

## Modification of Carbon Steel by Laser Surface Melting: Part I: Effect of Laser Beam Travelling Speed on Microstructural Features and Surface Hardness

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### ABSTRACT

The present study aims to improve the surface hardness of carbon steel by application of laser surface melting of effective conditions. The travelling speed of laser beam during this treatment is one of the important treatment conditions. This study aims to investigate the effect of laser surface melting with different beam speeds on macro and microstructure as well as the hardness distribution through the thickness of carbon steel. To achieve this target, three different travelling speeds (1500, 1000 and 500 mm min<sup>-1</sup>) at a constant beam power of 800 W were chosen in this study. 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 laser treated areas with all used travelling speeds results in melted and solidified zone on the surface of the steel. In the same time, 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. By increasing the travelling speed, the depth of the laser treated zone was decreases, while travelling speed has much less significant effect on the laser treated zone width. The size of the formed martensite plates was increased by decreasing the travelling speed from 1500 to 500 mm min<sup>-1</sup>. On the other hand, the travelling speed has a straight effect on the length of the acicular martensite; as the travelling speed increases, the acicular martensite became longer, while it shows fine acicular martensite at lower travelling speeds. The depth that full martensite structure can be reached is increased by increasing travelling speed. At lower travelling speed (500 mm min<sup>-1</sup>), large amount of bainite structure is observed at the center of the treated zone up to its lower end. The fast travelling speed (1500 mm min<sup>-1</sup>) show higher hardness on the free surface than that of slow travelling speed (500 mm min<sup>-1</sup>). On the other hand, the travelling speed has a reverse effect on the depth of this hardness increment; the slower travelling speed give deeper areas of high hardness than that of fast speed. The Heat Affect Zone (HAZ) areas were increased by decreasing the travelling speed. In all conditions, the heat affected zone areas were composed of partially decomposed pearlite in ferrite grains. Finally, the microstructure of the base metal far from the laser treated areas show normal ferrite-sound pearlite microstructure.

**Keywords:** X 52 Steel, Laser Surface Treatments, Laser Surface Melting, Martensitic Structure, Nanostructure, Microhardness, Failure of Engineering Components

### 1. INTRODUCTION

The ability of metals to resist corrosion or wear attacks is determined by the composition and structure of the

surface properties (Yudai *et al.*, 2013). Therefore, to prevent or at least minimize surface dependent failures, the microstructure and/or composition of the surface layers are tailored by some surface treatments. Surface cladding is

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considered one of these surface treatments which improve the surface properties. On the other hand, conventional cladding requires high heat input which often leads to materials distortion or deformation (Xinhong *et al.*, 2006). For over 25 years, laser surface engineering techniques involving the subsequent rapid solidification of the molten surface have been used to improve wear, corrosion and erosion resistance (Yao *et al.*, 2010; Yadroitsev and Smurov, 2011). The unique advantages of laser surfacing compared to alternative processes are: Chemical cleanliness, minimal heat input, no machining required, low cost and laser emits a beam of energy in the form of either continuously or pulsed (Carcel *et al.*, 2011; Xu *et al.*, 2006). The following processes have been developed for laser modification: Surface melting, surface alloying, cladding and amorphisation (Zhang, 2012; Fernandez-Vicente *et al.*, 2012). Generally, laser surface treatment is a process of altering the metallurgical and mechanical properties of the material surface with laser irradiation. It is mostly used to produce hard, high wear-resistant regions on the workpiece while retaining the bulk material unaffected (Majumdar *et al.*, 2003). As reported in (Bhadeshia, 2012), the surface performance of the specimens treated by Laser Surface Melting (LSM) is modified mainly by the homogenization and refinement of the microstructure. In addition, hard phases such as martensite are formed due to fast cooling rates. Laser surface melting produces an increase of the hardness, toughness and wear resistance of the material surface in a very short time (Darmawan *et al.*, 2007). The laser melted surface has a homogenous and very fine martensite microstructure. The fine grained martensite structure is responsible for the increment in surface hardness (Benyounis *et al.*, 2009).

