Laser Surface Modification of AISI 1025 Low Carbon Steel using Pulsed Nd:YAG Laser for Enhanced Surface Properties

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Keywords: Laser surface modification, Nd:YAG laser, low carbon steel

Abstract. This paper presents laser surface modification of AISI 1025 low carbon steel for enhance surface hardness properties. An Nd:YAG laser system with pulse mode was used in order to modify 10 mm thick plate surface. Three controlled parameters were laser power, pulse duration and overlap percentage which ranged from 100 to 200 W, 0.4 to 1.0 ms and 50 to 90% respectively. The treated samples was characterised for metallographic study and hardness. Metallographic study was conducted using optical microscope for laser modified layer thickness and grain size. Hardness properties were measured using Vickers indenter. The result show that hardness of laser treated area increased due to fine grain size produced in the laser modified layer. The overlapping rates increase significantly with decreasing laser scanning speed. These findings indicate potential application of low carbon steel in high wear resistant applications through laser surface modification.

Introduction

Over the past few years, laser surface treatment has been a way to overcome premature failure in semi-solid casting by developing amorphous layer on die surface [1]. Rapid development in surface engineering field leads to utilisation of advanced heat source such as plasma, laser, ion, and electron [2]. Tool and die industries pay attention to the technology of laser surface treatment due to its precision of operation, short processing time and localized treatment effects [3]. Laser heating produced local changes at the surface of the material whilst thus leaving the properties of bulk of a given component unaffected [5]. A number of different laser sources such as Nd:YAG (Neodymium:Yttrium-aluminium-garnet), CO_2 (carbon dioxide), fibre laser and HPDL (High Power Direct Diode) laser system have been widely studied. The wavelengths of these lasers are between 800 and 10,600 nm which offers better light absorption at shorter the wavelength [4].

Laser processing can be conducted either by pulse or continuous mode. Previous researchers that using continuous laser beam found that defects such as porosity and bubbles occur easily on the treated layer [7]. CO_2 laser with multi K-Watts of power has been widely used in laser surface treatment. However, the advantages of using Nd:YAG as laser source is established ever since. Comparing with CO_2, Nd:YAG has various advantages such as a higher energy density and higher energy absorption rate on the sample [4]. The wavelength of the laser light of 1.06μm allows the beam to be delivered with relatively small energy losses [6].

Surface heat treatment with laser beam experienced self-quenching that cooled rapidly into materials without cooling agent. In laser surface modification of tool steels, rapid solidification produced finer grains which increased hardness properties. Materials with high thermal conductivity properties produced a thick laser modified layer due to ease of heat penetration into the substrate [10]. Found that, the time for the energy of laser irradiation which converted into heat is shorter that

pulse duration or laser interaction time. The resulting temperature profile highly depends on the energy profile consumed and thermal diffusion rate during laser irradiation as given by Eq. 1.

$$D = k / (\rho C_P), \quad (1)$$

where D is thermal diffusivity, k is thermal conductivity, C_P is specific heat and ρ is the density [10]. Tool steels exhibit lower thermal conductivity of 24.3 W/m K while carbon steel like AISI 1025 has higher thermal conductivity of 51.9 W/m.K. From previous findings, CO_2 laser modified H13 layer thickness ranged between 0.51 to 2.83 µm [11]. The objective of this study was to modify a flat plate of AISI 1025 low carbon steel surface for enhanced hardness properties with modified layer of more than 300 µm thickness using Nd:YAG laser system.

Experimental

As-received AISI 1025 low carbon steel plate of 10 mm thickness was processed and analysed in this study. Chemical composition of AISI 1025 steel in Table 1 was analysed using OXFORD INSTRUMENT Foundry-Master spectroscopy. An Nd:YAG JK300HPS laser system with TEM_{00} mode was used to process the sample surface with average laser power of 300 W. The smallest laser spot size was 0.48 mm at focal length of 160 mm. The maximum laser scanning speed was 900 mm/min while pulse repetition frequency was 1000 Hz. During the processing, sample was stationary while laser head was translated linearly by CNC motion control system. The laser processing was conducted using pulse mode in an inert argon atmosphere.

