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The mechanical properties of medium carbon steel processed by a biomimetic laser technique

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ABSTRACT

We investigate the effects of biomimetic laser surface treatment on the mechanical properties of medium carbon steel. Steel surface was strengthened by laser-treated or -hardened area (the biomimetic strengthening spots). Microhardness, UTS and YS are simultaneously improved by the martensitic microstructure with nano-sized carbides due to the self-quenching effect of laser treatment. The ductility is also increased but not continuously. This is because the laser-induced martensite is detrimental to ductility. In addition, thermal fatigue behavior of medium carbon steel is improved. Fewer cracks are found after thermal fatigue test. Crack nucleation and propagation are hampered by the strengthening spots. The biomimetic sample, as compared with the as-received counterpart, has a slower crack growth.

1. Introduction

Medium carbon steel has been considered as one of the most important structural materials because of its stable chemical properties and good mechanical properties [1–3]. It is mainly applied to the automobile, ship-making, and military industries due to its proper alloying concentrations that give this wide availability. As our requirements to the safety and service grow, studies [4–7] are carried out to better its service by improving relative properties.

Hot or cold working is a good way for this purpose. Clayton and Jin [1] employed a cooling process to develop a microstructure of medium carbon steel, which comprises carbide-free bainite ferrite laths, with or without lath boundary retained austenite. This microstructure is the best of all samples in that work and exhibits a wear resistance comparable to that of Hadfield's austenitic steel under severe rolling/sliding contact. In the meanwhile, another study [7] shows that an intercalated protective layer by co-precipitation provided additional resistance to corrosion as a corrosion inhibitor and reduced corrosion rate.

We have developed a new method to improve the mechanical properties of steels and irons, namely the biomimetic strengthening technique [8–12]. This method is as effective as those aforementioned [1,4,7]. By mimicking the nature or structure of some creatures like pangolins and leaves that completely adapt to their environment, similar surfaces on steels can be acquired. Notwithstanding some biomimetic techniques employed casting [13] and etc., most of them prefer laser surface process (melting or remelting) [12,14]. This is because laser can be easily operated and moreover it can mimick many complex surfaces, such as spots and networks. One of our previous studies [14] reported an improvement of mechanical properties of H13 die steel led by the surface with biomimetic strengthening spots (convex units). This structure mimicks the outer skin of some beetles and the convex structure gives them excellent resistance to wear conditions. Results show that the ultimate tensile strength, yield strength and elongation were increased due to it. Zhang et al. [8] studied the thermal fatigue properties of medium carbon steel using this method and related mechanisms were discussed but further studies are still needed with regard to the importance and potential of this material. In another study, Zhou et al. [15] also investigated the effects of biomimetic strengthening stripes on the thermal fatigue behavior of steel. It indicates that nevertheless the biomimetic laser technique can fabricate strengthening structure in different shapes; these structures benefit the surface properties of steel.

Here we provide a detailed study on effects of biomimetic laser technique on the mechanical properties of medium carbon steel, in order to fulfill the vacancy of this field. The microstructure, mechanical properties and their relation were discussed.

2. Materials and methods

The No. 45 steel was chosen to represent medium carbon steel. Its chemical compositions are 0.48 wt% C, 0.2 wt% Si, 0.45 wt% Mn,

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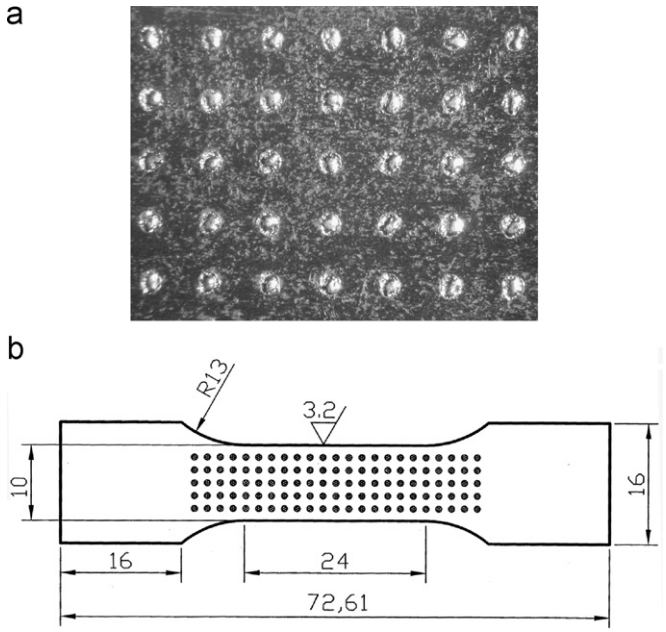

Fig. 1. The surface morphology of biomimetic samples: (a) Biomimetic strengthening spots on sample surface, each spot represents one laser surface treatment; (b) overview of the biomimetic samples for tensile test.

0.03 wt% S, 0.01 wt% P and Fe in balance. This material is the one studied in Ref. [8]. Samples were cut in the dimension of $40 \times 20 \times 3$ mm^3 using an electro-discharge machine. The biomimetic laser technique was described elsewhere [14–17]. So it is only briefly introduced here. An Nd:YAG laser with the wavelength of 1.06 μm was employed to prepare the biomimetic surfaces on samples. The surface morphology of the samples was engineered to mimick that of beetles covered by some convex spots. This feature is believed to provide excellent adaptability in their corresponding habitats [18]. The surface morphology of the samples is shown in Fig. 1a. Our previous study [17] shows that changing some key parameters, such as the current and the wavelength, led to the change of treatment effects like the effective strengthening depth. So in this study, the laser parameters are same for all samples. The diameter of diomimetic strengthening spots is 0.7 mm, and they are lined in two directions, along the tensile direction and perpendicular to it. The spacing between every two spots is 1.5 mm. The schematic of a tensile test sample is shown in Fig. 1b.

