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

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صهر طبقة سطحية للصلب الكربوني باستخدام الليزر:

الجزء الأول: تأثير سرعة مرور شعاع الليزر على ملامح البنية الميكروسكوبية والصلادة السطحية

ملخص باللغة العربية:

يعد البري الميكانيكي أحد أنماط الانهيار الرئيسية في العديد من المكونات الهندسية. وإن صلادة السطح هي عامل رئيسي في تحديد مقاومة البري. تهدف هذه الدراسة إلى تحسين صلادة سطح الصلب الكربوني من خلال تطبيق الليزر بظروف فعالة لذوبان طبقة سطحية. سرعة مرور شعاع الليزر خلال هذا المعالجة هي أحد الشروط المهمة لها. تهدف هذه الدراسة إلى فحص تأثير ذوبان السطح بالليزر عند سرعات مختلفة للشعاع على البنية الماكرو- مجهرية فضلا عن توزيع الصلادة خلال الطبقة المتأثرة بالمعالجة للصلب الكربوني. لتحقيق هذا الهدف، أجريت المعالجة عند ثلاث سرعات مختلفة لمرور الشعاع (١٥٠٠، ١٠٠٠، و ٥٠٠ مم / دقيقة) عند طاقة شعاع ثابتة ٨٠٠ وات وباستخدام غاز النتروجين للتغطية والحماية بضغط ومعدل تدفق ٠,٥ بار و ٢٧ لتر / دقيقة، على التوالي. كان طول مسافة التركيز ١٠ مم. وقد تم فحص ماكرو-مجهرى لبنية العينات المعالجة باستخدام المجهر الضوئي والمجهر الإلكتروني الماسح. أجريت قياسات صلادة أيضا من خلال سمك الطبقة المتأثرة بالمعالجة. تسبب إجراء المعالجة في السرعات التي اختيرت في صهر طبقة سطحية من الصلب المعالج وتصليدها. في الوقت نفسه لجميع الظروف التجريبية تقريبا ، لوحظ تكون بنية من المارتنزيت الأبري على السطح وفى طبقة قريبة منه يليها في العمق تكون بنية من الباينايت داخل حبوب الفيريت. بزيادة سرعة مرور الشعاع يقل عمق المنطقة المعالجة بالليزر، بينما لسرعة المرور للشعاع تأثير أقل بكثير على عرض المنطقة المعالجة بالليزر. تم زيادة حجم المارتنزيت من خلال خفض سرعة مرور الشعاع من ١٥٠٠ مم / دقيقة إلى ٥٠٠ مم / دقيقة. من ناحية أخرى، لسرعة مرور الشعاع تأثير على طول المارتنزيت الأبرى؛ فكلما زادت السرعة ، أصبح المارتنزيت الأبري أطول، في حين أنه يظهر مارتنزيت أبري دقيق عند انخفاض السرعة. ويزداد عمق طبقة المارتنزيت عن طريق زيادة السرعة. عند السرعة المنخفضة (٥٠٠ مم / دقيقة)، يلاحظ تكون كمية كبيرة من بنية الباينايت في وسط المنطقة المعالجة وحتى النهاية السفلى لها. سرعة مرور الشعاع العالية (١٥٠٠ مم / دقيقة) تظهر صلادة سطحية أعلى من التي نحصل عليها في حالة السرعة المنخفضة (٥٠٠ مم / دقيقة). من ناحية أخرى، لسرعة مرور الشعاع تأثير عكسي على عمق الطبقة ذات الصلادة العالية، فالسرعة المنخفضة تعطي مناطق مصلدة أعمق من تلك التي تنتج في

حالة السرعة العالية. زادت المناطق المتأثرة بالحرارة من خلال خفض سرعة مرور الشعاع. على أية حال، كانت المناطق المتأثرة بالحرارة تتألف من برليت متحلل جزئياً في حبوب الفريت. وأخيراً تتكون البنية المجهرية للصلب البعيدة عن المناطق المعالجة بالليزر من الفريت والبرليت السليم.

