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Experimental Investigation on the Effect of Masked Multiple Passes Abrasive Waterjet Machining Surface Texturing on Coefficient of Friction

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ABSTRACT

The surface texturing method is popular because of its ability to improve surface properties, specifically surface functioning, and friction control. It is a common technique used on material surfaces to improve friction performance. Laser surface texturing is the popular choice; however, this method suffers drawbacks such as cracking, heat-affected zone, and generation of hazardous fumes. The Abrasive Water Jet Machining (AWJM) was chosen is that, because the eroded material is carried by the waterjet, the process is clean and does not produce dust, chips, or chemical contaminants. This experiment examines the influence of AWJM and investigates how crater density and a multiple-pass machining path affect the stainless-steel friction characteristics when sliding in dry conditions. The texture was applied on the surface of stainless steel by masked multi-passes AWJM technique. According to the findings, there is less friction in craters with greater densities because there are more craters in the contact zone, which improves the trapping of debris particles and reduces friction, when the crater density rises from 4% to 18%, there is a greater chance of worn debris becoming trapped, which reduces friction. The coefficient of friction and crater roughness of the stainless-steel surface are all proportionally affected by the multiple-passes approach. The coefficient of friction increases with higher machining passes. There is more erosion and greater roughness when there are more jet passes. It is concluded that the masked multiple passes AWJM Surface Texturing technique has a significant impact on the Coefficient of Friction (COF).

1. Introduction

Friction is involved in almost all everyday life situations. Friction occurs between two mating components, whether it is in kinetic or static conditions. The simplest effort to overcome friction was to use water and, later natural oils to lubricate moving contacts. It not only consumes a lot of energy

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but also is an important cause of mechanical parts failure. In some applications, friction reduction is desirable but, in some applications, friction improvement is desirable. To control friction, we need to understand friction.

Significant interest has been shown in the behaviours of friction in textured and non-textured surfaces [1]. The study for textured and non-textured surfaces with a friction coefficient for sliding contact shows a significant relation under certain conditions [2]. For these reasons, the concern of controlling friction in the industry-academic conjunction has received considerable attention in the academic literature, with key issues such as surface texture being comprehensively explored. Friction does not only consume high energy but can also cause wear and mechanical failure. Inside the engine, efficiency is essential. However, Nakada [3] found out that the total energy developed by an automotive engine is subjected to 40% engine friction loss. The sliding of a piston inside the liner and rotating engine bearings contribute to 7% of total friction dissipation [4]. According to Holmberg *et al*., [5] internal combustion engines suffer 11.5% of energy loss from total dissipated by fuel energy just to overcome engine friction and concluded that the piston/cylinder system accounts for 45% of the internal combustion engine friction. This situation shows that the need to reduce friction is significantly required. Friction reduction of a surface for energy saving is one of the popular methods for increasing efficiency and lowering energy loss. The texture of a surface significantly affects its friction and wear characteristics [6].

Conversely, Dunn *et al.,* [7] found that surface texture can also enhance friction coefficient in dry friction settings in various applications that depend on friction to function properly. Aluminium substrates with micro- and nano-textured surfaces had measured surface frictions that were 1.26 times and 2.69 times higher than those of smooth surfaces under dry surface conditions [8]. Surface patterns could trap wear particles, which reduced the scratching impact of wear particles and abrasive wear. On the other hand, surface texture treatment enhanced sample roughness. When under pressure, the contact area of surface micro protrusions and texture boundary experienced terrible shear damage [9]. Mechanical interlocking can be achieved by arranging and coordinating the surface topography of both surfaces, enhancing static and kinetic friction [10]. Only when the tribological system benefits from a higher frictional coefficient, as is the case with dry sliding contact surfaces, a textured surface can be used to better effect [11].

The application of surface texturing is inspired and adapted by nature. Han *et al*., [12] define biomimetics as biologically inspired design, adaptation, or derivation from nature, which means mimicking biology or nature. Latif *et al*., [13] study the surface roughness and the COF of “kiambang” leaves that can be used in existing technologies.