A deep understanding of the metallurgical aspects is necessary when laser parameters are to be selected. The

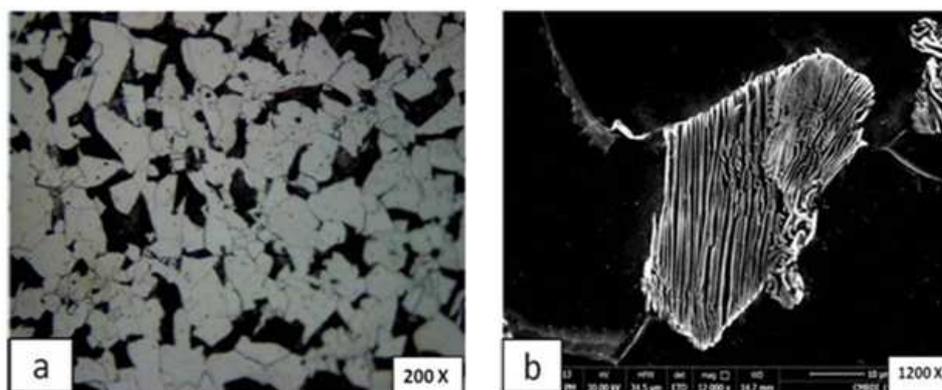
modification can be improved by controlling of the treatment parameters. The travelling speed of laser beam is one of the main process parameters. X52 steel alloy is one of steels that subjected to wear in many applications. Therefore, the effect of the laser beam travelling speed on microstructural features and hardness of surface and subsurface layers of this steel was studied in this article.

## 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. 1a**. This laminated pearlite structure is clearly appeared in **Fig. 1b**. The mechanical properties of the base metal are tabulated in **Table 2**. The laser machine operated at laser beam scanning speeds of 500, 1000 and 1500 mm min<sup>-1</sup> and a focusing distance of 10 mm. The experiments included single pass of the laser beam on the specimen surfaces with no overlapping. The pressure and flow rate of N2 gas: 0.5 bar and 27 L min<sup>-1</sup>, 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 was evaluated using a microhardness tester. Effect of laser beam speed on microhardness has been studied. Finally, the processing zones for the surface melting and hardening have been derived following a detailed structure-property correlation.

**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.



**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

**Table 2.** Mechanical properties of the base metal

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

### 3. RESULTS

#### 3.1. Effect of Treatment Conditions on the Microstructure

Three passes of laser surface melting were carried out at travelling speed of 1500, 1000 and 500 mm min<sup>-1</sup> at fixed power of 800 W. The treated (melted and solidified layer) and Heat Affected Zone (HAZ) produced by application of the laser surface melting at power of 800 W and at different travelling speed and the untreated zone were investigated using both optical and scanning electron microscopes. **Figure 2-7** show the optical micrographs and SEM images, respectively for the different zones in the treated sample.

The travelling speed of 1500 mm min<sup>-1</sup>, as shown in **Fig. 2a**, results in a treated zone of about 3 mm width and about 0.95 mm depth. The microstructures revealed that large batches or plates of long acicular martensitic structure are formed in the upper layer of the melted and solidified layer (**Fig. 3a to 4b**). This is may be due to the fast cooling rate by the fresh air touching the free surface after melting. At areas far from the free surface, the cooling rate becomes slower and not enough to form full martensite. So bainite structure is appeared as clearly shown in **Fig. 4c and d**. At the end or at the edge of the laser treated zone, heat is not enough to reach to the austenite region. Only the laser heat can decompose the laminated pearlite as described in **Fig. 3c**, while at areas far from the treated zone, it shows normal annealed ferrite-pearlite microstructure, as shown in **Fig. 3d**.