الكلمات الدالة بالعربية: الصلب X52 ، انهيار المكونات الهندسية، المعالجات السطحية بالليزر، صهر طبقة سطحية بالليزر ، البنية المارتنزيتية ، البنية النانومترية، الصلادة الميكروسكوبية.

Abstract

Wear is one of the most important failure mechanisms in many engineering components. The surface hardness is a major factor in determining the wear resistance. The present study aims to improve the surface hardness by the application of laser surface melting of effective conditions. The travelling speed of the laser beam during this treatment is one of the key treatment parameters. The effect of laser surface melting with different beam speeds on a macro and microstructure as well as the hardness distribution through the thickness of carbon steel is investigated. Three different travelling speeds (1500, 1000, and 500 mm/min) at constant beam power of 800W were selected. All the experimental tests were done using Nitrogen, as a shielding gas, at pressure and flow rate of 0.5 bar and 27 *l*/min, respectively. The beam focusing distance length was 10 mm. The resulted laser treated specimens were characterized in a macro and microscopic 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, at the different travelling speeds, resulted in melted and solidified zone on the surface of X52 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 with ferrite grains are detected in its lower part. By increasing the laser beam travelling speed, the depth of the laser treated zone was decreased, while it 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 mm/min to 500 mm/min. Moreover, the travelling speed has a straight effect on the length of the acicular martensite; as the travelling speed increased, the acicular martensite became longer, while it showed fine acicular martensite at lower travelling speeds. The depth that full martensite structure can reach is increased by increasing travelling speed. At lower travelling speed (500 mm/min), 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) showed higher hardness on the free surface than that of slow travelling speed (500 mm/min). Furthermore, the travelling speed has a reverse effect on the depth of this hardness increment; the slower travelling speed gave deeper areas of higher hardness than that of fast speed. The heat affected zone (HAZ) areas were increased by decreasing the travelling speed. In all conditions, the HAZ areas were composed of partially decomposed pearlite with ferrite grains. However, the microstructure of the base metal far from the laser treated areas showed normal ferrite- pearlite microstructure.

Keywords: X 52 steel, Failure of engineering components, Laser surface treatments, Laser surface melting, Martensitic structure, Nanostructure, Microhardness.

1. INTRODUCTION

The improvements of wear and corrosion resistance are the two main targets of the surface treatments [1]. The wear occurs on the surface layer and the fatigue cracks are also initiated on the surface [2]. In addition, corrosion can also occur on the surface [2].

The ability of metals to withstand corrosion or wear is determined by the composition and structure of the surface layers [3]. Therefore, to prevent or at least minimize surface dependent deterioration, the microstructure, and /or composition of the surface layers are tailored by some surface treatments. Conventional cladding requires high heat input which often leads to material distortion or deformation [4]. This process also involves pre-machining of the surface so that a layer of weld can be applied and machined to the original specifications of the component. Chrome plating is no longer acceptable due to its environmental restrictions [4]. 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 [5,6]. The unique advantages of laser surfacing compared to alternative processes are: Chemical cleanliness, minimal heat input, no machining is required, low cost, laser emits a beam of energy in the form of either continuously or pulsed [7]. Laser surface hardening is a promising process for enhancing the surface properties of a component. It has been used to improve the tribological properties of the metal alloys and ceramics [8-13], or their corrosion behavior [14,15].

The following processes have been developed for laser modification: surface melting, surface alloying, cladding and amorphisation [16]. Laser surface processing proved to be superior to the conventional surface treatments. 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 [17-19]. As reported in [20], 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, 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 [20]. Laser surface melting produces an increase of the hardness, toughness and wear resistance of the material surface in a very short time [21,22]. This process has been investigated by different authors by use of high power lasers. CO_2 or Nd:YAG lasers have been the most used [21, 22]. The rapid melting of the surface layer induced by irradiating with a laser beam, and its rapid solidification in contact with the cold substrate, are the main characteristics of this treatment. At the melted surface, this process produces a high homogenous and very fine dendritic microstructure, without the large typical carbides of tool steels [22]. The modification of surface microstructure of hot-work tool steel X40CrMoV5-1 by means of laser technology was studied by some researchers [23].

