Modification of Carbon Steel by Laser Surface Melting: Part II: Effect of Laser Beam Power on Microstructural Features and Surface Hardness

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ABSTRACT

The surface hardness has an important effect on the wear resistance of different materials. The present study aims to improve the surface hardness of carbon steel through the application of laser surface melting with suitable conditions. The laser beam power and travelling speed are the main factors that affect the properties of the treated zone. In this study, three different conditions of laser beam power (1800, 1500 and 1200 W) at fixed travelling speed of 1000 mm min^{-1} were chosen to study the effect of laser beam power. The resulted laser treated specimens were investigated in macro and microscopically scale using optical and scanning electron microscope. Hardness measurements were also carried out through the thickness of the laser treated zones. The laser treated areas with all used powers results in melted and solidified zone on the surface of the steel. The laser power of 1800 W results in the deepest value of the laser treated zone (about 1.7 mm). Moreover, by increasing the laser power, the width of the treated zone was slightly increases. At areas near the free surface, large martensite plates were observed in higher laser power (1800 W), while longer acicular martensite was observed in lower laser power (1200 W). For laser power of 1800 W, the bainite structures in ferrite grains were more pronounced in larger areas and in closer areas to the free surface. On the other hand, the lower laser power shows higher hardness on the free surface than that of higher power. The sizes of Heat Affect Zone (HAZ) areas were increased by increasing the laser beam power. In all conditions, the heat affected zone areas were composed of partially decomposed pearlite in ferrite grains.

Keywords: X 52 Steel, Laser Surface Treatments, Laser Surface Melting, Martensitic Structure, Nanostructure, Microhardness

1. INTRODUCTION

In different industrial sectors, there is an urgent need to improve the performance of material surface under wear and corrosion environments, which cannot be fulfilled by the conventional surface modifications and coatings. Arai (1992) reported that the Conventional Surface Engineering (CSE) techniques such as carbonizing, nitriding, Chemical Vapor Deposition (CVD), physical vapor deposition (PVD) and Thermo Reactive Deposition and diffusion (TRD) improve the wear resistance, only under appropriate conditions. Laser represents one of the most important inventions of 20th century. With their development, it is possible to get highly intensive, monochromatic, coherent and highly polarized light waves (Hoffmann and Dierken, 2003; Yasavola *et al.*, 2013). One way to improve the surface properties of materials is the laser surface engineering. Laser surface engineering encompasses several applications that are mainly related to enhancing one of the surface dependent properties, like hardness, friction, fatigue and resistance to wear, corrosion

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(Majumdar *et al*., 2010). The surface of metals can be modified by the application of one or more of suitable laser surface treatments (Costa *et al*., 2004; Kanapenas, 2001). The simplest application of laser processing, laser heating, involves the rapid heating of the surface layers to a temperature just below the melting point, followed by rapid cooling (Baker, 2010).

The Laser Surface Melting (LSM) (Benyounis *et al*., 2009), Laser Surface Alloying (LSA) (Sun *et al*., 2010) and Laser Surface Cladding (LSC) (Liu *et al*., 2007) are examples of the suitable treatments which can also be applied for surface modification. Some of the advantages of these surface treatments include flexibility and the possibility of treating small areas, leaving the others parts unaffected. In laser surface melting, no additional alloying elements are incorporated. Since the bulk of the material is unaffected by the laser, a large heat sink is provided for the subsequent rapid cooling of the melted surface. This can result in non equilibrium fine microstructures with superior homogeneity, which may confer substantial increases in hardness and wear resistance of the material surface in a very short time (Darmawan *et al*., 2007; D'Oliveira *et al*., 2001). Moreover, laser surface treatments have little thermal penetration, resulting in little distortion, process flexibility due to software control and possibilities of automation. As reported in (Bhadeshia, 2012), the surface performance of the specimens treated by LSM is modified mainly by the homogenization and refinement of the microstructure. In addition, different precipitates may be formed in some alloys and the supersaturation of some phases increased due to nonequilibrium solidification. However, the modification is limited, because the composition of the melted layer is the same with respect to the substrate. The modification can be improved by controlling of the treatment parameters. The power and travelling speed of laser beam are main process parameters. Therefore, the effect of these parameters were studied in the present and another articles. The present work aims to study the effect of laser beam power on microstructural features and hardness of surface and subsurface layers of X52 carbon steel.