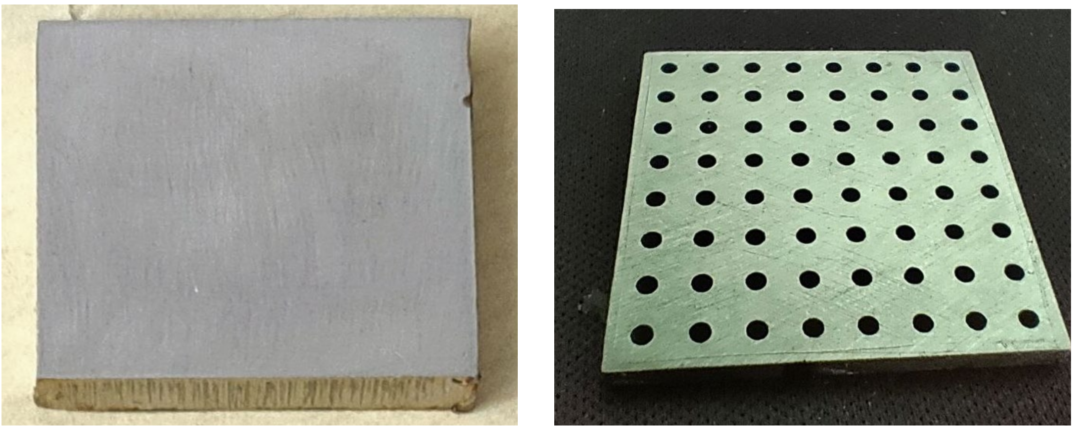
Surface texturing for modifying a material's surface can be accomplished using various methods, including chemical etching, laser ablation, and sandblasting. Abrasive jet machining, electro-chemical micro-machining, pellet pressing, electric discharge texturing, laser surface texturing, electrodeposition, discharge texturing, reactive ion etching, and whirling electrical discharge texturing are just a few of the techniques used to create surface texturing. The laser surface texturing method has been widely used in tribological applications, particularly in the automotive industry [14]. Shorter pulses have been utilised more often in laser texturing, and femtosecond lasers are now commonly employed, increasing the variety of materials that can be processed, including metals, ceramics, and glasses. Vilhena *et al*., [15] stated that laser surface texturing is the most often used method because of the flexibility of a laser system to create microstructures on a target surface. The most common option is laser surface texturing, however, there are certain disadvantages to this technique, including heat-affected zones, cracking, and the release of dangerous chemicals [14].

AWJM as compared to other technologies is primarily more versatile, ability to work with virtually any type of material, and is the most environmentally friendly due lack of any thermal deformation of the material machined [16]. Surprisingly, the potential of AWJM was not fully utilized in the surface texturing field as compared to another machining method. This manifestation demonstrates the critical need to study the AWJM potential on friction.

2. Methodology

2.1 Materials

In this experiment, we used SS 304 stainless steels as our workpiece to observe the surface roughness. The reason SS 304 stainless steels have been chosen is because it is corrosion-resistant and commonly used in industry. A stainless-steel sheet is a crucial component in engineering since stainless-steel SS 304 stainless steel has less carbon than other workpiece materials, and it prevents carbide precipitation. 50% of the production and consumption of stainless steel worldwide is SS 304 stainless steel [17]. SS 304 stainless steel is a type of stainless steel that has a ductile behavior; yet, it is a material that is difficult to cut due to its strong resistance to heat and corrosion, strength, durability, minimal maintenance, fabrication, flexibility, and high hardness [18]. The dimension for the workpiece is 5.0 mm thickness x 25.0 mm width x 25.0 mm height refer to Figure 1(a). In this experiment, we want to test certain refining surface roughness by using the ideology from the previous study [19] we created a simple hole masking referred to in Figure 1(b). The masking template was designed using CATIA V5R21 software. Then the template was produced using a laser machine to get an accurate dimension. The template dimension is 2.0 mm thickness x 25.0 mm width x 25.0 mm length containing (a) 36 holes (b) 81 holes (c) 144 holes measuring 1.0 mm in diameter. We use the template in Figure 1(b) as a medium for the water jet to flow efficiently according to the template pattern.



