1 Introduction

Surface textures have been demonstrated to have a positive effect on the friction reduction. However, sharp edges of the normally textured patterns usually cause stress concentration and severe wear during sliding, especially for non-conformal contacting pairs. In this study, protrusion-type textures were fabricated at different area ratios on stainless steel discs and edge profiling was performed for the protrusions, and friction tests were conducted in water to investigate the tribological properties. The results show that the friction was reduced markedly by edge profiling due to the formation of wedge contact and improvement of lubricant supply to the contact interfaces under low load. Under high load, severe wear destroyed the wedge contact resulting in high friction as those of the normally textured pairs. High area ratio exhibited better friction reduction effect. The stress analysis via ANSYS indicated that much high stress concentrated at the edges of the protrusions and could be reduced significantly by edge profiling.

2 Experimental details

2.1 Laser surface texturing of the specimens

The mirror-finished AISI 420 stainless steel discs with a diameter of 40 mm and thickness of 10 mm were used to fabricate the protrusion-textured specimens. The composition of the steel is carbon (C) 0.38%, silicon (Si) 0.8%, chromium (Cr) 13.6%, manganese (Mn) 0.5% and vanadium (V) 0.3% balanced with iron (Fe). The Rockwell hardness C (HRC) of the discs is 54 corresponding to about 6 GPa. A fibre laser marker with a minimum marking diameter of 15 µm and a wavelength of 1064 nm was used in the fabrication. The power and the repetition rate were set at 1 W and 40 kHz, respectively.

As shown in Fig. 1, after the laser fabrication, the discs were slightly polished by ultrafine sandpapers to obtain the normal textured specimens, and some of the normal textured specimens were further wet polished by 0.5 µm of alumina on a long tumenonum pad to obtain the edge-profiled texture specimens. The diameter of the protrusions was 300 µm. Three groups of textured specimens were prepared at the protrusion area ratios of 35, 44 and 58%.

The feature of the protrusions was measured by an optical interferometer (VK-X200K, Keyence) to analyse the contact stress via ANSYS. The Young’s modulus of AISI 420 discs and 316 L stainless steel balls used in the calculation are 230 and 220 GPa, respectively, and the Poisson’s ratio is 0.3 [11, 12].

2.2 Friction test

The friction tests were carried out by a ball-on-disc reciprocating tribometer in deionised water. AISI 316L stainless steel balls with a diameter of 12.7 mm were used as the counterparts. The composition of the balls is C<0.03%, Si<1%, molybdenum 2%, Cr 17% and nickel 14% balanced with Fe. The Brinell hardness of
the balls is about 100 MPa. Before the test, all the discs and balls were cleaned for 10 min in acetone, anhydrous alcohol and deionised water, respectively. The applied loads were 3 and 5 N. The reciprocation stroke was 10 mm and the frequency was 4 Hz. Two or three times of tests were carried out under each contact condition to obtain the average friction coefficient and the wear of the balls.

3 Results and discussion

3.1 Stress analysis

To investigate the contact stress, the features of the normal and edge-profiled protrusions were measured by an optical interferometer and the cross-section profiles obtained from the textured specimens with 44% area ratio are given in Fig. 2. It is clear that the transfer from the top surface to the lateral surface of the edge-profiled protrusions is much smoother than that of the normal protrusions without edge profiling. The difference in the features of the normal and edge-profiled protrusions will result in different stress distributions and sequential tribological properties under contact conditions. These measured features were used to analyse the stress distribution by the finite element method and discuss the effect of the edge profiling on the tribological properties under loading.

According to the Hertz theory of elastic contact, the calculated initial contact diameter of the mirror-finished disc and the ball pair is about 120 µm under 5 N. It is smaller than the diameter of the protrusions and the stress concentration of the textured discs and the balls’ pairs should appear when the counter ball is contacted with two protrusions equally. Thus, the contact models were established using hexahedron elements considering the ball contact equally with two protrusions for the finite element analysis. Since the contact region is symmetrical about the normal plane at the centre of the counter ball, the half model was used for simulation to simplify the stress calculation.

Fig. 3 gives the nephogram and the equivalent stress profile along the path calculated for the normal and edge-profiled protrusions of the specimens with 44% area ratio at 5 N. The nephogram and the stress profile of the normal texture specimen show that the maximum contact stress locates at the edge of the protrusion and the maximum stress is about 1950 MPa. For the edge-profiled protrusion, the maximum stress concentrates at the centre of the contact area, where the top surface begins to transfer to the lateral surface of the protrusion, and the maximum stress is about 1200 MPa which is about 38% lower than that of the normal protrusions.

The stress distributions of the other specimens are similar to the specimens with 44% area ratio and the maximum stresses are given in Fig. 4. The maximum stresses for the normal texture specimens with the area ratios of 35 and 58% are 3910 and 2320 MPa, respectively. In the case of the edge-profiled specimens, they are 2020 and 1650 MPa and are much lower than those of the normal specimens by 48 and 29%, respectively. It is clear that the maximum contact stress is reduced markedly for the textured surfaces by edge profiling, and the reduction efficiency is...
much significant for the specimens with low area ratio. All the maximum stresses are higher than that of the mirror-finished specimen pair, about 510 MPa. Scratch under high contact stress should be the main cause of the high friction for the normally textured specimen pairs.

