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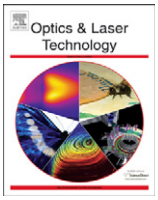

Effect of biomimetic non-smooth unit morphology on thermal fatigue behavior of H13 hot-work tool steel

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ABSTRACT

The thermal fatigue behavior of hot-work tool steel processed by a biomimetic coupled laser remelting process gets a remarkable improvement compared to untreated sample. The 'dowel pin effect', the 'dam effect' and the 'fence effect' of non-smooth units are the main reason of the conspicuous improvement of the thermal fatigue behavior. In order to get a further enhancement of the 'dowel pin effect', the 'dam effect' and the 'fence effect', this study investigated the effect of different unit morphologies (including 'prolate', 'U' and 'V' morphology) and the same unit morphology in different sizes on the thermal fatigue behavior of H13 hot-work tool steel. The results showed that the 'U' morphology unit had the optimum thermal fatigue behavior, then the 'V' morphology which was better than the 'prolate' morphology unit; when the unit morphology was identical, the thermal fatigue behavior of the sample with large unit sizes was better than that of the small sizes.

1. Introduction

In practice, hot-work tool steel is repeatedly subjected to the rapid alternations in its surface temperature which results in thermal stress. In fact, the thermal fatigue damage as a consequence of alternating thermal stress is one of the major reasons which lead to the failure of hot-work tool steel [1]. Therefore, it is important to investigate and enhance the thermal fatigue behavior of hot-work tool steels.

In recent years, we have investigated the thermal fatigue behavior and the wear behavior of hot-work tool steel and cast iron with non-smooth surface (including 'spot' shape, 'striation' shape and 'lattice' shape) processed by laser to imitate the cuticle of some soil animals. Results have indicated that the hot-work tool steel and the cast iron with non-smooth surface not only could enhance the thermal fatigue behavior but also could enhance the wear behavior compared with untreated sample [2–7]. For the thermal fatigue behavior, due to the non-smooth surface effect, the units not only inhibit the initiation of thermal fatigue cracks, but also hinder the propagation of thermal fatigue cracks. These functions of non-smooth units, according to different unit shapes on the surface of samples, are called the 'dowel pin effect' ('spot' shape), the 'dam effect' ('striation' shape) and the 'fence effect' ('lattice' shape), respectively. The 'dowel pin effect', the 'dam effect' and the 'fence effect' are the main reason of the remarkable improvement of the thermal fatigue behavior of hot-work tool steel and cast iron processed by laser.

Different kinds of sharks in nature have different cuticles morphologies which lead to different swimming speed [8,9]. In the field of material engineering, as is well known, the materials, which are treated by different technologies, have different microstructure morphologies which lead to different properties. Different unit morphologies have very important function to the 'dowel pin effect', the 'dam effect' and the 'fence effect' and different influence on the thermal fatigue behavior. Researchers have investigated the effect of non-smooth sample with single unit morphology on the thermal fatigue behavior, but the effect of different unit morphologies on the thermal fatigue behavior has not received much attention. Therefore, the objective of this study was to investigate the effect of different unit morphologies (including 'prolate', 'U' and 'V' morphology) on the thermal fatigue behavior of H13 hot-work tool steel, in order to find out the optimum unit morphology to effectively enhance the thermal fatigue behavior. In additional, the effect of the same unit morphology in different sizes on the thermal fatigue was investigated. Moreover, the mechanism of enhanced thermal fatigue behavior of different unit morphologies was studied.

2. Experimental

2.1. Material

As-annealed H13 hot work tool steel with a chemical composition listed in Table 1 was selected in the present study. Fig. 1

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Table 1
Chemical compositions of the H13 steel (wt%).

Composition	C	Si	Mn	Cr	V	Mo	Ni	P	S	Fe
Content	0.46	0.78	0.25	5.07	0.83	1.38	0.10	0.007	0.001	Bal.

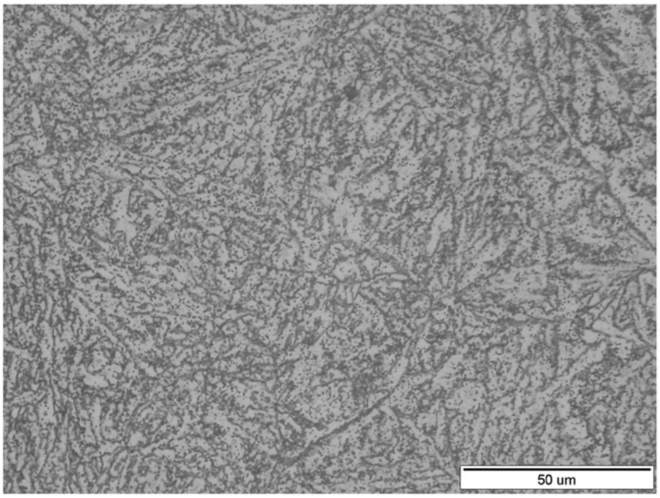

Fig. 1. Microstructure of annealed H13 hot work tool steel.

shows that the microstructure of test material, which is composed of pearlite and carbide.

