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Bionic Coupling of Hardness Gradient to Surface Texture for Improved Anti-wear Properties

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Abstract

This work investigates the potential of combining hardness gradient with surface texture (an example of bionic coupling) to improve anti-wear properties. The bionic coupling of hardness gradient and Hexagonal Texture (HT) was achieved by laser heat treatment on steel specimens with pre-engraved hexagonal surface texture. The successful establishment of decreasing hardness from surface to internal bulk was verified by hardness measurements along the depth of cross-sectioned specimens and correlated with the observations from metallurgical microscopy. The tribological performance of bionic coupling specimens (HT-L) was examined under dry contact condition, together with respective control specimens of individual bionic features, e.g. HT-H (of similar surface hardness generated by conventional heat treatment but without hardness gradient) and SS-L (of smooth surface treated by the same laser processing as for HT-L). It is found that HT-L not only exhibits lower friction coefficient and less friction fluctuation than HT-H and SS-L, but also demonstrates a >50% reduction of wear loss compared to HT-H and SS-L (0.0343 g for HT-L vs. 0.0723 g for HT-H, $P<0.001$; 0.0343 g for HT-L vs. 0.0817 g for SS-L, $P<0.001$). Corroboratively, observations with scanning electron microscopy revealed a relatively smooth surface for worn HT-L specimen, contrasting with the rugged and grooved surfaces of worn HT-H and SS-L specimens. These results indicate that the bionic coupling of hardness gradient to hexagonal texture can indeed improve anti-wear properties, affording a new strategy to wear and friction management.

Keywords: anti-wear, bionic coupling, hardness gradient, surface texture, hexagonal texture

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1 Introduction

Wear is a major reason for many mechanical failures and thus tremendous efforts have been made to improve anti-wear properties for a variety of materials. Steel is one of widely investigated materials in anti-wear research owing to its broad range of industrial applications. These works are mainly focused on reinforcing the hardness of steel, resulting in either an overall hardness increase as in the case of conventional heat treatment[1], or a hardness elevation confined to the surface, which has been well demonstrated by various coatings[2–4], thermochemical treatment[5], laser heat treatment[6–9], *etc*.

Over the past decades, surface texture has also been found to play important roles in enhancing the tribological performance of mechanical parts. Pettersson and Jacobson have shown that mesh textures on piston surface can substantially decrease friction fluctuation under a condition close to an actual hydraulic motor[10]. Tong and coworkers have demonstrated that a variety of biomimetically textured surfaces can improve the tribological responses of furrow opener[11]. Etsion and colleagues have shown that the surface textures on bearing, piston, and other mechanical parts can extend their service lives[12]. More recently, Greiner *et al.* have fabricated bio-inspired scale-like surface textures by laser texturing and demonstrated friction reduction for these biomimetic surface morphologies[13,14]. These endeavors have corroboratively proved that engineered textured surfaces, as frequently found in nature, can be utilized to reduce wear and friction.

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However, textured surface morphology is not the only answer nature has given us to manage wear and friction. Indeed, the decreasing hardness gradient from hard surface to soft inner layers, as observed in sand boa and other sand-living reptiles[15–17], is also known to contribute to wear and friction reduction. In many animals, such a benefit is often coupled to the effect of surface texture to synergistically yield anti-wear properties, which has been referred to as an example of "bionic coupling" in recent publications[18,19]. Although anti-wear properties have been individually studied for a range of surface-textured or hardness-reinforced materials[20,21], investigations on bionic coupling effects, particularly for combining hardness gradient with surface texture, are still rare.

In this present work, it is envisioned that the bionic coupling of hexagonal texture and hardness gradient may synergistically improve the anti-friction and anti-wear performance of steel. Hexagonal patterning is frequently found in nature due to the fact that it is the most effective way to pack the largest number of similar objects in a minimum space, and has been applied to various parts, including tool pins, glass, *etc.*[22]. It is also known that bionic hexagonal texture can be used to reduce friction on elastomer[23]. Hence, for the current investigation, hexagonal patterning is chosen as the surface texture to be coupled with the hardness gradient, which is expected to be established by laser heat treatment.

Herein, the bionic coupling of hardness gradient and Hexagonal Texture (HT) was achieved by laser heat treatment on steel specimens with pre-engraved hexagonal surface texture. The successful establishment of decreasing hardness from surface to internal bulk was verified by hardness measurements along the depth of cross-sectioned specimens and correlated with the observations from metallurgical microscopy. The tribological performance of bionic coupling specimens (HT-L) was examined under dry contact condition, together with respective control specimens of individual bionic features, e.g. HT-H (of similar surface hardness generated by conventional heat treatment but without hardness gradient) and SS-L (of smooth surface treated by the same laser processing as for HT-L). It is found that HT-L not only exhibits lower friction coefficient and less friction fluctuation than HT-H and SS-L, but also demonstrates a substantial reduction of wear loss compared to HT-H and SS-L. Corroboratively, observations with scanning electron microscopy revealed a relatively smooth surface for worn HT-L specimen, contrasting with the rugged and grooved surfaces of worn HT-H and SS-L specimens.

2 Experimental

2.1 Materials

Commercial AISI 1045 steel (Jilin Steel Factory), GCr15 alloy steel (Jilin Steel Factory), acetone (A.R., Beijing Chemical Factory), ethanol (A.R., Beijing Chemical Factory), and graphite (C.P., Tianjin Guangfu Fine Chemical Research Institute) were used as received.

2.2 Fabrication of specimens

To prepare specimens for tribotesting, commercial AISI 1045 steel was first machined into cylinders with a diameter of 25 mm and a height of 16 mm. Then a Computer Numerical Control (CNC) engraving machine was utilized to fabricate hexagonal textures on the top surfaces of the cylinders (Fig. 1). The length of the hexagon side is 3 mm, while the width of the groove between adjacent hexagons is 1 mm. The depth of the groove (or the height of the hexagons) is also 1 mm.

The bionic coupling specimens of textured surface and hardness gradient were prepared by laser heat treatment with a five-axis CNC laser processing machine (SLC-X15*30, Shanghai Instrument Factory, China). Briefly, laser heat treatment was performed on the surface of specimens with pre-engraved hexagonal texture as depicted above. The diameter of the defocused laser was 3.2 mm. The power of laser heat treatment used was 1000 W, whereas the scanning speed was 300 $\text{mm}\cdot\text{min}^{-1}$.

Conventional heat treatment of specimens was performed with a furnace (JXL1400, Zhengzhou Equipment Co., Ltd., China). A typical conventional heat treatment process included six major steps: the first temperature elevation to 850 ˚C, 30-minute tempering at 850 ˚C, quenching in water, the second temperature elevation to 200 ˚C, 30-minute tempering at 200 ˚C, and cooling in air.

GCr15 steel was chosen as the material to prepare the counter-disks used in the tribotesting, which was first machined into cylinders with a diameter of 80 mm and a height of 14 mm, and subsequently treated by