Study on Friction and Wear Performance of Bionic Coupling Surface Moving Pair of 45 Steel

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Abstract. From the perspective of wear-resistant biological prototypes, the three non-smooth appearances of pits, stripes and grids are simplified abstractly. The shape, structure and material are organically coupled through reasonable mosaic and distribution. It was "replicated" on the surface of the 45 steel by using mechanical and laser processing methods. The wear test was conducted by using a microscopic wear tester. According to the test results, the wear mechanism of the biomimetic coupling morphology and the roles of the three coupling elements in form, structure and material in the wear resistance were analyzed. In this experimental condition, the wear resistance of the mesh shape is best under the same conditions; The coupling element of material plays the minimum of 3.52% in the wear resistance and the maximum will not exceed 64.2%; The pitch is between 0.65 mm and 1.1 mm. In the meanwhile, the wear resistance of the machined sample is higher than that of the laser processed smooth sample; When the distance is more than 1.2 mm, the abrasion resistance of the laser processed sample is higher than that of the mechanical processing sample. This study has important reference value for the reasonable selection of coupling elements and coupling methods to improve the wear resistance of metal surfaces.

1. Introduction
Organisms have evolved a variety of rich forms and complex structures under the laws of survival and elimination of nature to adapt to the environment and meet the survival demands. Various factors such as morphology, structure and materials have become the most adaptable and coordinated system. They are coupled to the living environment through optimized coupling. Based on the theory of biological coupling, the laser and mechanical processing methods have been adopted to form a non-smooth shape which is similar to a biological surface in this paper. The shape, structure and material are organically coupled through reasonable mosaic and distribution in this bionic manufacturing technology. To form a new type of bionic coupling surface with excellent abrasion resistance, low material and manufacturing cost, the role of the coupling element in the wear resistance of the material is analyzed for the first time.

2. Bionic Coupling Unit Design and Sample Processing

2.1 Bionic Coupling Unit Design
(1) Topography design of bionic coupling unit body
The ant's head, pangolin scales and shells' wear-resistant surfaces were used as biological prototypes to imitate their surfaces. Biomimetic coupling designs were carried out from the morphology, size, distribution and materials. The bionic coupling topography design is shown in Fig. 1.
The pit shape of ant’s head is shown in Fig. 1(a). To satisfy the experimental needs and limitation in processing conditions, the basic elements such as its shape and size are extracted and simplified, and the corresponding bionic coupling samples are obtained as a planar distribution of dots. The circular pit has a non-smooth surface; The undulating stripes of the pangolin scales is shown in Fig. 1(b), which are visualized and simplified in the same way to obtain a flat, non-smooth, striped surface; In Fig. 1(c), the striped surface of the cross-section of the shell surface is simplified as a planar, non-smooth, meshed surface.

![Fig. 1. Bionic prototype with different shapes and simplified coupling diagram](image)

(2) The size and structure design of biomimetic coupling units

By observing the biological prototype wear-resisting structural unit body, it can be found that its size ranges from tens of micrometers to several millimeters, and the distribution varies with different parts of different organisms. Therefore, in the biomimetic coupling surface design, the actual conditions and process of processing are taken into account in accordance with the biological prototype, in the three models of pits, stripes and grids, the sizes of the cell body are 500μm, 1000μm and 1500μm respectively. The evenly distributed spacings are 500 μm, 1000 μm and 1500 μm respectively.