By reducing the travelling speed from 1500 mm min<sup>-1</sup> by one third to be 1000 mm min<sup>-1</sup>, some changes are noticed in the macro and micro scale, as shown in **Fig. 5 and 6**. Firstly, the treated zone depth was increased to about 1.1 mm, while its width remaining with the same value of 1500 mm min<sup>-1</sup> (about 3 mm), as shown in **Fig. 2b**. The decreasing of the travelling speed increases the heat input per unit area and thus, increasing the depth of the treated zone. On the other hand, the width of the treated zone depends mainly on the laser machine focus length, which remains constant in all conditions.

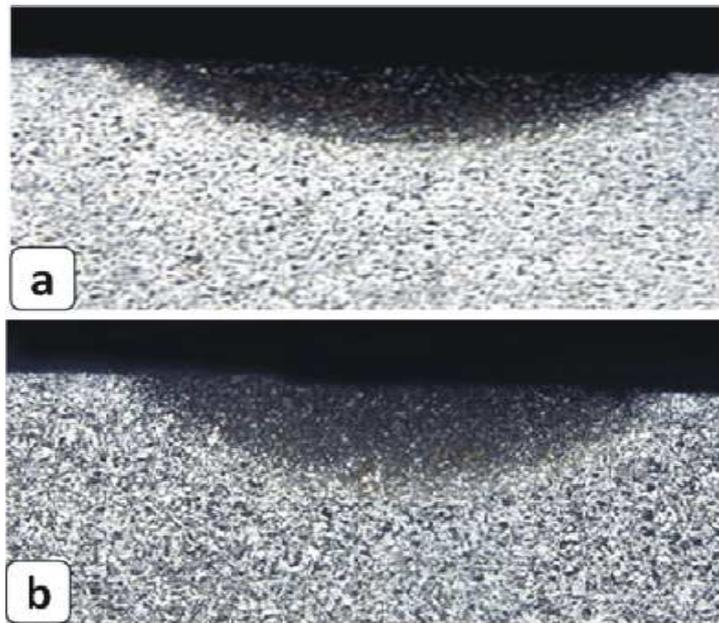
Similarly to the previous condition, near the free surface, large batches of plates of martensite structure is produced as shown in **Fig. 5a to 6b**. The main differences between the two structures are that the acicular martensite structure of 1000 mm min<sup>-1</sup> appeared to be finer than that of 1500 mm min<sup>-1</sup>. On the other

hand; the martensite plates appeared to be larger than that of 1500 mm min<sup>-1</sup>. This is due to that the relatively slow cooling after laser surface melting of travelling speed of 1000 mm min<sup>-1</sup> give the martensite plates to become courser. On the other hand, the acicular structure of the martensite needs fast cooling. Also, the bainitic structure appeared in a lower depth from the free surface than that of 1000 mm min<sup>-1</sup> (starts at the center of the treated zone) as clearly shown in **Fig. 6c and d**. This is may be due to that lower travelling speed gives the material a chance to reserve some heat up on heating, which decrease the cooling rate to the bainite zone.

