Optics & Laser Technology 64 (2014) 227–234

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

The characteristics of treated zone processed by pulsed Nd-YAG laser surface remelting on hot work steel

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ARTICLE INFO

Article history:
Received 10 February 2014
Received in revised form
11 May 2014
Accepted 15 May 2014

Keywords:
Steel
Laser remelting
Microstructure

ABSTRACT

In this study, the surface of H13 steel was treated using laser surface remelting. Some important characteristics of the treated zone (biomimetic strengthening units) were investigated, e.g. size, cross-sectional morphology, microstructure and hardness as functions of average peak power density and effective peak power density. The results indicate that different combinations of average peak power density and effective peak power density could vary the appearance of cross-sectional morphology, microstructure and hardness. An appropriate range of EPPD for preparing the treated zone was acquired: 595–1448 W/mm^2. In this range, the depth/width ratio of 0.31–0.47 and microhardness of 559–667 HV were obtained.

1. Introduction

Surface physicochemical and mechanical properties play an important role in the working life of the materials. For example, the improved pitting corrosion resistance of titanium sheet by laser surface remelting can enlarge its application range in harsh environments [1]. The better wear resistance of cast iron with biomimetic surface processed by laser led to the higher serve life of vehicle brakes [2]. For die-casting tooling, the in-service life, to large extent, depends on the thermal fatigue resistance of materials [3]. Due to the wide applications of steel and cast iron, many traditional techniques have been carried out to improve their surface properties, such as surface coating, electric plating, heat treatment, vapor deposition process and laser transformation hardening, etc.

Bionics has placed profound effects on the development of materials science over the past 30 years. The unique, desirable morphology and structure of animals and plants mainly come from their evolution and adaption to the environment for millions of years. It inspires development of materials science in many aspects. For instance, Neinhuis and Barthlott studied surface design of water-repellent, anti-adhesive and waxy leaves based on 200 water-repellent plant species [4]. As a result, water-repellent, self-cleaning or anti-adhesive materials were fabricated; Bechert et al. studied the drag reduction mechanisms of shark skin by analyzing various riblet shapes immersed in a viscous Couette type shear flow and found that the short staggered riblets have reduced drag [5], which reduced the liquid friction force of materials such as "sharkskin" swimwear; etc.

In a traditional point of view, the surfaces of components should be smoothest, to reduce the contact friction or adhesion [6]. However, opposite to this conception, the body surfaces of some animals such as shark [7], dung beetle [8] and pangolin [9] are characterized by respective non-smooth, rough surface structures, which make them move quickly in the water or under the ground without injuring their body. The crossing veins on leaves protect/support the leaf structure. So leaves can withstand natural force from rain water, wind and occasional impact. The shell surface consists of two alternate layers: hard aragonite and soft organic materials. This is because the hard aragonite can withstand natural force of water and attacks from predators, and moreover, the soft organic material provides sufficient ductility and reduces stress concentration. The particular surface morphology of each animal mentioned here is the result of development during millions of years so it results in excellent adaptability to the particular living environment.

Since many applications are related to surface of materials, e.g. wear, thermal fatigue and corrosion, modification of surface microstructure is pivotal to these properties. Laser can harden/

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http://dx.doi.org/10.1016/j.optlastec.2014.05.015
0030-3992/

melt the surface material. It is an important method in the aforementioned applications, without processing the entire material. So due to the characteristics of the natural surface of the species introduced earlier, the study on biomimetic non-smooth surface was inspired. A new technique, biomimetic coupled laser remelting (BCLR) treatment, has been applied to fabricate non-smooth surfaces on the die and tool steels. Sample surface was treated selectively using laser. The treated zone was arrayed/engineered similar with the particular surface appearance of particular species, such as the convex spots of beetles or the hard-soft surface structure of shell, whose studies would be mentioned later. The treated zone was thereby named as biomimetic strengthening unit. Then the treated sample exhibited better service and performance [9,10].

The wear resistance of 3Cr2W8V, H13 and HD die steel with non-smooth surfaces was improved; note that the size of non-smooth units was a major factor [11]. In another study [12], a BCLR method was adopted to process a hot work tool steel, which resulted in improvement in strength and ductility simultaneously. The unit size had a significant effect on the tensile property of non-smooth surfaces. Similarly, a study on BCLR for enhanced thermal fatigue behavior of die steel was carried out [13], in which, the thermal fatigue resistance of 3Cr2W8V die steel with biomimetic surface was investigated. It was found that the units with different sizes had various effects on preventing thermal fatigue cracks. Meng et al. [14] studied the improved thermal fatigue resistance of H13 die steel with various unit morphologies (including ‘prolate’, ‘U’ and ‘V’ morphology) beneath the surface; the optimum thermal fatigue behavior of unit with ‘U’ morphology was reported.

