Tribological and vibrational effects of laser surface texturing on steel-steel sliding contact

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Abstract. Laser surface texturing (LST) not only can significantly improve the tribological performance of various tribological contacts, but also can significantly reduce the frictional noise and vibrations generated from sliding contacts. In order to investigate the tribological effect of laser surface texturing, sixteen stainless steel specimens with different surface textures, and different textured area ratios are designed and processed on the surfaces of specimens by means of laser surface texturing technique. Four different operation speeds are carried out using a standard friction and wear testing machine (UMT-TriboLab) under rich oil lubrication condition. The experimental results show that the diameter of surface circular dimple had the most significant effect on the tribological properties of steel-steel sliding contacts, followed by texture depth, texture area density, and sliding speed. The effect of laser surface texturing on the frictional noise and vibration generated from steel-steel in dry sliding contacts is also investigated. Laser surface texture has significant effect on the reduction of noise generated from steel-steel dry sliding contacts in both time and frequency domains. The conclusion is that laser surface texturing has significant effects on the tribological, vibrational, and other physical performance of functional surfaces. To get the best tribological and vibrational performance, the functional surface texture should be optimized considering the coupled effects of surface texture, lubrication, and contact condition.

1. Introduction

Studies have shown that the rougher surfaces with certain micro-structures have better friction, wear, lubrication, and vibration and noise reduction performance. Etsion et al. [1-4] have carried out various studies on the tribological effects of LST in automotive applications. Martin and Andres [5] used the laser marking technique to manufacture circular pits and intermittent grooves in the end face of the ring block, and studied the effect of two micro surface shapes on frictional behavior under spherical point contact interface. Schreck and Zum Gahr [6] reported that compared with the polished steel and ceramic surfaces the coefficient of friction (COF) of laser micro-textured surfaces can be reduced by 30%. Wang et al [7] investigated the effects of shapes and textured area ratio of LST on friction and wear of steel ball reciprocating sliding on flat surface of cast iron block. The effects of residual stress due to LST on the wear resistance of cast iron was also investigated in this study.

Sudeen et al [8, 9] experimentally investigated the friction and vibration behaviors of lubricated concentrated point contacts with ground, lapped and textured lapped flat surfaces under reciprocating motions. In Sudeen's study, the coefficient of friction reduced by 30% in some of the cases and vibrations associated with lubricated point contacts generated between textured surfaces/balls reduced significantly at resonance frequency in comparison to polished surfaces/balls.

In the presenting study, in order to optimize the surface textures the tribological effects of circular
dimple diameter, depth, and area density are studied. Also, the noise generated from steel-steel dry sliding contacts with and without laser surface texture is compared in order to investigate the effect of laser surface texture on noise reduction.

2. Experimental Study

2.1 Test specimen preparation

The tribo-pair is composed of a circular stainless steel plate and a stainless steel ball. The steel ball (ϕ5mm) is the upper stationary specimen, and the circular plate (ϕ70mm) is the lower rotation specimen. Sixteen lower specimen with different surface textures were manufactured by means of a laser machine. The dimensional parameters of surface textures are listed in Table 1. According to the principle of DOE (Design of Experiment), sixteen specimens were prepared and their topographies are shown in Fig. 1.

**Table 1.** Dimensional parameter of surface texture and sliding speed.

|     | A Texture Diameter (μm) | B Texture depth (μm) | C Texture area density (%) | D Sliding speed (m/s) |
|-----|--------------------------|----------------------|-----------------------------|-----------------------|
| 1   | 100                      | 5                    | 10                          | 0.25                  |
| 2   | 120                      | 10                   | 20                          | 0.50                  |
| 3   | 140                      | 15                   | 30                          | 0.75                  |
| 4   | 160                      | 20                   | 40                          | 1.0                   |

![Figures showing different textures](image-url)
2.2 Test rig

Figure 2 and 3 shows the UMT-TriboLab friction and wear testing machine and the contact of friction pair, respectively.

![Test rig diagram](image)

**Figure 2.** The UMT-TriboLab (a) testing machine and (b) sliding friction pair.

2.3 Experimental methodology

For the UMT-TriboLab, the upper specimen is stationary, but the lower specimen is rotating and sliding contact with the upper specimen. Above the upper specimen, the tester is equipped with a force sensor and a torque sensor that can real-time measure the normal contact force and frictional force of the contact, respectively. The friction coefficient can be obtained via the data acquisition system. After tests, specimens were ultrasonic cleaned and the wear losses (depths and volumes) of both upper and lower specimens were measured using a white light interference surface profiler (Bruker Contour GT-K 3D Optical Microscope).

