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Effects of different bionic units coupling on the sliding wear of gray cast iron

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ABSTRACT

To enhance the sliding wear resistance of gray cast iron under starved lubrication conditions, two kinds of bionic units were generated by using a pulsed Nd: YAG laser and a drill on the surface of the specimens. The microstructure and microhardness of the bionic strip unit were examined. Comparing the wear resistance of five groups of specimens (an untreated specimen; a specimen with a surface that was completely melted by the laser; a specimen containing only bionic pit unit; a specimen containing only bionic strip unit and a specimen coupling two kinds of bionic units), the results indicate that the wear resistance of the bionic unit coupling specimen is better than that of the others. The result of a stress analysis of the specimen surface shows that the bionic strip unit plays a supporting role and can reduce the stress concentration on the edge of the bionic pit unit. On the other hand, the bionic pit unit can supply lubricating oil to the wear gap, change the moving model of abrasive grains and improve the lubrication performance. The two kinds of units can protect and promote each other under starved lubrication conditions, improve the resistance to sliding wear.

1. Introduction

A machine tools guide is one of the most important components in a machine tool, because its mechanical accuracy directly determines the quality of the tool. Gray cast iron (GCI) has been used for machine tool guides for a long time because of its superior wear resistance, low cost, excellent machinability, etc. [1–4]. In addition, GCI can be used to absorb shock that occurs during the work of the machine tools, because of its microstructure that the amount of flake graphite spreads well in an iron matrix. The dominant failure types of a machine tool guide are abrasive wear and adhesion wear [5], which directly affect the life span of the tool. Therefore, it is necessary to improve the wear resistance of GCI. Many researchers have focused on improving the wear resistance of cast iron which surface was melted by a laser [6–9], furthermore, reinforced particles such as the W-, or Ni-based surface film was fabricated by a high energy beam like a gas tungsten arc and a laser [10,11].

Living creature is a continuing source of inspiration in engineering field. The perfect performances on the surface of some animals are derived from the coupling of their different materials, structures and morphologies [12]. Such coupling with different elements brings inspiration to design and study on the bionic coupling surface designed with multiple factors which can interact on each other in engineering. Previously, we fabricated the trails by laser technology or other methods on the relatively soft substrate materials [13,14]. We called the trails as bionic unit which has a better performance than the substrate. Researchers have become aware that many types of bionic coupling elements, such as structures, functions and materials, which are the result of the biological evolution of animals and plants as they adapt to the living environment, could be applied in the field of engineering. Zhou et al. have applied the bionic principle on tool and die steel surfaces to process a series of bionic units using a laser; this has enhanced resistance to thermal fatigue [13–16], improving the abrasive wear resistance [17–19] and strengthening the mechanical properties [20,21]. In fact, animals and plants almost always apply the coupling effects of various elements. However, most of the current research in this area has concentrated on studying the functions of a single coupling element; little work has been done on the combined effect of two or more coupling elements to solve a problem.

In this paper, two kinds of bionic units are coupled on the surface of GCI. Their different characteristics protect and promote each other to improve sliding wear resistance under starved lubrication conditions.

2. Experiments

2.1. Experimental materials

GCI codename HT250, which is widely used for machine tool guides, is applied as the base material. Fig. 1 shows the micrograph of the GCI, the microstructure of which consists of flake graphite (G) surrounded

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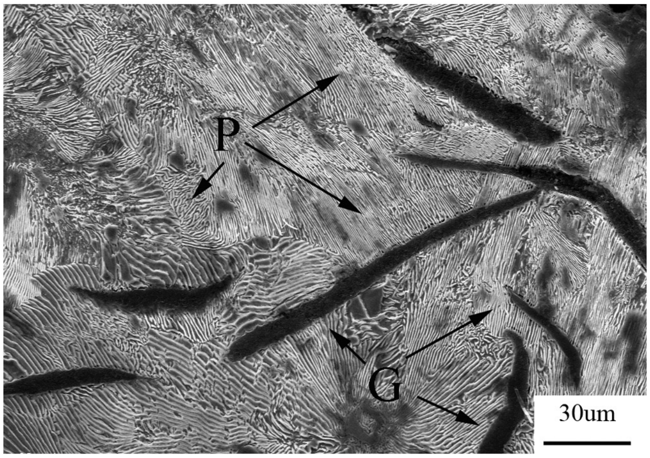

Fig. 1. Microstructure of HT250 gray cast iron.

by pearlite (P). The ultimate strength was 133 ± 3 MPa, the yield strength was 115 ± 3 MPa. The composition of the GCI is listed in Table 1.

2.2. Specimen preparation and bionic prototype

The structure of a bivalve mollusk shell was chosen as one bionic prototype because of its strong wear resistance, which evolved in a beach environment (Fig. 2(a)). Though the shells suffered significant abrasive wear from the mixture of water, mud and sand, they were still well preserved. Observation shows that the nacreous layer of the shell is made of an aragonite layer (hard) and an organic layer (soft). Moreover, the structure of alternately soft and hard layers is one important factor that could enhance the wear resistance and toughness of the nacreous layer [22,23]. Inspirited by the shell structure, a bionic strip unit (BSU) was processed on the specimen surface using laser melting. The purpose during fabrication was to ensure the BSU and matrix had optimal hard and soft alternate structure. The distribution of the BSU was designed as a grid, because a grid has the best wear resistance among the three kinds of distributions (convex, stria and grid) in the same wear environment [5]. As shown in Fig. 3(c), the angle between BSUs and the direction of wear is designed as 45°. The distance between the BSUs is designed as 8 mm.