2. MATERIALS AND METHODS

Grade X 52 steel of chemical composition listed in **Table 1** was used as a base metal. The microstructure of the base metal consisted of annealed ferrite (white region) and full laminated pearlite (dark region) microstructure, as shown in the optical micrograph in **Fig. 1**. The mechanical properties of the base metal are tabulated in **Table 2**.

Table 1. Chemical analysis of base metal (wt %)

C	Si	Mn	P	S	Cr	Fe
0.22	0.21	1.22	0.05	0.01	0.05	Bal

Table 2. Mechanical properties of the base metal.

Yield strength, MPa	Ultimate tensile strength, MPa	Elongation, %	Hardness, Hv0.1
307	417	32	176

The laser machine operated at powers of 1200, 1500 and 1800 W, at a fixed travelling speed of 1000 mm min^{-1}.The focusing distance was 10 mm. The pressure and flow rate of N_2 gas: 0.5 bar and 27 L min^{-1}, respectively. The microstructures of the treated zone and base metal were investigated using optical and scanning electron microscopes. The microhardness of treated zone and subsurface layers at different conditions was evaluated using a microhardness tester.

3. RESULTS

3.1. Effect of Treatment Conditions on the Microstructure

Macro and microscopic appearances of the treated (melted and solidified layer) and Heat Affected Zone (HAZ) produced by application of the laser surface melting of different laser powers are shown in **Fig. 2-8**. In general, the depth of the treated zone was decreased by decreasing the laser power, as clearly shown in **Fig. 2**. At laser power of 1800 W, the heat input became very large and in consequence, the cooling rate became relatively slow. As a result of this main address, the depth of the laser treated zone reached 1.7 mm. When the laser power decreased to 1500 W, The generated heat input reduces the cooling rate and in subsequence affect on the depth of the treated zone which reduced to about 1.3 mm. By reducing the laser power to be 1200 W, the resulted treated zone depth was slightly decreased to about 1.2 mm.

