a real train brake disc, the other four discs were ordered from a commercial manufacturer. The main material properties are shown in Table 1, in which the density and the Young modulus are provided by the supplier company while the hardness is measured by a hardness tester (MVK-21) in the main authors’ laboratory. The diameter of the disc specimen is 25 mm and the thickness is 3 mm. The disc specimens of five kinds of materials were first polished with silicon carbide abrasive paper, then polished with cloth until they achieved the initial average roughness (*Ra*) (measured by a profilometer) of the surfaces approximately at 0.06 μm. The pad was made from a composite material of train brake friction lining, whose density is 1±0.5 g/cm3; Young’s modulus is *E*≤1×103 MPa; hardness is HR 50-90. And the thickness of the pad is 15 mm and its cross section is 10×10 mm, thus the contact area is a square with length of 10 mm. The interface roughness (*Ra*) of pad is approximately 0.4 μm, which was measured by a profilometer before the tests. And the pad surface was examined to show its typical morphology before the experiments and the EDX patterns were also shown in Figure 2. In this work, the friction radius is 6.5 mm.

Before the stick-slip vibration experiments, the dynamic mechanical analysis (DMA) was conducted to measure the loss factor of each kind of disc material, which is used to characterize damping in materials [27]. In this work, the DMAQ800 dynamometer was used to conduct the DMA tests. The compression mode was chosen and the frequency of vibration of the drive cylinder was set to be 40 Hz. The temperature during the test was controlled at 35 °C. The range of the strain amplitude was 0-80 μm. The DMA test results are illustrated in Figure 3 and it can be found that the loss factor shows similar trends and increases with the increasing amplitude, and the loss factor value of Mn-Cu damping alloy is the highest (reaching 0.031) among the five kinds of materials. The forged steel and cast iron show similar values, and their highest loss factor value is about 0.021. In addition, the highest loss factor values are about 0.012 and 0.017 for Al alloy and Mn-Cu alloy, respectively.

## **2.3 The parameters of experiment**

Before conducting the experiments of stick-slip oscillation, a series of preliminary tests were carried out with different values of normal loads and disc speeds. Selected experiments at normal force of 80 N, 100 N and 120 N (with the disc velocity of 1 rpm) and at disc speed of 1 rpm, 2 rpm and 3 rpm (with the normal force of 120 N) were conducted. Therefore, the stick-slip vibration tests were conducted under this condition to explore the potential of the Mn-Cu damping alloy to suppress the stick-slip vibration, compared with the other four kinds of disc materials. And the test time was set to be 1 hour for each disc material.

Considering the randomness of the friction-induced vibration, every kind of disc specimen was tested three times in this study to ensure the repeatability of experiment results. In order to characterize interface contact and wear behaviours of the contact interface, an optical microscopy (OM) and a white light interferometer were used to examine the topographies of the disc surfaces; and a scanning electron microscope (SEM) was used to examine the topographies of the pad surfaces; energy dispersive X-ray spectroscopy (EDX) analysis of the wear debris on the pads of the friction pairs were conducted after the stick-slip oscillation tests. All experiments were conducted in a controlled ambient environment (the temperature of 27–30 °C and the relative humidity of 60±10%).

1. EXPERIMENTAL RESULTS AND DISCUSSION

Firstly, as presented in Figure 4, the stick-slip behaviours of five kinds of materials are examined under the selected working conditions in this investigation. For the forged steel and cast iron, stick-slip oscillation can be observed in all of the working conditions. In contrast, both the Al alloy and Mn-Cu damping alloy show pure sliding within these disc velocity and normal force ranges. The Mn-Cu alloy exhibits different vibration phenomenon: the stick-slip oscillation can be found when the normal force is 120 N, and the stick-slip oscillation vanishes and pure sliding occurs as the normal force is reduced (i.e. 80 N and 100 N); the Mn-Cu alloy shows stick-slip oscillation when disc velocity is 1 rpm and produces pure sliding when disc velocity is 2 rpm and 3 rpm.

To briefly investigate the different stick-slip behaviours among the five kinds of materials, the friction characteristics of each kind of material are analysed in detail at only one kind of working condition (normal force of 120 N and disc velocity of 1 rpm) and then compared with those of the other materials in the following sections.