The pit morphology on head of a dung beetle was chosen as the other bionic prototype, because the pit morphology easily stores air when the beetle's head suffers extrusion and friction from the soil (Fig. 2(b)). The pit morphology could reduce the atmospheric pressure, thereby reducing the friction. According to the pit morphology, the bionic pit unit (BPU) was processed on the specimen surface using a drill. The pit is a cone with a diameter of 1.8 mm. The angle of the cone is 120°. The distance between BPUs is 8 mm (Fig. 3(d)).

In order to compare the wear resistance, five groups of specimens were prepared (Fig. 3): an untreated specimen (S_I) (Fig. 3(a)), a specimen with a surface that was completely melted with the laser melted parameter (S_{II}) (Fig. 3(b)), a specimen containing only BPU (S_{III}) (Fig. 3(c)), a specimen containing only BSU (S_{IV}) (Fig. 3(d)) and a specimen coupling two kinds of bionic units (S_V) (Fig. 3(e)).

All specimens were cut to the same size, 30 mm (L) × 20 mm (W) × 6 mm (D), using a wire electrical discharge machine (Huadong Group, DK77, China). All surfaces of the specimens were polished using progressively finer grades of silicon carbide impregnated emery paper to remove all the surface irregularities and machining marks, then cleaned with anhydrous ethanol before being drilled and laser processed. The roughness (Ra) of the specimens was 200 μm.

A pulsed Nd: YAG laser with 1.06 μm wavelength and rated power of 300 W was employed to create the BSU using a circular pattern Gaussian beam. Fig. 4 shows the schematic of the experimental set-up of the laser processing. The laser head was mounted vertically in the *Z*-direction and was stationary, while a four-axis displacement machine with numerical control system (G code) carries out the spatial displacement. During the laser process, the samples were placed on the displacement machine. Movement along *X* and *Y* axes was used to process the bionic strip units while that along *Z*-axis was to adjust the desired defocusing amount. The specimens were fabricated using this equipment at room temperature and using argon as the shielding gas in order to preventing the oxidation of BSU. Table 2 provides the parameters of the laser melting. After the fabrication process, the surface and side-face of the specimens were mechanically polished using the emery paper and then cleaned with anhydrous ethanol.

Table 1
Chemical compositions of HT250 (wt%).

Elements	C	Si	Mn	P	S	Cu	Cr	Fe
Composition (wt%)	3.25	1.57	0.92	0.06	0.059	0.5	0.27	Bal.

2.3. Experimental methods

The BSU was cut along the vertical direction of the strip. The cross sections of the BSU were obtained for microstructural analysis and measurement of the microhardness; the equipment used was a JSM-5600LV scanning electron microscope and a Vickers Microhardness Tester (model 5104, manufactured by Buehler Co. Ltd., USA). A Wyko NT9100 Optical Profiler (manufactured by Veeco, Ltd., USA) was employed for observing and recording the surface morphology and roughness of the specimens after they were wear tested. Phases formed in the BSU were identified by D/max-RC X-ray diffraction (XRD) with Cu Kα radiation operated at a voltage of 40 kV, a current of 40 mA, and a scanning rate of 40/min. In the process of sliding wear, the value and distribution of the von Mises stress on the surfaces of the specimens were estimated by the finite element method.

Sliding wear tests were performed using a self-made wear tester (Fig. 5). The eccentric wheel was put in motion along with the rotation of gear reducer by electromotor, which makes the moving part of the simple go on straight line reciprocating movement along with the connecting rod, and the load is located at the top of the moving part. The speed of the wear test was controlled by the frequency converter, which was linked to the electromotor. The pressure of wear test was adjusted by the load's adding or subtracting. The friction pair was a high-frequency induction quenching GCI with an average hardness of 50HRC. The average speed of the wear test was 7 cm/s. The time of wear was 24 h under a load of 120 N at room temperature. The setting of these experimental parameters was the purpose that tried to simulate the working environment of a machine tools guide. Usually, the surface of the machine tools guide is no longer added with the lubricant on the work. Therefore, the surfaces of specimens and friction pairs were covered with the lubrication oil at the beginning of the wear. Due to no longer add the lubrication oil, starved lubrication was formed in the process of wear. In such a test, it is incorrect to record the mass loss of the specimens, since the GCI adsorbs lubricating oil in the wear process under starved lubrication conditions. In present paper, the indentation method was utilized to demonstrate the degree of wear, in which the D-value of measured indentation areas before and after the wear test reflected the volume of mass loss. The microhardness measurement was carried out by a Vickers Microhardness Tester (model 5104, manufactured by Buehler Co. Ltd., USA) at a load of 0.2 kg and a dwell time of 10 s. Before the wear test, the microhardness was measured; namely, the indentations were manufactured with a 500 N load in multiple different regions, and the positions and areas of those indentations (A_1) were recorded. After the wear test, the areas of the same indentations were measured again (A_2). The thickness was obtained by