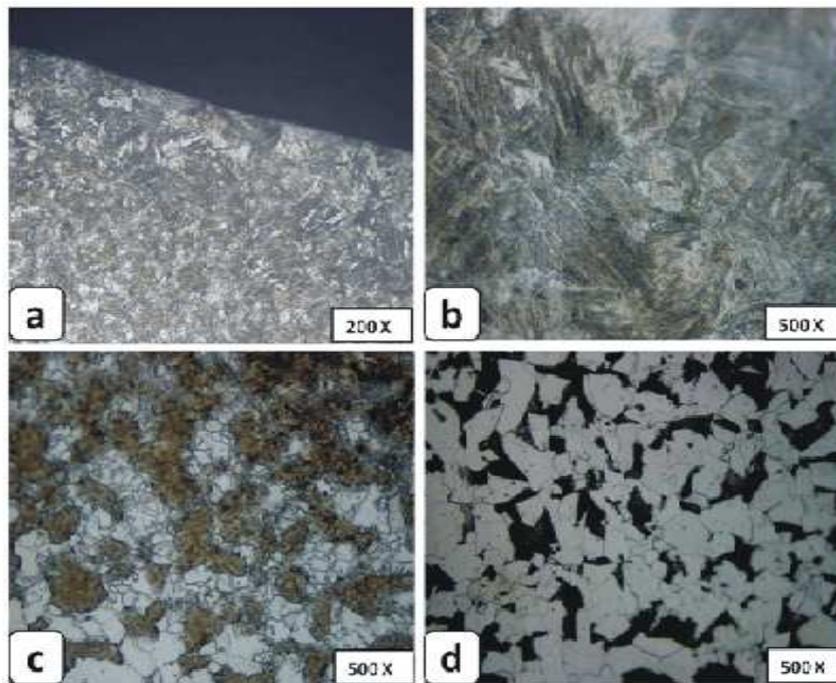
The results of laser treated areas produced by travelling speed of 500 mm min<sup>-1</sup> were shown in **Fig. 7**. For this very slow travelling speed, the depth of the laser treated zone became about 1.2 mm. This is the largest depth between the 3 conditions. This is due to the much heat input per unit area by this lower travelling speed. For the micro-scale, the plates of martensite structure became more larger with a more finer acicular structure, as shown in **Fig. 7**. Moreover, these martensite structures with its features appeared in deeper areas. The slower travelling speed of 500 mm min<sup>-1</sup> give a large amount of heat to the treated zone to a level that most of the nugget zone forms large plates of martensite structure. On the other hand, this large heat input reduces the length of the acicular martensite to be fine acicular martensite.

#### 3.2. Effect of Treatment at Different Speeds on Surface Hardness

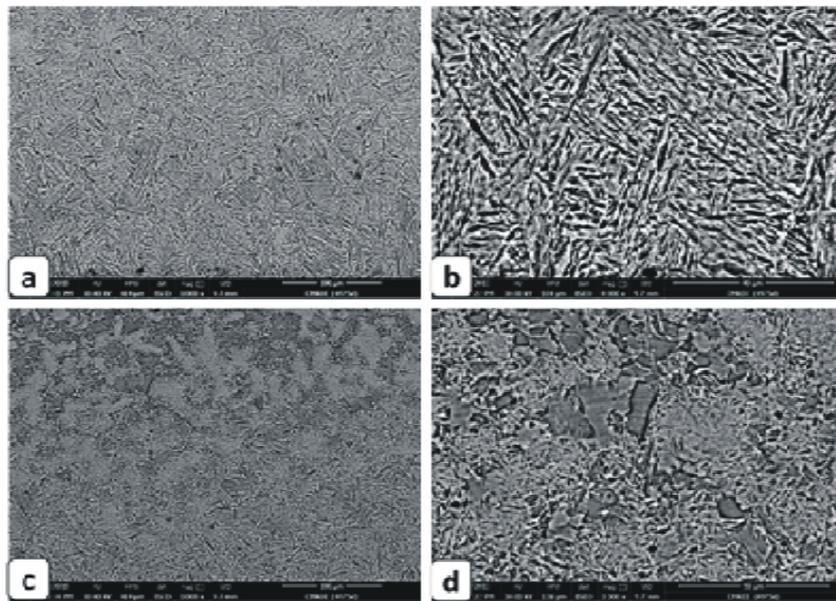
The hardness of the base material is in the range of 173-183 HV<sub>0.1</sub>. **Figure 8** shows the hardness profile beneath the surface for the steel at different travelling speeds. It was clearly shown that the travelling speed affect the hardness in different two ways. The first one is the hardness value at or near the free surface. The hardness at or near the free surface shows higher values at the higher travelling speed. For example it shows about 480 HV at 1500 mm min<sup>-1</sup>, while it shows only less than 400 HV at travelling speed of 500 mm min<sup>-1</sup>. The second way is the depth of the higher hardness. The travelling speed has a reverse effect on the depth of the higher hardness. Although the lower travelling speed of 500 mm min<sup>-1</sup> show only 400 HV on the surface, it continue at higher values to deeper distance than that of higher travelling speed of 1500 mm min<sup>-1</sup>.