## **3.1 Friction forces corresponding to various discs**

To study the friction property of the friction system with each kind of disc material, the friction force against time is shown in Figure 5. The frictional force curves for five kinds of disc materials in steady-state are presented.

From Figure 5, it can be observed that the forged steel and cast iron present visible stick-slip oscillation. The friction force is found to increase slowly before reaching the break-away force during the stick episode, and then suddenly drop from break-away force to the dynamic friction force when the relative motion switches from stick to slip, and the stick time (as shown in Figure 5, the time of stick episode for one stick-slip event [28]) of each stick-slip event varies slightly for them. It can also be noticed that the stick-slip amplitude (as shown in Figure 5, the difference between the break–away force and the dynamic friction force [29]) of the forged steel is higher than that of the cast iron. For the Mn-Cu alloy, the friction force exhibits stick-slip vibration, but the stick time durations look irregular. Moreover, the stick-slip amplitude is lower than those of the forged steel and the cast iron. In contrast, no stick-slip oscillation can be found from the Al alloy and Mn-Cu damping alloy. The friction forces of the Al alloy and Mn-Cu damping alloy are rather uniform without stick-slip vibration during the steady-state. Another visible phenomenon is that the Al alloy shows the highest friction force among the five materials. The Mn-Cu damping alloy exhibits the similar value of friction force to the break-away force of the Mn-Cu alloy. The break-away forces of the forged steel and cast iron are the lowest. The above phenomenon indicate that Al alloy and Mn-Cu damping alloy produce relative higher friction force and they are able to suppress the stick-slip oscillation effectively as compared with the forged steel and cast iron.

Stick-slip amplitude and stick time are two very important evaluation indicators for the intensity of stick-slip oscillation [18, 28-30] — the higher intensity of stick-slip oscillation always accompanies with higher stick-slip amplitude and longer stick time. To compare the difference in the stick-slip oscillations more precisely, the stick-slip amplitude and stick time for the forged steel, cast iron and Mn-Cu alloy are presented in Figure 6. From Figure 6 (a), it can be found that the forged steel shows the highest stick-slip amplitude of 3.95 N, which is followed by the cast iron with the stick-slip amplitude of 3.54 N. And the stick-slip amplitude of Mn-Cu alloy is the lowest, whose value is 2.20 N. In Figure 6 (b), it can be observed that the forged steel and cast iron share the same stick time of 1.7 s. Obviously, the stick-slip time of the Mn-Cu alloy (0.64 s) is shorter than that of the other two kinds of materials. The results indicate that, among these three kinds of materials which exhibit stick-slip oscillation, the intensity of the oscillation for the forged steel is the strongest with the highest stick-slip amplitude. And the Mn-Cu alloy shows the weakest stick-slip intensity with the lowest stick-slip amplitude and shortest stick time. It is suggested that the Mn-Cu alloy can reduce the stick-slip vibration to a certain degree compared with the forged steel and cast iron.

Figure 5 suggests that the both Al alloy and Mn-Cu damping alloy can suppress the stick-slip vibration, but is there any difference in the manner of this suppression for them? [16] suggested that the stick-slip vibration was commonly generated at the starting stage of the friction test. And to answer this question, the friction forces of these two kinds of materials at the starting stage are presented in Figure 7. It can be found that in this period, the Al alloy exhibits obvious stick-slip vibration; on the contrary, no stick-slip vibration can be observed for the Mn-Cu damping alloy. The results in Figures 5 and 7 indicate that Al alloy cannot supress the stick-slip vibration at the starting stage, but it can do so as the tests proceed. But the Mn-Cu damping alloy displays a great capability in supressing the stick-slip vibration in the whole process (as shown in Figures 5 and 7). It can be deduced that although the Al alloy and the Mn-Cu damping alloy can supress the stick-slip in the steady-state stage, the suppression mechanisms are different, which will be explored in the following.

## **3.2 Stick-slip vibration associated with different discs**

To further investigate the intensity of the stick-slip oscillation for the different disc materials, the vibration accelerations measured by the accelerometer (as shown in Figure 1) in the tangential direction during the whole experimental process are shown in Figure 8. Firstly, to briefly describe the differences of tangential vibration acceleration, the sudden jumps and the non-stick-slip oscillation are marked as shown in Figure 8.

