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Microstructure related enhancement in wear resistance of tool steel AISI D2 by applying laser heat treatment followed by ultrasonic impact treatment

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ABSTRACT

The surface layers of tool steel AISI D2 were modified by laser heat treatment (LHT) conducted using the solid state fiber-laser, by ultrasonic impact treatment (UIT) and by the combined LHT + UIT process. The paper is focused on the establishing the correlation between the microstructure, hardness and wear resistance of the modified layers. XRD analysis and TEM observations show that the LHT process results in the formation of microstructure comprised submicronic ferrite/austenite grains, martensitic needles and secondary carbides while the combined LHT + UIT process leads to the formation ultra-fine grained structure (~80–250 nm) with grain boundaries fixed with fine secondary carbides (~20 nm), and some areas of martensitic feathers. The observed microstructural features and phase compositions are shown to affect the wear resistance of the AISI D2 steel surface measured both in quasi-static and dynamic conditions. The modified layers demonstrate almost double, triple and four times decrease in the wear losses in dynamic conditions with regard to the initial surface after the LHT, UIT, and combined LHT + UIT processes, respectively. Theoretical evaluations of the wear resistance $W^{-1}{}_{th}$ using the Archard expression correlate well with the experimental data $W^{-1}{}_{exp}$, especially when the local plasticity characteristics δ_H describing the retained plasticity was taken into account.

1. Introduction

The reliability and durability of die tools are largely provided with both the surface microrelief and microstructure/phase composition of tool steels. These characteristics determine the hardness of the surface layers, which undergo the most significant loads during the operation life [1]. The working surfaces of tools are exposed to impact loads of highly concentrated stresses. As a consequence, the surface layers become the weakest sites prone to thermal or mechanical fatigue, oxidation and mechanical wear, especially at the elevated temperatures. Therefore, the enhanced wear resistance of the working surfaces of tool steels is currently a goal of high topicality in mechanical engineering.

Laser treatment is one of the most common methods for surface modification. It can be used for the laser heat treatment (LHT) of the surfaces of the end-products [1–5], which results in the hardening by means of the structure modifications and phase transformations related to the formation of fine-grained martensitic structures [2–9] and fine carbides [2,5]. Additionally, the surface layers can be restored owing to the LHT induced alloying/cladding [3,5,7–11]. A lot of studies regarding the impact of laser radiation on the structure and properties of tool steels can be found in the literature [6,8,10], which however mainly devoted to laser melting treatment [5,7–10]. In particular, the authors of [5] have shown that the melting zone was characterized by the reduced microhardness due to complete dissolution of carbides and a significant increase in the volume fraction of the retained austenite. It was therefore suggested to perform LHT of highly alloyed steels without or with a minimal melting of superficial microasperities [12]. The influence of LHT on the wear resistance of tool steels was also analyzed [13,14]. However, the outcomes of the LHT performed using a fiber laser and scanner without melting of the surface layer were addressed insufficiently [15,16].

Recently, to reduce mechanical wear of metallic products by the hybrid processes consisted of the laser-mechanical hardening [17], alloying [18,19], cladding [11] and severe plastic deformation (SPD)

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attracted more attention. When the plastic straining of the surface is implemented at the cooling stage of the subsurface layers previously heated to the austenitization temperature [20], then it promotes the simultaneous improvement of the parameters of the surface microrelief and the formation of ultra-fine grained microstructure in the surface layer, which may possess an enhanced microhardness, increased plasticity, and compressive residual macrostresses [12,18]. It was shown that previous heating promotes plastic deformation to higher extents owing to the temporary softening of the material [12,20].

Another technological solution is to apply the SPD methods after the laser hardening [21–24]. Ultrasonic burnishing treatment [21,22], ultrasonic impact treatment [16,23] or shot peening [24], and surface mechanical attrition treatment (SMAT) [25] are the most common dynamic SPD methods, which were used to remove possible disadvantages of LHT.

Use of LHT followed by roller-burnishing resulted in more fragmented grain structure and in a higher increase in the surface hardness and wear resistance as compared to the solely applied LHT. For instance, the wear resistance and friction coefficient of steel AISI 420 were significantly increased using such a hybrid treatment [2,12]. It was shown that the combined (hybrid) laser-mechanical process for surface hardening is effective for improvement of the wear resistance of both small [21,22] and large [16,19,23,24] parts made of tool steel. Though, the laser transformation hardening combined with shot peening does not provide uniform hardening depth and regular surface microrelief [24].

This work is aimed to evaluate the wear and friction behaviours of the tool steel AISI D2 hardened by laser heat treatment, ultrasonic impact treatment and laser heat treatment followed by ultrasonic impact treatment by means of the quasi-static and dynamic wear tests. The special attention was given to identify the correlation between the wear resistance and hardness of the surface layers both caused by microstructural and phase transformations induced by thermal (LHT) and deformation (UIT) hardening.

