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Effects of External Hard Particles on Brake Friction Characteristics During Hard Braking

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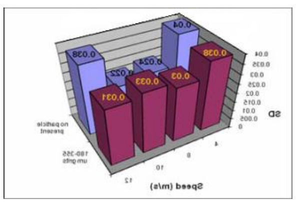
Graphical abstract



Abstract

The effects of external hard particles on the friction coefficients and its oscillation amplitudes during hard braking were investigated. Silica sands of the size between 180 to 355 µm were used during the experiments. The results were compared to the results obtained without the grit particles present in order to determine the change in friction coefficient and the fluctuation of frictional oscillation amplitude. Different sliding speeds were applied and external hard particle of different size is found to significantly affect the friction coefficient and standard deviation of friction oscillation amplitude values. The friction coefficients increase with hard particle due to the rapid changes of the effective contact area and the abrasion mode. Some embedded particles operating in two body abrasion mode help to increase the disc surface roughness and influence the stopping time of the disc. The standard deviation values of friction oscillation amplitude however were stable due to more wear debris produced and get compacted to form friction films assisting friction and they tend to reduce at medium speeds because many contact plateaus and effective contact area started to stabilize.

Keywords: External particles, hard braking, friction coefficients, friction oscillation amplitude

■1.0 INTRODUCTION

High and stable coefficient of frictions (CoF) is desired during braking operation. Despite its importance, fluctuations in CoF during braking are not fully understood. This is due to the nature of the braking contact surfaces which is covered and hidden between the pad and the disc. It is expected that the CoF should be stable irrespective of temperature, humidity, age of the pads, degree of wear and corrosion, the presence of dirt and water spraying from the road (El-Tayeb and Liew, 2009 and Eriksson *et al*., 2002). Thus, brake frictional materials are designed to provide stable frictional performance over a range of vehicle operating conditions and also to exhibit acceptable durability. Despite the fact that brakes operate under a variety of environmental conditions, many laboratory tests of brake materials are conducted mostly in dry conditions and only limited studies were conducted in the presence of hard grit particles or under the wet braking conditions (El-Tayeb and Liew, 2008).

The open design and the position of the disc brake is often linked to the presence of dirt and hard particles derived from the environment (Polak and Grzybek, 2005). Particles of different sizes and shapes can enter the brake gap and affect the average friction force and momentary peak values of friction force at the braking interface (Polak *et al*., 2005). Therefore, factors such as humidity, presence of dirt and hard particles from the environment can influence the tribological characteristics at the friction interface and indirectly affect the braking effectiveness. The brake interface interactions occur when the brake pad and disc are applied against each other. Initially, the abrasion takes place between metal fibres and abrasive hard particles that are included in the brake pad with the brake disc. Ostermeyer and Muller (2006) suggested that when the brake is applied, the contact between cast iron disk and softer polymer matrix of brake pad produce wear particles. Some wear particles get expelled to the environment and some will remain in the contact to mix with other contaminants before they start to agglomerate and get compacted to form contact plateau and friction film before the next braking operation. This cycle of braking operation will continue till the end of the brake pad life. Contact plateaus and friction film build up of several micrometers in thickness due to agglomeration and compaction of the wear particles that remained in the contact was reported by Eriksson *et al*. (2001). The contact plateau changes with time very rapidly and depends more on the rolling and mixing of other wear particles. Berthier (2005) used the term third body flow that described the action of the wear particles detached, agglomerated and moved during the deformations and relative movement of brake pad and disc. The friction film is assumed to have compositional mix materials from both the brake pad and the disc. It can also consists of tribo-oxidation product (Fischer, 1992). Few researchers found friction films that consist of product such as iron oxides, barium sulphate, copper oxide, copper sulphide, and carbonaceous graphite particles after braking operation. However, these films are highly dependent on the braking condition and the composition of the brake material (Filip *et al*., 2002, Rhee, 1990 and Jacko, 1989). Most friction material suppliers used abrasive to control the level of friction force and to control friction films build up at the sliding interface (Jang and Kim, 2000; Syahrullail et.al., 2005). Therefore it is believed that the friction film affects the friction and plays important role in brake efficiency and stability. However, more information is needed to understand the friction films behavior and characteristics to fully utilize their presence in the brake interface.