(a) (b)

Fig. 1. (a) The workpiece (b) Masking template

2.2 Equipment

The abrasive waterjet machining (AWJM) was used because this method is clean and does not create dust, chips, and chemical pollutants since the eroded material is carried by the waterjet, thereby removing dust, air pollution, and as a result, it is environmentally beneficial [20]. The usage of water as a tool is beneficial for the reason that during the water jet impingement, the water was able to cool hot surfaces during the machining process [21]. A commercial waterjet cutting machine with a computer numerical control (CNC) system that can produce pressures of up to 200 MPa was used in the experimental setting. The waterjet cutting machine is outfitted with a tungsten carbide nozzle that measures 0.76 mm in diameter and 76.2 mm in length. The specific commercial waterjet machine employed in this particular experiment is shown in Figure 2 and the abrasive water jet machine fixed parameter is shown in Table 1.

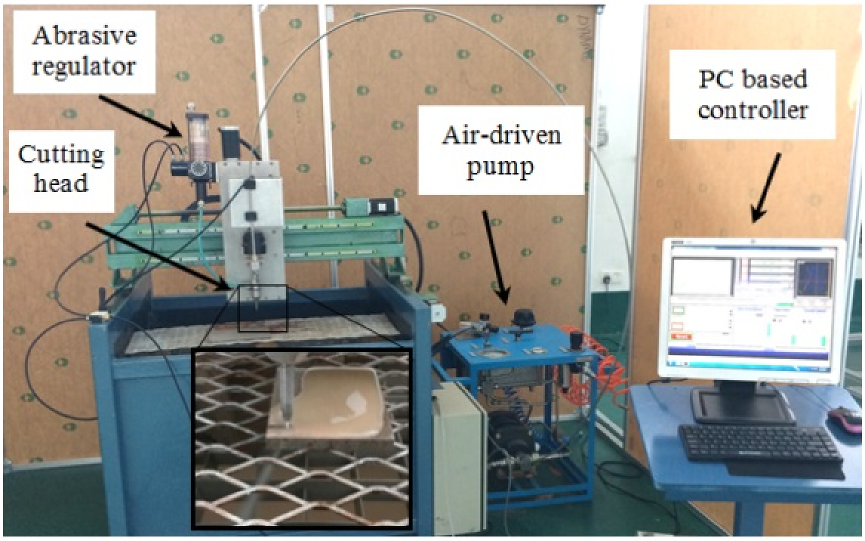


Fig. 2. Specific commercial waterjet machine

Table 1
Abrasive water jet machine fixed parameter

Parameters	Type
Abrasive type	Garnet
Abrasive airflow	0.6 MPa
Jet impact angle	90^o

2.3 Measurement of Friction

The Coefficient of Friction (COF) of various metal-to-metal sliding concepts is frequently measured on a laboratory scale using the pin-on-disc testing method. Using a pin-on-disk testing technique, coefficients of friction were determined for dry sliding with a constant load. These pin-on-disc tests method were frequently conducted to evaluate the tribo system's wear and friction properties [22]. Figure 3 shows the pin-on-disk tribometer used to measure the friction in the workpiece. The friction measurement parameter setup was tabulated in Table 2. A load from the higher pin was applied to the surface of a flat disc specimen. Dead weights with the loading direction parallel to the axis of rotation were positioned on top of the top pin to control the amount of the normal force. Strain gauges were used to measure the frictional force and were fixed to the holder. We next computed the coefficient of friction using these two force measurements. One of the two methods used to modify the test speed was to adjust the arm length holding the pin or the disc's rotational speed. The coefficient, COF was determined by using Eq. (1) in conjunction with ASTM G99-05 (2016) standard similar to the previous study by [23]

