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Crack growth behavior at thermal fatigue of H13 tool steel processed by laser surface melting

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ABSTRACT

Biomimetic specimens with striation-shape and diamond-shape morphologies were obtained by laser surface melting on an H13 die steel surface in quenched and tempered state using Nd:YAG laser. The thermal fatigue resistance behavior of the specimens with man-made crack sources was measured. For a set of number of thermal fatigue cycles, the two biomimetic specimens demonstrated decelerated crack growth that indicated better fatigue resistance as compared to the untreated one. The microstructures of the laser melting zone were finer than those of the untreated H13 specimen, and the microhardness of the former was higher than that of the latter after same number of thermal fatigue cycles.

1. Introduction

H13 steel has high hardenability, and good thermal fatigue performance and retains toughness and strength at high temperatures and it is widely used in hot-work dies, such as die casting dies. In die casting production, the die material is repeatedly subjected to rapid alternations of its surface temperature which results in thermal gradients on the die surface. Compression stress is induced in the die surface during heating, and tension stress during cooling [1,2]. With increasing numbers of thermal cycles, the hardness and microhardness of H13 die tool steel can change, which eventually results in loss of mechanical strength and plastic deformation. Thermal cracks are generated due to the cyclic compressive and tensile stress conditions, which result in the die failure [3]. Recently, many methods have been developed in the field of die steel surface treatments which seek to prolong die service life. These include surface coating techniques, vapor deposition and laser surface strengthening [4,5].

Lasers, which are a source of high density monochromatic radiation, are used in a variety of applications in the surface engineering of die materials. These applications are classified into laser cladding, laser quenching and laser melting. Laser surface melting (LSM) involves laser heating of the steel surface to above the melting temperature followed by self-quenching, inducing a martensitic transformation on the surface of die material, which improves surface properties [6–8]. Khalid Imran et al. studied bimetallic dies with direct metal-deposited steel on Moldmax for high pressure die-casting application [9].

Through natural selection over thousands of years, animals and plants have developed biological structures adapted to living with minimal energy costs in their natural habitats [10–12]. As shown in Fig. 1, lotus leaves have rough surface structures, which are helpful to gather water on the leaf and benefit the plant by keeping the leaves moist and clean for a long time. Dragonfly wings have evolved to have a high density of main and branch veins that enable them to flap their wings at a high frequency. The scutes of pangolins and oyster shells are composite structures of both soft and hard substances, which give them excellent wear resistance and mechanical properties. Inspired by these wonderful biological structures, researchers have been able to solve many engineering problems. Ren et al. [13] presented a theory on biomimetic non-smooth surfaces after they studied soil animals. They applied biomimetic structures to die and tool surfaces made of 3Cr2W8V using laser melting and found that the wear resistance [14] and thermal fatigue resistance [15,16] were improved. Tong et al. [17] applied laser surface melting to gray iron to generate different laser produced patterns to improve the thermal fatigue resistance. Jia et al. [18,19] carried out a series of studies using a biomimetic laser melting process (BLRP) on die-casting dies of H13 and SKD61 under actual production conditions, and found that the regions with biomimetic units had properties which enhanced the die service life.

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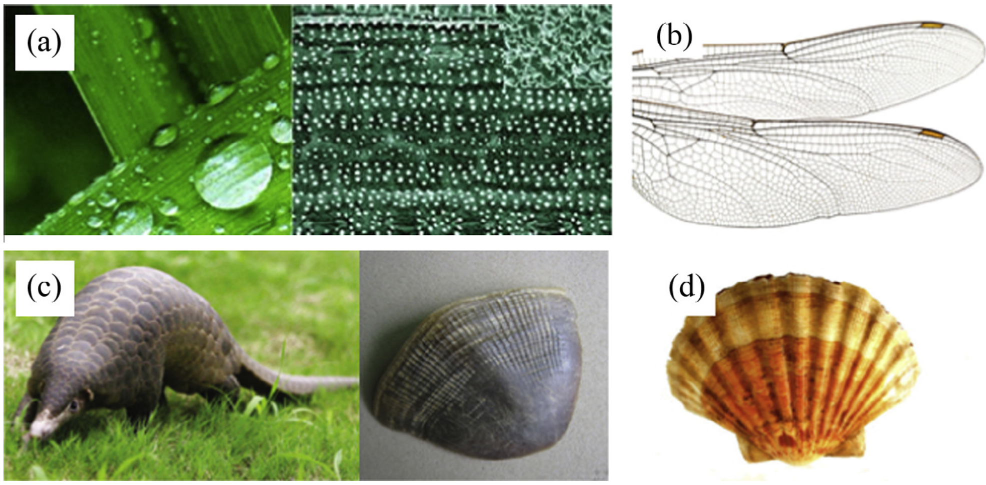

Fig. 1. Various surface structures of animals and plants: (a) convex shape of rice leaves; (b) lattice pattern on a dragonfly wing; (c) scutes of a pangolin; (d) organic and aragonitic structure of oyster shells.