Under non-conformal contact of textured surface and ball pairs, concentrated stress at the texture edges usually causes severe wear of the counter balls to change the contact geometry and sequentially reduce the friction [4]. The calculated result shows that much high stress concentrates at the edges of the textured protrusions compared with the mirror-finished specimens. It seems that severe wear will occur to the counter balls during sliding.

3.2 Friction and wear behaviours

The friction coefficient versus the sliding time of the specimens with 58% area ratio at the load of 3 N is given in Fig. 5. The normal texture specimen showed a friction coefficient around 0.2 at the beginning of the sliding and gradually increased to a relatively steady value of about 0.24. For the edge-profiled texture specimen, the friction coefficient increased from about 0.12 to 0.15. At the stable stage, the friction coefficient of the edge-profiled specimen is markedly lower than that of the normal specimen. The similar friction behaviours were obtained for all the textured specimens.

The average friction coefficient of the specimens at 3 and 5 N is given in Fig. 6. For comparison, the friction coefficient obtained from a mirror-finished disc without texture is also shown in Fig. 6 marking the area ratio as 100%. The mirror-finished discs at 3 and 5 N, as well as the normally textured disc with 35% area ratio at 3 N show the highest friction coefficient of about 0.3. The other textured specimens show lower friction coefficient than these specimens. It is noteworthy that each edge-profiled texture specimen shows lower friction coefficient than the normal texture specimen at the same area ratio. The friction coefficient of the edge-profiled texture specimen with the area ratio of 35% is about 0.2 and is reduced markedly by about 30% due to edge profiling. The friction coefficient decreases with increasing the area ratio and the load. The result indicates that the friction of steel pairs in water can be reduced by protrusion texturing and further reduced by edge profiling of the protrusions.

After the tests, the worn surface was observed and the optical micrographs of the textured specimens with 58% area ratio and the mated balls are shown in Fig. 7. From the worn surface of the normal texture specimens, a large number of grooves running through the top protrusion surfaces were observed indicating that severe abrasive-wear occurred during sliding. However, in the case of the edge-profiled texture specimens, the worn scars appeared only at the centre region of the protrusions with some adhered materials, and no obvious grooves were observed under the load of 3 N. For the edge-profiled specimen tested at 5 N, the worn scars of some protrusions almost cover the whole top surface with some slight grooves running through the protrusion surfaces indicating that the wear of the protrusions under this condition is relatively severe. It is noteworthy that the worn surfaces of the balls against the edge-profiled specimens are smoother than those against the normal texture specimens. The result suggests that due to edge profiling, the main wear mechanism changed from abrasive wear to chemical and abrasive wears. The worn surface of the balls mated with the mirror-finished specimens shows similar morphology to those mated with the normal texture specimens.

Fig. 8 gives the worn scar diameter of the counter balls paired with the textured and the mirror-finished specimens. The balls paired with the mirror-finished specimens show the smallest worn scars at 3 N
and the largest worn scars at 5 N. The worn scars on the balls paired with the edge-profiled texture specimens with the area ratio of 35 and 44% are slightly smaller than those on the balls paired with the normal texture specimens at 3 N. At the load of 5 N, the balls paired with the edge-profiled texture specimens with 35% area ratio also show relatively small scars compared with those paired with the normal texture specimens. The effect of edge profiling on the wear of the counter balls is not confirmed for the texture specimens with 58% area ratio at 3 N and with the area ratio of 44 and 58% at 5 N. The worn scar diameter at 5 N is slightly larger than that at 3 N for each pair. However, the difference in the worn scar diameters is not significant as shown in Fig. 8. In some cases at 5 N, the balls paired with the textured specimens even showed slightly small diameters, especially when the edge-profiled specimens were used. It is well known that for mirror-finished specimen pairs sliding in water, the lack of water at the interfaces is the main cause of adhesive wear and high friction.

During the sliding of textured specimen pairs, water network on the textured surface could maintain continuous water supply to the contact interfaces, and water at the interfaces reacts with the worn surfaces to form oxides, which can suppress adhesive wear and reduce friction between steel pairs. The smoother worn ball surfaces against with the edge-profiled texture specimens indicate that chemical wear occurred for the edge-profiled specimen pairs suggesting that more water entered the interfaces. In another word, besides reduction of the edge effect, edge profiling also forms wedge contact features for the protrusions, which is beneficial for supplying lubricant to the interfaces. Under high load, severe wear made the top surfaces of the protrusions become flat resulting in the same friction behaviour as that of the normal texture specimen pairs.

4 Conclusions

To understand the edge effect factor causing stress concentration at the edges and high friction and wear of the textured materials, the edge profiling effect on the contact stress and the tribological behaviours of stainless steel disc and ball pairs were investigated. It is found that the maximum contact stress of the textured specimen pairs is much higher than that of the mirror-finished specimen pairs. By edge profiling, the maximum stress and the friction of the protrusion textures can be reduced markedly.

Also, edge profiling forms wedge contact features for the protrusions and can increase lubricant supply to the interfaces resulting in lower friction and lower wear of the counter balls. The friction coefficient decreases with increasing the area ratio of the protrusions in this work. However, under high load condition, severe wear of the protrusions generates flat top surfaces and makes the edge-profiling effect disappear. To prolong the helpful effect due to edge-profiling, anti-wear coatings such as amorphous carbons are needed.

5 References

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