Table 1: Chemical composition of AISI 1025 low carbon steel

Element	C	Mn	Si	Cr	Ni	Al	V	Cu
wt%	0.20-0.28	0.42-0.90	0.23-0.47	0.03-0.19	0.03-0.14	0.002-0.007	0.002-0.005	0.019-0.02
	Co	**Nb**	**Ti**	**Pb**	**W**	**Sn**	**Fe**	
	0.0010-0.0014	0.014-0.033	0.002-0.016	0.025-0.032	0.02-0.46	0.002	balance	

Sample surface was cleaned and processed at variation of average power, pulse repetition frequency (PRF), pulse width (τ) and scanning speed (v) as shown in Table 2. The outcome parameters from the settings were peak power (P_p), energy (E_P), residence time (T_R), power density (I) and spot size. Samples S1, S2, S3 and S4 was processed with same parameters except S1 was processed at a higher peak power of 2500 W. Sample S2, S3 and S4 were processed at different scanning speeds which resulted in overlapping pulses and constant power, PRF and energy. Sample S5, S6 and S7 were processed at different focal lengths and constant power, PRF and speed. Duty cycle was calculated to shorten pulse width thus controlled interaction time between material surface and beam. Significant amount of energy to melt the sample surface for each parameter setting was calculated from the settings.

Laser modified surface was prepared for metallographic study. Chemical etching was conducted using 2% nital solution after grinding and polishing to reveal the modified layer and grain distribution. Metallographic study and hardness measurement were conducted on cross sections of the modified surface. IM7000 Series Inverted Optical microscopes with Progress Capture 28.8 Jenoptik Optical System image analyser software were used for imaging purpose. Hardness properties of were measured using MMT Matsuzawa Vickers Hardness tester with 10kgf load.

Table 2: Laser parameter for AISI 1025 low carbon steel processing.

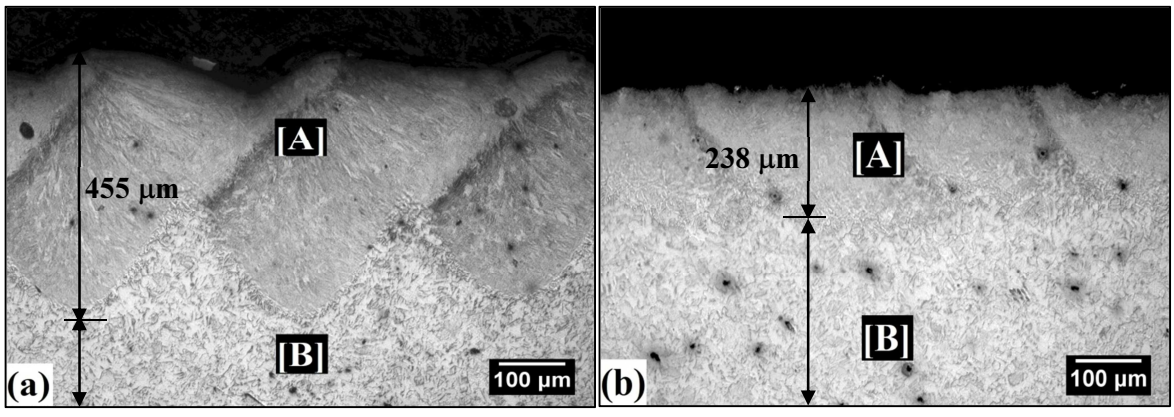
Sample	Set Parameters					Outcome Parameters				
	P_{Ave} (W)	PRF (Hz)	τ (ms)	*v* (mm/ min)	Focal Length (mm)	P_P (W)	E_P (J)	Spot Size (mm)	T_R (ms)	I (W/mm^2)
S1	100	50	0.8	800	157.5	2500	2.0	0.6	0.018	29,473.11
S2			1.0	600		2000			0.023	23,065.87
S3									0.030	17,683.83
S4				1000					0.018	29,473.06
S5	150	150	0.3	300	160.0	3300	1.0	0.48	0.043	22,901.65
S6					157.5			0.60	0.054	14,589.17
S7					155.0			0.68	0.061	11,395.62

Result and Discussion

Metallographic study

Micrographs in Fig 1 shows cross-section of laser modified sample S1 and S2 which were processed at constant average power of 100 W The modified layer is labelled as region [A] while [B] represents substrate. Sample S1 in Fig 1 (a) was processed at a higher peak power of 2500 W and 0.8 ms pulse duration and resulted in a modified layer of 455 μm thickness. Sample S2 produced 238 μm which processed at 2000 W peak power and 1.0 ms pulse duration. A higher power density of 29,473.11 W/mm^2 was emitted by sample S1compared to 23,065.87 W/mm^2 in sample S2. Though similar laser energy applied to both samples, sample S1 produced almost twice the thickness achieved in sample S2 due to power density effect. The higher power density allowed deep penetration of energy into the substrate and melted the surface. The layer thickness in both samples were higher than in previous study due to higher steel surface absorption towards Nd:YAG laser wavelength and high thermal conductivity properties of AISI 1025 steel [11].

Grain refinement occurred in the modified layer as shown in Fig 1 (c) where large grain size observed in the substrate region [B]. At 500x magnification, the reduced grain size in molten pool [A]was unnoticed. Heat affected zone labelled as [C] was visible at the higher magnification with finer grains formation. Changes of laser power varied surface heating and cooling rates, thus resulting in different grain sizes in the modified layer surface and heat affected zone. In previous work, nano and ultrafine-grain size were produced in the modified surface due to large undercooling produced from laser processing [11]. Dark shades on the laser treated area were affected by surface oxidation which related to surface temperature distributions [4].