$$\text{COF} = \frac{\text{Force(N)}}{\text{Load (N)}} \quad (1)$$

Table 2
Friction measurement setting

Applied Load	Sliding speed	Sliding distance
5N	11.53 cm/s	850m

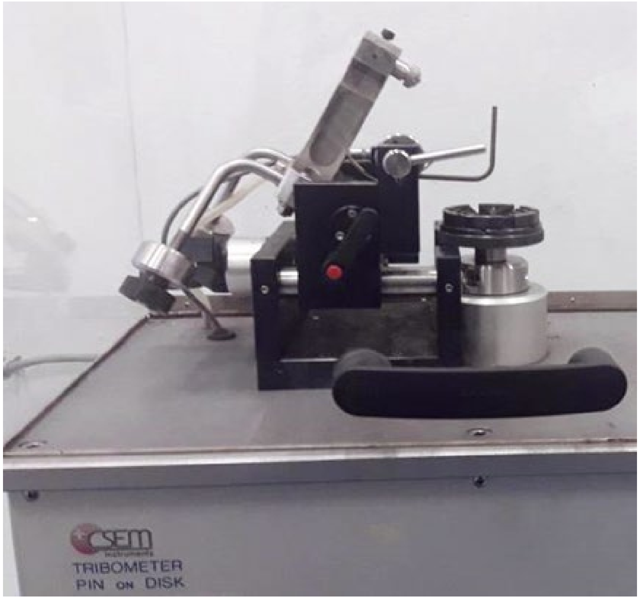
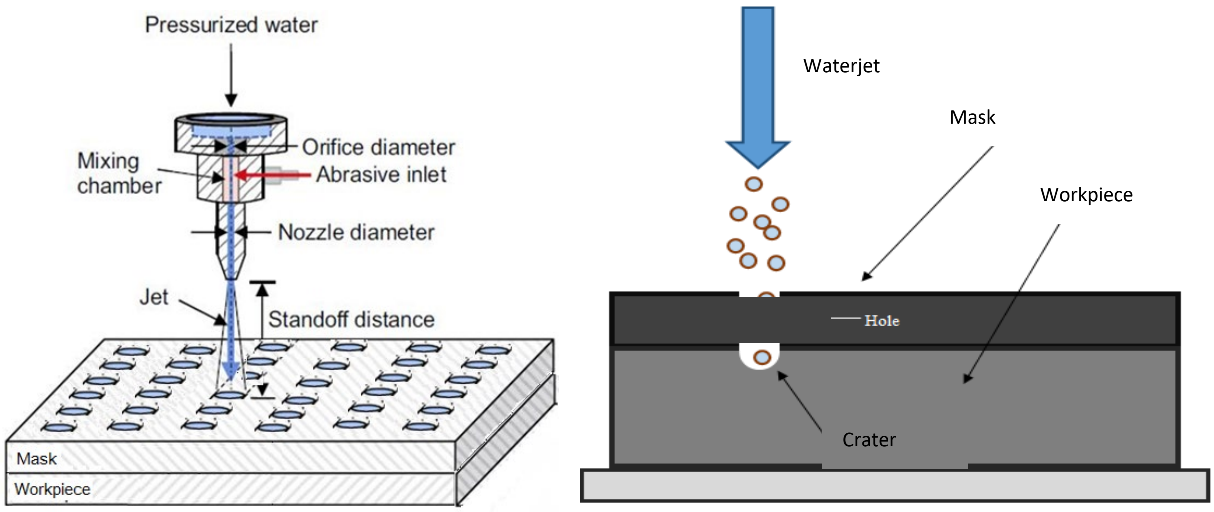
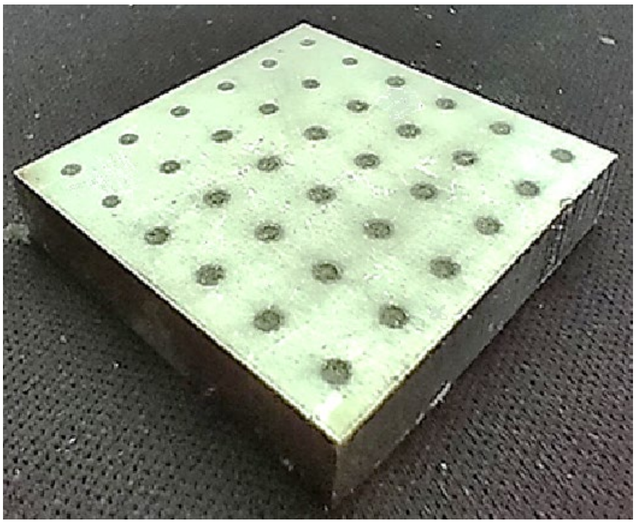