The microstructures of the treated zone after laser power of 1800 W, are shown in **Fig. 3 and 4**. The cooling rate after this huge amount of heat input is not fast enough to form full martensite structure even at or near the treated zone free surface. The results show that the martensite appeared inside a ferrite grains even near the free surface. At areas little bit far from the free surface, mixed acicular martensite and lower bainite are appeared in large ferrite grains. Moreover, the results show large heat affected zone due to this lower cooling speed.
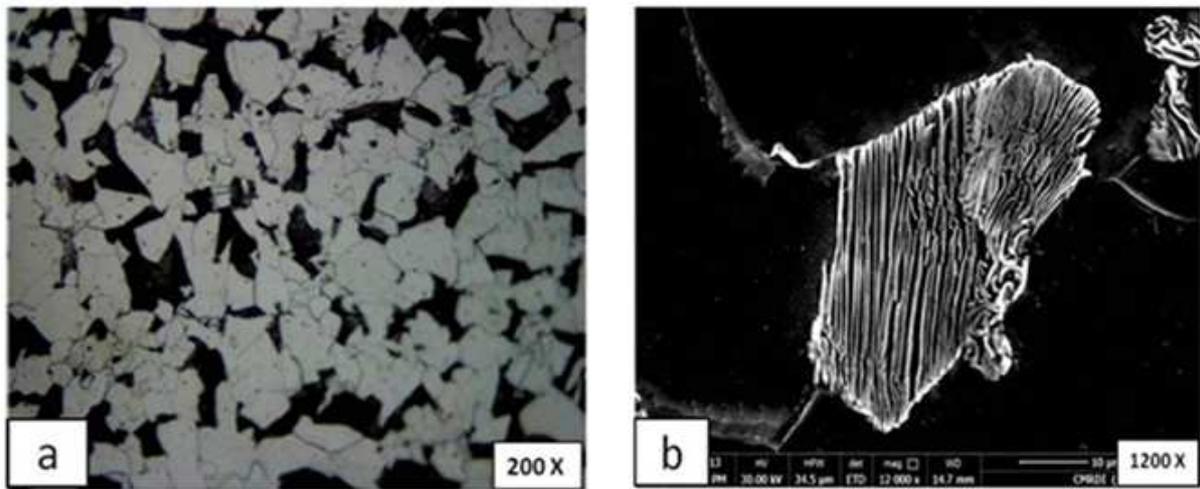
Fig. 1. Microstructure of the untreated steel (a) Optical micrograph showing normal ferrite (white color)-pearlite (dark color) structure and (b) SEM image showing full laminated pearlite structure with larger magnification
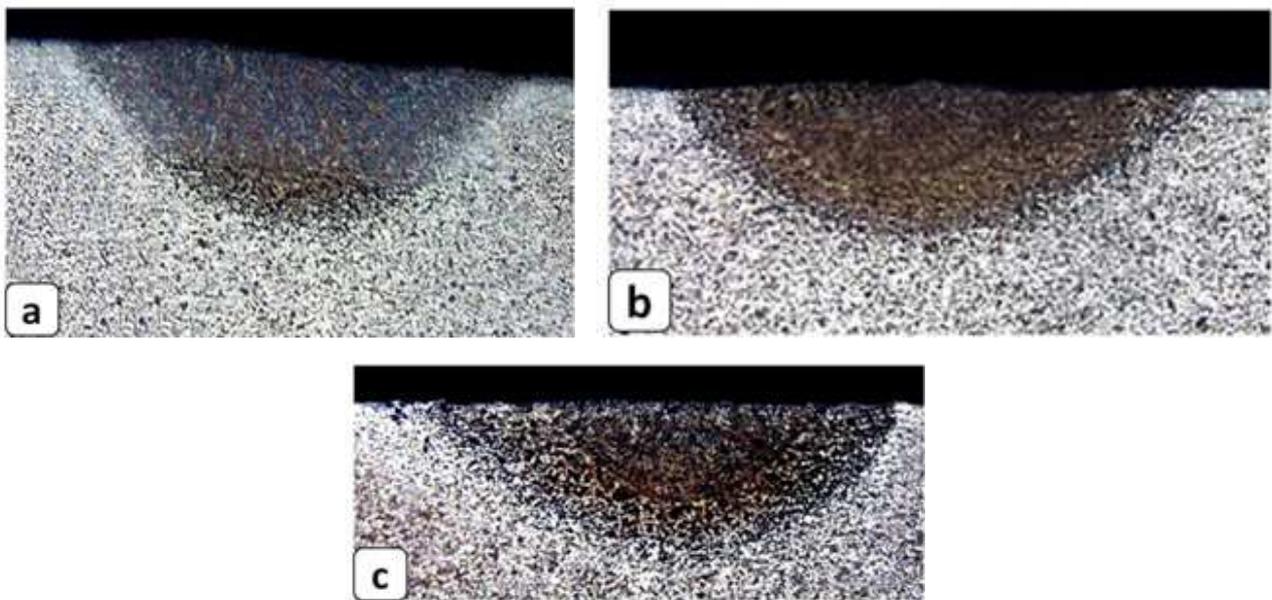
Fig. 2. Optical macrographs for treated zones produced by laser power of (a) 1800, (b) 1500 and (c) 1200 W