Investigations of and enhancements to the mechanical properties and thermal behaviors of H13 steel have been carried out [7,20–25] by the group from Jilin University, China. Meng et al. [20] investigated the thermal fatigue behavior of H13 steel in quenched and tempered states with different biomimetic non-smooth shapes. They investigated the effects of different temperature thermal cycles on the microhardness and microstructure of the laser affected area and the matrix. Cong et al. [21,22] compared the thermal fatigue resistance of annealed H13 steel repaired by a laser remelting process and laser alloying. Meng et al. [23] employed laser cladding to fabricate non-smooth samples of annealed H13 material and compared the effects of laser cladding and laser surface melting on thermal fatigue behavior. Cong et al. [24] did experiments to repair annealed H13 die steel specimens with cracks using laser filler wire. Meng et al. [25] investigated the effect of biomimetic non-smooth unit morphology on thermal fatigue behavior of annealed H13 hot-work tool steel and demonstrated that the 'U' morphology unit had the optimum thermal fatigue resistance.

Quenched and tempered H13 steel with a hardness range of 480–520 HV is the most commonly used die steel for die casting dies. In the abovementioned works, many attempts were made to understand the effect of laser surface melting and laser cladding on the thermal fatigue behavior of annealed H13 steels [21–25]. Few studies (only references [18,7]) were done on specimens of H13 that were quenched and then tempered, which are the same conditions that the die casting dies experience when used.

In this paper, the laser melting process is employed to obtain biomimetic shapes on quenched and tempered H13 die material. Specimens were made with two types of morphologies, striation-shape and diamond-shape, which were obtained by laser surface melting using an Nd:YAG laser. The thermal fatigue resistance behavior of specimens with a man-made crack source was carried out which simulate the die casting working condition. The microstructure, the microhardness, crack propagation, and related mechanisms are discussed.

2. Materials and methods

2.1. Materials

In this study, H13 steel was used the sample material. The H13 steel was quenched at 1030 °C and then tempered at 550 °C, which is the same heat treatment used in the production of die casting dies. The chemical composition of H13 steel is listed in Table 1.

2.2. Specimen preparation

As shown in Fig. 2, rectangular thermal testing specimens were cut into a $30 * 18 * 3.5$ mm using an electro-discharge machine (EDM). On each specimen, a notch shaped as an isosceles right triangle with isosceles edges of length 2 mm was made in the long edge using an EDM with a molybdenum wire diameter of 0.18 mm, and a man-made crack source 1.5 mm long was cut at the end of the notch. To avoid the effects of surface machining marks on the fatigue life, specimens were mechanically polished using progressively finer grades of silicon carbide impregnated emery paper prior to the thermal fatigue test.

Before the laser melting process, the specimens were cleaned using a NaOH solution and then alcohol to remove oxide scales from the surface. In order to study the influence of LSM on the thermal fatigue behavior of H13 material, two macroscopic morphologies of biomimetic specimens were designed: striation-shape and diamond-shape. As shown in Fig. 2(a) and (b), the designed dimensions of the LSM morphologies are: $D = 1.5$ mm, $S = 1.8$ mm, $L = 4$ mm, $\alpha = 135°$. An untreated specimen of the same size was prepared and used as the reference.

A pulsed solid-state Nd:YAG laser source with a wavelength of 1.06 μm and maximum power of 300 W was employed to obtain different morphologies on the biomimetic specimens. The circular spot size of Gaussian laser beam on the specimen surface was 1.6 ± 0.1 mm. The laser parameters are listed in Table 2. The macroscopic morphologies of the specimens after LSM are shown in Fig. 2(c) and (d).

To mimic the working surface of a die-casting die, after LSM the specimens were ground to remove the top 0.15 mm and polished using 2500 grade silicon carbide impregnated emery paper to remove the rough surface layer. The morphology of a specimen after LSM and polishing is shown in Fig. 3.

Thermal fatigue testing was carried out by a self-restraint thermal fatigue testing machine, as shown in Fig. 4. The specimen is heated by an electromagnetic induction heating coil and the temperature of specimen rises quickly. It is cooled by running water which is opposite to the V-notch of the specimen. The machine can heat and cool the specimen according to the setup parameters

Table 1
Chemical composition of H13 steel in wt%.

C	Si	Mn	Cr	Mo	V	P	S
0.41	0.88	0.34	4.89	1.66	0.9	0.02	0.02