STUDIES ON TRIBOLOGICAL PERFORMANCE OF LASER TEXTURED BEARING STEEL

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By

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CHAPTER-6

CONCLUSIONS

The present investigation on the evaluation of the tribological performance of laser textured bearing steel may be concluded in the two sections corresponding to two aspects covered in this study: (i) characterization and friction and wear performance of laser textured bearing steel under dry sliding and (ii) friction and wear performance of laser textured bearing steel under lubricated sliding.

6.1 CHARACTERIZATION AND FRICTION AND WEAR PERFORMANCE OF LASER TEXTURED BEARING STEEL UNDER DRY SLIDING

6.1.1 CHARACTERIZATION OF LASER TEXTURED BEARING STEEL

1. Laser surface texturing can be successfully used to create textures on bearing steel. Pulsed Nd:YAG nanosecond laser of 1064 nm wavelength has been used to fabricate two different shapes of the dimples with 7% and 20% densities in the spiral array. The laser power of 20 W with 3 passes has been performed to create the required feature.
2. The non-contact optical 3D profilometer confirmed the shape and size of the dimples. The average depth measured 8 µm, and size about 500 µm. The distance between two dimples is more than 7% in comparison to 20% dimple density.
3. Laser surface texturing of bearing steel with the nano-second laser showed typical bulges around the brim of the dimples.

6.1.2 FRICTION AND WEAR BEHAVIOUR UNDER DRY SLIDING

4. At 15 N load and 0.2 m/s, the variation of the coefficient of friction with the number of revolutions has been observed to display a typical fluctuating tendency for all the specimens i.e., UT, CT7, CT20, BT7, and BT20. The amplitude of variation has been observed to be more significant for UT and CT20 at 0.6 m/s. The variation in amplitude

for all the samples fairly reduces at 1.0 m/s. A similar fluctuating tendency with a significantly smaller amplitude of variation has been observed under 30 N load for all the samples at all the speeds barring the exception of UT and CT7 at 0.2 and 0.6 m/s speeds. An initial rise in the coefficient of friction has been observed at all the speeds and loads which remained stable thereafter until the end of the test.

5. At a low load of 15 N, textured samples have exhibited a relatively lower coefficient of friction compared to UT at all the speeds, i.e., 0.2,0.6 and 1.0 m/s, except for CT7 at 1 m/s speed. The average coefficient of friction has been found to be the highest for 0.6 m/s and lowest for 0.2 m/s for all the textured specimens, i.e., CT7, CT20, BT7, BT20, barring one exception for BT20 at 1.0 m/s whereas the average coefficient of friction for 1.0 m/s is found to lie in-between. The increase in friction coefficient from 0.2 to 0.6 m/s has been attributed to the presence of worn particles at the interface due to the wearing out of bulges on the brim of dimples, which resulted in an increase in the coefficient of friction.
6. At a load of 15 N and speed of 0.2 m/s, the average coefficient of friction has been observed to decrease linearly as one moves from CT7 to CT20. The friction coefficient has been found to remain stable for BT7 with an increase for BT20. BT7 and CT20 have shown the lowest coefficient of friction, about 0.54 under this condition. However, for a speed of 0.6 m/s, the average coefficient of friction has been observed to increase and has been attributed to the more entrapment ability of worn particles by BT20 than BT7.
7. At a load of 15 N and speed of 1.0 m/s, the average coefficient of friction has been observed to decrease for CT7, CT20, BT7, and BT20. BT20 has shown the lowest coefficient of friction of 0.56, and it has been attributed to the absence of loose debris

at the interface due to the formation of a transfer layer which helps in reducing metal-metal contact.

8. At a load of 15 N, the wear rate for UT has been found to be higher than the textured samples for all the speeds. At 0.2 m/s, the wear rate has been found to decrease from CT7 and CT20 and remained constant till BT7, followed by an increase for BT20. An increase in wear for BT20 has been attributed to the abrupt wear of bulges which leads to an increase in material loss. The wear rate at 0.6 m/s has been observed to decrease from CT7 to CT20, followed by an increase for BT7 and a decrease thereafter for BT20. This has been attributed to the more entrapment ability of CT20 and BT20. The wear rate has been found to drop from CT7 to CT20 at 1.0 m/s sliding speed, which remained constant for BT7 followed by a decrease for BT20. This has been ascribed to the formation of a transfer layer at this load and speed, which inhibits metal-metal contact resulting in reduced material loss.
9. The wear rate has been found to be the highest for 0.6 m/s and the lowest for 0.2 m/s for all the textured specimens barring an exception for BT20, which exhibited maximum wear at 0.2 m/s. It has been attributed to increasing wear at 0.6 m/s, which reduced further at 1 m/s due to the formation of a transfer layer.
10. Bi-triangular dimples with 20% density have been found to exhibit the lowest average coefficient of friction and wear rate at 0.6 m/s and 1.0 m/s under 15 N load. However, at 0.2 m/s, the lowest coefficient of friction and wear rate has been observed for BT7 and CT20. Bi-triangular dimples with a curved edge have been found more effective in debris entrapment than circular shape dimples.
11. At a load of 30 N and speed of 0.2 m/s, the average coefficient of friction has been found to decrease from CT7 to CT20, before increasing for BT7, followed by a decrease for BT20 to 0.59. A similar behaviour has been observed at 0.6 m/s with the lowest