The treated (melted and solidified layer) and Heat Affected Zone (HAZ) produced by application of the laser surface melting at 1500 W and 1000 mm min^{-1} are shown in **Fig. 5 and 6**. The heat input that generated by laser power of 1500 W reduces the cooling rate and in subsequence affect macro and microscopically of the resulted treated zone. Large batches or plates of martensite appeared again in areas very near to the free surface. This is due to the fast heat dissipation by radiation to the surrounding fresh air. In the center of the treated zone, batches of mixed martensite and bainite inside fine grained ferrite structure are clearly recognized. In this zone, the resulted cooling rate is suitable for production of this mixed microstructure. The power density in this case is lower than that in case of power 1800 W. Accordingly, the batches of martensite and bainite mixed structure are larger and the ferrite grains are finer.
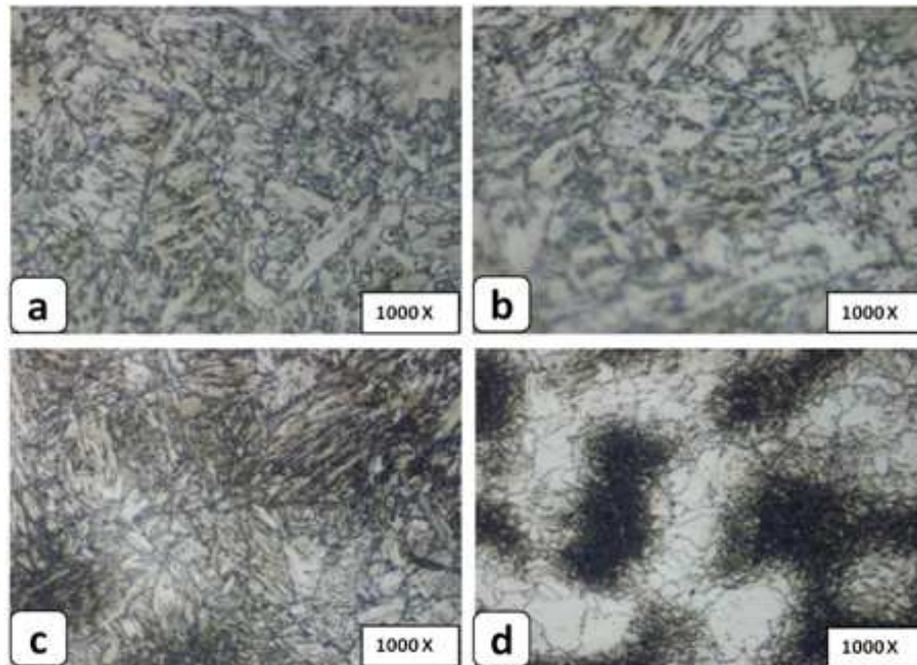
Fig. 3. Optical micrographs for microstructures produced by laser Power of 1800 W, where (a) near the free surface of the treated zone, (b) at the center of the melted and solidified zone, (c) at the end of the melted and solidified zone, and (d) at the Heat Affected Zone (HAZ) of the treated zone
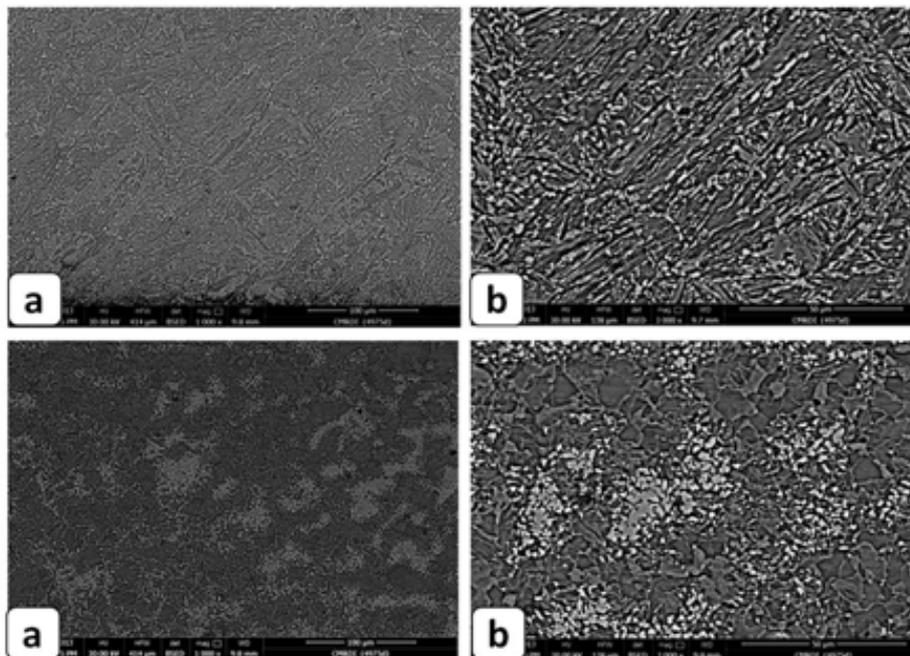
Fig. 4. SEM images of microstructure produced by laser Power of 1800 W, where (a) and (b) near the free surface of the treated zone and (c) and (d) at the lower part of the treated zone
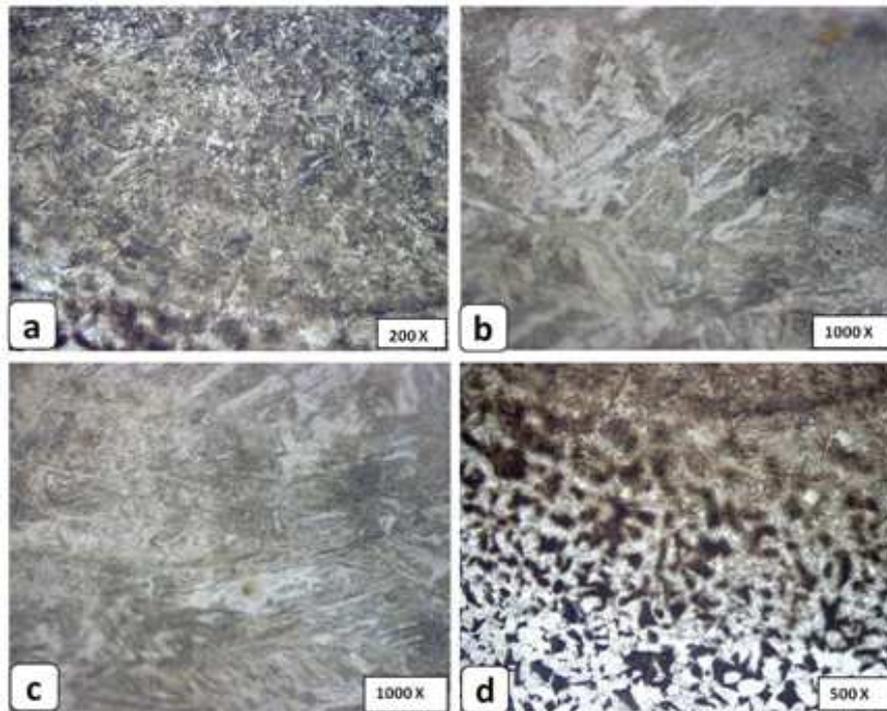
Fig. 5. Optical micrographs for microstructures produced by laser Power of 1500 W where, (a) Low magnified micrograph of the melted and solidified zone, (b) and (c) High magnified micrographs of the melted and solidified zone and (d) Low magnified micrograph at the interface between the laser treated and untreated zones
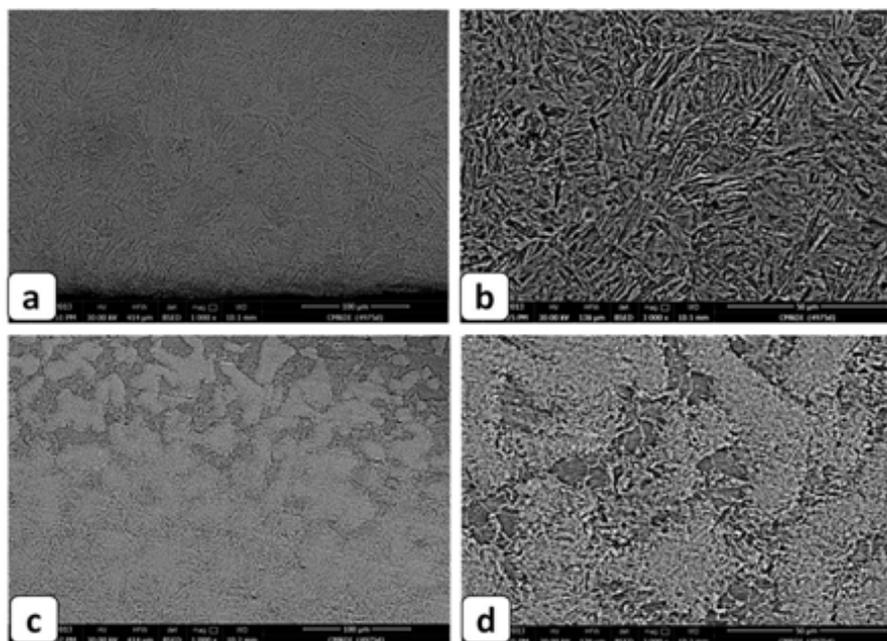