It can be found that for the forged steel and cast iron, the tangential vibration accelerations experience sudden jumps due to the sudden switching from stick episode to slip episode. Moreover, such jumps happen periodically because the episodes vary from stick to slip periodically. And there is no significant difference in the sudden jumps for the forged steel and cast iron. However, the non-stick-slip oscillation for the forged steel is not as uniform as that of the cast iron. For the Mn-Cu alloy, the tangential vibration acceleration also shows the sudden jumps periodically owing to the stick-slip oscillation. And compared with the forged steel cast iron, the non-stick-slip oscillation is reduced for the Mn-Cu alloy. Finally, for the Al alloy and Mn-Cu damping alloy, the acceleration experiences a uniform non-stick-slip oscillation without any sudden jumps. This is consistent with the fact that there is no stick-slip oscillation in this friction system with Al alloy or Mn-Cu damping alloy disc.

In order to comprehensively evaluate the influence of the disc materials on the stick-slip oscillation, the values of root-mean-square (RMS) of the tangential vibration accelerations for five disc materials are calculated, and the results are presented in Figure 9. It can be found that the RMS of the tangential vibration acceleration for the forged steel, cast iron and Mn-Cu alloy are higher, which are 0.673, 0.597 and 0.522 m/s2, respectively. For the Al alloy and Mn-Cu damping alloy, the RMS of tangential vibration acceleration are reduced to different degrees. They are 0.193 and 0.279 m/s2 for the Al alloy and Mn-Cu damping alloy, respectively. The results further indicate that the Al alloy and the Mn-Cu damping alloy can reduce stick-slip vibration significantly.

After the analysis in the time domain, the characteristics of the stick-slip oscillation in the frequency domain are investigated. Fast Fourier Transform (FFT) is used to convert the signals of the vibration acceleration from the original time domain to the frequency domain. The results of power spectral density (PSD) in the frequency domain are obtained and presented in Figure 10. Obviously, the spectra of the five kinds of disc materials have a similar pattern. Furthermore, they all display a typical frequency doubling phenomenon and even share the similar base frequency at 40 Hz, and the energy levels are the highest at the frequency of 160 (4×40) Hz for them.

Another visible phenomenon is that the energy levels of the forged steel and cast iron are higher than those of the energy levels of the Mn-Cu alloy, Mn-Cu damping alloy and Al alloy in descending order. Special attention is paid at the energy levels at the main frequency of 160 Hz, as shown in the enlarged figure within the dotted rectangle, which are 104.8 and 102.9 dB for the forged steel and cast iron, respectively. The energy levels for the Mn-Cu alloy, Mn-Cu damping alloy and Al alloy are reduced to 99.9, 97.9 and 96.6 dB. The PSD results in Figure 10 further confirm that the friction system with the Mn-Cu alloy, Mn-Cu damping alloy or Al alloy disc can reduce the vibration to a certain degree compared with forged steel or cast iron disc [31, 32]. Furthermore, the Mn-Cu damping alloy and Al alloy show a greater ability to reduce vibration compared with the Mn-Cu alloy in this investigation.

## **3.3 Wear properties of friction pairs**

A search of the rich relevant literature suggested that the interface of the friction pair had a significant influence on friction-induced vibration, and wear at the interface had a close relationship with stick-slip oscillation [17, 26, 33, 34]. For the sake of establishing the relationship between the wear behaviour and the stick-slip oscillation for the five kinds of discs, the OM images of the disc surfaces are analysed and shown in Figure 11. There are visible wear marks on the surfaces of these five kinds of discs and they are parallel to the disc velocity.

From Figure 11 (a)-(b), it can be found that there is no evident wear debris accumulation for the forged steel and cast iron. Only mild wear with shallow scratches can be observed, and surface damage is very slight, especially for the forged steel. For the cast iron, detachment can be found on the surface.

For the Mn-Cu alloy in Figure 11 (d), wear debris accumulation can be found, and the wear is severer and the scratches are also deeper compared with those of the forged steel and cast iron. Ploughings can be found on the surface too.