2. Experimental procedures

2.1. Material

The AISI D2 tool steel often employed for production of the parts working in extreme conditions and contained high contents of chromium and carbon was studied in this paper. The nominal chemical composition of the steel given in wt% is the following: 11.5% Cr, 1.5% C, 0.83% Mo, 0.72% V, 0.46% Mn, 0.42% Si, 0.15% Ni, 0.06% Cu and balance Fe. Specimens were machined in the plate shape of 69 × 9 × 69 mm. Prior to the laser and ultrasonic treatments, the specimens were subjected to annealing at 850 °C, then they were slowly cooled in the furnace to 650 °C (10 °C per hour), and then they were cooled in the ambient air. The original structure of the steel after heat treatment contained the alloyed α-ferrite and carbide phases.

2.2. Treatment details

2.2.1. Laser heat treatment

Preliminary the LHT process was performed by single passes without overlapping of the laser tracks to avoid formation of the over-tempered microstructures with inhomogeneous and reduced hardness in the overlapped areas [26]. Then, the laser hardened surfaces were subjected to ultrasonic strain hardening taking into account that the UIT produced track completely covers the LHT induced one.

The LHT process was implemented using a strategy of the remote surface hardening (Fig. 1(a)) using a machine tool with numerical control specially designed for laser processing of the material surfaces. A solid state fiber laser Rofin Sinar FL010 of 1 kW power output and of 1.064 μm wavelength was used to heat treatment of the specimens. A focusing head (scanner) produced by SCANLAB was mounted on the machine tool as shown in Fig. 1(a), which work area is 120 × 120 mm. The laser beam was guided to the focusing head by an optical fiber that provides a beam diameter of 100 μm. The focal plane was adjusted to obtain a defocused laser spot of $d_{lb} = 1$ mm on the specimen surface. Then, the track of the required width ($b_{sc} = 10$ mm) and length (60 mm) was treated using the same scanning parameters (the scanning speed V_{sc} along the width b_{sc}) of the laser beam controlled by special software [16] and by the chosen feed rates S of specimen, respectively.

The LHT process was performed using a strategy of constant heating temperature, which was controlled by means of a digital proportional-integral-differential (PID) controller and infrared pyrometer Impac Igar 12LO. In particular, the surface temperature in real time was measured without contact by two-spectral radiation that gives the actual value of the surface temperature. Then, the measured surface temperature was delivered through the PID controller to a special board that transforms the digital signal into the analogous signal inducing the required laser power needed to maintain a constant temperature in the area affected by the laser beam [27].

The appropriate heating temperature range was previously determined taking into account the ternary iron carbon chromium phase diagram and the magnitudes of the laser power density, as well as the thermo-kinetic [28] and thermo-physical [29] models, the limiting maximum of the heating (surface) temperature ($A_{C3} < T$ (°C) $< T_m$) and the duration of the laser action ($0.01 < t_l$ (s) < 1.5) that provide a thermal hardening without melting of the surface.

In the present work, the experimental results of the laser surface hardening of tool steel AISI D2 are given for the heating temperature of $T = 1270$ °C, the scanning speed $V_{sc} = 1000$ mm/s, the laser track width $b_{sc} = 10$ mm, and specimen feed rate $S = 40…140$ mm/min. At

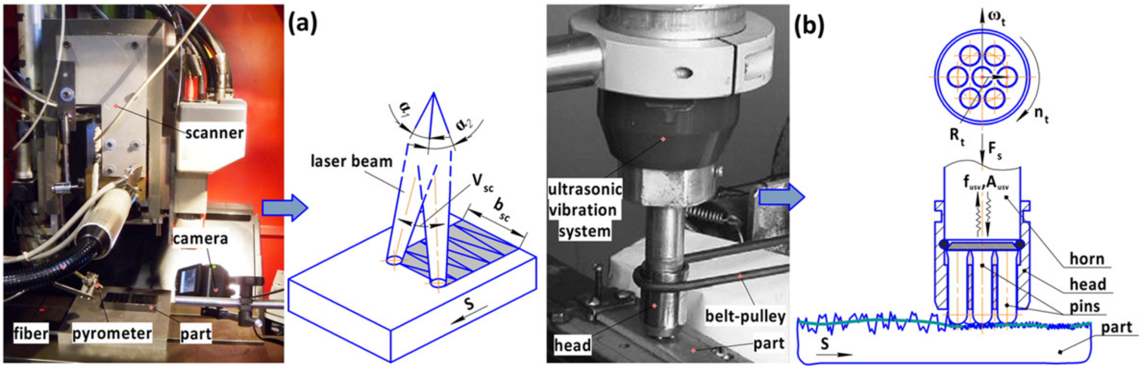

Fig. 1. General views of equipment and schemes for LHT (a) (V_{sc} is scanning speed, b_{sc} is the track width, S is the feed rate of specimen) and UIT (b) (F_s is static loading of head, A_{usv} and f_{usv} are the vibration amplitude and frequency of ultrasonic horn, S is the specimen feed rate, n_t is the rotation frequency of the head, R_t is the distance between the pin and the head rotation axis, ω_t is the rotational speed of the pin).