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Tensile property of a hot work tool steel prepared by biomimetic coupled laser remelting process with different laser input energies

Chuanwei Wang[a], Hong Zhou[a,*], Zhihui Zhang[b], Yu Zhao[c], Peng Zhang[a], Dalong Cong[a], Chao Meng[a], Fuxing Tan[d]

[a] The Key Lab of Automobile Materials, The Ministry of Education, Jilin University, Changchun 130025, PR China
[b] The Key Lab of Terrain Machinery Bionics Engineering, The Ministry of Education, Jilin University, Changchun 130025, PR China
[c] School of Materials Science and Engineering, Changchun University of Technology, Changchun 130012, PR China
[d] Changchun Railway Vehicles Co., Ltd. Changchun 130062, PR China

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ABSTRACT

Coupled with the biomimetic principle, a hot work tool steel (4Cr5MoSiV1) was manufactured using a laser with different input energies. Results of tensile tests confirmed that the biomimetic coupled laser remelting (BCLR) process had an advance effect on improving the strength and ductility of 4Cr5MoSiV1 steel simultaneously. Microstructure examinations demonstrated that a fine microstructure along with nano scale carbide was acquired in the BCLR units, which produced an accumulative contribution of grain refinement, precipitation strengthening and a mixed microstructure. Based on the well distribution of the BCLR units, the beneficial effect of stress transfer from the matrix to the units on tensile property was also analyzed.

1. Introduction

As a hot work tool steel, 4Cr5MoSiV1 steel (the designation of hot work tool steel in the Chinese standard T1299-2000), the chemical composition of which is similar to that of AISI H13 steel, is the tool material that is used almost exclusively on extrusion dies as well as for tools for hot pressing of copper alloys and steel forging. It is characterized by high strength and ductility, good tempering resistance, and moderate cost [1,2]. Many efforts have been made to improve its properties, such as stress-strain properties, surface mechanical properties and thermal fatigue resistance [3–5]. Inspired by the excellent properties of the corneum of soil animals, such as good anti-adhesion, wear-resistance, considerable strength and toughness and so on [6–8], our research group applied biomimetic coupled laser remelting (BCLR) method on the die and tool steel to form a series of biomimetic units in its surface layer. After the BCLR treatment, there displayed a considerable improvement not only on inhibiting the initiation and propagation of thermal fatigue cracks [9,10] but also on wear resistance [11,12], indicating an attractive combination of strength and toughness of materials with these biomimetic units. However, little had been done to investigate the enhanced degree of the strength and toughness of the hot work tool steel produced by BCLR process, and the strengthening and toughening mechanisms of the materials with biomimetic units are still not clear.

In regard to the corneum of soil animals, in spite of significant differences in dimensional, mechanical, chemical and dynamical situations, the most basic building block of biological corneum appears to be a simple and elegant structure consisting of constriction units embedded in a matrix [13]. According to the structural shape of the constriction units, it was found that the units always fall into the categories as follow: peg, squama, bristle and ripple [6]. The biological prototype of peg-shaped units derives from the soil-burrowing animals [14], e.g. dung beetle and ground beetle as shown in Fig. 1. Moreover, further investigation discovered, via analysis and measurement that the microstructures in these basic constriction units are different with those in the matrix, and the alternately unit and matrix structure plays a key role in understanding the excellent properties of the corneum. Based on the above researches of biological corneum of soil animals, in this work, the structure of the biomimetic corneum was abstracted to a model with characteristics of alternately unit and matrix, while 'peg' type was selected as the shape of the units. Therefore, 4Cr5MoSiV1 steel with peg-shaped biomimetic units was subsequently processed by a pulsed Nd: YAG laser with different laser input energies. Tensile tests and microstructure examinations were carried out to investigate the effect of the BCLR treatment on tensile property and further

* Corresponding author. Tel.: +86 431 8509 4427; fax: +86 431 8509 5592.
E-mail address: cwwang11@mails.jlu.edu.cn (H. Zhou).

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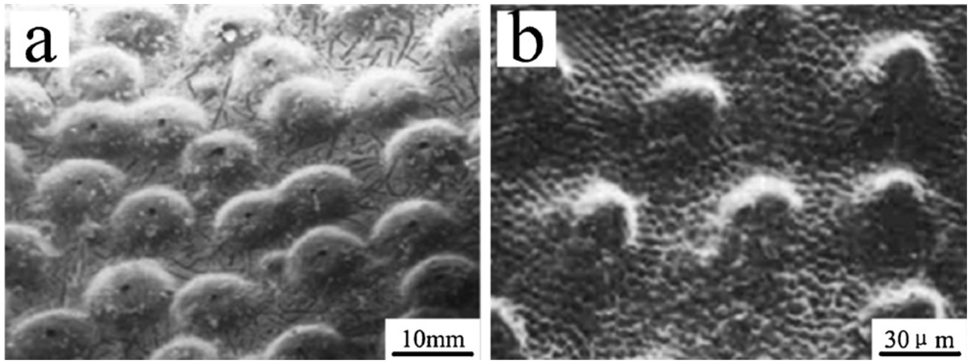

Fig. 1. Typical peg-shaped units of the corneum of soil animals [14]: (a) peg-shaped units of the head of dung beetle, (b) peg-shaped units of the elytrum of ground beetle.

study the strengthening and toughening mechanism of it. Furthermore, the influence of laser input energy on tensile property of BCLR samples was also analyzed.