Moreover, there is obvious wear debris accumulation on the surfaces of Al alloy and Mn-Cu damping alloy discs from the Figure 11 (c) and (e) and the OM images show that the scratches are quite deep on the disc surfaces. These phenomena indicate that apparent ploughing behaviour happens between the contact interfaces in the sliding process. Moreover, visible wear debris can be found in the wear tracks. Especially, the Al alloy has the most severe scratches, furthermore, the wear tracks are covered with visible wear debris.

To further study the wear state of these disc surfaces, the 3-D profiles of the wear tracks are measured using the white light interferometer and presented in Figure 12. 5 places of the transversal profile of worn tracks on the surface of each disc are used to evaluate the amount of wear of the five kinds of discs and the average profiles of the wear scars are presented in Figure 12 (f). It can be seen that the surface morphologies of these disc surfaces are significantly different from each other.

Firstly, only some detachments can be observed on the surfaces of the forged steel and cast iron discs, and the wear depth is about 1.43 μm for these two kinds of discs (as shown in Figure 12 (f)). The smooth 2-D profiles for the forged steel and cast iron discs also show that the wear tracks are shallow and the wear is slight. Furthermore, the average surface roughness (*Ra*) of the forged steel and cast iron discs is 0.517 and 0.934 μm after the tests (see Table 2), respectively.

For the Mn-Cu alloy disc, some wear debris and visible ploughing can be found on the disc surface, and the wear depth is about 5.33 μm, and *Ra* is 1.114 μm after the test. These further indicate that the wear of the Mn-Cu alloy discs is more severe than that of the forged steel and cast iron.

For the Mn-Cu damping alloy and Al alloy discs, there is obvious ploughing on the disc surfaces and the 2-D profiles also indicate that there are deep pits on the disc surfaces. The wear depths for Mn-Cu damping alloy and Al alloy discs are around 7.66 and 16.99 μm, respectively. *Ra* values of 2.836 and 5.508 μm for Mn-Cu damping alloy and Al alloy discs further indicate much more severe wear than that of the forged steel and cast iron discs.

To compare the wear evolution of the five kinds of discs more clearly, their wear volumes were measured by a white light interferometer and the results are presented in Table 3. It can be found that wear magnitudes of the forged steel and cast iron are obviously lower than others, whose wear volumes are 2.034×10-4 and 4.033×10-4 mm3, respectively. On the other hand, the Al alloy suffers the highest wear volume of 1.43×10-1 mm3, and the wear volumes of the Mn-Cu alloy and Mn-Cu damping alloy are 6.632×10-3 and 2.87×10-2 mm3, respectively.

Moreover, the wear of each pad mating with each disc is observed by SEM, and the results are shown in Figure 13. Obviously, the pads corresponding to forged steel and cast iron discs show a significant difference from those corresponding to Al alloy, Mn-Cu alloy and Mn-Cu damping alloy discs: the contact surfaces of the former look rather “clean” (almost no wear debris); in contrast, the surfaces of pads for the latter are covered with a large amount of visible and loose wear debris, which are not highly compressed.

EDX analysis of the wear debris on the pads of the friction pairs is conducted. For the friction pair with the Al alloy disc, point A reveals a very high content of Al-element and Mg-element which are main elements of the Al alloy disc, which indicates material transfer from the disc specimen to the pad specimen during the test. And for the friction pair with the Mn-Cu alloy and Mn-Cu damping alloy discs, points B and C show a high content of Mn-element which is the main element of the Mn-Cu alloy and Mn-Cu damping alloy discs, which also indicates the disc materials transfers to pad specimens. As a consequences, adhesive wear and oxidative wear happen for these three kinds of friction pairs.

Moreover, considering the friction forces in Figure 5, the rougher surfaces of the Al alloy and Mn-Cu damping alloy produce the higher friction forces and the lower non-stick-slip oscillation of tangential vibration acceleration (Figure 8) compared with the other three kinds of materials [35-38]. The lower surface roughness may lead to the lower friction force for the forged steel and cast iron. What is more, based on the results in Figures 5-10 and the wear analysis, it can be concluded that the milder wear and smoother disc (the forged steel and cast iron) will produce stronger stick-slip oscillation in this work, and the finding is consistent with the results in [15]. To clearly show the effect of the wear and surface roughness on the stick-slip oscillation, the schematic diagram of the inherent relation of wear with stick-slip oscillation will be presented in Figure 14.