The fine grained martensite structure is responsible for hardness increase of the alloyed layer [23]. Oil field tools are routinely subject to abrasion and corrosion, degrading their surface integrity both mechanically and chemically [24]. These tools can also be treated using laser surface melting to increase their wear and corrosion resistances.

A combined treatment of the conventional laser surface melting and water-quenching was proposed and applied to two sets of specimens from the two types of steels [25]. In the case of alloy steel, treated zone of fine microstructure was observed [25]. The large carbides of high- speed steel (HSS) were completely melted in the treated zone and partially dissolved in the HAZ [25]. An appreciable increase in surface hardness was obtained by the application of conventional laser surface melting treatment [25]. Higher improvement in surface hardness was achieved by application of the combined treatment [25]. Further, the increase of laser beam (processing) speed during the combined treatment was accompanied by a decrease in width of the heat affected zone (HAZ) and a remarkable improvement in the surface hardness [25]. In case of the HSS, HAZ of high hardness was produced due to application of the combined treatment [25]. In laser cladding process, only a thin surface layer of the workpiece melts together with the additive material to form a coating layer [20]. Laser cladding technology also offers a revolutionary layered manufacturing and prototyping technique that can fabricate complex components without intermediate steps [26].

Deep understanding of the metallurgical characteristics is necessary when a laser melting is to be chosen or the processing parameters are to be selected [26-29]. In laser surface melting treatment, the surface layer modification is limited, because the composition of the melted layer is the same with respect to the substrate [20]. 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 is one of steels subjected to wear in some 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. Experimental work:

Grade X 52 steel of chemical composition listed in Table (1) was used as a base metal. Specimens of 150 mm length, 60 mm width and 6 mm thickness were used in this work. The length of treated zone was 100 mm. 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 (a). This laminated pearlite structure is clearly appeared in Fig. 1 (b). The mechanical properties of the base metal are tabulated in Table (2). CW CO_2 laser machine operated at laser beam scanning speeds of 500, 1000 and 1500 mm/min 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 N_2 shielding gas were 0.5 bar and 27*l*/min., respectively and remained constant during the treatments. 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 also 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 (X52 steel).

Chemical compositions (wt.%)									
C	Si	Mn	P	S	Cr	Mo	Ni	V	Fe
0.22	0.21	1.22	0.053	0.011	0.05	0.003	0.02	0.08	Bal.

Table (2) Mechanical properties of the base metal (X52 steel).

Yield Strength, MPa	Ultimate Tensile Strength, MPa	% ،Elongation	Hardness, Hv0.1
٣٠٧	٤١٧	٣٢	١٧٦