In order to determine the relationship between mechanical properties and microstructures, tensile and thermal tests were carried out. The sample for tensile test is pictured in Fig. 1b. Microhardness was also examined using a Knoop and Vickers Hardness Table (USA), under a load of 25 g. The thermal fatigue tests were carried out on a self-controlled thermal fatigue testing machine. A complete cycle consists of heading for 80 s up to the maximum temperature of 650 °C in resistance furnace, and then water cooling for 3 s to the minimum temperature of 25 °C in water tank. Plain-view and cross-sectional microstructures of the samples were characterized by scanning electron microscopy (SEM, JSM-5600LV, Japan) equipped with energy dispersive specstrometers (EDS). X-ray diffraction (XRD) was also used to examine samples.

3. Results

Fig. 2 shows the SEM microstructures of the as-received No. 45 and laser-treated steels. Apparently the as-received microstructure comprises ferrite and austenite (see Fig. 2a). This characteristic was once reported elsewhere [8,15]. In comparison, the microstructure

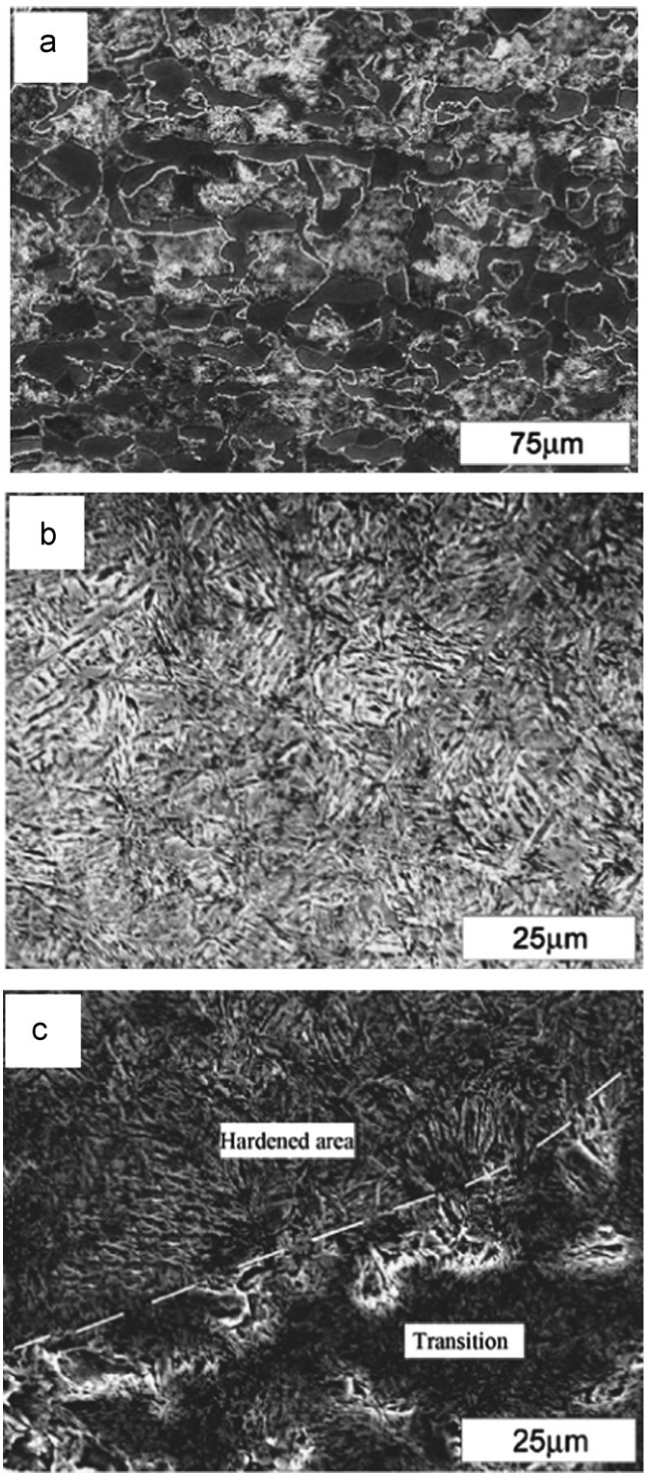

Fig. 2. The plain-view SEM micro-structure of the as-received and laser-treated steels: (a) microstructure of as-received No. 45 steel; (b) laser-treated (a); part (c) shows the boundary of a and b with a transition zone between them.

of the strengthening spots mainly consists of martensite. The two microstructures were shown simultaneously in Fig. 2c and in addition, a transition area between them was acquired.

XRD (Fig. 3) better identified phases in microstructure. The biomimetic strengthening spots exhibit a microstructure with reduced austenite (Fig. 3b), compared with its as-received counterpart. As inferred from both Figs. 2 and 3, the laser treatment gave rise to martensitic transformation [19] and the mechanism will be discussed later.