Next, analyses of the worn surface morphology and stick-slip oscillation are combined to give a reasonable explanation on how the Al alloy and Mn-Cu damping alloy discs suppress the stick-slip oscillation, as presented in Figure 14. As presented in [39-41], two contacting rigid bodies can be visualized to make contact at the interfaces through a large number of elastic bristles, and the bristles can deflect like springs, which will give rise to a friction force when a tangential force is applied.

As shown in Figure 14 (a), for the smooth contact interfaces, the bristles contact with each other in stage I , and there is no relative motion because the tangential force is not sufficient (corresponding to the stick 1). As the tangential force increases, the bristles deflect so much in stage II that the pad slides on the disc surface (corresponding to the slip). This slip motion releases the large elastic forces in the bristles and they recover so that new contact is established and the pad sticks to the disc surface again (corresponding the stick 2). For the smooth disc and the pad, the relative motion will switch from stick to slip periodically. In contrast, when the contact interface is worn, and especially when the interface is covered with wear debris, as shown in Figure 14 (b), fewer bristles are in contact with each other directly, the interface between the pad and the disc is affected by the “third body flow” of wear debris which cause pure sliding for these two bodies [42].

Based on the results in Figures 11-13, the worn disc surfaces of the forged steel and cast iron are relatively smooth and the amounts of wear debris are smaller compared with the others. Thus it can be speculated that the real contact areas and the number of direct contact bristles at the pad and disc interface will be larger for the forged steel and cast iron, and they will show a higher tendency to produce the stronger stick-slip oscillation (as shown in Figure 5) under the low velocity [30]. In contrast, the Mn-Cu alloy, Al alloy and Mn-Cu damping alloy undergo more severe wear and produce more complex and rough contact surfaces with the large amount of wear debris and the real contact areas will be reduced [37]. Moreover, it is difficult for wear debris under the low velocity, and the “third body” of loose wear debris will impede direct contact of the bristles for the Mn-Cu alloy, Al alloy and Mn-Cu damping alloy. All of these factors make contributions to reducing the stick-slip oscillation for them [16, 30]. The larger amount of wear debris on the Al alloy may help to suppress the stick-slip vibration in steady-state stage; but wear debris were limited in the starting stage, so the Al alloy still exhibits the stick-slip vibration in this stage (as shown in Figure 7). However, for the Mn-Cu damping alloy, no stick-slip vibration can be found in either the starting stage or steady-state stage. This may be owing to the relatively high damping capacity (as shown in Figure 3) of this material and wear debris [43, 44].

To prove the role of the wear debris, the wear debris were removed from the Al Alloy disc (called “cleaned worn disc” for short) and stick-slip oscillation test is conducted on this cleaned worn disc. Its friction force is presented in Figure 15 and it can be found that the friction force shows visible stick-slip oscillation. A comparison of the friction force of the Al alloy disc covered with the wear debris (called “uncleaned worn disc” for short) further proves that the wear debris act as the third body “lubricant” between the interface of pad and disc and reduces the stick-slip oscillation.

**4. CONCLUSIONS**

In this work, vibration experiments are performed to study the ability of Mn-Cu damping alloy (Mn-20Cu-5Ni-2Fe) to suppress stick-slip oscillation working as the friction pair material (disc) with the selected normal force of 80 N, 100 N and 120 N (with the disc velocity of 1 rpm), and disc speed of 1 rpm, 2 rpm and 3 rpm (with the normal force of 120 N). Moreover, four other discs respectively made from forged steel, cast iron, Al alloy (7075) and Mn-Cu alloy (Mn-20Cu-5Ni-2Fe without heat treatment) are also tested for comparison. The main conclusions can be summarized as follows:

1. The forged steel and cast iron show visible stick-slip oscillation at all selected working conditions. In contrast, the Al alloy and Mn-Cu damping alloy exhibit pure sliding no matter how the normal force or disc speed vary. The Mn-Cu alloy only shows stick-slip oscillation when the normal force is 120 N and the disc speed is 1 rpm, but pure sliding under other working conditions.
2. The vibration results show that the forged steel and cast iron exhibit obvious stick-slip oscillation. The stick-slip oscillation is reduced at a certain level for the Mn-Cu alloy compared with the forged steel and cast iron. For the Al alloy, no stick-slip oscillation is found in the steady-state stage, however, the ability to suppress the stick-slip oscillation at the starting stage is limited. In contrast, the Mn-Cu damping alloy can suppress the stick-slip oscillation in the whole stage.
3. The wear test results show that forged steel and cast iron discs undergo slight wear and its wear volume is much lower than the other three materials. The Mn-Cu damping alloy and Al alloy suffer much more severe wear than the others — obvious deep ploughing and a large amount of wear debris can be observed and their wear volumes are also very high.
4. In this work, it is confirmed that the wear debris on the surface of Mn-Cu alloy, Mn-Cu damping alloy and Al alloy discs act as a third body “lubricant” and contribute to reduction of the stick-slip oscillation. Moreover, the high damping capacity of the Mn-Cu damping alloy may be another important factor to suppress the stick-slip oscillation in the whole experimental stage.

This work is a fundamental study of stick-slip oscillation. It is expected to be useful to reduce stick-slip oscillation from a material point of view when selecting the friction pair material in engineering. Further work is planned to produce damping alloy with higher damping capacity and wear resistance to suppress stick-slip oscillation in the future. It should be noted that the findings of this work are valid for the pad specimen made from a particular composite material as the counterpart friction pair of the disc. Stick-slip behaviour of other pad materials will be investigated in future.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support of the National Natural Science Foundation of China (No. 51675448, No. 11672052). The first author would like to acknowledge the China Scholarship Council (CSC) for sponsoring her visit to the University of Liverpool where part of this research is conducted.

REFERENCES

[1] Feeny, B, Guran, A, Hinrichs, N, Popp, K. A historical review on dry friction and stick-slip phenomena. Applied Mechanics Reviews. 1998, 51(5): 321-341.

[2] Berger EJ. Friction modeling for dynamic system simulation. Applied Mechanics Reviews. 2002, 55(6): 535-577.

[3] Ibrahim RA. Friction-induced vibration, chatter, squeal, and chaos—part I: mechanics of contact and friction. Applied Mechanics Reviews. 1994, 47(7): 209-226.

[4] Ibrahim RA. Friction-induced vibration, chatter, squeal, and chaos—part II: dynamics and modeling. Applied Mechanics Reviews. 1994, 47(7): 227-253.

[5] Li Z, Ouyang H, Guan Z. Friction-induced vibration of an elastic disc and a moving slider with separation and reattachment. Nonlinear Dynamics. 2017, 87(2): 1045-1067.

[6] Moirot F, Nguyen QS, Oueslati A. An example of stick–slip and stick–slip–separation waves. European Journal of Mechanics - A/Solids. 2003, 22(1): 107-118.

7] Behrendt J, Weiss C, Hoffmann NP. A numerical study on stick–slip motion of a brake pad in steady sliding. Journal of Sound and Vibration. 2011, 330(4): 636-651.

[8] Popp K, Rudolph M. Vibration control to avoid stick-slip motion. Modal Analysis. 2004, 10(11): 1585-1600.

[9] Poop K, Stelter P. Stick-slip vibration and chaos. Phil. Trans. Roy. Soc. London A, 1990, 332: 89-105.

[10] Fulleringer N, Bloch JF. Forced stick-slip oscillations allow the measurement of the friction force: Application to paper materials. Tribology International. 2015, 91: 94-98.

[11] Gao Q, Cao X. The stick-slip vibration and bifurcation of a vibro-impact system with dry friction. The Open Mechanical Engineering Journal. 2014, 8: 308-313.

[12] Thomsen JJ, Fidlin A. Analytical approximations for stick–slip vibration amplitudes. International Journal of Non-Linear Mechanics. 2003, 38(3): 389-403.

[13] Denny M. Stick–slip motion: an important example of self-excited oscillation. European Journal of Physics. 2004, 25(2): 311-322.

