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Investigation and characterization of hardening of AISI 4140 steel using Nd:YAG laser

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ABSTRACT

Purpose: In this research, our aim was to propose an alternative to the conventional hardening methods, laser spot welding, thus laser hardening through the solid state reaction.

Design/methodology/approach: Instead of diode lasers, the Neodymium:YAG Laser was used by applying different voltage, time and depths of laser and the parameters of hardening and the differences induced in the hardness's of the specimens were investigated.

Findings: The hardness of the specimens depending on the depths laser, from the edge to the deep of the specimens were measured. The metallographic examination (transformation due to the heating-cooling cycles) and the SEM analysis was made to complete the characterization.

Research limitations/implications: Using Nd:YAG laser, the hardening process was easy to operate offering several advantages such as possibility of working in very small and narrow areas altering the voltage and depths of laser facilely and obtaining high hardness values due to transformation of microstructure without need of secondary quenchant.

Originality/value: In this work, an alternative to the conventional hardening methods, laser spot welding was applied to AISI 4140 steel surface, which is widely used in the industry, thus laser hardening through the solid state reaction was achieved.

Keywords: Laser spot welding; Laser spot hardening; Surface treatment; Mechanical properties; AISI 4140 hardness

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Used for several surface heat treatment applications, laser is offering different options for surface modifications by controlling the power density and traversing speed. While at high density power and slow traversing speed mode, the alloying or homogenization of melted area is the case, the low density power and rapid traversing speed can be utilized for surface hardening without needing a secondary quenching process [1]. The rapid traversing time causes less interaction between the laser beam and the work piece surface, thus less concentration of the absorbed energy on the surface whereas there is a distinct gradient of heat between the inner and outer parts of the material [2]. During laser hardening of steels, the solid state martensitic phase transformation occurs due to rapid cooling of the heated material above the austenitization temperature to convert the phase from cementite/ferrite mixture to austenite and then the transformation into pearlite or martensite [1,3]. This solid state reaction has several benefits on the manufacturing process of several machine parts such as piston rings used in marine diesel engines or as trimming dies by increasing the surface hardness and improving wear resistance of ferrous materials with little or negligible dimensional modifications or distortions, thus augmenting the service life of the parts compared with induction and through-hardening treatments [3]. Also the possibility of selective hardening without need of any quenchant, the limited post-machining, rapid fabrication, good mechanical properties and easy control of case depth are other advantages of this method [4,5]. The Nd:YAG laser used for laser hardening and laser spot welding process owing to its adequate beam quality and wavelength – 1.064 μm – which is ten times smaller than CO_2 laser produces very small spots rendering possible working with very small areas. They are also very effective on metals and controllable [3,5].

In this work, an alternative to the conventional hardening methods, laser spot welding was applied to AISI 4140 steel surface, which is widely used in the industry, thus laser hardening through the solid state reaction was achieved.

2. Materials and method

In this study, AISI 4140 (with composition summarized in Table 1) was used as the substrate material [6]. The cylindrical specimens were cut, ground to remove oxidation and decarburization layers, then polished with 3 μm diamond paste as illustrated in Figure 1 [7].

Table 1.
Composition of AISI 4140 steel [6]

Elements	C	P	Mn	S	Si
Content, %	0.38-0.43	0.035 (max.)	0.75-1.0	0.040 (max.)	0.20-0.35
Elements	Cr	Mo	Ni	N	
Content, %	0.80-1.10	0.15-0.25	-	-	

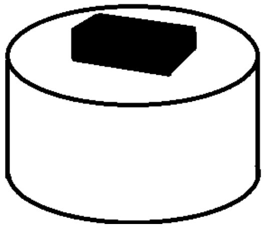

Fig. 1. Illustration of specimens prepared for laser hardening applications. The laser pulses were applied onto the rectangular part coloured in black [7]

Laser star 7000 series Nd:YAG laser was used for the laser hardening. Different voltage, time and depths of laser were applied and summarized in Table 2.

