Influence of Design Parameters on The Low Temperature Tribological Performance of Surface Textured Aluminium Alloy

Tao Ye 1,a, Jian-wei Ma 1,b*, Zhen-yuan Jia 1,c

1 Key Laboratory for Precision and Non-traditional Machining Technology of the Ministry of Education, School of Mechanical Engineering, Dalian University of Technology, Dalian, Liaoning, China

aemail: 857880289@qq.com, cemail: 16404476@qq.com

*b Corresponding author: Jian-wei Ma bemail: mjw2011@dlut.edu.cn

Abstract: In this study, micro-grooves with varying design parameters were fabricated on 5A06 aluminium alloy by a nanosecond pulsed laser. Dry sliding wear tests were performed on a ball-on-disc tribometer at the temperature as low as -100°C to evaluate the influence of design parameters on the friction and wear characteristics of laser surface textured 5A06 aluminium alloy. The mechanism of surface texture is analysed from two aspects of friction behaviour and wear morphology. The experimental results show that the design parameters of the laser surface texture have an important influence on the tribological performance of 5A06 aluminium alloy. Reasonable laser surface texture can successfully enhance the tribological performance, thanks to its ability to capture debris to prevent secondary wear.

1. Introduction

Aluminum alloys have shown broad prospects in aerospace applications, such as cryogenic valves used in launch vehicle propulsion systems [1], mainly ascribed to their high specific strength, excellent thermal conductivity and low susceptibility to hydrogen embrittlement. However, poor tribological properties limit their further application under friction and wear conditions, where the efficiency, life and reliability of aluminum alloy moving parts are greatly weakened. Many efforts have therefore been devoted to find effective methods to enhance the tribological performance of aluminium alloys. Of particular interest is laser surface texturing (LST). In the past few decades, LST has witnessed a substantial progress as it is considered a promising surface modification technology that fabricates micro-patterns (such as grooves or dimples) on the contact surface to enhance the tribological properties of mechanical components [2, 3]. There are an increasing number of mechanical parts treated by LST to achieve the improvement of surface performance under different working conditions.

As we all know, the friction and wear characteristics of materials depend on many factors. In particular, temperature is one of the most important factors, because it significantly affects the tribological properties of materials by changing their microstructure and physical properties [4]. The mechanical properties of aluminium alloys at low temperature are significantly different from those at room temperature and high temperature. So far, although there have been many meaningful studies on the tribological behaviour of surface textured materials at different temperatures, most of them are mainly concentrated on the temperature range from room temperature to high temperature [5, 6]. Besides, numerous experimental and theoretical studies have demonstrated that the introduction of surface
texture may also have a negative effect on the tribological performance when surface textures with unreasonable design parameters [7]. In view of the above-mentioned status, researches pertaining to the influence of design parameter on the low temperature tribological properties of laser surface textured aluminium alloy is urgently needed.

In the present study, micro-grooves with varying design parameters (depth, width, interval) were fabricated on the surface of 5A06 aluminum alloy by a nanosecond pulsed laser. By performing a series of dry linear reciprocating sliding wear tests on a ball-on-disc tribometer at the temperature as low as -100°C, the friction and wear characteristics of the laser surface textured 5A06 aluminum alloy were examined. After that, a lot of imaging characterization were conducted. According to the obtained results, the influence of design parameters on the low temperature tribological properties of laser surface textured 5A06 aluminum alloy was discussed. The research results of this work are of great significance to broaden the application range of surface textures at different temperatures.

2. Experimental

2.1. Textured surface preparation

5A06 aluminum alloy discs with a diameter of 30 mm and a thickness of 1.5 mm were selected as the base materials. 01Cr18Ni9Ti stainless steel balls with a 6 mm diameter were used as the counterpart material. As shown in Fig. 1, laser surface texturing experiments were performed using a Nd: YVO4 nanosecond pulsed laser with the maximum laser power of 9.5 W, wavelength of 532 nm, and pulse duration of 15 ns. The laser process parameters adopted to manufacture micro-groove textures were laser single pulse energy density 23 J/cm², pulse frequency 10 kHz and scanning speed 2.5 m/min. After the micro-grooves were manufactured, the textured surface was polished to remove the recast layer induced from the laser thermal effect.