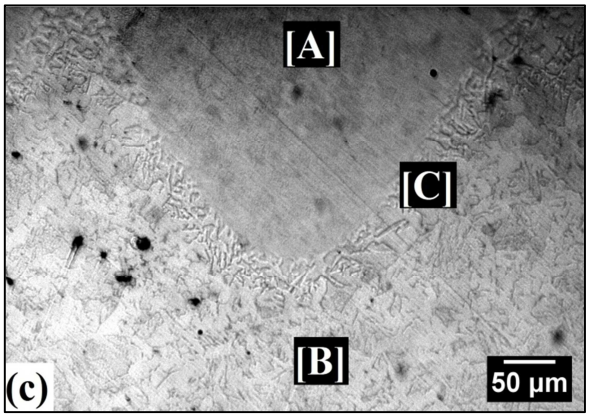
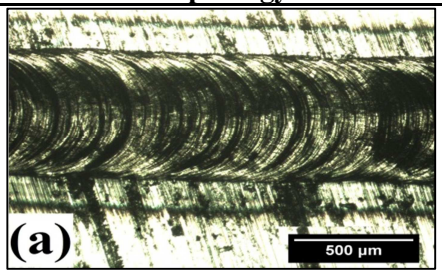
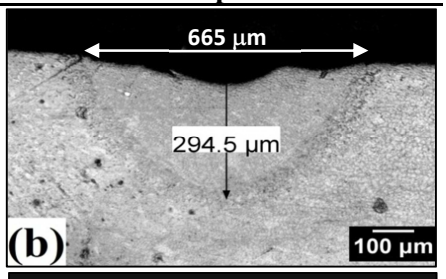
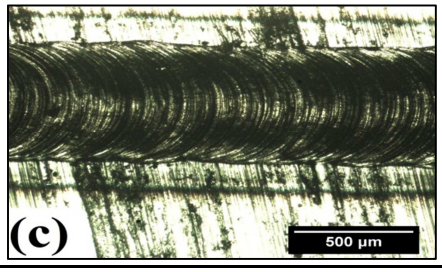
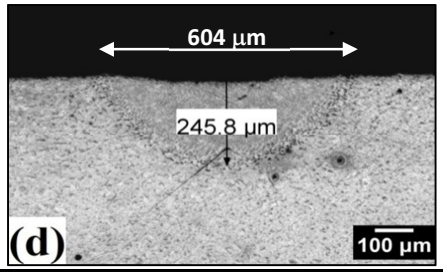
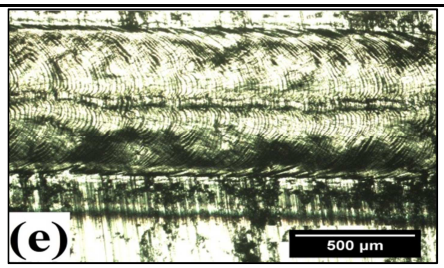
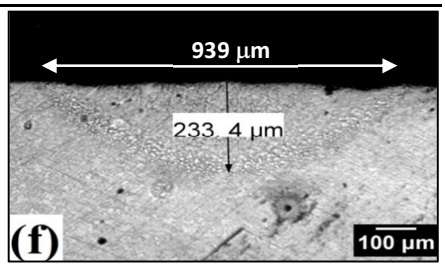


Fig 1: Micrographs of laser modified layer [A] on AISI 1025 steel substrate [B] in sample S1 (a) and S2 (b). A higher magnification of molten pool in sample S1 (c).

Changes of molten zone dimension due to different focal positions are shown in Table 3. Increasing laser spot size produced larger width of molten pool. Micrograph (a) shows laser modified surface morphology of sample S5. Micrograph (b) of Table 3 shows the resulting cross section of sample 5 with molten pool dimension of a 655 µm wide and 294.5 µm deep at 0.48 mm spot size, the deep molten pool dimension was due to high power density of 22,901.65 W/mm^2. The corresponding depth of sample S6 in micrograph (c) is shown by micrograph (d). A smaller dimension of molten pool of 245.0 µm deep and 604 µm wide was measured in sample S6 when a larger spot size of 0.60 mm was used. Micrograph (f) in Table 3 shows the largest spot size of 0.68 mm achieved when defocused at 5.0 mm beneath the sample surface. Defocusing laser spot caused changes of interaction distance between laser beam profile and sample surface, which altered dynamics and geometric profile of processed surface [9].