Fig. 3. Pin on disk tribometer

2.4 Machining Method

Figure 4 shows the masked multiple passes abrasive waterjet machining surface texturing machining method. The mask was fixed on the top of the workpiece. To produce craters on the surface of the workpiece displayed in Figure 4 (a), the waterjet nozzle was moved over the mask. Figure 4 (b) displays the surface texture mechanism and Figure 4 (c) shows a finished machined workpiece with circular crater surface texturing on its surface.





(c)

Fig. 4. The illustration of AWJ texturing machining method (a) Schematic diagram of the masking template effect (b) The mechanism of the surface texturing process (c) Surface textured on stainless steel surface

3. Effect of Waterjet Texturing Parameters on Friction

3.1 Effect of Number of Passes on Friction

The effect of the number of passes on the coefficient of friction is shown in Figure 5. The influence of the number of passes demonstrates that a larger number of jet passes leads to a higher coefficient of friction. For a single pass, the COF value is 0.118 µm, two pass value is 0.141 µm and the three passes have a value of 0.174 µm. At a higher number of jet passes, there are significant changes in the coefficient of friction. Higher COF are expected due to repeated bombardment of waterjet onto the surface. Repeated bombardment also generates a higher bulge on the crater edge that causes higher COF. The bulge can be seen in Figure 6(a). Surface patterns had the potential to trap wear particles which can be observed in Figure 6(b), by decreasing the plough effect of debris such as wear particles and abrasive wear. In contrast, surface texture modification increased sample roughness. When the object was subjected to pressure, the contact region between the surface micro protrusions and the texture boundary suffered severe shear damage [9]. This suggests that the surface becomes rougher as a result of the successive passes, which are responsible for creating the harsher surface. In other words, the succeeding passes do not eliminate the peaks that were left by the preceding passes; rather, they introduce new peaks on the surface of the workpiece, which increases the surface COF of the workpiece.