During the braking operation, two modes of abrasion, i.e. the two and three body abrasion mode are usually present. Most of the researchers are of the opinion that two-body abrasion mode dominates during braking operation. However, few researchers assumed that the effect of three-body abrasion tends to be a dominating mechanism while the effect of two-body abrasion is rather small (Fan *et al.*, 2008). Axen *et al*. (1994) stated that the prerequisite for the two to three body abrasion transition to take place is that the hard particles are sufficiently strong to resist the shearing forces. If the hard particles are crushed then no cutting or micro-cutting can take place. Therefore, the abrasion modes and transition between the two and three abrasion modes are important in determining the friction and wear performance of the braking system and they depend on the factors such as particle size, shape volume percent, and the pad's particle-matrix bonding strength (Kho *et al*., 2009 and Trezona *et al*., 1999)

In this paper the effect of hard particles (i.e. the silica sand) during hard braking on the friction characteristics of braking system was studied. Experiments were carried out using a model brake test rig at different sliding speeds and constant applied pressure in order to compare the changes in friction coefficient and the fluctuation of frictional oscillation amplitude during hard braking stop mode. Investigation was also carried out to find correlation between disc sliding speed, friction coefficient and standard deviation values of friction oscillation amplitude.

2.0 MATERIALS AND METHODS

2.1 Test Rig

A brake test rig was developed to conduct the experiments during hard braking stop mode. The schematic diagram with the photo of the test rig is shown in Figure 1. The test rig consists of a 1.0 horse power, three-phase, variable speed induction motor (from Baldor) driving a grey cast iron disc mounted vertically on the shaft. Vertical mounting of the disc allow for close simulation of the orientation of frictional contact encountered during the real brake operation compared to the horizontal pin-on-disc laboratory brake tribotesting. A high performance AC motor drive is used to control the speed of the induction motor. For better deflection resistance and inertia effect, a flange and flywheel are mounted next to the disc brake. Thrust-washer is used to absorb any applied force to the motor. Brake pad is attached to a solid cylinder steel and applied to the rotating disc at the 3 o'clock position from the disc front view. Force is applied to the brake pad specimen using a mechanical weight loading system. A lever arm is used to apply the required force to the pad via the solid cylinder steel. Full bridge strain gauges are fitted to the lever arm and inner side of the end shaft support to record the instantaneous normal force and friction force at the brake interface. A small hopper is fitted at the end shaft support to hold the hard particles. A hard particle feeder tube is attached to the hopper to direct the hard particles to the brake gap. A manually control valve is used to regulate the amount of hard particles needed for the test. A transparent cover is used to avoid splashing of the hard particles during the experiments.

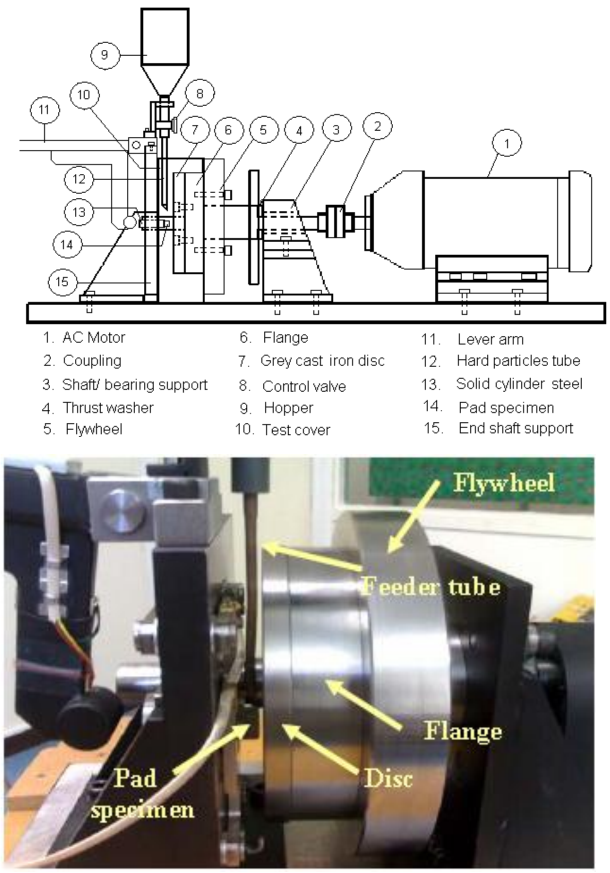


Figure 1 Schematic diagram (above) and picture of the test rig (below) used for the tests