Experiments were carried out in both lubrication and dry conditions. In lubrication condition, the lower specimen was fully covered by automotive lubrication oil. The tests were carried out at room temperature, and each experiment last for the same contact distance 100 meter under the same normal load of 10 N in lubrication condition, while each experiment last for the same contact distance of 20 meter under 2 N normal load in dry condition. Each experiment was repeated for three times at the same operation condition with lubrication, but repeated for two times under dry condition. After all tests, the tested specimens were ultrasonic cleaned, dried and weighed.
During the tribological tests, the noise generated by sliding contacts was also measured using a sound pressure, in order to investigate the effect of laser surface texture on the noise generation from steel-steel sliding contacts under both lubrication and dry conditions. The orthogonal design of the experiments (ODOE) was carried out, and four factors (texture diameter, depth, textured area density, and relative sliding speed) and four levels in each factor were used. Table 2 presents the detailed arrangement of the ODOE.

Table 2. The orthogonal design of experiments \( L_4^5(4^4) \).

|   | A Texture Diameter (μm) | B Texture depth (μm) | C Texture area density (%) | D Sliding speed (m/s) | E Empty |
|---|------------------------|---------------------|---------------------------|----------------------|---------|
| 1 | 100(1)                 | 5(1)               | 10(1)                     | 0.25(1)             | -       |
| 2 | 100(1)                 | 10(2)              | 20(2)                     | 0.50(2)             | -       |
| 3 | 100(1)                 | 15(3)              | 30(3)                     | 0.75(3)             | -       |
| 4 | 100(1)                 | 20(4)              | 40(4)                     | 1.0(4)              | -       |
| 5 | 120(2)                 | 5(1)               | 20(2)                     | 0.75(3)             | -       |
| 6 | 120(2)                 | 10(2)              | 10(1)                     | 1.0(4)              | -       |
| 7 | 120(2)                 | 15(3)              | 40(4)                     | 0.25(1)             | -       |
| 8 | 120(2)                 | 20(4)              | 30(3)                     | 0.50(2)             | -       |
| 9 | 140(3)                 | 5(1)               | 30(3)                     | 1.0(4)              | -       |
|10 | 140(3)                 | 10(2)              | 40(4)                     | 0.75(4)             | -       |
|11 | 140(3)                 | 15(3)              | 10(1)                     | 0.50(2)             | -       |
|12 | 140(3)                 | 20(4)              | 20(2)                     | 0.25(1)             | -       |
|13 | 160(4)                 | 5(1)               | 40(4)                     | 0.50(2)             | -       |
|14 | 160(4)                 | 10(2)              | 30(3)                     | 0.25(1)             | -       |
|15 | 160(4)                 | 15(3)              | 20(2)                     | 1.0(4)              | -       |
|16 | 160(4)                 | 20(4)              | 10(1)                     | 0.75(3)             | -       |

2.4 Experimental results and analysis

2.4.1 Friction and wear from lubricated tests. Figure 3 demonstrates the measured coefficients of friction (COFs) of all tests including one test without surface textures and sixteen tests with various surface textures. It can be seen that the surface textures significantly reduced the COFs in all tests although they were not so significant in the first 20 s of the tests, because the first 20 s was the transit state of sliding contacts. In comparison, the average COF of the test 16 was the lowest one and followed by the test 15. For the wear loss of lower specimens, the wear loss of specimen 15 was the smallest one and followed by 12.
Figure 3. Measured COFs from surfaces without texture and with textures of samples 1-16.

A white light interference surface topography instrument was used to measure the wear losses (depths) of the tested specimens. Figure 4 shows the wear losses (depths) of different surface textured specimens from the UMT-TriboLab tests. A detailed analysis of the effects of surface texture parameters on the tribological properties (friction and wear) will be presented in section 2.5.
Figure 4. Measured wear loss (depth) of samples 1-16.
2.4.2 Analysis of tribological effect of laser surface texture. After obtaining the friction coefficients of all sixteen tests, the average steady friction coefficient was taken for the analysis, as shown in Table 3. Since the experimental results have two parameters, the average friction coefficient and the wear depth, in order to take into account the effects of the two parameters, a comprehensive scoring method was used to determine the total score of each test. The total score was used for the analysis of the tribological effect of laser surface textures.