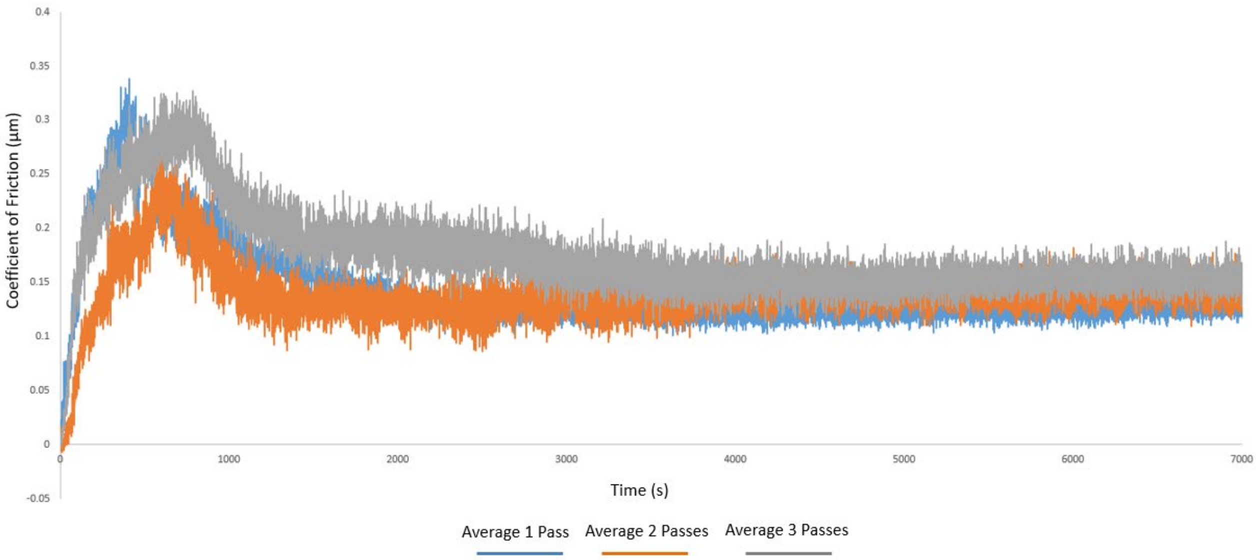
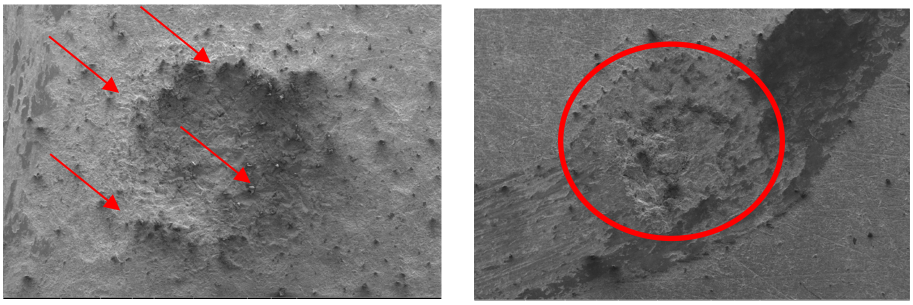


Fig. 5. Effect of passes on the Coefficient of Friction



(a) (b)

Fig. 6. (a) Bulge on crater (b) Images of the trapped debris following dry friction test

3.2 Effect of Texturing Densities on Friction

The effect of texturing density was studied by varying intervals between textures. Figure 7 shows that the magnitude of the friction coefficient changed as the area density changed.

