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Influence of different temperatures on the thermal fatigue behavior and thermal stability of hot-work tool steel processed by a biomimetic couple laser technique

Chao Meng [a], Hong Zhou [a,*], Ying Zhou [a], Ming Gao [a], Xin Tong [b], Dalong Cong [a], Chuanwei Wang [a], Fang Chang [a], Luquan Ren [c]

[a] The Key Lab of Automobile Materials, The Ministry of Education, Jilin University, Changchun 130025, PR China
[b] The Department of Materials Surface Engineering, Guangzhou Research Institute of Non-ferrous Metals, Guangzhou 510651, PR China
[c] The Key Lab of Terrain Machinery Bionics Engineering, The Ministry of Education, Jilin University, Changchun 130025, PR China

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ABSTRACT

Three kinds of biomimetic non-smooth shapes (spot-shape, striation-shape and reticulation-shape) were fabricated on the surface of H13 hot-work tool steel by laser. We investigated the thermal fatigue behavior of biomimetic non-smooth samples with three kinds of shapes at different thermal cycle temperature. Moreover, the evolution of microstructure, as well as the variations of hardness of laser affected area and matrix were studied and compared. The results showed that biomimetic non-smooth samples had better thermal fatigue behavior compared to the untreated samples at different thermal cycle temperatures. For a given maximal temperature, the biomimetic non-smooth sample with reticulation-shape had the optimum thermal fatigue behavior, than with striation-shape which was better than that with the spot-shape. The microstructure observations indicated that at different thermal cycle temperatures the coarsening degrees of microstructures of laser affected area were different and the microstructures of laser affected area were still finer than that of the untreated samples. Although the resistance to thermal cycling softening of laser affected area was lower than that of the untreated sample, laser affected area had higher microhardness than the untreated sample at different thermal cycle temperature.

1. Introduction

Hot-work tool steels, such as AISI H13 steel, belonged to the chromium hot work tool steels with high hardenability, high strength and ductility, good tempering resistance and moderate cost [1,2]. Owing to these advantages, in many industries, hot-work tool steels play an important role on materials processing such as die-casting, extrusion and forging. Thermal fatigue cracking, which results from the rapid alterations in die surface temperature, is one of the major reasons for the failure of hot-work tool steel in applications [3]. Therefore, it is important to investigate and enhance the thermal fatigue behavior of hot-work tool steels.

The biological structures have developed gradually to adapt to the environment during billions of years of natural selection and evolution [4]. Fauna and flora have different morphologies of non-smooth surface in order to acclimatize themselves to different life environments [5–8]. Inspired by the excellent properties of non-smooth surface, many researchers have investigated the non-smooth surfaces of biological organisms and designed mechanical components with non-smooth surfaces which have been identified as superior in performance compared to the smooth surface ones [9–12]. In this paper, laser has been employed to process different non-smooth surfaces (such as spot-shape, striation-shape, and reticulation-shape) on the hot-work tool steel, which simulates the morphologies of cuticles of soil animals, as shown in Fig. 1. The functionality of the non-smooth surface is like the nacreous layer of the shell which is made up of Aragonite Layer (hard) and Organic Layer (soft), as shown in Fig. 2 (a). In Fig. 2(b), the crack is unable to penetrate the aragonite layer directly and causes deflection at the interface of Aragonite layer and Organic layer [7]. The structure of the nacreous layer is abstracted to a model with characteristics of alternately soft and hard. For biomimetic coupled laser remelting process, laser affected area serves as the Aragonite Layer (hard) and substrate serves as Organic Layer (soft). Previous researches suggested that hot-work tool steel and cast iron with non-smooth surface could enhance not only the thermal fatigue behavior but also the wear behavior and tensile property compared with the untreated sample [13–17].

* Corresponding author. Tel.: +86 431 85094427; fax: +86 431 85095592.
E-mail address: laser.bio.lab@gmail.com (H. Zhou).

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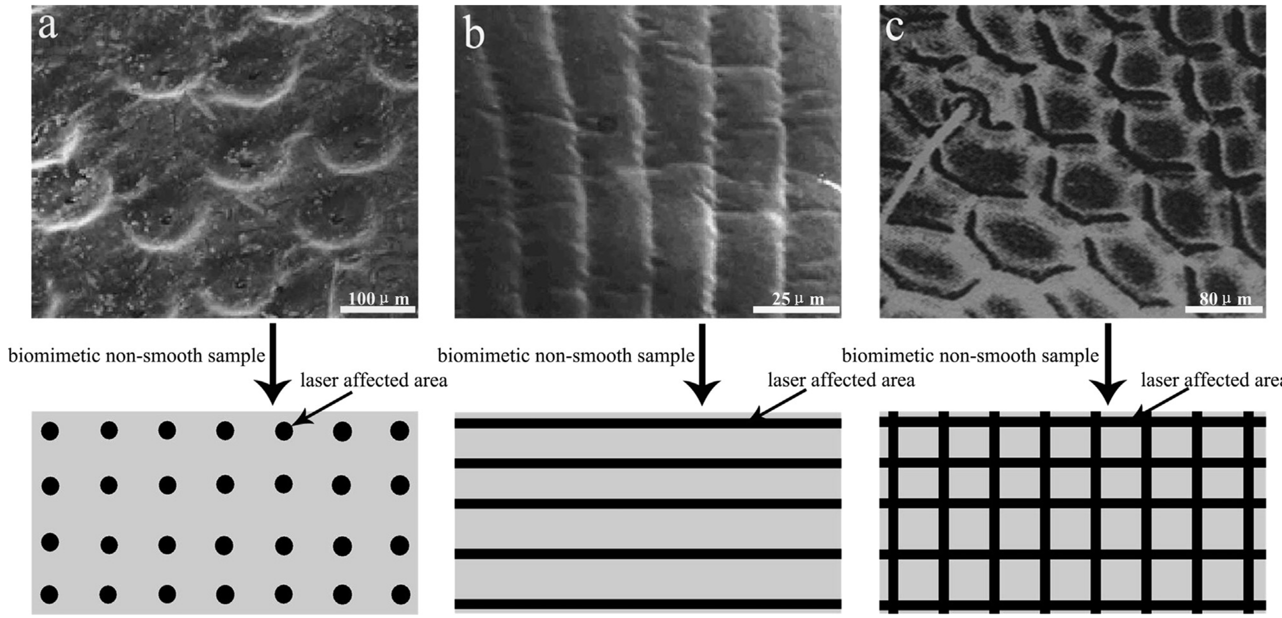