[14] Dankowicz H, Nordmark AB. On the origin and bifurcations of stick-slip oscillations. Physica D: Nonlinear Phenomena. 2000, 136(3-4): 280-302.

[15] Lee SM, Shin MW, Lee WK, Jang H. The correlation between contact stiffness and stick–slip of brake friction materials. Wear. 2013, 302(1-2): 1414-1420.

[16] Dong C, Shi L, Li L, Bai X, Yuan C, Tian Y. Stick-slip behaviours of water lubrication polymer materials under low speed conditions. Tribology International. 2017, 106: 55-61.

[17] Dong C, Yuan C, Bai X, Qin H, Yan X. Investigating relationship between deformation behaviours and stick-slip phenomena of polymer material. Wear. 2017, 376: 1333-1338.

[18] Park JS, Lee SM, Joo BS, Jang H. The effect of material properties on the stick–slip behavior of polymers: A case study with PMMA, PC, PTFE, and PVC. Wear. 2017, 378-379: 11-16.

[19] Tanji T, Moriwaki S, Mio N, Tomaru T, Suzuki T, Shintomi T. Measurement of damping performance of M2052 alloy at cryogenic temperatures. Journal of Alloys and Compounds. 2003, 355(1-2): 207-210.

[20] Wang W, Zhou B. The correlation of damping capacity with grain-boundary precipitates in Fe–Cr-based damping alloys annealed at high temperature. Materials Science and Engineering: A. 2004, 366(1): 45-49.

[21] Wu YQ, Yin FX, Hono K. The decomposed γ-phase microstructure in a Mn–Cu–Ni–Fe alloy studied by HRTEM and 3D atom probe. Scripta Materialia. 2002, 46(10): 717-722.

[22] Huang H, Chang WS, Mosalam KM. Feasibility of shape memory alloy in a tuneable mass damper to reduce excessive in-service vibration. Structural Control and Health Monitoring. 2017, 24(2): e1858.

[23] Baik SH, Kim JC, Han DW, Kim TH, Back JH, Lee YK. Fe–Mn martensitic alloys for control of noise and vibration in engineering applications. Materials Science and Engineering: A. 2006, 438-440: 1101-1105.

[24] Fukuhara M, Yin F, Kawahara K. Acoustic characteristics of high damping Mn73Cu20Ni5Fe2 alloy. Physica Status Solidi (a). 2004, 201(3): 454-458.

[25] Fukuhara M, Yin F, Ohsawa Y, Takamori S. High-damping properties of Mn–Cu sintered alloys. Materials Science and Engineering: A. 2006, 442(1-2): 439-443.

[26] Wang DW, Mo JL, Ouyang H, Zhou ZR. Improving dynamic and tribological behaviours by means of a Mn–Cu Damping Alloy with grooved surface features. Tribology Letters. 2018, 66(2): 1-16.

[27] Lu YC, Shinozaki DM. Temperature dependent viscoelastic properties of polymers investigated by small-scale dynamic mechanical analysis. Experimental Mechanics. 2010, 50(1): 71-77.

[28] Leine RI, Van Campen DH, De Kraker A, Van Den Steen L. Stick-slip vibrations induced by alternate friction models. Nonlinear Dynamics. 1998, 16(1): 41-54.

[29] Urbakh M, Klafter J, Gourdon D, Israelachvili J. The nonlinear nature of friction. Nature. 2004, 430(6999): 525-528.

[30] Yoon SW, Shin MW, Lee WG, Jang H. Effect of surface contact conditions on the stick–slip behavior of brake friction material. Wear. 2012, 294-295: 305-312.

[31] Zhang Q, Mo JL, Lu XD, Zhao J, Wang DW, Zhou ZR. Grooved-structure design for improved component damping ability. Tribology International. 2018, 123: 50-60.

[32] Lu XD, Zhao J, Mo JL, Zhang Q, Zhang X, Zhou ZR. Improvement of dynamical and tribological properties of friction systems by introducing parallel-grooved structures in elastic damping components. Composite Structures. 2018, 192: 8-19.

[33] Neis PD, Ferreira NF, Fekete G, Matozo LT, Masotti D. Towards a better understanding of the structures existing on the surface of brake pads. Tribology International. 2017, 105: 135-147.