Dry sliding wear tests of the laser surface textured 5A06 aluminum alloy were performed on the ball-on-disc tribometer (Anton Paar TRB³) in linear reciprocating motion at -100°C, as shown in Fig. 2. A normal load of 2 N, a frequency of 1 HZ, and a sliding speed of 20 mm/s were used in all wear tests. All tests were carried out for 600 s. During the sliding wear test, the counterpart ball was stationary while the disc performed linear reciprocating motion. Thereafter, the wear morphology of the worn surface was characterized by the 3D confocal scanning optical microscope (Alicona InfiniteFocus G5) and scanning electron microscopy (FEI Q45).
2.2. Single factor experimental design
The friction coefficient of the laser textured surface is taken as an index, and the design parameters that have a great influence on the performance of the micro-groove texture are selected, including the width, depth, and interval. Considering that it is difficult to accurately obtain the preset value of the microgroove depth during laser processing, the number of scans is selected to characterize the depth. The specific values of the design parameters are as follows: the width \((W)\) is 100 \(\mu\)m, 300 \(\mu\)m, 500 \(\mu\)m, 700 \(\mu\)m and 900 \(\mu\)m, the number of scans \((D)\) is 2, 4, 6, 8, and 10, and the interval \((I)\) is 100 \(\mu\)m, 300 \(\mu\)m, 500 \(\mu\)m, 700 \(\mu\)m and 900 \(\mu\)m. Input parameters design matrix are illustrated in Table 1.

| Expt. No. | Types of textures   | \(W\) (\(\mu\)m) | \(D\) | \(I\) (\(\mu\)m) |
|-----------|--------------------|-------------------|------|------------------|
| 1         | Untextured         | /                 | /    | /                |
| 2         | Micro-groove       | 100               | 6    | 500              |
| 3         |                    | 300               | 6    | 500              |
| 4         |                    | 500               | 6    | 500              |
| 5         |                    | 700               | 6    | 500              |
| 6         |                    | 900               | 6    | 500              |
| 7         |                    | 500               | 2    | 500              |
| 8         |                    | 500               | 4    | 500              |
| 9         |                    | 500               | 6    | 500              |
| 10        |                    | 500               | 8    | 500              |
| 11        |                    | 500               | 10   | 500              |
| 12        |                    | 500               | 6    | 100              |
| 13        |                    | 500               | 6    | 300              |
| 14        |                    | 500               | 6    | 500              |
| 15        |                    | 500               | 6    | 700              |
| 16        |                    | 500               | 6    | 900              |
3. Results and discussion

3.1. Surface morphology of the micro-groove texture
After laser surface texturing, a part of the 3D morphology of the ablated micro-groove texture fabricated on 5A06 aluminium alloy is depicted in Fig. 3. The colour change in the figure indicates the depth change of the micro-groove texture. It is obvious that the width of the micro-groove is generally larger than the preset value, and the corresponding interval is smaller than the preset value, both of which are ascribed to the influence of the heat-affected zone during the laser processing. However, the size deviation rate of the microgrooves is less than 5%, so its influence on the experimental results could be ignored.

3.2. Friction behaviour of the laser textured 5A06 aluminium alloy
Fig. 4 depicts the evolution and average of the friction coefficient obtained from the sliding wear test conducted at -100°C. It can be seen that as time increases, all friction coefficient curves first increase rapidly, then decrease slightly, and finally remain in a relatively stable range after the time reaches 120 seconds. The friction coefficients during the stable section of the laser textured surface with different design parameters are smaller than those of the untextured surface, which indicates that LST can indeed improve the tribological properties of 5A06 aluminum alloy. And the improvement effect has a lot to do with design parameters.

Specifically, when the number of scans is 6 and the interval is 500 µm, the friction coefficient changes of samples with various width 100 µm, 300 µm, 500 µm, 700 µm and 900 µm are described in Fig. 4(a). It is obvious that the average friction coefficient is larger than that of the untextured surface when the width of micro-groove texture is 100 µm. This may be attributed to the fact that the texture width is too small, which not only cannot keep the abrasive grains, but also increases the surface roughness, thus presenting a negative effect on improving the surface friction performance. When the width of the micro-groove texture is greater than 300 µm, the average friction coefficient is lower than that of the untextured surface, and when the texture width is 900 µm, the maximum reduction amplitude reaches 0.22. Fig. 4(b) shows that the friction coefficient decreases as the depth of micro-groove texture increases when its width and interval are 500 µm. However, the friction coefficient curve of the depth D2 encounters a sharply increase at 300s, which is remarkably different from the evolution of the friction coefficient