2.2. Sample preparation

Experimental samples were machined into 40 mm long × 20 mm width with thickness of 6 mm by an electric spark machine, and a 3 mm diameter round hole at one side of each sample in order to be capable of fixing on the plate of thermal fatigue machine. To avoid reducing thermal fatigue life due to premature crack initiation from surface machining marks, the specimens were subjected to a standard metallograhic procedure starting with grinding on grit papers, followed by polishing, prior to the thermal fatigue tests, in order to remove all the surface irregularities and machine marks.

A solid state Nd-YAG laser of 1.06 μm and maximum 300 w was employed to fabricate different unit morphologies. The sample's number and their corresponding laser processing parameters were listed in Table 2. Argon gas was used as shielding gas with constant flow rate of 5 l/min. Through controlling the displacement of the working-bench, the distance of the parallel striations unit on the surface of the specimens was kept on 4 mm.

2.3. Experimental method

Transverse sections of units were obtained after laser processing and standard methods of metallography were followed to study the microstructure, dimensions, and micro-hardness. The component phases of each unit morphology and matrix were characterized by scanning electron microscope and X-ray diffraction instrument. The Jade software was employed to calculate the full width at half maximum (FWHM) of X-ray diffraction peaks. The cross-section appearances of the units were observed by optical microscope. Typical thermal fatigue crack propagation on each sample surface was assessed by stereomicroscope. Micro-hardness in the cross-section was measured by a Knoop and Vickers Hardness Table. Pulse energy was measured by a laser energy meter.

Table 2
The laser processing parameters of corresponding samples.

No.	Pulse energy (J)	Pulse duration (ms)	Frequency (Hz)	Scanning speed (mm/s)
A1	10.08	4	7	1
A2	6.21	4	5	1.25
B1	13.62	10	6	1.25
B2	8.27	10	7	0.5
C1	15.39	10	5	1
C2	11.51	8	7	0.75

Thermal fatigue test was carried out by a self-restrain thermal fatigue testing machine, which was designed to install multiple specimens simultaneously in order to give a good comparison under identical testing condition and could record number of thermal cycles automatically. The specimens were heated by a high temperature electric resistance furnace, and cooled by running water. The surface temperature of samples was monitored throughout the tests by thermocouple which was welded to the specimen at the center of its length. The duration of a complete thermal fatigue cycle was 63 s, with 3 s for cooling, and 60 s for heating. Thermal fatigue test was carried out in a temperature range between 700 °C and 25 °C, and the samples were free from any externally applied load. The samples were taken out to observe the cracks every 400 cycles. Then the thermal fatigue behavior of different unit morphologies was evaluated.

3. Results and discussion

3.1. The dimensions, micro-hardness and microstructure of non-smooth unit

In Fig. 2 cross-sectional views of different unit morphologies processed by laser are depicted. The 'prolate' morphology units are showed in A1 and A2; the 'U' morphology units are showed in B1 and B2; the 'V' morphology units are showed in C1 and C2. Fig. 3 shows the surface morphology of the samples with different unit morphologies. It can be seen that the surfaces of units are without holes or cracks which may become the initiation sources of thermal fatigue cracks so that harm the thermal fatigue behavior of samples. The dimensions and micro-hardness values of different unit morphologies are listed in Table 3. The micro-hardness values were obtained at five different locations on the polished and etched cross-section of each sample.

Fig. 4 shows the microstructures of the samples in Table 2. The microstructures of melted zone of different unit morphologies are very fine cellular structures due to the rapid cooling rate after laser processing. It also can be seen from Fig. 4 that unequal sizes of the cellular structures indicate the unevenly cooling rates in the laser treated region.

3.2. The composition phases of different unit morphologies

Fig. 5(a)–(c) show X-ray diffraction of untreated sample and the samples in Table 2. The constitutional phase of the untreated sample is ferrite. The FWHM of X-ray diffraction peaks of untreated sample is 0.407°. The FWHM of X-ray diffraction peaks of A1 through C2 samples are 0.561°, 0.565°, 0.522°, 0.562°, 0.441°and 0.536°, respectively. As shown in Fig. 5(a)–(c), the samples in Table 2 have identical diffraction peaks locations which indicate that the composition phases of non-smooth samples are similar. The results of the FWHM indicate that the laser processing causes the X-ray diffraction peaks to broaden compared with untreated sample, which indicate that martensite has generated after processed by laser. Therefore,