Fig. 6. SEM images for microstructure produced by laser Power of 1500 W where, (a) and (b) at areas very near to the free surface and (c) and (d) at the end of the treated zone
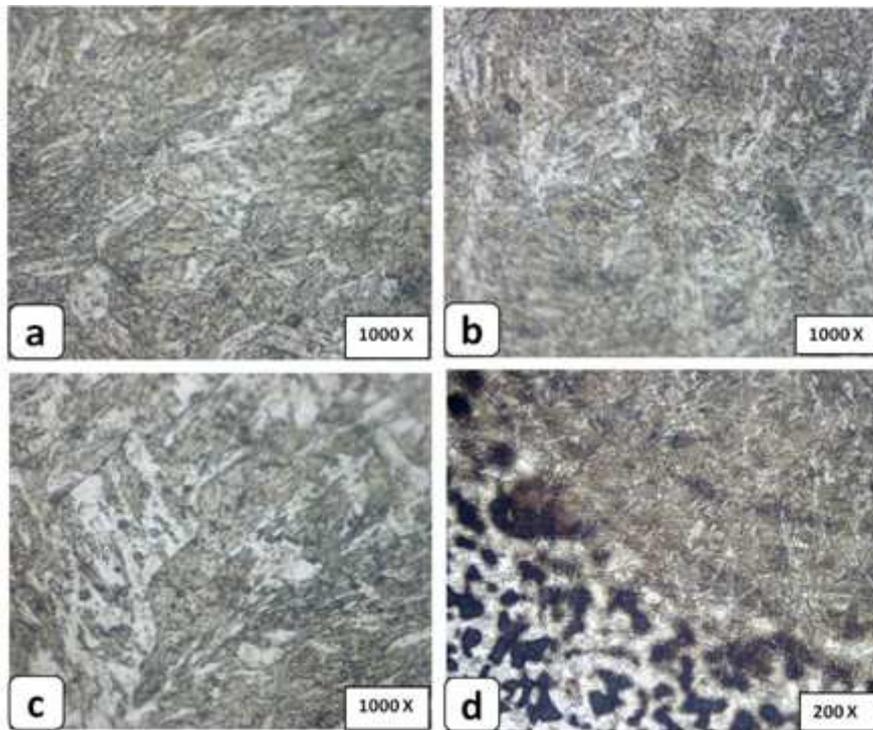
Fig. 7. Optical micrographs for microstructures produced by laser power of 1200 W where, (a) at areas very neat to the free surface, (b) at the center of the melted and solidified zone, (c) at areas near the lower part of the treated zone and (d) at the interface between the laser treated and untreated zones
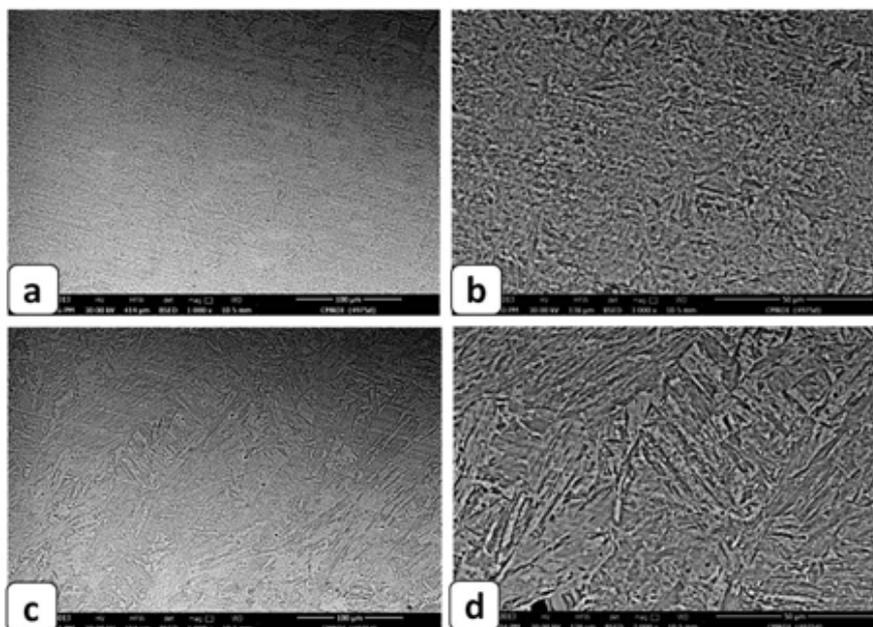
Fig. 8. SEM images for microstructure produced by laser power of 1200 W where, (a) and (b) at areas very near to the free surface and (c) and (d) at the center of treated zone
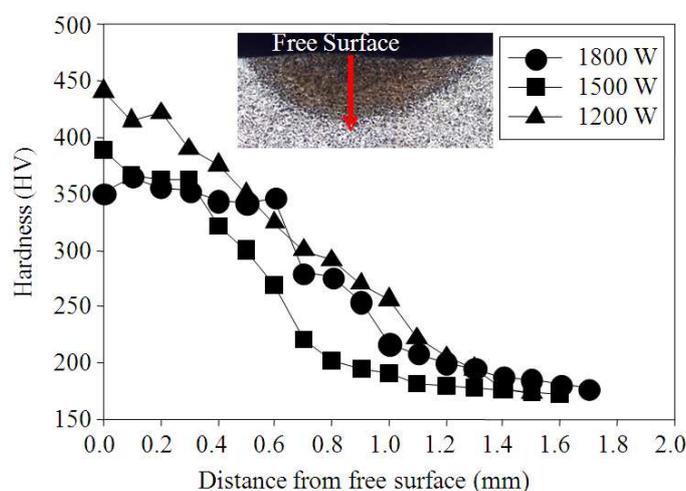
Fig. 9. Hardness distributions through the depth of laser treated zone at different laser powers at fixed travelling speed of 1000 mm min^{-1}