Table 3: Micrographs of laser modified AISI 1025 sample processed with spot size focusing on (a) and (b) sample surface, (c) and (d) -2.5 mm defocused from sample surface, and (e) and (f) -5.0mm defocused from sample surface.

Spot size (mm)	Laser modified surface morphology	Cross section of molten pool depth
0.48		
0.60		

0.68		

Hardness Properties

Hardness properties of all laser modified samples cross-sectional area were plotted in Fig 3. Three regions measured were molten zone, HAZ and substrate. In Figure 3, the molten region thickness varied between samples, while hardness decreased across the molten zone, heat affected zone (HAZ) and substrate. The molten region was measured in range of 0.23 to 0.46 mm depth from surface. The hardness values of substrate were 140 and 150 $HV_{0.1}$. The molten zone hardness was as high as 450 $HV_{0.1}$. The energy density input was in the range of 1.3 J/mm^2 to 2.0 J/mm^2. High density of laser beam irradiated on the surface produced homogenous austenite phase in a very short time and rapidly solidified to form finer grains. When approaching HAZ, the hardness decreased due to lapse time for carbide melting in performing the homogenous austenite [8]. Lower solidification rate in HAZ produced larger grain size than in molten zone, thus decreased hardness exhibited.

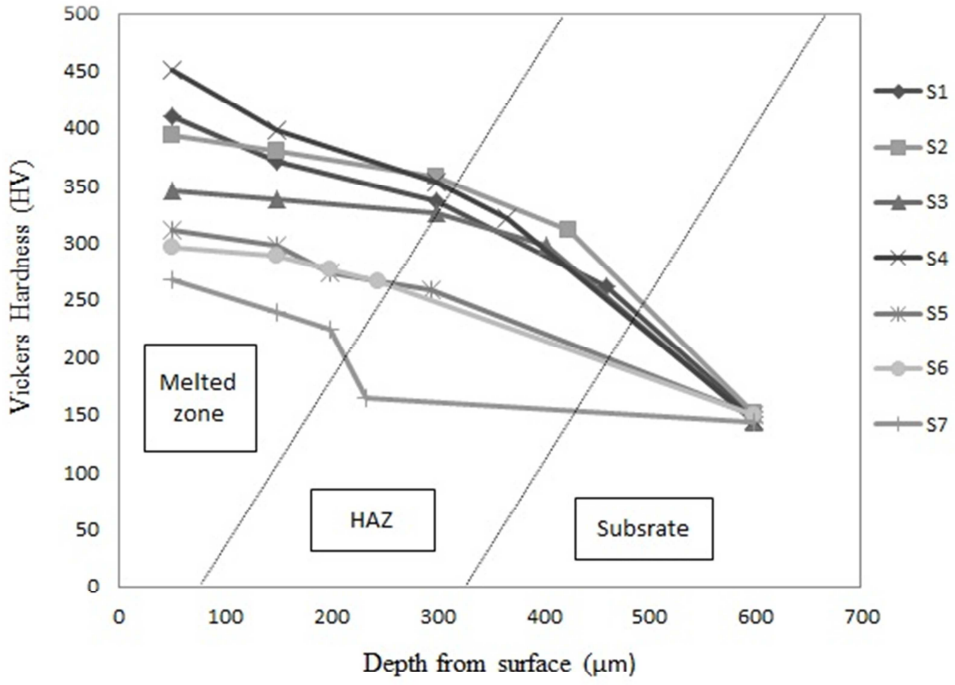


Fig. 2: Hardness of laser modified AISI 1025 steel surface across sectional area.

The hardness properties of sample S2, S3 and S4 in Fig 2 increased directly proportional to the scanning speed. Referring to Table 2, sample S4 was processed at the highest speed of 1000 mm/min while S2 and S3 were at 800 and 600 mm/min speed respectively. Low overlapping pulses percentage occurred at high scanning speed caused grain refinement with rapid solidification. Whereas the higher overlapping rate from low scanning speeds of 600 and 800 mm/min caused longer interaction time between laser beam and sample surface. Longer laser beam-surface

interaction time due increased surface temperature. A higher surface temperature delayed solidification rate and resulted in larger grain size formation.

Conclusion

Hardness of AISI 1025 was enhanced three times from the as-received substrate. The maximum hardness of 450 $HV_{0.1}$ was obtained at translation speed of 1000 mm/min, average power of 100 W and PRF of 50 Hz. A higher thickness and specified melt zone profile of laser modified layer can be obtained by adjusting laser focal positions. The highest thickness of modified layer was 455 μm which resulted from a higher peak power of 2500 W and 2 J laser energy. These findings signify potential use of AISI 1025 low carbon steel in high wear resistant applications.

Acknowledgement

This work was supported by Universiti Malaysia Pahang and Fundamental Research Grant Scheme-RDU120105 from Ministry of Higher Education Malaysia.

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