[34] Barros LY, Neis PD, Ferreira NF, Pavlak RP, Masotti D, Matozo LT, et al. Morphological analysis of pad–disc system during braking operations. Wear. 2016, 352-353: 112-121.

[35] Wang AY, Mo JL, Wang XC, Zhu MH, Zhou ZR. Effect of surface roughness on friction-induced noise: Exploring the generation of squeal at sliding friction interface. Wear. 2018, 402-403: 80-90.

[36] Eriksson M, Bergman F, Jacobson S. Surface characterisation of brake pads after running under silent and squealing conditions. Wear. 1999, 232(2): 163-167.

[37] Bergman F, Eriksson M, Jacobson S. Influence of disc topography on generation of brake squeal. Wear. 1999, 225-229: 621-628.

[38] Wang XC, Mo JL, Ouyang H, Lu XD, Huang B, Zhou ZR. The effects of grooved rubber blocks on stick–slip and wear behaviours. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2018: 0954407018811039.

[39] De Wit C, Olsson H, Astrom KJ, Lischinsky P. A new model for control of systems with friction. IEEE Transactions on automatic control. 1995, 40(3): 419-425.

[40] Edeler C, Meyer I, Fatikow S. Modeling of stick-slip micro-drives. Journal of Micro-Nano Mechatronics. 2011, 6(3-4): 65-87.

[41] Pennestrì E, Rossi V, Salvini P, Valentini PP. Review and comparison of dry friction force models. Nonlinear Dynamics. 2016, 83(4): 1785-1801.

[42] Sextro W. Dynamical contact problems with friction. Springer-Verlag Berlin Heidelberg, 2007.

[43] Tonazzi D, Massi F, Baillet L, Culla A, Di Bartolomeo M, Berthier Y. Experimental and numerical analysis of frictional contact scenarios: from macro stick–slip to continuous sliding. Meccanica. 2015, 50(3): 649-664.

[44] Di Bartolomeo M, Massi F, Baillet L, Culla A, Fregolent A, Berthier Y. Wave and rupture propagation at frictional bimaterial sliding interfaces: From local to global dynamics, from stick-slip to continuous sliding. Tribology International. 2012, 52: 117-131.

**List of figure captions**

Figure 1. Schematic diagram of the test setup.

Figure 2. SEM morphology (a) and EDX analysis of the pad surface (b).

Figure 3. The loss factors of five kinds of disc materials.

Figure 4. Stick-slip behaviours for five kinds of disc materials under various working conditions: at normal force of 80 N, 100 N and 120 N (with the disc velocity of 1 rpm) (a); at disc speed of 1 rpm, 2 rpm and 3 rpm (with the normal force of 120 N) (b).

Figure 5. The various friction forces for five kinds of disc materials.

Figure 6. The stick-slip amplitude (a) and stick time (b) for forged steel, cast iron and Mn-Cu alloy.

Figure 7. The friction behaviour of Al alloy and Mn-Cu damping alloy discs at starting stage.

Figure 8. The tangential vibration acceleration for five kinds of disc materials.

Figure 9. The RMS of the tangential vibration acceleration for five kinds of discs materials.

Figure 10. PSD of vibration acceleration for five kinds of discs materials.

Figure 11. The OM images of five kinds of disc materials: forged steel (a); cast iron (b); Al alloy (c); Mn-Cu alloy (d); Mn-Cu damping alloy (e).

Figure 12. The 3-D profiles of the wear tracks of five kinds of disc materials: forged steel (a); cast iron (b); Al alloy (c); Mn-Cu alloy (d); Mn-Cu damping alloy (e) and average 2-D profile of five kinds of materials (f).

Figure 13. The SEM morphologies of pad wear corresponding to five kinds of discs: forged steel (a); cast iron (b); Al alloy (c); Mn-Cu alloy (d); Mn-Cu damping alloy (e).

Figure 14. The schematic diagram of the inherent relation of wear with stick-slip oscillation.

Figure 15. The friction forces of Al alloy uncleaned/cleaned worn disc.

**List of table captions**

Table 1 Material parameters of the discs.

Table 2. The surface roughness of the discs after the tests.

Table 3. The wear volume of the discs.