Table 2.
Laser application conditions of Nd:YAG laser [7]

Specimen	Voltage	Millisecond	Depth, micrometre
S1 type	350	50	400 or Close to surface
S2 type	350	25	300 or Close to surface
S3 type	200	25	50 or Close to surface

The hardness measurements of the samples were done using Shimadzu Corporation (Scientific Instruments, Japan) Microhardness Tester, 500 g load for 15 s was the threshold to find out the hardness of the coating. The metallographic examination and the SEM (JEOL Ltd., JSM-5910LV) also EDS analysis (OXFORD Industries INCAx-sight 7274) were made to complete different zones' characterization. After treatment specimen were mounted, subsequently ground, polished and finally etched by Nital etching solution (5%) for AISI 4140 steel about 10 sec. The microstructure were observed by optical microscope (Olympus). The coating thicknesses were measured during SEM analysis.

3. Results and discussion

In Tables 3 and 4 [7], the hardness modifications of specimens depending on the depths laser, from the edge to the deep of the specimens are summarized. The cooling rate are decreasing from edge to the deep, thus the microstructures of the laser hardened layer are coarsen inducing the hardness of the material diminished. In Fig. 2 [7] of the specimen 1, a single laser hardened layer was observed while in Fig. 3 [7] of the specimen 3 and in Figs. 4, 5 and 6 [7] of the specimen 2, there are 2 different hardened layers, the one on the edge was differentiated from the one in the deep by the grain size of the particles. In SEM images shown in Fig. 7 [7] the melted and rapidly cooled area as a proof of a possible martensitic structure which was difficult to diagnose using optical microscope. According to the calculation made during SEM analysis, the thickness of laser hardened zone was very homogenous and 110±15 μm. The EDS measurement was inutile to perform as the elements remained unchanged after the process and in back scattering mode of SEM, no difference was detected.

Table 3.
The hardness values of the specimens in the different depths of laser [7]

Specimen	Energy, V	Time, ms	Hardness, HV0.5	Depth, micrometre
S1-D	350	50	564.7	400
S2-D	350	25	540	300
S3-D	200	25	558.9	50

Table 4.
The hardness values of the specimens close to the surface (edges) after laser hardening [7]

Specimen	Energy, V	Time, ms	Hardness, HV0.5	Depth, micrometre
S1-C	350	50	641.3	Close to the surface
S2-C	350	25	686.2	Close to the surface
S3-C	200	25	648.2	Close to the surface

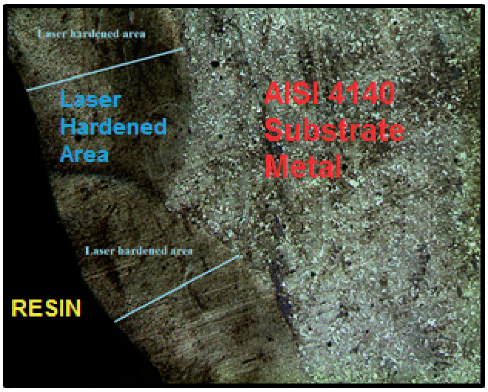

Fig. 2. Optical microscope image of S1 type specimens after etching with Nital reagent (5%) for 10 sec (magnification 50x). The resin, laser hardened areas and substrate metal are also labelled in the image [7]

Fig. 3. Optical microscope image of S3 type specimens after etching with Nital reagent (5%) for 10 sec (magnification 50x). The lighter edges where the laser beam was applied close to the surface are distinct [7]

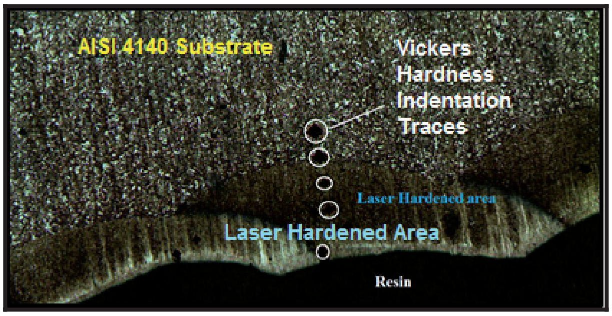

Fig. 4. Optical microscope image of S2 type specimens after etching with Nital reagent (5%) for 10 sec (magnification 50x). The indentation traces of the diamond from the edge to the deep after Vickers indentation testing are circumscribed [7]