In fact, biomimetic surface processed by the BCLR process is characterized by the coupled surface structure which is composed of structural units and matrix material. These units have different microstructures or chemical compositions from the matrix material. The morphological factors include spacing and distribution (such as spots, stripes and network) of units. Thus, the chemical compositions of unit and biomimetic surface morphologies play pivotal role in affecting properties of materials. For instance, Tong et al. [15] investigated the thermal fatigue characteristics of gray cast iron with biomimetic surface treated by laser alloying using Cr powder. The treated sample had superior resistance to thermal fatigue, compared with laser melting treated sample. Zhang et al. [16] studied microstructure, hardness, and thermal fatigue behavior of H21 steel with several treatment morphologies (strengthening spots, stripes and network) processed by laser surface remelting and reported that amongst all the three laser-treated morphologies, strengthening network led to the best thermal fatigue resistance. Another study [17] reported effects of strengthening stripes on the surface of the medium carbon steel and showed that the specimen with 2-mm-spacing striation had the highest resistance to thermal fatigue of all. Meanwhile, aforementioned geometric characteristics of units beneath the treated surface should be considered as a significant factor influencing the surface property. On the other hand, the cross-sectional morphology and mechanical properties of units are both dependent on laser processing parameters. Due to it, it is necessary to investigate the relationship between the characteristics of biomimetic units (size, cross-sectional morphology, and mechanical property) and processing parameters.

Note that in pulsed laser surface remelting (LSR), a series of overlapping points make up the scanning track [18]. Laser pulse energy, duration, and scanning speed all place important effects. In addition to the processing parameters such as pulse energy, pulse width, frequency and scanning speed, overlapping ratio is another significant factor in pulsed LSR. A previous study [19] showed that the same average peak power density obtained from different combinations of energy and pulse width can lead to obviously different characteristics in molten zone. Particular surface morphology (the melting and vaporization of surface material, surface roughness and maximum peak-to-valley height) of a single laser track on 3Cr2W8V steel led to the high quality of non-smooth biomimetic unit by Zhang et al. [20]. Then the penetration depth and the surface roughness of units were optimized [21]. However some crucial characteristics of treated zone (or biomimetic unit, with BCLR) coupled with laser processing parameters were less studied, such as the cross-sectional morphology, microstructure and the mechanical property.

The goal of this work is to investigate the effects of laser processing parameters on the geometric characteristics, microstructure and mechanical property of treated zone and optimization of related processing parameters.

2. Materials and methods

As-annealed hot work steel, AISI H13, was used as the base material in this study. The chemical composition of the base plate is listed in Table 1.

The schematic of laser treatment in this work is shown in Fig. 1. The pulsed solid-state Nd:YAG laser source (Han's Laser, WF300, China) with maximum power of 300 W and wavelength of 1.06 μm was used here. The movement of laser beam was controlled by a self-sustaining robot (Motoman, MH6, Japan) with precision of ± 0.08 mm. The spot diameter of laser beam on the sample surface was 1.6 ± 0.1 mm. Pure argon gas was employed to protect the treated surface, through a side nozzle with the flow rate of 5 l/min. As-received samples were cut into 20 mm in length, 10 mm in width and 6 mm in thickness, using EDM (Electrodischarged Machining). Prior to processing, specimens were prepared to reach the surface roughness of 0.25 μm R_a. Laser treatment in this work was designed with different parameters, as presented in Table 2.

Cross-sectional morphology of biomimetic units was characterized by an optical microscope (Zeiss, Axio.Imager.A2m, Germany). A three dimensional confocal scanning laser microscope (OLYMPUS, LEXT-OLS3000, Japan) was used to examine the surface morphology. Microstructural studies were conducted using a scanning electron microscope (Zeiss, Evo18, Germany). The phase structures were identified by X-ray diffraction (D/Max, 2500PC, Japan). The Cu Kα radiation was operated at a voltage of 40 kV and current of 40 mA with the irradiation angle of 0.02°. The Vickers hardness profiles were obtained using a microhardness tester (Buehler, 5104, USA) with the applied load of 200 g for 10 s. Each result for microhardness was conducted five times to calculate the average values.

3. Results

In pulsed LSR in Fig. 2, overlapping factor (OF) is usually calculated [22,23] as

$$\mathrm{OF}(\%) = \frac{L - L_0}{L} \times 100 = \left(1 - \frac{L_0}{L}\right) \times 100$$

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

C	Si	Mn	Cr	Mo	V	Ni	P	S	Fe
0.47	0.93	0.38	4.88	1.19	0.92	0.07	0.007	0.002	bal.