By reducing the laser power to be 1200 W, the resulted treated zone shows some changes, as shown in details in **Fig. 7 and 8**. Firstly, the treated zone depth was slightly decreased to about 1.2 mm. when the laser power is decreased, the heat input will be also decreased. As a subsequence, the depth of the metal that is affected will be decreased. Regarding the width of the treated zone, it records about 3 mm.

Microscopically, small plate of fine acicular martensite is appeared near the free surface. Going inside the laser treated zone, larger plates of the martensite are recognized. Near the end of the treated zone, large martensite plates are found inside ferrite grains.

3.2. Effect of Laser Treatment on Surface Hardness

The hardness data is obtained through the micro hardness tester. The average value of hardness for the untreated base material is 176.4 HV$_{0.1}$. The hardness distributions through the depth of the laser treated zone at different powers are shown in **Fig. 9**. The results indicated that laser power has a significant effect on the hardness of the surface and subsurface layers. The hardness of the free surface of near from it shows higher values at lower laser power. For example, at power of 1800 W, the hardness reaches to only 350 HV, while of that of 1200 W can reach to 440 HV. On the other hand, the laser power has a straight effect on the depth of the hardness. As the laser power increases, the depth of the higher hardness went to a deeper depth inside the materials (Compare the plot of hardness of 1800 W and