2.2 Specimen Materials and Testing Procedures

A square-faced specimen (12.7×12.7 mm^2) cut out from a commercial car brake pad was used in all the experiments with a flat pad on a flat rotating disc contact geometry. Total thickness of the pad including the backing plate, is approximately 9 mm. The brake disc of 160 mm in diameter and 10 mm thick was machined from a grey cast iron plate and was a non-ventilated disc type. The radial distance from the center of the pad specimen to the center of the turning disc was 63.65 mm. The arithmetic surface roughness of the discs (R_a), was measured before and after the brake test with a profiling profilometer. The microstructure of the pad material being in the mixture of shiny metallic constituents of steel fiber and barium sulphate and non-metallic particles of silicon oxide within a polymeric binder of phenolic resin was analyzed using optical microscope. The grey cast iron disc material contains of graphite flakes which suggest a typical cast dendritic microstructure (White, 1990).

A series of hard braking tests conducted at four different sliding speeds of 4 m/s, 8 m/s, 10 m/s and 12 m/s at a constant pressure of 1.0 MPa were used to evaluate the hard braking effects on the change of friction coefficient, friction oscillation amplitude and particle embedment. Change of friction coefficient and oscillation amplitude values related to the consistency of friction force at sliding interface, is referred to friction stability, i.e., a good friction stability means to maintain a steady level of friction force at different braking conditions. Analysis of the particle embedment was conducted using scanning electron microscopy (SEM) and optical microscopy to determine the percentage area of particle embedment and to study its correlation with friction coefficients and oscillation amplitudes values at different sliding speeds. The details of the test are shown in Table 1. The experimental data was collected using the USB multifunction data acquisition system. Parameters such as sliding speed, pad normal force, friction force, and instantaneous friction coefficient were recorded for each test. A data sampling rate of 120 Hz was used during all the experiments.

Table 1 Hard braking testing details

	Hard braking (Without hard particles)	Hard braking (With 180-355 um hard particles)
Pressure (MPa)	1	1
Speed (m/s)	4, 8, 10, 12	4, 8, 10, 12
Frequency	3x*	3x*

*10 second interval was applied after each braking

3.0 RESULTS AND DISCUSSION

3.1 Study of Hard Braking Effects on the Friction Coefficient (CoF)

The hard particles effect on the friction coefficient (CoF) changes during hard braking was investigated. Hard braking test is applied to fully stop the disc while maintaining the same level of friction force. Figure 2 shows the CoF values with and without the hard particles during hard braking. CoF values tend to lower with the presence of hard particles especially at medium and high speeds. The formation, growth and disintegration in effective contact area are the main factors affecting the changes in CoF values. Disc sliding speed is assumed to influence the rolling and mixing process between the grit particles and wear debris in the brake gap which determine how rapid the changes of effective contact area. The time to completely stop the disc was also recorded and compared between the two cases. The time to stop the disc was shortened from 11 second to 7 second compared to 26 second to 6 second without hard particle present. Figure 3 shows the time taken to fully stop the disc for both cases with and without the hard particle present.

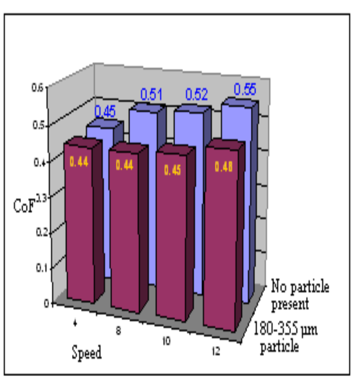


Figure 2 CoF values between no particle and 180-355 µm hard particles at 1.0 MPa contact pressure

