Surface & Coatings Technology 280 (2015) 216–224

Contents lists available at ScienceDirect

Surface & Coatings Technology

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

Effect of LASER shock peening on microstructure, mechanical properties and corrosion behavior of interstitial free steel

Y. Shadangi [a],*, K. Chattopadhyay [a], S.B. Rai [b], V. Singh [a]

[a] Department of Metallurgical Engineering, Indian Institute of Technology (BHU), Varanasi, India
[b] Department of Physics, Banaras Hindu University, Varanasi, India

ARTICLE INFO

Article history:
Received 16 June 2015
Revised 5 September 2015
Accepted in revised form 7 September 2015
Available online 12 September 2015

Keywords:
IF steel
LASER shock peening
Hardness
Tensile properties
Corrosion behavior

ABSTRACT

LASER shock peening (LSP) is an effective process of surface modification. This work is concerned with the effect of LSP on the modification of microstructure, hardness, microhardness profile, residual stress, tensile properties and corrosion behavior of interstitial free (IF) steel. In order to study the effect of pulse energy on hardness, samples were subjected to LSP at pulse energy of 170, 230, 290 and 340 mJ respectively. The effect of LSP time on hardness, microhardness profile and tensile properties was investigated by processing the samples for 5, 10, 15 and 20 min at pulse energy of 230 mJ and there was found to be significant increase in tensile strength. There was grain refinement to nano level in the surface region due to LSP. Hardness was observed to increase by LSP up to 10 min and tensile strength increased up to LSP of 5 min. However with the increase in LSP time beyond 10 min there was prominent ablation and melting. The effect of overlapped (OV) LASER shocks was also studied by comparing their behavior with that of single shock. The potentiodynamic polarization study showed significant increase in corrosion resistance of the LSPed IF steel.

1. Introduction

Interstitial free steel is being used in automotive sector for the last two decades for body panels of automobiles because of its easy drawability in to intricate shapes due to its high formability and non aging behavior [1]. In automobile sector there is thrust on weight reduction, increase in fuel eficiency and safety. Strength of IF steel is much lower in comparision to other grades of steels like dual phase and HSLA steels used for automobile body panel.

In most of the cases like that in fatigue, corrosion and wear failure of structural components occurs from the surface, hence thus there is much need for the improvement of surface properties the structural components [2]. One of the important means of improving surface properties of such components has been grain refinement and there have been several processes of grain refinement.

Severe plastic deformation (SPD) is an effective means of producing bulk ultrafine - grained (UFG) structures. The process of SPD of polycrystals increases their free energy and generates much more defects and interfaces (grain boundaries) [3]. SPD induced microstructures are substantially grain refined and inherit high internal stresses and high energy non equilibrium boundaries [3]. However due to limitations of the process synthesis of ideal bulk nanocrytalline materials free from contamination and porosity with uniformity in grain size is a challenging task [4].

High plastic strain of the order of several hundreds of percent can be produced by various techniques, such as equal-channel angular pressing (ECAP), high-pressure torsion, sliding wear, ball milling, shot blasting, ultrasonic shot peening, and LSP to varying depths from the surface [2,5].

LSP is an established and effective process of surface modification of metallic materials [6]. Surface hardness and fatigue strength of a number of alloys have been improved by LSP [7–10]. The increase in fatigue strength has been attributed to compressive residual stresses generated on LSPed surface by shock waves [11,12]. The increase in surface hardness and yield strength (YS) has been attributed to generation of dislocations on the LSPed surface [12].