that of 1500 W). The enhancement in hardness can mainly be attributed to the formation of fine martensitic structure. It was observed that the finer microstructure shows higher hardness values, especially at lower laser powers. This is due to rapid solidification processes in the surface melted and solidified zone. In the sub melted zone, lower hardness values were observed. This is due to the lower cooling rate which produces batches of mixed martensite and bainite inside fine grained ferrite structure. In all cases, the hardness values for the treated and heat affected zones are higher than those for the base metal. Moderate hardness in the transition zone was obtained due to the ferrite-partially decomposed pearlite structure produced in the HAZ.

4. DISCUSSION

The power of the laser beam is one of the main factors in laser surface melting which alter the depth and width of melted and heat affected zones to obtain desired surface properties. The above results indicated that this process parameter has a significant effect on the microstructural features and hardness of surface and subsurface layers. The heat input has a direct relationship with the laser power. When the laser power is increased, the heat generated is increased and in consequence, the depth of melted zone is increased. On the other hand, the higher power deceases to some limit the cooling rate after solidification. As consequence, the relatively slow cooling rate (that of higher power) decreases the amount of formed martensite and give the bainite structure and

ferrite grains to be appeared in large areas as clearly shown in the previous micrographs. The rapid cooling after laser surface melting of lower laser powers (up to 10^6°K/s) leads to formation of fine martensite structure at the surface which improve the surface hardness (Luangpaiboon, 2011).

Moreover, the rapid cooling can also refine the microstructure, which improve not only the wear resistance, but also the corrosion and fatigue resistance. On the other hand, the depth of this higher hardness is limited by the lower power.

Solid state transformations occurring in the heat affected zone are due to carbon diffusion phenomena. As an assumption, cementite and ferrite plates which formed pearlite of the base metal are distant from, pearlite dissolution requires a diffusion of carbon atoms along a certain distance and a suitable time is required. In the present investigation, the treatment conditions applied are not suitable for complete decomposition of the pearlite. As a result, partial decomposition of pearlite is resulted. Therefore, there is an increase in hardness in this zone but with value lower than that in the melted and solidified zone. Generally and as shown in **Fig. 9**, in the sub melted zone, due to lower cooling rate, batches of mixed martensite and bainite inside fine grained ferrite structure of hardness lower than that of full martensitic structure formed in the melted zone but higher than that of the HAZ. In all cases, the hardness values for the treated and heat affected zones are higher than those for the base metal. Moderate hardness in the transition zone was obtained due to the ferrite-partially decomposed pearlite structure produced in the HAZ.

5. CONCLUSION

The surface of grade X52 steel was laser treated with different powers (1800, 1500 and 1200 W) at fixed travelling speed of 1000 mm min^{-1}. The resulted laser treated specimens were investigated in macro and microscopically scale using optical and scanning electron microscope. Hardness measurements were also carried out through the thickness of the laser treated specimens. The results obtained can be summarized as follows:

- The laser treated areas with all used powers results in melted and solidified zone on the surface of the steel
- Plates of acicular martensite structure were observed within the upper part of the melted and solidified zone in almost all experimental conditions, while

some bainite structure in ferrite grains are detected in its lower part

- The laser power of 1800 W results in the deepest value of the laser treated zone (about 1.7 mm). By increasing the laser power, the width of the treated zone was slightly increases
- Near the free surface, large martensite plates were observed in higher laser power (1800 W), while longer acicular martensite was observed in lower laser power (1200 W)
- For laser power of 1800 W, the bainite structures in ferrite grains were more pronounced in larger areas and in closer areas to the free surface
- The lower laser power show higher hardness on the free surface than that of higher power
- The Heat Affect Zone (HAZ) areas were increased by increasing the laser power. In all conditions, the heat affected zone areas were composed of partially decomposed pearlite in ferrite grains
- The microstructure of the base metal far from the laser treated areas show normal ferrite-sound pearlite microstructure

6. ACKNOWLEDGEMENT

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