Surface & Coatings Technology 278 (2015) 108–120

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Surface microrelief and hardness of laser hardened and ultrasonically peened AISI D2 tool steel

D.A. Lesyk [a], S. Martinez [b], V.V. Dzhemelinskyy [a], A. Lamikiz [b], B.N. Mordyuk [c,*], G.I. Prokopenko [c]

[a] Department of Laser Physics and Applied Technologies, National Technical University of Ukraine "KPI", 37 Peremohy Ave., UA-03056 Kyiv, Ukraine
[b] Department of Mechanical Engineering, University of the Basque Country UPV/EHU, Alameda Urquijo s/n, SP-48013 Bilbao, Spain
[c] Department of Solids Acoustics, Kurdyumov Institute for Metal Physics, NAS of Ukraine, 36 Academician Vernadsky Blvd., UA-03142 Kyiv, Ukraine

ARTICLE INFO

Article history:
Received 17 April 2015
Revised 15 July 2015
Accepted in revised form 23 July 2015
Available online 27 July 2015

Keywords:
Laser surface hardening
Ultrasonic impact treatment
Surface roughness
Surface waviness
Hardness
Tool steel

ABSTRACT

This paper is focused on experimental analysis of the effects of laser surface hardening (LSH) combined with subsequent ultrasonic impact treatment (UIT) on the surface microrelief, hardness and microstructure in near-surface layers of AISI D2 high-chromium, cold worked tool steel. The LSH provides fast heating of the near-surface layers to the temperature above that of the phase transformation and temperature then rapidly cools by a self-quenching process. The formed heat affected zone is hardened thanks to the rapid heating/cooling process affecting microstructure, phase composition and carbide formation. Conversely, the UIT induces multiple impact loads providing severe plastic deformation of near-surface layers, and the hardening occurs by a dislocation mediated process. The optimal parameters of each process were determined to obtain maximum hardness and regular surface microrelief. Further, complete analysis of the effect of combined treatment (LSH + UIT) on the surface hardness, microhardness depth profile and surface microrelief was performed. Results show that the combined LSH + UIT process provides almost triple, double and a 10% increase in hardness in comparison with those of the initial, UIT-processed and LSH-treated states, respectively. The surface microrelief, waviness and roughness parameters were respectively diminished after LSH + UIT by approx. 50, 65, and 90%. XRD analysis was carried out after LSH and LSH + UIT processes, which showed essential α-Fe peak broadening due to the formation of microstrains (0.27% and 0.47%, respectively) and reduction in crystallite size (84 nm after LSH + UIT). Favorable compressive residual stresses (−205 MPa and −409 MPa, respectively) were also observed in the near-surface layers of ~350 and 80 μm thick, respectively. The obtained results demonstrate that the combined LSH + UIT process is a feasible surface treatment for the quality improvement of the tool steel components including both the surface microrelief and hardness characteristics.

1. Introduction

One of the most important problems solved by mechanical engineering is to enhance the operational properties of products and components, which work in extreme conditions at high motion speeds, cyclically variable temperatures, high specific pressures, and under the actions of abrasive and aggressive environments. The performance of this group of products is largely dependent on the quality of their surfaces. Frequently, traditional technological processes for surface finishing don't fully satisfy the ever changing requirements. Much attention is now given to investigate the high energy methods for surface finishing [1,2].

Currently, finishing treatments used either highly concentrated energy sources [3,4] or high energy multiple impacts inducing severe plastic deformation of the surface [5,6]. The laser surface processing [7,8] resulting in melting [9], transformation hardening [10] or severe plastic deformation [11] of metallic surfaces, the surface treatments using electron beam [12], and plasma arc [13], as well as surface mechanical attrition treatment [6], deep ball-burnishing [14], ultrasonic impact treatment (UIT) [15–17], and ultrasonic nanocrystal surface modification [18] are promising cost-effective methods for surface hardening, surface polishing and formation of regular microrelief. As compared to the traditional energy sources for thermal hardening laser surface hardening (LSH) used the focused laser beam has the advantage over the other techniques. Continuous action of high energy density laser beam irradiating a local area allows both heating the surface and near-surface layers and rapid cooling by a self-quenching due to conduction from the substrate. Rapid heating and cooling of thin surface layers promote microstructural changes via phase transformations in many steel products [4,8]. Conversely, strain hardening at surface by severe plastic deformation (SPD) causes structural changes by increasing the dislocation density, grain refinement, and formation of residual macro-stresses [2,14]. However, the temperature increases during operational life may

* Corresponding author.
E-mail address: mordyuk@imp.kiev.ua (B.N. Mordyuk).

http://dx.doi.org/10.1016/j.surfcoat.2015.07.049
0257-8972/© 2015 Published by Elsevier B.V.

cause partial or complete degradation of this material properties induced by the surface hardening methods [19]. Thus, development of novel techniques is a very topical task.

Combined thermo-straining methods may be a promising treatment to improve magnitude and stability of surface hardening/finishing effects. Thus, the static roller burnishing [14,20] or dynamic action by ultrasonic treatment [21] or shot peening [22,23] used after laser hardening treatment has shown good results. There are several publications that have reported on the characteristics of the structure and hardness of steel surfaces [24,25] after the laser treatment followed by room temperature ultrasonic treatment [26,27]. However, to the best of the authors knowledge data describing the effects of combined action of the laser surface hardening and subsequent SPD process is practically absent.

The aim of this work is to determine the optimal regimes of the laser hardening process and ultrasonic impact treatment for surface finishing and hardening of AISI D2 tool steel. Particular attention was paid in establishing the links between the parameters of the combined laser surface hardening and ultrasonic impact treatment, on the one hand, and surface microrelief, and hardness coupled with microstructure in the treated near-surface layers, on the other hand.