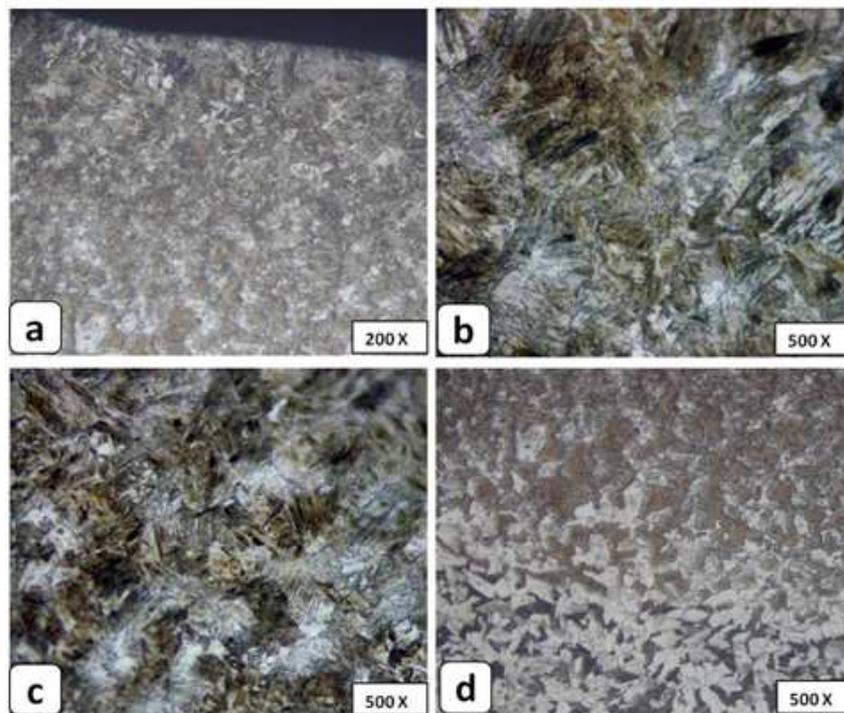
**Fig. 2.** Optical macrographs for treated zones produced by laser of power 800 W and travelling speed of (a) 1500 mm min<sup>-1</sup> and (b) 1000 mm min<sup>-1</sup>



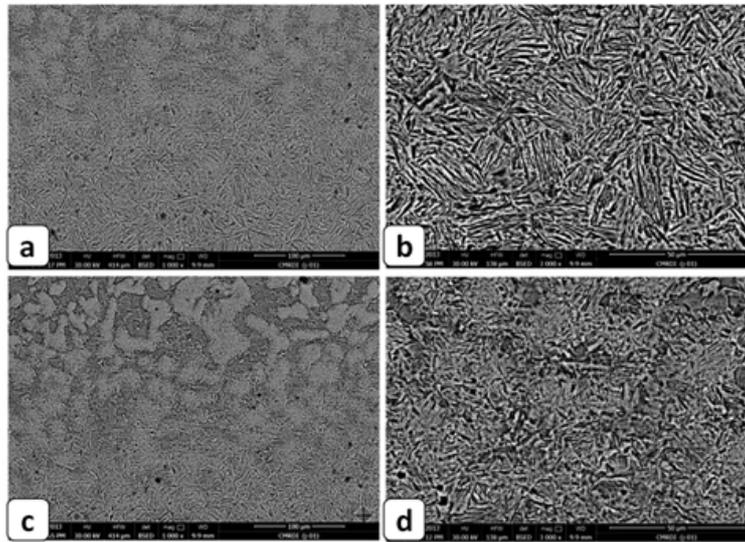
**Fig. 3.** Different magnified optical micrographs for microstructures produced by laser travelling speed of 1500 mm min<sup>-1</sup>. (a and b) at the melted and solidified zone (very neat to the free surface), (c) at the end of the melted or treated zone and (d) at area far from the treated zone