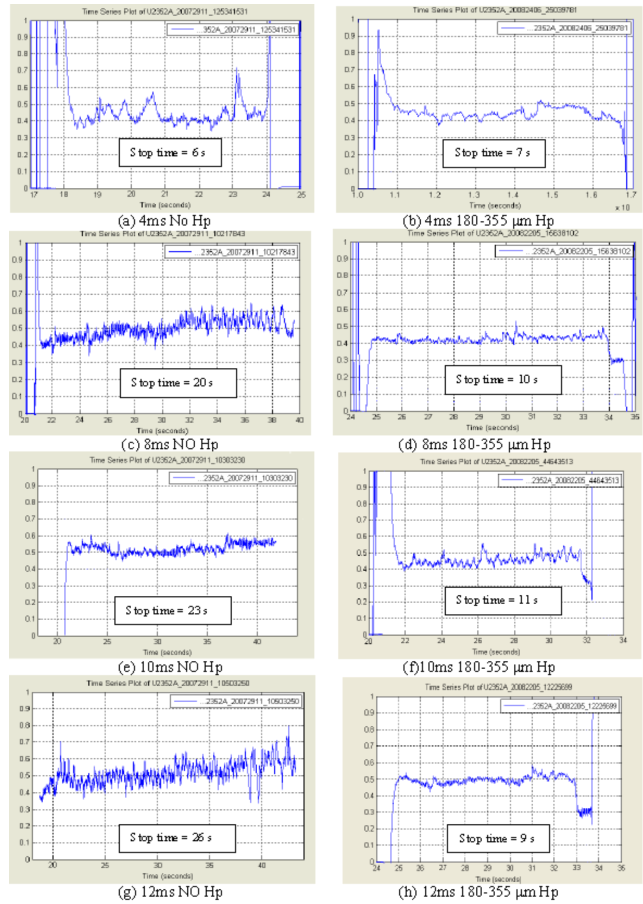


Figure 3 Graphs of CoF variations vs. time with and without hard particle presence at four different sliding speeds (a – h)

This finding is quite interesting as the presence of hard particles is reducing not only the CoF values but also stopping time significantly. This might be due to the role of hard particles to increase the surface roughness of brake pad and the disc. Also, the hard particles reduced the original effective contact area at sliding interface by forming the effective contact area themselves before they mixed with other wear debris. Continuous hard braking results in longer contact time for hard particles to roll, interact, mix and generate more wear debris. Fan *et al*. (2008) reported that increase of braking time, results in wear debris forming friction films covering the worn surface of brake disks which lower the contact area of friction surface. In addition, fragmentation and embedment into the pad of some hard particles occurred during hard braking. This results in further changes of contact areas as some embedded particles in the size range of 50-150 µm were observed on SEM images as shown in Figure 4. The embedded hard particles also acted in two-body abrasion mode enhancing the disc surface roughness. Higher surface roughness may also increase the grip of the braking and might be one of the reasons for the shortening of the stopping time with hard particles present.

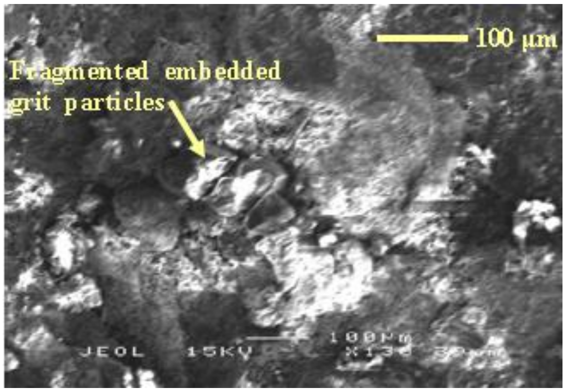


Figure 4 SEM image of the embedment of fragmented hard particles on the brake pad

3.2 Study of Hard Braking Effects on the Friction Coefficient Oscillation Amplitude

Friction oscillation amplitude was analyzed by calculating the standard deviation (SD) of the CoF values. This parameter is important in determining the stability of the braking operation as stability is associated with braking effectiveness. As for hard braking, the SD values are more stable with hard particles present. Initially, high SD values were recorded for both cases at low sliding speeds due to slow mixing of wear debris and greater changes of effective contact area. Both SD values then reduced at sliding speed of 8 m/s due to the faster mixing but less rapid changes of effective contact area. Finally, the SD values started to increase at higher sliding speeds with faster mixing and rapid changes of effective contact area. Figure 5 shows the comparison of SD values with and without hard particle. SD values are closely related to the sliding speed, disc surface roughness, pad topography and the built up of wear debris.