2. Experimental details

2.1. Material

The specimens of AISI D2 tool steel (69 mm × 69 mm × 9 mm) were initially heated to 850 °C, then slowly (10 °C per hour) cooled in the furnace to 650 °C, and then removed and cooled in air. The chemical composition and mechanical properties of the tool steel are given in Table 1. The resulting structure was composed of the alloyed α-ferrite and carbide phases.

2.2. Treatment details

2.2.1. Laser surface hardening

Before the use of combined treatment, which consisted of LSH and subsequent UIT treatment in this study, a wide range of the individual parameters of the processes were evaluated first. The preliminary temperature range of laser surface hardening without melting was determined in accordance with the ternary iron–carbon–chromium phase diagram [27,28].

A Kondia Aktinos B500 machine with numerically programmed control and total working area of 500 × 300 mm was used for LSH. Scanlab Hurry Scan 25 2D scanner with total scan area in focal plane of 120 × 120 mm was placed into the machine, which contains two rotatable mirrors that allow moving the laser beam across a rectangular area on the specimen surface. Laser radiation was transported by optical fiber to the scan head of a Rofin Sinar FL010 fiber laser operated in continuous mode with a maximum power output of 1 kW and a wavelength $\lambda = 1.07\ \mu m \pm 10$ nm (Fig. 1). The scanning velocity V of the laser beam was controlled using the software of the scanner [29]. The optical fiber ensured cylindrical spot of approx. 1 mm in diameter, d_{lb}, and multimode energy distribution in the focal plane. An Impac Igar 12LO two-color pyrometer was used to measure the temperature in the zone irradiated with the laser beam, and a special proportional integral controller was used to maintain a constant temperature in the working area [29].

Laser surface hardening was carried out with a scanning velocity $V = 1000$ mm/s which produced the track 10 mm wide on the specimen surface (Fig. 1). The temperature range was between 900…1340 °C, the specimen feed rate was between 40…140 mm/min. Specimens were laser processed in the atmosphere. The main parameters trialed for the LSH regimes are shown in Table 2.

When using continuous laser radiation two strategies can be adopted to heat the surface either using a strategy of constant power (Fig. 2a) or a strategy of constant temperature (Fig. 2b). Optimal temperatures for these strategies were determined by our previous studies [29,30]. In this paper, the latter strategy was used, and an automated control system was employed to change the applied power of the laser beam to maintain the processing temperature.

Unlike the strategy of constant laser beam power (Fig. 2a), the strategy of constant temperature (Fig. 2b) allows avoiding undesirable surface melting in the sites where the surface relief of the specimen is markedly changed. To maintain the necessary temperature regime several parameters need to be calculated to correctly control the laser beam power. Thus, a permissible heat energy density of laser beam, E_{lb} in [J/cm^2], in the irradiation area of treated surface was calculated for continuous mode as [31]:

$$E_{lb} = CP/d_{lb}S, \tag{1}$$

where, P is the power of the laser beam in [W], d_{lb} is the diameter of the laser beam in [mm] and S is the specimen feed rate of the treated surface in [mm/min], and $C = 6000$ is a dimensionality coefficient. The interaction time of the laser beam is determined by the feed rate S of the laser beam on the treated surface. The obtained magnitudes of the energy density fall into the range between 20…90 kJ/cm^2.

Accounting for the absorption ability of the material, $A = 0.8$, and dimensions, h_{lb} and l_{lb}, of rectangular-shaped laser spot produced by the laser beam the heating temperature for continuous energy supply was determined by absorbed power density of the laser beam [32–34]:

$$W_{lb} = \frac{AP}{h_{lb} l_{lb}}. \tag{2}$$

The calculated power density, W_{lb}, falls into the range of 10^3…10^4 W/cm^2 at interaction time between 0.42 and 1.5 s, which is known to provide the surface hardening without melting [35]. In this study, maximum depth of the heat affected zone (HAZ) was approx. 0.3…0. 4mm (Table 2).

2.2.2. Ultrasonic impact treatment

Severe plastic straining of near-surface layers was induced by UIT carried out using the equipment described in detail elsewhere [36–38]. The equipment contained an ultrasonic generator power output of 0.3 kW and a frequency of 21.6 kHz, an acoustic system with a piezoceramic transducer and step-like horn, the impact head placed on the horn tip (Fig. 3). At the UIT process, the amplitudes, A_{usv}, of ultrasonic horn vibration used were 15 and 18 µm, the acoustic system was pressed to the treated surface with a static force of $F_s = 50$ N, and shifted along the specimen surface with the feed rate $S = 600$ mm/min (Table 3). The high frequency ($f_i \approx 3 \pm 0.5$ kHz) impacts were produced

Table 1
Chemical composition and mechanical properties of AISI D2 tool steel.

Chemical composition, %										Mechanical properties[a]						
C	Cr	Mo	V	Mn	Si	Ni	Cu	P, S	Fe	σ_Y [MPa]	σ_U [MPa]	δ [%]	E [GPa]	μ	ρ [kg/m^3]	HB
1.55	11.3	0.8	0.8	0.4	0.3	<0.4	<0.3	<0.03	~84	≥320	≥710	≥16	200	0.25	7700	210

[a] σ_Y is the tensile yield strength, σ_U is the tensile ultimate strength, δ is the relative elongation, E is the Young's modulus, μ is the Poisson's ratio, ρ is the density, and HB is the Brinell hardness number.