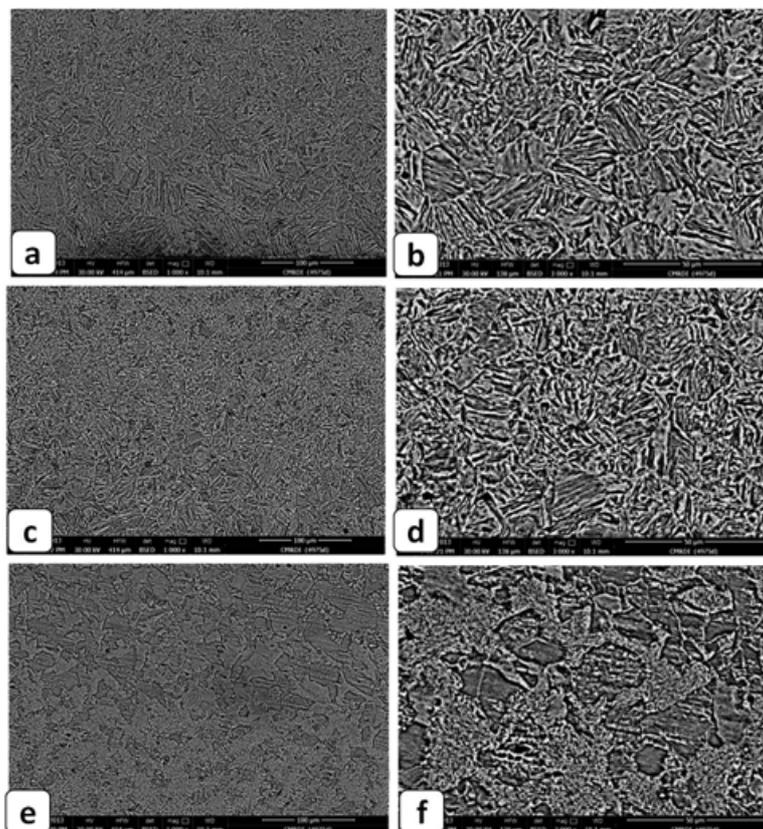
**Fig. 4.** Different magnified SEM images for microstructure of laser treated zone produced at travelling speed of  $1500 \text{ mm min}^{-1}$



**Fig. 5.** Optical micrographs for microstructures produced by laser treated zone produced at travelling Speed of  $1000 \text{ mm min}^{-1}$ . (a and b) at the melted and solidified zone (very neat to the free surface), (c) at the center of the melted and solidified zone and (d) near the end of the melted and solidified zone



**Fig. 6.** SEM images for microstructure of laser treated zone by travelling Speed of  $1000 \text{ mm min}^{-1}$ . (a and b) at area very near to the free surface and (c and d) at the center of the laser treated zone



**Fig. 7.** SEM images of the laser treated zone by travelling Speed of  $500 \text{ mm min}^{-1}$ . (a and b) at areas very near to the free surface, (c and d) at the center of the treated zone and (e and f) at the end of the laser treated zone