average coefficient of friction value of 0.51 exhibited by BT20. At the speed of 1.0 m/s, the average coefficient of friction has been found to maintain almost a constant value for CT7, CT20, and BT7, followed by a decrease for BT20 to the value of 0.52. It has been ascribed to the formation of a transfer layer, which promoted smooth running, and increased entrapment of worn particles due to increased dimple density.

12. At 30 N load, UT has been found to exhibit a higher wear rate than the textured ones for all loads and speeds. The wear rate has been observed to decrease with an increase in speed. At a load of 30 N and speed of 0.2 m/s, wear rate has been observed to decrease from CT7 to CT20 and again increase for BT7 and BT20. This behaviour has been attributed to the generation of more wear particles that remained at the interface as the dimples get completely filled.
13. At a load of 30 N and speed of 0.6 m/s, the wear rate has been found to decrease continuously from CT7 to BT7 before increasing for BT20. Similar behaviour has been observed at 1.0 m/s sliding speeds. This behaviour has been attributed to wear of the bulges at these speeds, and the presence of a transfer layer.
14. The textured surface with 20% density has been found to exhibit a lower coefficient of friction at 30 N load. BT7 has exhibited a 7.5% reduction in the average coefficient of friction compared to CT7 and a 13.1% reduction attributed to BT20. The wear rate has been found to decrease with an increase in density from 7% to 20% for circular dimples and bi-triangular dimples with 7% density under this load. However, bi-triangular dimples with 20% density have exhibited slightly more wear at this load
15. A comparison of the friction and wear performance of circular and bi-triangular shapes reflected a better performance for bi-triangular dimples than circular dimples. Under the speeds and loads used in the current study, BT20 having a bi-triangular shape and

spiral array of dimples with 20% density, showed the best performance under dry contact.

6.1.3 FRICTION AND WEAR PERFORMANCE UNDER LUBRICATED SLIDING

16. At all the loads, i.e., 10, 30, and 50 N, and speeds, textured samples have been found to exhibit a lower average coefficient of friction than the untextured ones under lubricated sliding. The textured surfaces under single drop lubrication have been found to exhibit a lifting effect caused by pressure build-up in the presence of lubrication resulting in the separation of two mating bodies and hence, a reduction in the coefficient of friction. However, the presence of this lifting effect has been observed to depend on the density & shape of the dimples, load and speed.
17. At 10 N load, untextured and textured samples have been found to exhibit a typical fluctuating tendency at all speeds, i.e., 0.2, 0.8, 1.4, and 2.0 m/s under single drop lubrication. However, the amplitude of variation in the coefficient of friction has been found fairly lower than the untextured one at all speeds except for 0.2 m/s. This has been attributed to the extent of surface contact depending on the magnitude of build-up pressure which leads to smooth sliding. A drop in the coefficient of friction of textured samples has been found after a few runs at all the speeds, which remained stable till the end of the test.
18. The average coefficient of friction has been observed to decrease with increasing load for UT at all the speeds used in the present investigation, i.e., 0.2, 0.8, 1.4 and 2.0 m/s. Also, the coefficient of friction shown by UT is the highest among all the specimens. The average coefficient of friction for textured specimens is found to decrease as the load is raised from 10 to 30 N and increase beyond that for all the speeds except 1.4 m/s

where BT7 has a shown a continuously decreasing trend and 2.0 /s at which CT20 has shown the same.

19. The wear rate for textured samples has been found to be lower than the untextured one at all loads and speeds except for BT20 and CT20 at 2.0 m/s under 10 N load. The wear rate has been observed to decrease with an increase in the speed at different loads; however, BT7, BT20, and CT20 showed an increase at 2.0 m/s under 50 N load. The wear rate for textured samples has been found to decrease with an increase in the load at different speeds; however, at 0.2 m/s, the minimum is observed at 30 N load. This has been attributed to the easy formation of build-up pressure under a 30 N load, avoiding direct metal-to-metal contact, and minimizing wear.
20. The dimples with 7% density have been found to exhibit a lower average coefficient of friction in comparison to 20% density under 10 N load. Bi-triangular dimples with 7% density have been observed to display better friction behaviour, varying from 0.074 to 0.086 at different speeds under this load which is lower than the others. At 30 N load, both BT7 and BT20 have been found to demonstrate a similar trend and a lower coefficient of friction varying from 0.07 to 0.09 than the circular dimples (0.08 to 0.09).
21. The lowest coefficient of friction of 0.025 has been exhibited by BT7 2.0 m/s under 50 N load; however, the surface texturing in single drop lubrication has not been observed much beneficial under this load except in a few cases. BT7, however, has been found to show better overall performance, particularly at higher speeds under this load. Surface texturing with a density of 7% has been observed to reduce overall friction by around 35% compared to the dimple density of 20% for BT7 and about 80% reduction in wear rate. The optimum behaviour of BT7 with 7% dimple density has been attributed to the symmetricity of the shape, which reduces hindrance to the movement of the counter element due to hard deposition, and its alignment in the direction of