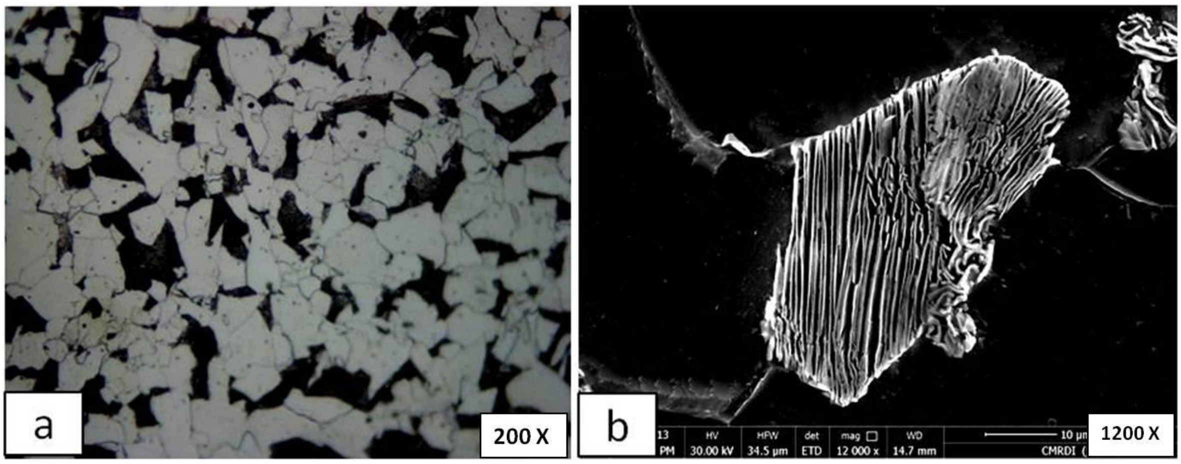

Figure 1 Microstructure of the untreated steel (a) Optical micrograph showing normal ferrite (white color)- pearlite (dark color)structure, and (b) SEM image showing full .laminated pearlite structure with larger magnification

3. Results and discussion:

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. and fixed power of 800 W. Under these conditions, the treated (melted and solidified layer) heat-affected zone (HAZ), and the untreated zone were investigated using both optical and scanning electron microscopes. Figures 2-8 show the optical micrographs and SEM images, respectively for the different zones in the treated sample.

The travelling speed of 1500 mm/min (see Fig. 2 a) 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 (see Figs. 3 a, 3 b, 4 a, and 4 b). This 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 appeared as clearly shown in Figs. 4 c, and 4 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. 3 c, while at areas far from the treated zone, it shows normal annealed ferrite – pearlite microstructure, as shown in Fig. 3 d.

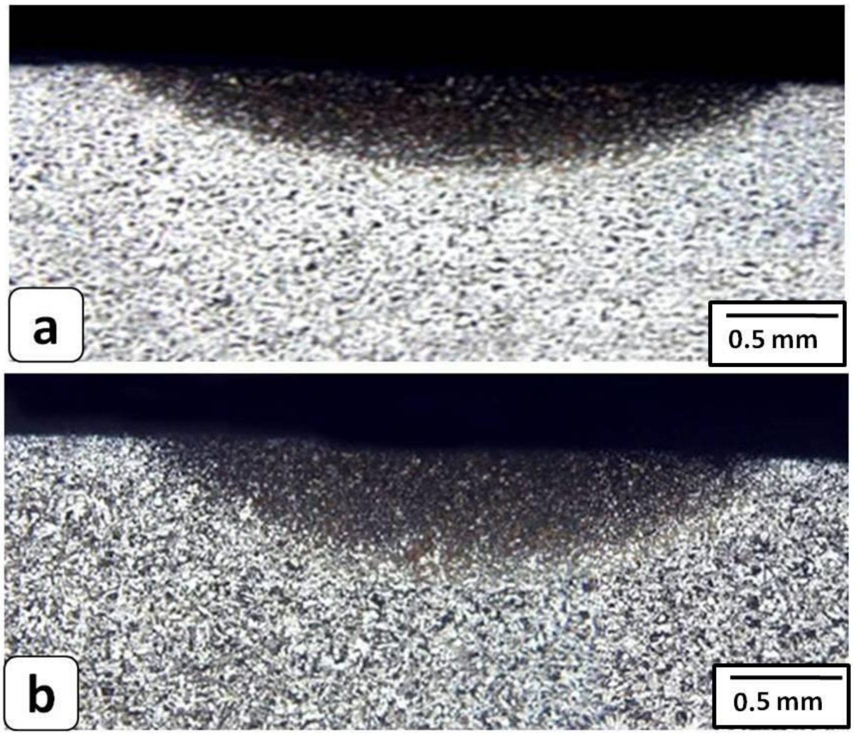

Figure 2 Optical macrographs for treated zones produced by laser of power 800 W and travelling speed of a) 1500 mm/min and b) 1000 mm/min.