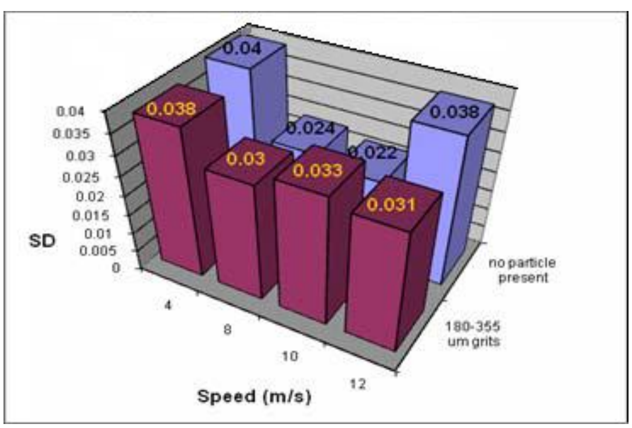


Figure 5 SD values for no particle and 180-355 µm hard particles case at four sliding speeds

Jang and Kim (2000) reported that built up of stable antimony oxide film on the friction interface can improve friction stability. In another work, they stated that friction oscillation amplitude is directly associated with brake roughness (Jang *et al*., 2001). As the brake is applied, surface roughness and effective contact area changed and more wear debris were generated. Figure 6 shows the wear debris generated on the brake pad using SEM with secondary electron (SE) mode at 1.0 MPa contact pressure.

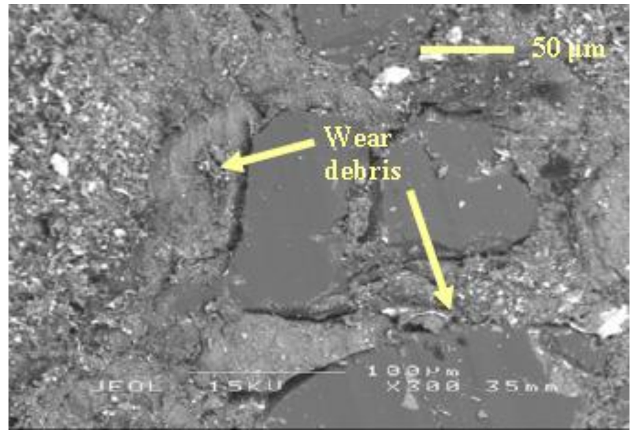


Figure 6 SEM image of the wear pad surface at 1.0 MPa with fine wear debris

The rolling and mixing of the hard particles also influence the SD values and result in the increase of the disc surface roughness and reduction of the effective contact area at the interface. In addition, there are also some embedded particles operating in two body abrasion mode abrading the disc. More wear debris was produced and more debris was compacted to form friction films affecting friction. This results in the reduced SD values. Figure 7 shows more wear debris was generated to form the secondary contact plateau. Secondary contact plateau consist of compacted wear debris formed next to the metal fibres or more wear resistant constituents (Eriksson *et al*., 2001).

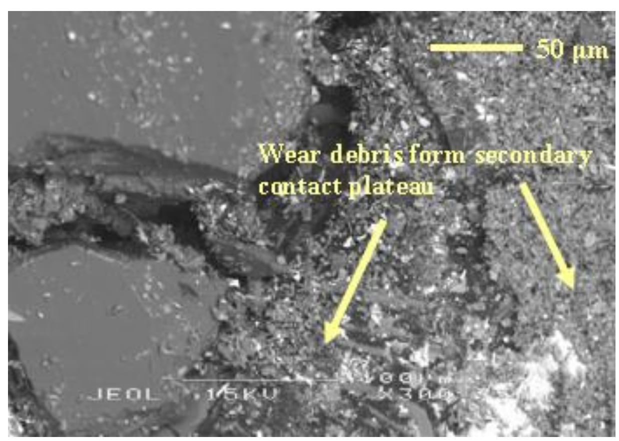


Figure 7 SEM image of wear debris generated to form secondary contact plateau

When the change of SD values was correlated with speed, it was found that they tend to exhibit bigger change at low and medium speeds due to the slower rolling and mixing processes. At higher speed, the particle mixing process is believed to be much smoother. Large SD values were also recorded at low sliding speeds at different applied pressures (Cho *et al*., 2008).