A 5-point system was used to score the friction coefficient and wear depth for all tests. For the coefficient of friction (COF), 5-point, 4-point, 3-point, 2-point, and 1-point represents the COF of 0.075 to 0.085, 0.085 to 0.095, 0.095 to 0.105, 0.105 to 0.115, and 0.115 to 0.125, respectively. For the wear depth, 5-point, 4-point, 3-point, 2-point, and 1-point represents the wear depth of 3.0 to 4.0, 4.0 to 5.0, 5.0 to 6.0, 6.0 to 7.0, and 7.0 to 8.0 micrometer, respectively. Based on the above scoring principle and the experimental results shown in Table 2, the average score of each factor in each level may be obtained from Eq. (1):

$$\bar{R}_j = K_{ij} / s$$  

where \( s \) is the number of occurrences of the i-level on column j. Since the number of occurrences at each level of this study was 4, then \( s = 4 \).

The optimal texture parameter may be determined based on the range \( R_j \), which can be calculated according to Eq. (2):

$$R_j = Max\{\bar{R}_i\} - Min\{\bar{R}_i\}$$  

The calculated results of the range \( R_j \) are shown in Table 4.

| A | B | C | D | E | Test Results |
|---|---|---|---|---|-------------|
| A Test | B Text | C Areal | D Speed | E Vacant | Friction Coefficient | Wear Depth |
| Texture diameter (µm) | depth (µm) | density (%) | (m/s) | column | (µm) |
| 1 | 100(1) | 5(1) | 10(1) | 0.25(1) | -(1) | 0.1172 | 6.03 |
| 2 | 100(1) | 10(2) | 20(2) | 0.5(2) | -(2) | 0.1039 | 7.06 |
| 3 | 120(2) | 15(3) | 30(3) | 0.75(3) | -(3) | 0.1016 | 4.39 |
| 4 | 120(2) | 20(4) | 40(4) | 1.0(4) | -(4) | 0.1113 | 5.86 |
| 5 | 120(2) | 5(1) | 10(1) | 1.0(4) | -(3) | 0.1048 | 4.62 |
| 6 | 120(2) | 15(3) | 40(4) | 10(1) | 0.25(1) | -(2) | 0.1077 | 4.06 |
| 7 | 100(1) | 20(4) | 30(3) | 0.5(2) | -(1) | 0.1131 | 5.17 |
| 8 | 100(1) | 5(1) | 30(3) | 1.0(4) | -(2) | 0.0963 | 4.29 |
| 9 | 120(2) | 10(2) | 40(4) | 0.75(3) | -(1) | 0.0925 | 4.43 |
| 10 | 120(2) | 15(3) | 10(1) | 0.5(2) | -(4) | 0.1025 | 4.32 |
| 11 | 120(2) | 20(4) | 20(2) | 0.25(1) | -(3) | 0.0905 | 3.35 |
| 12 | 120(2) | 20(4) | 30(3) | 0.75(3) | -(3) | 0.1155 | 6.68 |
| 13 | 120(2) | 5(1) | 40(4) | 0.5(2) | -(3) | 0.0951 | 4.39 |
| 14 | 120(2) | 15(3) | 20(2) | 1.0(4) | -(1) | 0.0896 | 3.27 |
| 15 | 120(2) | 20(4) | 10(1) | 0.75(3) | -(2) | 0.0831 | 4.38 |
| 16 | 0 | 0 | 0 | 0 | 0 | 0.1211 | 5.87 |
Table 4. Range analysis.

|      | A     | B      | C     | D     |
|------|-------|--------|-------|-------|
| $\kappa_{ij}$ | 19    | 18     | 26    | 25    |
| $\kappa_{2j}$  | 23    | 26     | 27    | 19    |
| $\kappa_{3j}$  | 31    | 29     | 26    | 29    |
| $\kappa_{4j}$  | 28    | 28     | 22    | 28    |
| $\overline{K}_{1j}$ | 4.75  | 4.5    | 6.5   | 6.25  |
| $\overline{K}_{2j}$ | 5.75  | 6.5    | 6.75  | 4.75  |
| $\overline{K}_{3j}$ | 7.75  | 7.25   | 6.5   | 7.25  |
| $\overline{K}_{4j}$ | 7     | 7      | 5.5   | 7     |
| $R_j$           | 3     | 2.75   | 1.25  | 2.5   |

Optimal Level

A$_3$, B$_3$, C$_2$, D$_3$

It can be seen from Table 4 that the best combination of factors and levels (texture parameters) is $A_3B_3C_2D_3$, i.e. texture diameter is 140 μm, texture depth is 15 μm, texture areal density is 20%, and sliding speed is 0.75 m/s. Table 4 also shows that the influence of each factor on the tribological property of steel-steel sliding contacts is different. The diameter of circular dimple has the most significant effect on the tribological performance of steel-steel sliding contact, followed by texture depth, sliding speed, and texture areal density under the operation conditions of this study.