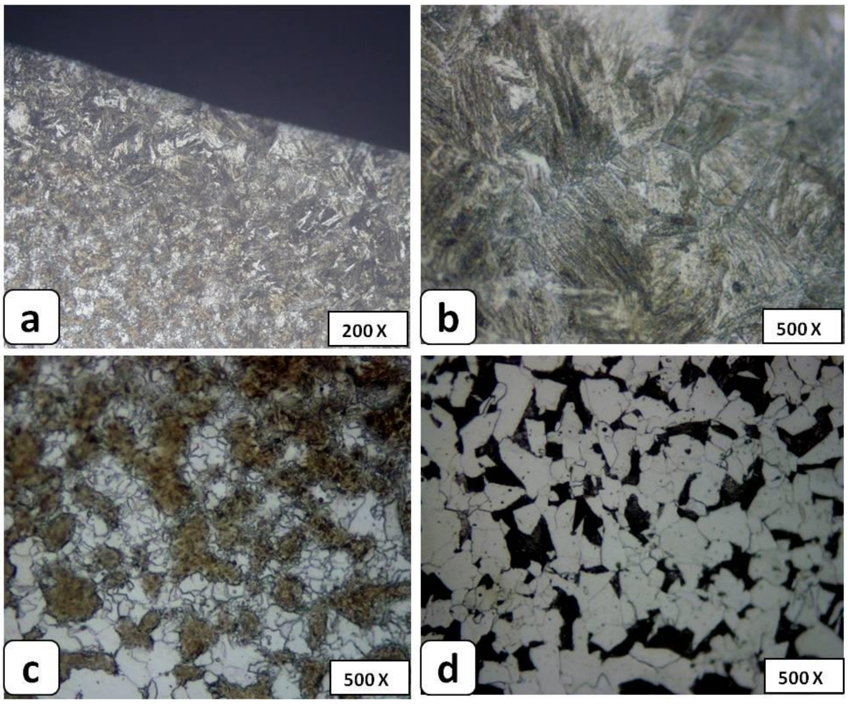

Figure 3: Different magnified optical micrographs for microstructures produced by laser of power 800 W and travelling speed of 1500 mm/min. (a) & (b) at the melted and solidified zone (very near to the free surface) showing large batches or plates of martensite structure., (c) at the end of the melted or treated zone, showing ferrite-partially decomposed or dissociated pearlite structure, and (d) at area far from the treated zone.

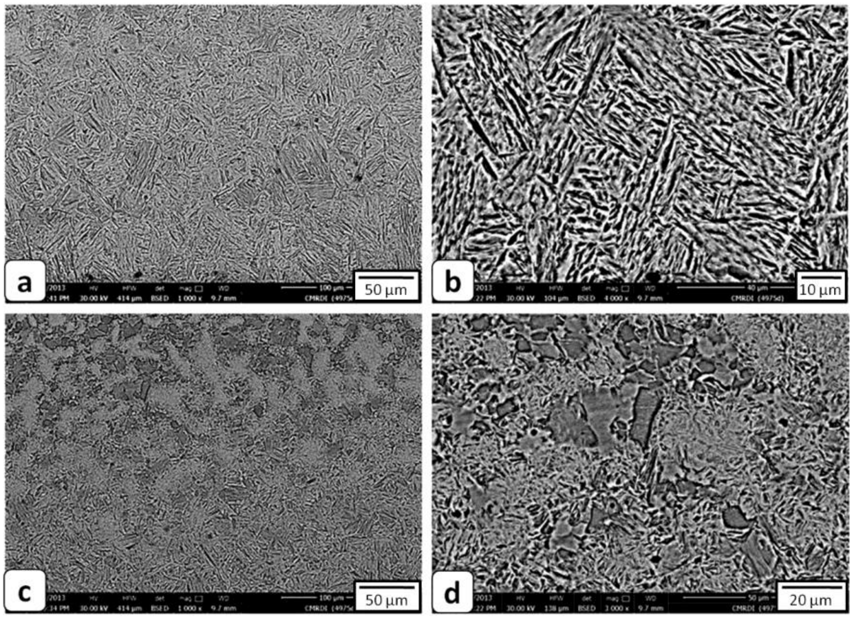

Figure 4 Different magnified SEM images for microstructure of laser treated zone produced at 800 W power and travelling speed of 1500 mm/min. (a) & (b) at areas very near to the free surface showing long acicular martensite structure., and (c) & (d) at the center of the laser treated showing bainite structure in ferrite grains.