In most of the work on LSP pulsed LASER was used with pulse width and energy in ns and J respectively [13,14]. Earlier work have been carried out to study the effect of LSP on surface microstructure and mechanical properties of low carbon steel, 316 L steel, ASTM: 410 L 00Cr12 steel, 55C1 steel, 1026 steel, 1045 steel, duplex steel, LY2 Al alloy, 7075 Al alloys and Ti-6Al-4 V [14–23]. Systematic investigation was carried out by Chu *et al.* to study the effect of LSP on low carbon steel with pulse energy upto 120 J. It was found to modify the microstructure and hardness up to the depth of ≈100 μm and generate dislocations on the treated surface [14]. The mechanical properties and corrosion behavior of LSPed 316 L steel without confining medium and thermo-protective coating was studied by S Kalainathan *et al.* Their study elucidated modification in the microhardness profile up to a depth of 800 μm, compressive residual stresses on surface and enhancement in corrosion resistance [16]. It has been reported by several

---

* Corresponding author.
E-mail address: yshadangi.met12@itbhu.ac.in (Y. Shadangi).

http://dx.doi.org/10.1016/j.surfcoat.2015.09.014
0257-8972/© 2015 Elsevier B.V. All rights reserved.

investigators that depth of effective modification varied with the impact geometry [9,17,18]. Peyre *et al.* reported decrease in plastically affected depth for impact geometry of 1 mm instead of 6 mm due to two-dimensional attenuation of shock waves [9]. *A. Vasu et al. have investigated the effect of LSP on plasticized depth and residual stresses for different specimen geometries (i.e. flat, concave and convex) [19,20]. They have reported increase in plasticized depth [19] and residual stresses [20] for concave geometry*. Several work have been carried to study the effect of overlapping and multiple impacts by LSP on residual stresses and fatigue life [9, 21–23]. Hu and Yao studied percentage of overlapping on depth of compressive residual stress. In their investigation Hu and Yao reported that 50–70% overlapping of LASER spots yielded best result compared to 30% and 90% overlapping [21]. Luo *et al.* had also reported that increase in the overlapping from 50% to 70% yielded only 8% increase in plasticized depth for Ti -6Al- 4 V [23]. Ballard *et al.* reported improvement in fatigue life of 35CD4-30HRC and 35CD4-50HRC steel from 13 to 32% from LSP, significantly higher than that resulting from shot peening [24]. However, no systematic study has been carried out with Nd: YAG LASER with pulse energy in mJ with thermo-protective coating on IF steel.

In the present study Nd: YAG LASER has been used to irradiate IF steel. In this process the target material is given a thermo-protective coating which prevents ablation of target metal from LSP. Due to volume expansion of plasma plume a shock wave is generated on the surface. This shock wave was applied to surface without any confining medium to refine and studies are made on modifications of microstructure, hardness, microhardness profile, residual stress, tensile strength, and corrosion resistance of IF steel.

2. Experimental details

2.1. Material and LSP

The interstitial free steel sheet of 200 mm × 200 mm × 4 mm size was procured from M/s Tata Steel, Jamshedpur, India, containing (by weight) 0.004% C, 0.01% Si, 0.0623% Mn, 0.153% Al, 0.042% Cu, 0.006% Nb, 0.068% Ti, 0.0038% N and balance Fe. The sheet was cut into rectangular pieces of 6 mm × 10 mm and mechanically polished by emery papers of different grades and finally using slurry of alumina powder of 0.024 μm size. The mechanically polished samples of 6 mm × 10 mm were LSPed using a solid state Nd: YAG LASER operated at a wavelength of 1064 nm and a pulse duration of 7 ns measured at full width half maximum (FWHM). The power density used in the present study was $\approx 10^8$ W cm^{-2} for LASER pulse energy of 170, 230, 290 and 340 mJ, and the LASER spot size on the sample was found to be 5.60 mm in diameter measured at FWHM of the near-Gaussian intensity profile. All the LSP treatments were given at room temperature in air. A thermo-protective layer was applied on surface of the sample to avoid the harmful melting of surface during irradiation that induces tensile residual stresses on the surface [25]. Black paint is commercially used in industry as absorbent/ thermo-protective coating [14,15]. A 40–50 μm thick layer of black paint was used as a sacrificial energy-absorbing coating in case of IF steel samples. This coating was partially ablated by the LASER and served to reduce surface melting of the IF steel. The plasma was allowed to freely expand and no confining layer was used since transparent material such as quartz is known to breakdown at the high optical power densities used for LSP [14]. The schematic of the experimental setup is presented in Fig. 1. The prepared samples were exposed to pulsed LASER for 5, 10, 15 and 20 min. Conditions of the treatments are mentioned in Table 1. All the samples were exposed to single shock. Also, overlap LASER shock was applied to IF steel for 5 min LSP treatment with 50% overlapping of LASER spots. For 50% overlapping of LASER impacts surface roughness was less compared to 30% and 70% overlapping and heat generated due to overlapping was less compared with 70% and 90% OV [22,23] . Therefore, 5 min LSP with 50% OV was chosen as a parameter for treatment, *however no systematic investigation was carried out to study the effect of overlapping percentage on different aspects of the LSPed IF steel.*