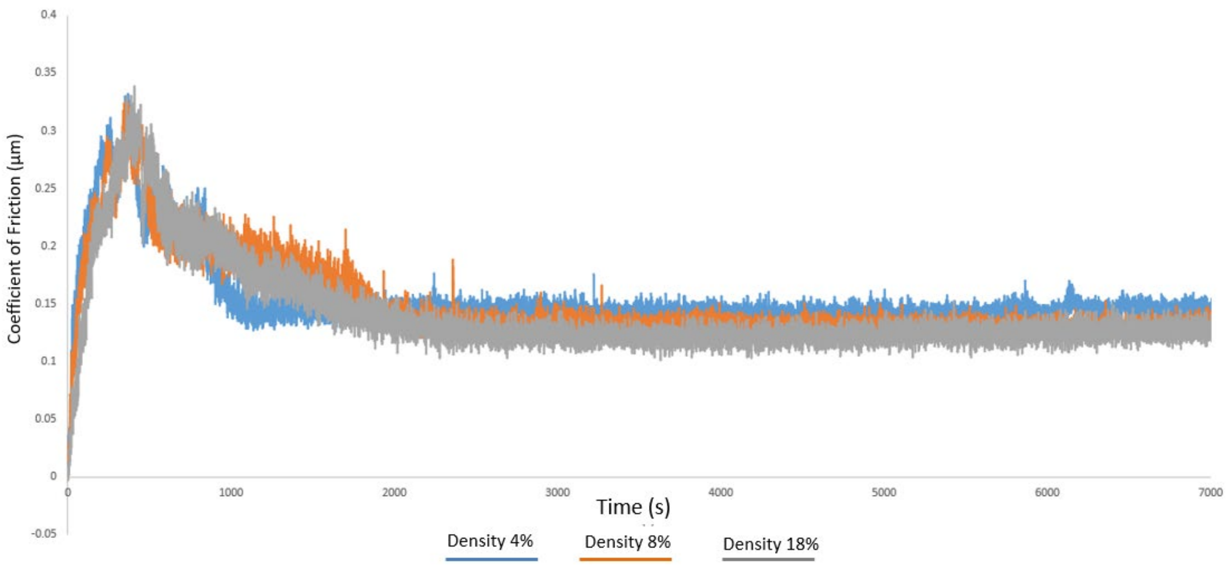


Fig. 7. Effect of Texturing Densities on Coefficient of Friction

The graph in Figure 7 shows that the COF reduces steadily as surface texturing densities increase from 4% to 8% but the COF reduces sharply when texturing density at 18%. The results showed COF at texture density 18% show the lowest value at 0.118 µm. A similar result pattern to the research done by [24-27]. At a density of 8%, the COF value is 0.151 µm and at 4% density, the COF value is 0.155 µm. Surface texturing craters are used in both lubricated and dry sliding to trap worn debris during two mating surfaces (Etsion, 2005). The reduction value of COF is also subjected to the reduction of contact surface. Few craters are created when the density is low and when the number of craters is high the density is high. More texture density leads to a smaller contact surface and narrower gaps between craters. The strong correlation between the distribution of micro-holes and the contact area is shown by surface texturing that lowers the coefficient of friction [26]. Xing *et al.*, [28] found that higher densities reduce the contact area of mating surfaces. By increasing the number of contact points between a substance and another surface, the texture formed on the surface can enhance friction. The texture of a surface significantly affects its friction and wear characteristics [6]. This finding supports the result in Figure 7 above which alternatively by reducing the area of contact points between two mating surfaces, the texture formed on the surface can reduce COF. The density of the texture has a significant impact on how friction and wear behave. The friction coefficient is discovered not to vary monotonically with texture density. However, there can be a perfect texture density where the textured surface performs at its best [25].

Figure 8 shows the optical micrographs of the worn surfaces of the textured samples after pin-on-disk dry sliding friction. It is observed that the wear scars are formed by the mechanical rubbing of all samples and some of the debris accumulated inside the crater. The crater accomplished the responsibility of the debris trap.

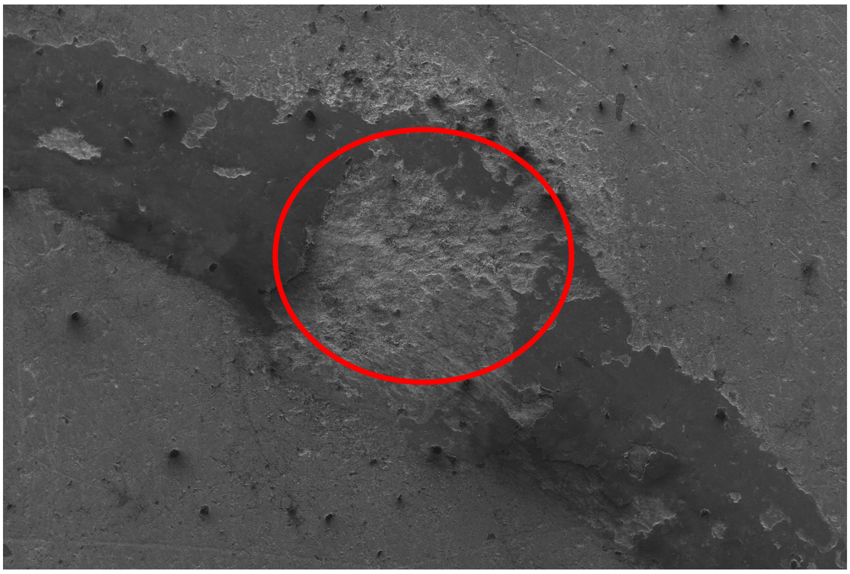


Fig. 8. Images of the trapped debris in the crater

3.3 Friction on the Untextured (Smooth) Surface

Figure 9 shows an unexpected additional peak due to debris for the untextured surface. The additional peak is available in untextured samples due to the debris that has been inflated on the surface causing damage such as ploughing, wear, and destruction of the surface. This finding is confirmed by the SEM images shown in Figure 10. The image shown in Figure 10 displays untextured samples that had shallow and non-uniform grooves due to the debris that plough through the surface of the metal.