The change of the friction oscillation amplitude when hard braking is repeatedly applied, in the presence of hard particles was also studied. Hard braking was applied at four different sliding speeds until the brake disc stopped. For each speed, the test was repeated 3 times at 10 second intervals. Figure 8 shows the SD values for all stop tests at different sliding speeds. At the beginning of the braking operation, high fluctuation of the friction oscillation amplitude was recorded for all the speeds. The high SD values are associated with the change of mating surfaces as the hard particles enter the sliding interface. With grit particles present the mating was not between brake pad and disc but between particles and disc/ pad surfaces. Depending on the hardness and size of the hard particles entering the sliding interface, the frictional and the wear behavior of the brake is affected to a certain degree. The hard particles roll and abrade both surfaces, i.e. the pad and the disc. Thus abrupt changes of the contact plateau and effective contact area occur and this results in the fluctuation of friction oscillation amplitude. The hard particles also act as the primary contact plateau and carry most of the load.

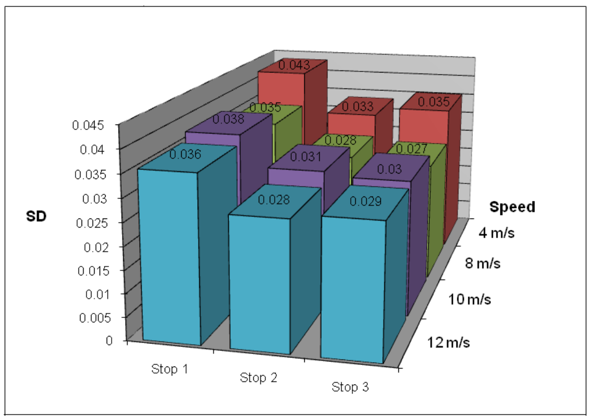
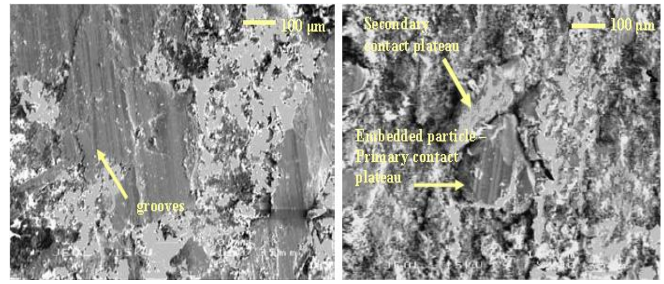


Figure 8 SD values for all stop tests at different sliding speeds with hard particle in the range of 180-355 µm present

The SD values for the second and third stops were low for almost all the speeds. This apparent reduction can be explained by the fact that the contact plateau and effective contact area has started to stabilize as the hard particles continue to roll and abrade the sliding surfaces. In addition, some hard particles embed into the pad and thus assisting the production of more wear debris. Only small amount of wear debris was ejected from the contact with some remaining in the sliding contact to form the secondary contact plateau. The secondary contact plateau stayed in the sliding contact and formed the friction film before being abraded and rejected from the contact. The presence of frictional films is assumed to help lessen the fluctuation of the frictional force and thus reducing and stabilizing the SD values. However, the embedded grits acting in two-body abrasion mode also contribute to abrade the disc and remove the friction film but the 3rd body abrasion mode is assumed to dominate the wear process. Figure 9 shows the contact plateau of brake pad with (a) grooving and (b) with embedded particle and secondary contact plateau at disc sliding speed of 8m/s. Compacted wear debris forms friction film and assist the friction as the brake is applied which results in the reduced SD values of friction oscillation amplitude.



(a) (b)

Figure 9 Contact plateau at the brake pad surface with (a) small groove and (b) with embedded particle and more secondary contact plateaus at disc sliding speed of 8 m/s

4.0 CONCLUSION

The external hard particles effect on frictional characteristics during hard braking was investigated using a specially developed brake test rig with silica sands of 180 to 355 µm. The following conclusions can be made:

- The CoF values were dependent on the presence of hard particles. The values of CoF decrease due to the active role of hard particle in reducing the effective contact area.
- Presence of hard particle shortens the stopping time significantly because they contribute to enhancement of disc wear while grit embedment tends to further damage the disc surface due to the two-body mode of abrasion.
- High initial SD values of friction oscillation at low sliding speed are related to abrupt changes in the contact as the hard particles enter the sliding interfaces.
- Reduced SD values of friction oscillation at medium speeds are related to contact plateau and effective contact area that were started to stabilize.
- High SD values at higher speeds due to faster mixing and rapid changes of the effective contact area and more wear debris got ejected.

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