The base material of the test specimen is 45 steel. After quenched and tempered, a large piece of 45 steel sheet-shaped steel is cut into a rectangular parallelepiped of 20mm×10mm×8mm by wire-electrode cutting. A total of 29 kinds of samples were designed, including 9 kinds of pit type, 9 types of stripe type and 9 types of grid type. One kind of smooth and one kind of full-scale laser scanning plane specimen. The specific dimensions are shown in Table 1.

| Sample No. | Pit type diameter (μm) | Pit type spacing (μm) | Pit type specimen No. | Stripe type Line width (μm) | Stripe type spacing (μm) | Stripe type specimen No. | Grid type Line width (μm) | Grid type spacing (μm) |
|------------|------------------------|-----------------------|-----------------------|-----------------------------|--------------------------|--------------------------|---------------------------|------------------------|
| 1          | 500                    | 500                   | 10                    | 500                         | 500                      | 19                       | 500                       | 500                    |
| 2          | 500                    | 1000                  | 11                    | 500                         | 1000                     | 20                       | 500                       | 1000                   |
| 3          | 500                    | 1500                  | 12                    | 500                         | 1500                     | 21                       | 500                       | 1500                   |
| 4          | 1000                   | 500                   | 13                    | 1000                        | 500                      | 22                       | 1000                      | 500                    |
| 5          | 1000                   | 1000                  | 14                    | 1000                        | 1000                     | 23                       | 1000                      | 1000                   |
| 6          | 1000                   | 1500                  | 15                    | 1000                        | 1500                     | 24                       | 1000                      | 1500                   |
| 7          | 1500                   | 500                   | 16                    | 1500                        | 500                      | 25                       | 1500                      | 500                    |
| 8          | 1500                   | 1000                  | 17                    | 1500                        | 1000                     | 26                       | 1500                      | 1000                   |
| 9          | 1500                   | 1500                  | 18                    | 1500                        | 1500                     | 27                       | 1500                      | 1500                   |
2.2 Processing of Samples
(1) Laser processing sample
The equipment in this test is YAG-150 laser marking machine of Shenzhen HAN'S LASER Co., Ltd. Some of the processed samples are shown in Table 2.

| Sample number | before wear | after wear |
|---------------|-------------|------------|
| 4             | ![Image](image1.png) | ![Image](image2.png) |
| 13            | ![Image](image3.png) | ![Image](image4.png) |
| 22            | ![Image](image5.png) | ![Image](image6.png) |
| 28            | ![Image](image7.png) | ![Image](image8.png) |

(2) Machining Sample
B-3V Mitsubishi CNC milling machine is used with a drill of 1000 um, processing diameter of 1000 um and pits with spacings of 500 um, 1000 um and 1500 um.

3. Friction and wear test of No. 45 steel test sample
In the course of the experiment, there are 29 kinds of test pieces. In order to reduce the influence of test errors, 3 sets tests are performed for each kind experiment. The test procedure is as follows:

1) In order to keep the surface of the test piece clean, and reduce the experimental error, the test piece is cleaned in the medical ultrasonic cleaner for 20 minutes before the test, then ultrasonically clean in the clean water for 10 minutes, and blow dry with a hair dryer. On the electronic balance, the weight is recorded as the weight before wear;

2) It is fixed on the microscopic tribology experiment machine (Figure 3). A GCr15 steel ball with a Rockwell hardness of HRC63 and a diameter of 4 was selected as the grinding parts. Apply a force of 100 N to the test piece for grinding, and rubbing the surface three times each time, about 90 minutes;
(3) Cleaning again by anhydrous ethanol in a medical ultrasonic cleaner for 20 minutes, then ultrasonically clean in clean water for 10 minutes, blow dry with a hair dryer, and weigh on an electronic balance as the weight after abrasion, weight loss $\Delta W = W_1 - W_2$.

4. Analysis of Wear Mechanism of Bionic Coupling Specimen

The weight loss of all samples after wear is plotted as a curve, as shown in Fig. 2.

![Fig.2. Weight loss after wear of the sample](image)

It can be seen from Fig. 2, the weight loss of the unprocessed sample is the largest, while under the same topography, the weight loss of the laser processing sample is the smallest, and the weight loss of the machined sample is centered. The above situation shows that the smooth unprocessed surface is the least resistant to abrasion, the surface of the laser-processed sample is the most wear-resistant, and the wear-resistance of the machined surface is centered.