2. Experimental procedures

2.1. Experimental materials

The material used here was an annealed hot work tool steel, 4Cr5MoSiV1, with a chemical composition of 0.37 C, 0.79 Si, 0.37 Mn, 1.29 Mo, 4.91 Cr, 0.92 V, 0.024 P and 0.0022 S (mass%).

2.2. Sample preparation

Dog-bone shaped tensile specimens with gauge length 24 mm, width 10 mm and thickness 1.7 mm were cut by an electric spark machine. To eliminate the surface and side-face roughness effect on tensile property, before the laser processing, the samples were mechanically polished using progressively finer grades of silicon carbide impregnated emery paper to remove all the surface irregularities and machining marks. Mimicking the corneum of beetles, peg-shaped biomimetic units were fabricated in an argon atmosphere at 22 °C by laser beam. The geometry and details of these biomimetic specimens were shown in Fig. 2, and the unit distance between two neighboring peg-shaped units on biomimetic specimens is 2 mm. Laser facility used here was an Nd: YAG laser in a pulse wave mode, operating at 1064 nm, maximum power 300 W with a Gaussian distribution of the energy in the beam. To investigate the influence of laser input energy on tensile property, the energies of single pulse were 70, 115, 160 and 205 J/cm^2 to form the units in the surface layers of BCLR specimens. These are named samples BCLR-1, BCLR-2, BCLR-3 and BCLR-4, respectively. The other processing parameters were defocusing amount 7 mm, laser pulse duration 5.0 ms, frequency 1 Hz, scanning speed 2 mm/s and a circular spot size 1 mm in diameter on the specimen surface. Untreated specimens were also prepared for comparing.

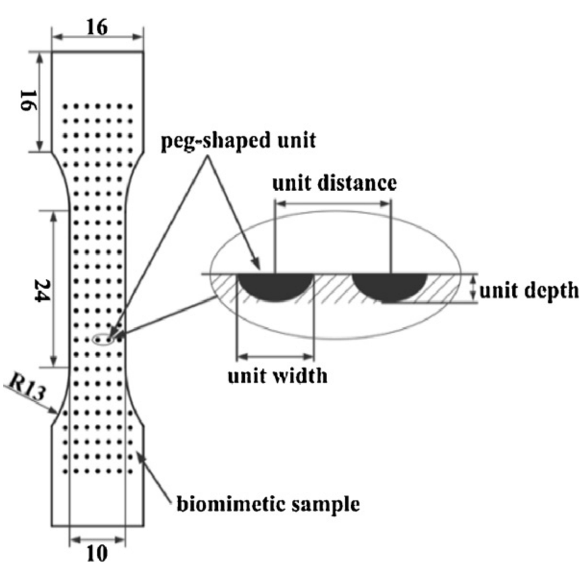

Fig. 2. A sketch of peg-shaped biomimetic sample.

2.3. Experimental methods

After the laser processing, a transverse section was obtained from each sample, and the standard method of metallography was followed to prepare the samples for the microstructure analysis, using a scanning electron microscope (Zeiss, Evo18, Germany). A confocal scanning laser microscope (OLYMPUS, LEXT OLS3000, Japan) was used to analyze the details of the biomimetic units for comparison purpose. Molten phase structures were identified by X-ray diffraction (D/Max, 2500PC, Japan). The Cu Ka radiation at 40 kV with a current of 40 mA was used as the X-ray source and the detector scanned the samples with an angle of 0.02°.

Tensile tests were performed on a material testing system equipped with a servo-controlled hydraulic testing system (MTS, 810, USA) at a strain rate $3.5 \times 10^{-4}\ s^{-1}$ and room temperature (22 °C). Four repeated tensile tests were performed on the tested samples for obtaining the average value.

3. Results and discussion

3.1. The dimensions and surface morphology of the BCLR units

Fig. 3 shows the units' transverse sections optical micrographs after BCLR treatment using different laser input energies, and they presented white and bright crescent surrounded by the parabola-shaped contour line. Within the narrow and dark contour line is the transition zone which presents the boundary between peg-shaped unit and substrate beneath. Table 1 illustrates the input energy of single pulse laser beam, the depth, the width and the area of the units' transverse sections. Dimensions of the units were the average of five measurements of each specimen. It is well known that the laser processing of materials is a course of energy exchange from light to heat. Therefore, the more light energy a single laser pulse irradiated the more heat energy the steel absorbed, which meant a bigger volume of the remelting steel. Consequently, it can be seen in Fig. 3 and Table 1 that the dimensions of units sort BCLR-1 < BCLR-2 < BCLR-3 < BCLR-4 by size. However, it's worth noting that when the laser input energy increased to the highest value at which not only remelting but also serious local evaporation took place, considerable material loss occurred during the laser processing and a