Fig. 1. Various non-smooth surfaces of soil animals and biomimetic non-smooth shapes: (a) punctuate non-smooth surface on the head of dung beetle and spot-shape laser affected area; (b) striate non-smooth surface on the elytrum of dung beetle and striation-shape laser affected area, and (c) reticulate non-smooth surface on the head of black ant and reticulation-shape laser affected area.

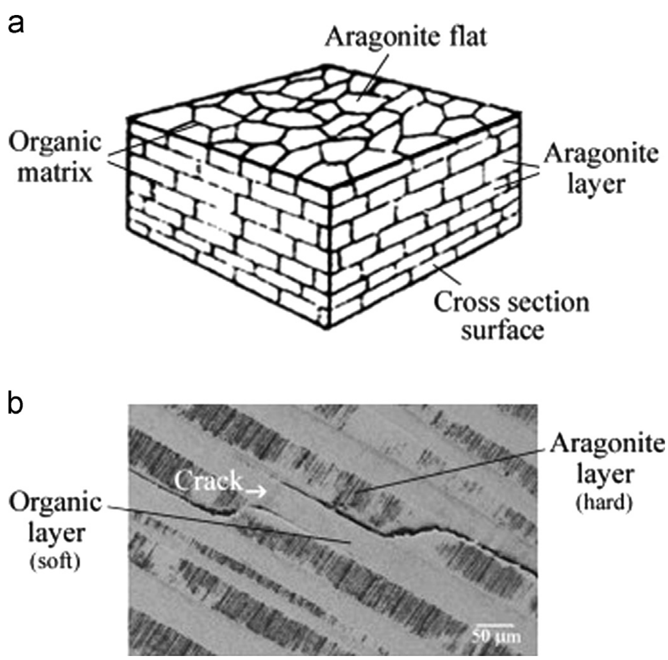

Fig. 2. The structure (a) and deflection of crack (b) [7] in the nacreous layer.

In practice, hot-work tool steel is repeatedly subjected to the rapid alternations in its surface temperature which results in thermal stress. The large thermal gradients create compression stress on the sample surface during heating and tension stress during cooling. Moreover, with increasing number of thermal cycles, the hot-work tool steel is not stable. The hardness and the microstructure can be modified by thermal cycle which finally results in the loss of mechanical strength of hot-work tool steel. Hot-work tool steels become so soft that the applied thermal stress is enough to cause plastic deformation. Then thermal fatigue crack is generated when the specimen no longer absorbs the plastic deformation due to the exhausted material ductility during the cyclic compressive and tensile stress condition. During die casting, different metals such as aluminum, magnesium or copper result in different surface temperature gradients of die which give rise to different thermal stability. Therefore, the objective of this study was to investigate the effect of different thermal cycle temperature on the microhardness and microstructure of laser affected area and matrix, as well as the thermal fatigue behavior of H13 hot-work tool steel with different biomimetic non-smooth shapes.

2. Material and methods

As one of the most important die casting materials, AISI H13 hot-work tool steel was chosen for this study. The chemical compositions of the H13 hot-work tool steel were 0.46 wt% C, 0.78 wt% Si, 0.25 wt% Mn, 5.07 wt% Cr, 0.83 wt% V, 1.38 wt% Mo, 0.10 wt% Ni and Fe in balance. Each sample was cut in the dimensions of 40 mm $\times$ 20 mm $\times$ 6 mm by an electric spark machine, and a 3 mm diameter round hole was drilled at one side of each specimen in order to fix it on the plate of thermal fatigue machine. A pulsed solid-state Nd-YAG laser source with a wavelength of 1.06 μm and maximum power of 300 w was employed to fabricate different biomimetic non-smooth surface shapes (spot-shape, striation-shape, reticulation-shape). The configuration and geometry of the manufactured biomimetic non-smooth samples are shown in Fig. 3. The laser processing parameters were pulse energy 22 J, pulse duration 10 ms, frequency 7 Hz, defocusing size 8 mm, scanning speed 1 mm/s. Argon gas was used as shielding gas with a constant flow rate of 5 l/min.

Before and after thermal fatigue testing, scanning electron microscope (Zeiss, Evo 18, Germany) combined with energy dispersive spectroscopy was applied for the microstructure investigation. The component phases were identified by an X-ray diffraction instrument (D/Max, 2500 PC, Japan). The cross-section appearances of the laser affected area were observed by an optical microscope (Zeiss, Axio Vert.A1, Germany). A stereomicroscope