The main reason for this effect is that the bionic coupling unit is distributed on the surface of the sample in a certain form and distribution. Because of coupling effect of the material, structure and morphology, the bionic coupling surface have good wear resistance.

(1) In terms of materials, the laser-processed biomimetic coupling unit body has a more dense structure with respect to the base body, so that the strength and hardness increase. It can play a supporting load and resist abrasion during the wear process;

(2) In terms of structure, the bionic coupling unit body with high strength and hardness can reduce the contact area between the sample base and the abrasive during the wear process, so that the decreasing wear of base body, and the bionic coupling unit body can make the surface area of the sample increasing, therefore, facilitates the release of frictional heat during wear. In addition, because of the characteristics that laser processing has no effect on the surrounding matrix, the bionic coupling sample can absorb energy and mitigate the impact of the load during the wear process with the advantages of the original sample;

(3) In terms of morphology, the bionic coupling element on the surface of the sample can change the movement way of abrasive particles: from sliding to rolling during the wear process, thereby this greatly reduces the scratches on the surface of the material and the wear of the furrow.

5. The function of coupling unit in wear resistance

The weight loss contrast curve of smooth surface sample, laser processed smooth sample, machined sample and non-smooth laser processing sample (dimple shape, diameter 1mm, spacing 0.5mm, 1.0mm, 1.5mm respectively) are shown in Fig.3. It can be seen from the figure that the weight loss rate of the sample with smooth surface is the largest which indicates that the wear resistance of the mechanically and laser-processed bionic coupling specimen is better than that of the smooth surface; the weight loss rate of the machined sample with the same size and shape is greater than that of the laser processing sample which indicates that the bionic non-smooth coupling surface has the best wear resistance.
5.1 The function of materials in abrasion resistance

![Graph showing weight loss rate comparison curve of mechanical and laser processing non-smooth sample. (diameter 1mm)](image)

Fig.3. Weight loss rate comparison curve of mechanical and laser processing non-smooth sample. (diameter 1mm)

The quantitative calculation shows that the weight loss rate of the smooth surface is 0.309%, and the weight loss rate of the laser-processed smooth surface is 0.0983%. It can be seen that the effect of the material modification on the wear resistance of the material after the laser processing is 68.2%, that is, the role of this coupling material unit in the wear resistance is less than 68.2%. If the effect of material, form, and structural coupling on the wear resistance is ignored, the role of the coupling unit of the material depends on the laser scanning area. Under this test condition, the diameter is 0.5mm and the center-to-center distance is 2mm. The shape of the sample, the smallest laser scanning area (the ratio of laser scanning area to total area is 5.16%): The mesh-shaped sample with stripe width of 1.5mm, center distance of 2mm, the laser scanning area is the largest (the ratio of laser scanning area to total area is 94.1%). From this, it can be inferred that the coupling unit of the material plays a minimum of 3.52% in the wear resistance and no more than 64.2% in the maximum.

5.2 The function of Form and Structure in Abrasion Resistance

Sometimes the weight loss rate of laser-processed smooth surfaces is higher than that of biomimetic non-smooth coupling samples, and sometimes lower than that of biomimetic non-smooth coupling samples. When the spacing is between 0.65-1.1mm, the wear resistance of the laser processed smooth samples is not as good as that of the bionic non-smooth samples, which means that in this case, the effect of form and structure is greater than the effect of material, which is indicates when the structural and morphological geometries are similar, the wear resistance of the samples is better.

5.3 The Selection and Combination of Coupling Unit

When spacing is greater than 1.2 mm, the wear resistance of biomimetic non-smooth coupled samples and bionic non-smooth samples is lower than that of laser processed smooth samples, which indicates the coupling effect of both structure and morphology or the three: material, structure, and morphology is not necessarily better than the effect of the single coupling unit of the material. It means that each coupling unit must be reasonably selected and organically combined to improve the wear resistance of the material.

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