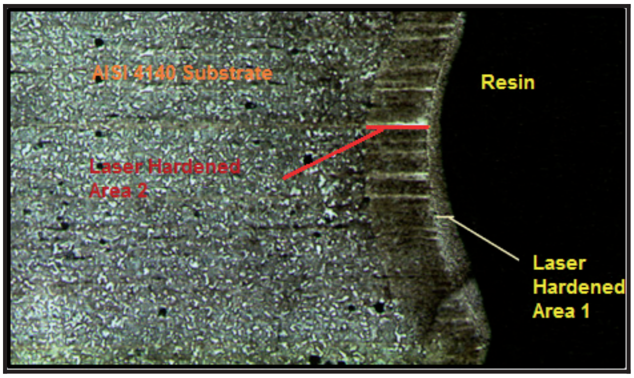

Fig. 5. Optical microscope image of S2 type specimens after etching with Nital reagent (5%) for 10 sec (magnification 50x). The two laser hardened layers are shown clearly and labeled onto the image [7]

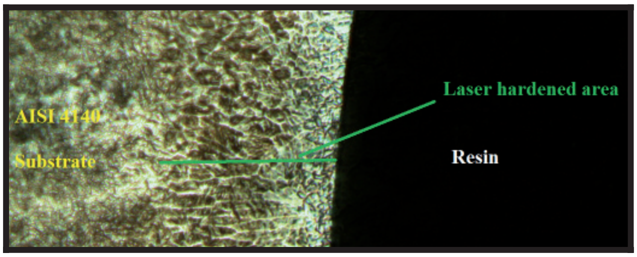

Fig. 6. Optical microscope image of S2 type specimens after etching with Nital reagent (5%) for 10 sec (magnification 200x). The grains of the laser hardened area from the edge to the deep are coarsening [7]

4. Conclusions

Using Nd:YAG laser, the hardening process was easy to operate offering several advantages such as possibility of working in very small and narrow areas altering the voltage and depths of laser facilely and obtaining high hardness values due to transformation of microstructure without need of secondary quenchant.

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a) b) c)

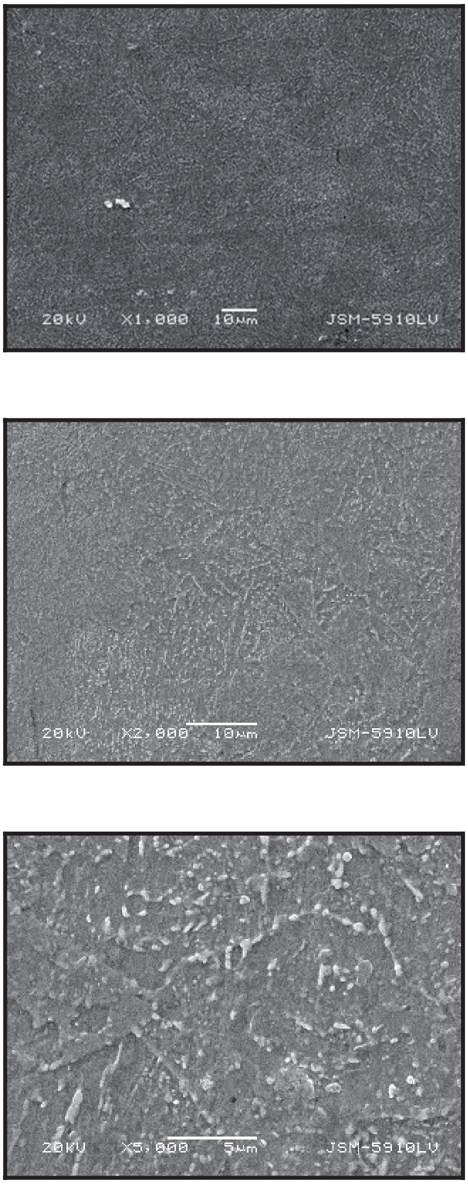

Fig. 7. SEM image of laser hardened zone of the part S2; a) magnification 1000x, b) magnification 2000x, c) magnification 5000x [7]

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