---

**Figure 3** 3D morphologies and depth distribution of the micro-groove texture.

| D6-W700-1500 | D8-W500-1500 | D6-W500-1700 |
|--------------|--------------|--------------|
| **Width (µm)** | **Depth (µm)** | **Interval (µm)** |
| 700          | 500          | 500          |
| 714.03       | 61.59        | 498.51       |
| **Preset value** | **Measured value** | **Preset value** |
| Width (µm) | Depth (µm) | Interval (µm) |
| 500          | 500          | 500          |
| 510.39       | 91.07        | 487.59       |
| **Preset value** | **Measured value** | **Preset value** |
| Width (µm) | Depth (µm) | Interval (µm) |
| 500          | 500          | 500          |
| 505.96       | 67.99        | 690.66       |
under others conditions. It is speculated that the micro-groove texture is gradually removed during the friction and wear process due to its shallow depth. When approaching the bottom of the micro-groove, the friction coefficient increases since the laser-processed surface is very rough (as shown in Figure 3); when the laser-processed surface is abraded, the friction coefficient decreases. Fig. 4(c) shows that the friction coefficient decreases approximately as the interval increases, and when the texture interval is 900 µm, the average friction coefficient decreases the most, decreasing by about 33.3%.

Figure 4 The evolution and average of the friction coefficient. (a) Width, (a) number of scans, and, (c) interval

3.3. Mechanism of surface texture on the tribological properties
The SEM micrograph of the worn scar is shown in Fig. 5. It can be seen from the morphology of the wear scars that the wear of the untextured surface is caused by furrows and adhesion. The wear of micro-groove textured surface is much lighter, and some wear debris remains in the micro-grooves, both of which indicate that the surface texture plays a role in capturing wear debris during the process friction and wear, thereby reducing abrasive wear.
4. Conclusions
In this paper, the friction and wear characteristics of laser surface textured 5A06 aluminium alloy at the temperature as low as -100°C were examined, and the influence of design parameters of surface texture was evaluated. The following conclusions could be drawn:
(1) The introduction of surface texture with reasonable parameters could improve the low temperature tribological properties of 5A06 aluminium alloy.
(2) The micro-groove texture with smaller width and shallower depth is less effective in improving tribological performance.
(3) The micro-groove texture with reasonable design parameters could reduce friction and wear of materials by means of capturing wear debris.

Acknowledgments
This work was supported by the Joint Fund of Advanced Aerospace Manufacturing Technology Research (U1937602), the National Natural Science Foundation of China (No. 51975098), the Liao Ning Revitalization Talents Program (XLYC1907006, XLYCYSZX1901, and XLYC1801008), the Science and Technology Innovation Fund of Dalian (2019CT01) and the Fundamental Research Funds for the Central Universities. The authors wish to thank the anonymous reviewers for their comments which led to improvements of this paper.

References
[1] Pinho J, Peveroni L, Vetrano MR, Buchlin JM, Steelant J. (2019) Strengart M. Experimental and numerical study of a cryogenic valve using liquid nitrogen and water. Aerosp. Sci. Technol., 93:105331.
[2] Fiaschi G, Di Lauro M, Ballestrazzi A, Rota A, Biscarini F, Valeri S. (2020) Tribological response of laser-textured steel pins with low-dimensional micrometric patterns. Tribol. Int., 149:105548.
[3] Xing W, Li Z, Yang H, Li X, Wang X, Li N. (2019) Anti-icing aluminum alloy surface with multi-level micro-nano textures constructed by picosecond laser. Mater. Des., 183:1–9.
[4] Lu J, Song Y, Hua L, Zhou P, Xie G. (2019) Effect of temperature on friction and galling behavior of 7075 aluminum alloy sheet based on ball-on-plate sliding test. Tribol. Int., 140:105872.
[5] Li J, Xiong D, Wu H, Zhang Y, Qin Y. (2013) Tribological properties of laser surface texturing and molybdenizing duplex-treated stainless steel at elevated temperatures. Surf. Coat. Technol., 228:S219–23.
[6] Oksanen J, Hakala TJ, Tervakangas S, Laakso P, Kilpi L, Ronkainen H, et al. (2014) Tribological properties of laser-textured and ta-C coated surfaces with burnished WS2 at elevated temperatures. Tribol. Int., 70:94–103.

[7] Meylan B, Saeidi F, Wasmer K. (2018) Effect of surface texturing on cast iron reciprocating against steel under cyclic loading in boundary and mixed lubrication conditions. Lubricants, 6:18–20.