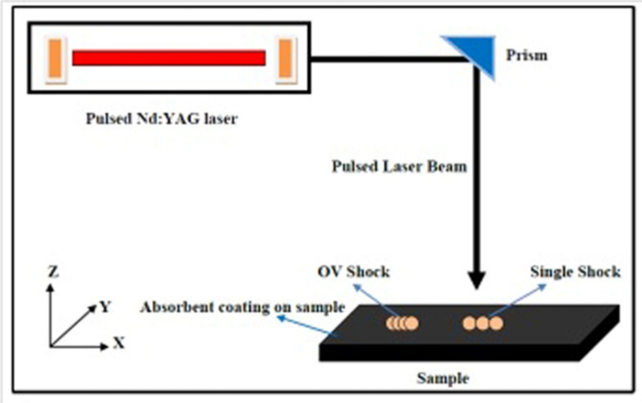

Fig. 1. Schematic representation LSP experiment.

2.2. Material characterization and mechanical properties

Following LSP, the remaining black paint coating was removed off using acetone. Mitutoyo (SURFTEST-SJ 410) surface profilometer was used to examine the specimen surface profiles before and after the LSP. To reveal the peak and valley in surface profiles these were accordingly magnified by Mitutoyo surface profilometer. Optical microscope (AX 10 model, Make-Zeiss) was used for analysis of transverse section. Scanning electron microscope (QUANTA 200 F) operated at 30 kV was used for analysis of surface morphology. Microstructural examination of LSPed deformed surfaces was carried out after light etching with 5% Nital solution following LSP. Transmission electron microscope (TECNAI $G^2$20) was used to examine the fine microstructural features of the sample LSPed for 5 min at 200 kV. Longitudinal slices of about 500 μm thickness, parallel to LSPed surface were sectioned from the LSPed samples using a thin diamond coated circular saw. Firstly, about 10 μm thick LSPed surface was removed by emery paper to flatten the uneven surface resulting from ablation and thickness of the longitudinal slice was reduced to 70 μm. Discs of 3 mm diameter were punched from the thinned longitudinal slice. TEM foils were prepared by electrolytic thinning in the electrolyte containing 5 vol.% of perchloric acid and 95 vol.% of methanol, cooled to −30 °C, at 30 V using a twin jet polisher (FISHIONE, Model 110). XRD (Rigaku) studies were carried out for identification of phases in the untreated and 5 min OV LSPed samples. CuK_{α} with wavelength of 1.5402 A^o and Ni filter was used. Samples of 2 mm thickness were sectioned using diamond coated circular saw for XRD study.

Vickers hardness tester (Leco LV700AT) was used to determine bulk Vickers hardness (VHN). Hardness of the as received and LSPed samples was determined at the load of 98.07 N with a dwell time of 10 s. For computing standard deviation, 10 to 15 readings were taken for each process parameter as mentioned in Table 1. Microhardness tester (SHIMADZU) was used to determine microhardness profile of the as received and LSPed samples from the treated surface towards interior, at an applied load of 430.05 mN with a dwell time of 5 s.

Panalytical ^TM X'Pert PRO MRD (Material research Differactometer) system with: X-ray lens (poly-capillary) on the target side and multi-

Table 1
LSP treatment of sample.

Sl. No	Time of exposure (min)	Pulse energy of LASER (mJ)
1	5	170, 230, 290, 340
2	10	230
3	15	230
4	20	230