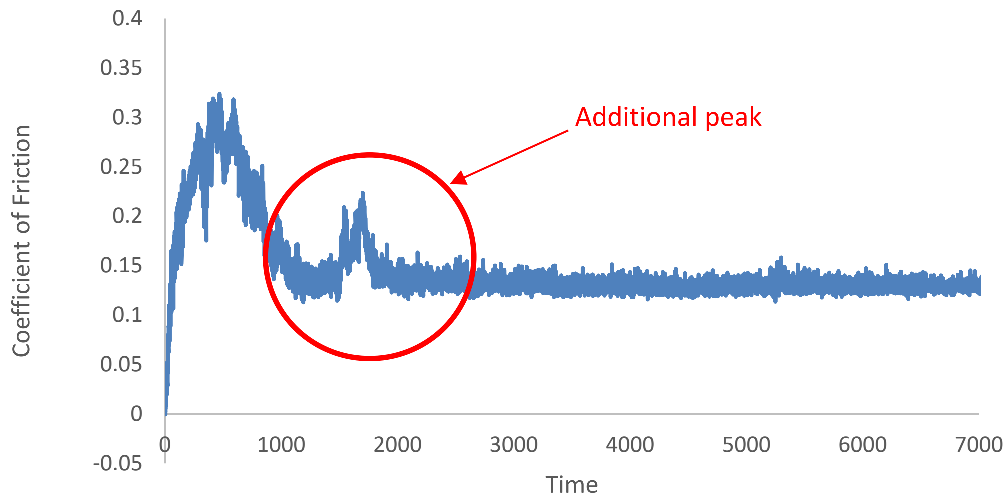
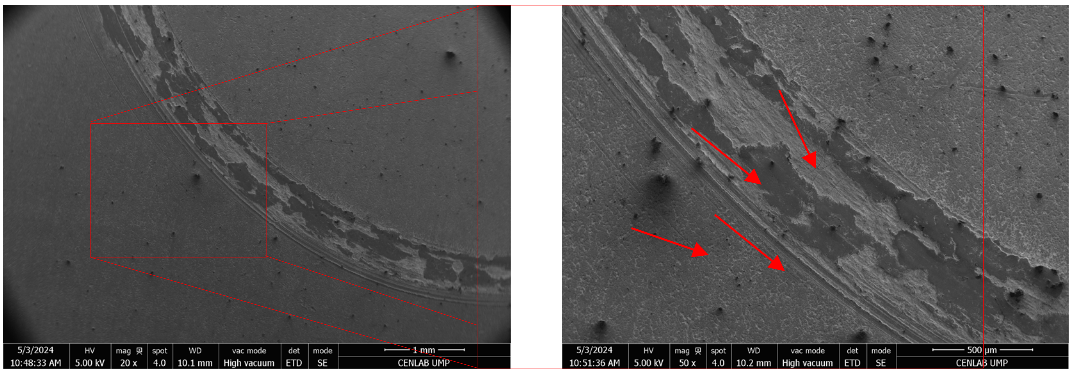


Fig. 9. Friction coefficient as a function of time for the untextured surface



(a) (b)

Fig. 10. Debris that causes the ploughing effect on the surface of the untextured surface (a) 20 X magnification (b) 50 X magnification

4. Conclusions

The following important findings are the result of the current investigation on how masked multiple passes AWJM affects the stainless-steel coefficient of friction:

i. The multiple-passes method has a significant impact on the stainless-steel surface's crater roughness and coefficient of friction. Higher machining passes result in an increase in COF.
ii. When the dimple density rises from 4% to 18%, more entrapment occurs, which as a result lowers the COF.
iii. A debris-related second peak on the smooth, untextured surface developed since there was no crater to collect the debris, which led to wear, ploughing, and eventually surface degradation.

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