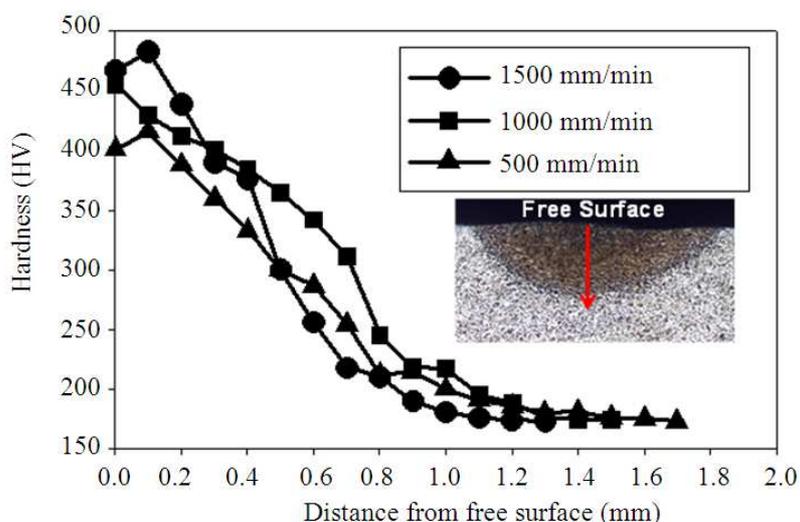


Fig. 8. Hardness distributions through thickness at different travelling speeds

#### 4. DISCUSSION

The previous results of microstructure show that, the travelling speed has an important effect on depth of melted zone and HAZ. The results clearly show that the travelling speed has a reverse relationship with the depth of the treated zone. As the travelling speed is decreased, the depth of melted zone and Heat Affected Zone (HAZ) are increased for the same power. This expected reverse effect may be due to the lower heat input per unit area in case of fast travelling speed. In the same time, the travelling speed has no relationship with the treated zone, which depends mainly on the focus length. On the other hand, the travelling speed has a reverse effect of the amount of size formed martensite plates. As the travelling speed increases, the amount and size of martensite plates are decreased. This is due to the higher cooling rate of the higher travelling speed in limited areas. For lower travelling speed, the martensite structure appeared in deeper areas. Regarding the size of the acicular martensite, the travelling speed has a straight effect. As the travelling speed increased, longer acicular martensite is appeared.

The microstructural features affect the properties. Accordingly, the refined structures with modified martensitic structure resulted in the melted and solidified zone improves the hardness. The hardening and strengthening of surface layers are important requirements required for improving wear, corrosion and fatigue failure resistances. These improvements in hardness can mainly be attributed to the effect of the

produced fine martensitic structure. In case of high travelling speed, the depth of the treated zone is reduced and as a result the specific energy is increased. With the increase of the specific energy the rates of heating and cooling are increased. The later resulted in fine martensite and consequently a remarkable improvement in hardness was achieved. In the same time the HAZ zone shows some grain refinement which induces relatively high hardness. Observed phenomena are related to rapid solidification processes. In laser treatments the heat transfer between the melted material and the substrate is very good and therefore high quenching rates (i.e., high isotherm speed) are obtained. The quenching rates values can reach  $10^6$  °K/s during the solidification process (Luangpaiboon, 2011).

#### 5. CONCLUSION

The surface of grade X52 steel was laser treated with different travelling speeds (1500, 1000 and 500 mm min<sup>-1</sup>). 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 travelling speeds 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
- By increasing the travelling speed, the depth of the laser treated zone was decreases, while travelling speed has much less significant effect on the laser treated zone width
- The size of the formed martensite plates was increased by decreasing the travelling speed from 1500 to 500 mm min<sup>-1</sup>. On the other hand, the travelling speed has a straight effect on the length of the acicular martensite; as the travelling speed increases, the acicular martensite became longer, while it shows fine acicular martensite at lower travelling speeds
- The depth that full martensite structure can be reached is increased by increasing travelling speed. At lower travelling speed (500 mm min<sup>-1</sup>), large amount of bainite structure is observed at the center of the treated zone up to its lower end
- The fast travelling speed (1500 mm min<sup>-1</sup>) show higher hardness on the free surface than that of slow travelling speed (500 mm min<sup>-1</sup>). On the other hand, the travelling speed has a reverse effect on the depth of this hardness increment; the slower travelling speed give deeper areas of high hardness than that of fast speed

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