2.4.3 Noise generated from dry sliding contacts. During tribological tests the noise generated from steel-steel sliding contacts under both lubrication and dry conditions was measured. The methodology of the noise measurements are described in Section 2.3. Since the noise generated in lubrication condition was less significant than that in dry condition, here only the noise generated in dry sliding condition is presented, as shown in Figs. 5 and 6.

It can be seen from Fig. 5 that the noise (RMS of sound pressure) generated from steel ball sliding contacted with textured stainless steel circular plates (sample 1-16) was much smaller than that generated from steel ball sliding contacted with surface polished stainless steel plate (sample 0) without surface texture.

It has been observed from Fig. 6 that there were two significant resonant peaks of noise generated from steel ball dry sliding contacted with polished steel plate without surface texture, 250 Hz with 0.85 Pa and 1450 Hz with 0.75 Pa. However, there was only one significant resonant peak of noise generated from most steel balls dry sliding contacted with steel plates with surface textures.

Table 5 demonstrates the RMSs of noise generated from dry sliding contacts in both time and frequency domains, and the maximum reduction of RMS of noise in time and frequency domain was 84% and 89%, respectively.
Figure 5. Frictional noise in time domain (a) from test 1-8 and (b) from test 9-16.

Figure 6. Frictional noise in frequency domain (a) from test 1-8 and (b) from test 9-16.
Table 5. RMSs of noise generated from dry sliding contacts in both time and frequency domains

| Test No. | RMS (Time domain) | RMS (Frequency domain) | Noise reduction (%) | Resonant frequency/Amplitude (Pa) |
|---------|-------------------|------------------------|---------------------|----------------------------------|
| 0       | 1.1693            | 0.0685                 | 0 0                 | 250Hz/0.85                       |
| 1       | 0.2423            | 0.0111                 | 79.28 83.8          | 1450Hz/0.12                      |
| 2       | 0.3710            | 0.0184                 | 68.27 73.14         | 1550Hz/0.22                      |
| 3       | 0.3247            | 0.0149                 | 72.23 78.25         | 1500Hz/0.21                      |
| 4       | 0.3164            | 0.0180                 | 72.94 73.72         | 200Hz/0.16                       |
| 5       | 0.1830            | 0.0095                 | 84.35 86.13         | 200Hz/0.08                       |
| 6       | 0.2870            | 0.0149                 | 75.46 78.25         | 250Hz/0.16                       |
| 7       | 0.2154            | 0.0075                 | 81.58 89.05         | 50Hz/0.06                        |
| 8       | 0.3411            | 0.0191                 | 70.83 72.12         | 1400Hz/0.25                      |
| 9       | 0.4727            | 0.0347                 | 59.57 49.34         | 200Hz/0.45                       |
| 10      | 0.3114            | 0.0180                 | 73.37 73.72         | 200Hz/0.21                       |
| 11      | 0.2682            | 0.0147                 | 77.06 78.54         | 200Hz/0.13                       |
| 12      | 0.2210            | 0.0075                 | 81.1 89.05          | 250Hz/0.07                       |
| 13      | 0.3787            | 0.0197                 | 67.61 71.24         | 200Hz/0.21                       |
| 14      | 0.5120            | 0.0086                 | 56.21 87.45         | 250Hz/0.09                       |
| 15      | 0.6248            | 0.0491                 | 46.57 28.32         | 200Hz/0.66                       |
| 16      | 0.5238            | 0.0337                 | 55.2 50.8           | 200Hz/0.51                       |

3. Conclusion

Experimental results from steel-steel sliding contacts show that LST had significant effect on the friction reduction and wear resistance under lubrication conditions. In this study, the diameter of surface texture had the most significant effect on the tribological properties of steel-steel sliding contacts, followed by texture depth, texture area density, and sliding speed.

Laser surface texture has significant effect on the reduction of noise generated from steel-steel dry sliding contacts in both time and frequency domains.

To get the best tribological and vibrational performance, the functional surface texture should be optimized considering the coupled effects of surface texture, lubrication, and contact condition.

4. References

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