motion plays an important role in friction reduction. The longer curved edge has been ascribed to help in better entrapment of loose particles and advancement of lubricants in the dimple.

6.1.4 REGIMES OF LUBRICATION

The influence of textures on the tribological performance of the system in a limited supply of lubricant has been observed to exhibit a combination of lubrication regimes based on characteristics of textures (shape, size, density), applied loads, and speeds. The lubrication regimes have been identified based on the observed average coefficient of friction as suggested by Wen and Huang (2012).

22. UT has been found to exhibit a boundary lubrication regime for all speeds and loads; however, based on the observed coefficients of friction, all the textured specimens have been found to depict a boundary, mixed regimes of lubrication. The textural design having large and shallow dimples has been observed to create hydrodynamic lift ideally under low load and high-speed situations in a limited supply of the lubricant, which helped in reducing both friction and wear.
23. At a load of 10 N, the bi-triangular dimples with 20% density have been found to fall under the boundary lubrication regime, whereas BT7 with 7% density has been found to remain in the regime of mixed lubrication at all speeds used in the present study. CT7 has been observed to be in a mixed lubrication regime at the speeds of 0.8 and 1.4 m/s and under boundary lubrication regime at 0.2 m/s and 2.0 m/s. CT20 has been observed to be in the mixed lubrication regime at 1.4 m/s, whereas a regime of boundary lubrication prevailed at the speeds of 0.2, 0.8, and 2 m/s. This has been attributed to the effect of dimple shape, density, and their behaviour at different speeds.
24. Based on the observed coefficients of friction, all the textured specimens have been found to be in a mixed regime of lubrication for all the speeds at 30 N load. This has

been attributed to the ideal operating conditions for circular and bi-triangular dimples with 7% and 20% densities.

25. Under a constant load of 50 N, a boundary lubrication regime has been observed for all the samples for all the speeds. However, BT7 has been found to remain in a mixed regime of lubrication at higher speeds of 1.4 and 2.0 m/s and CT20 in a regime of mixed lubrication at the highest speed of 2 m/s used in the present study.
26. A comparison of the dry and lubricated conditions indicates that the average coefficient of friction is greatly reduced in the case of single drop lubrication. The average coefficient of friction in dry contact ranged from 0.513 to 0.686; however, it varied from 0.025 to 0.282 in lubricated contact. The wear rate also decreased significantly in the presence of the lubricant, aided further by the transfer layer formation. However, after the oil is exhausted and dimples are filled, the textured and untextured surfaces exhibited the similar behaviour.

To summarize, the textured surfaces initially acted as micro-reservoir in the single drop lubrication and reduced direct contact between the mating bodies due to micro-hydrodynamic action and forming lubrication regimes. It also acted as entrapment for wear debris. After the lubricant is exhausted and the dimples are filled, the transfer layer was formed due to heat caused by the action of load and speed. The formation of the layer helped in reducing the friction and wear to a larger extent in the textured specimens. It can also be concluded that laser surface texturing offers a lot of possibilities for reducing the friction and wear behaviour of steel-steel tribo-pairs at low loads and low-to-high speeds. The results also suggest that bi-triangular textures with optimum density can be used in improving the tribological performance of machine elements and components, and the technique offers an alternative way for a cleaner, greener, and sustainable environment.

6.2 FUTURE SCOPE

Tribological behaviour of laser textured surfaces having bi-triangular dimples has been explored in dry and single drop lubrication in the present study under conformal (pin-on-disc) contact conditions under low load and low-to-high speed. The potential of bi-triangular texturing can also be explored under high load and full lubrication condition. Some of the below-mentioned studies may be undertaken in future.

1. Development of a numerical or computational model as an alternative to the current experimental inquiry used for laser surface texturing optimization.
2. Investigations on the tribological behaviour of bi-triangular dimples with various densities on steel with filled solid lubricants.
3. The potential of bi-triangular dimples can be exploited for different applications like piston rings, manufacturing dies etc. The tribological performance of bi-triangular dimples can be identified in the case of ceramics, polymers and other tribo-pairs.