By reducing the travelling speed from 1500 mm/min by one third to be 1000 mm/min, some changes are noticed in the macro and micro scales, as shown in Figs. 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 (about 3 mm), as shown in Fig. 2 b. The decrease of the travelling speed increases the heat input per unit area, 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.

Similar to the previous condition, near the free surface, large batches of plates of martensite structure is produced as shown in Figs. 5 a, 5 b, 6 a, and 6 b. The main differences between the two structures are that the acicular martensite structure of 1000 mm/min appeared to be finer than that of 1500 mm/min. On the other hand; the martensite plates appeared to be larger than that of 1500 mm/min. This is due to the relatively slow cooling after laser surface melting of travelling speed of 1000 mm/min that gives the martensite plates to become coarser. 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 (starts at the center of the treated zone) as clearly shown in Figs. 6 c and 6 d. This 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.

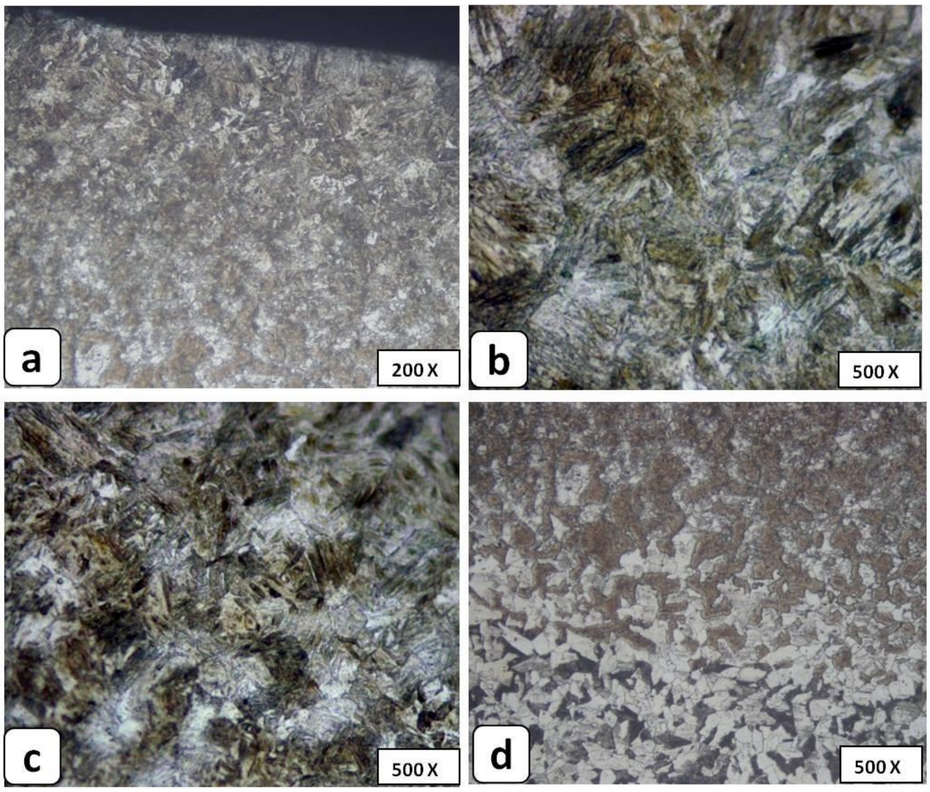

Figure 5: Optical micrographs for microstructures produced by laser treating of 800 W power and travelling Speed of 1000 mm/min. (a) & (b) at the melted and solidified zone (very neat to the free surface) showing large batches or plates of martensite structure, (c) at the center of the melted and solidified zone showing batches or plates of martensite structure inside small ferrite grains, and (d) near the end of the melted and solidified zone showing islands of bainite structure inside large ferrite grains.

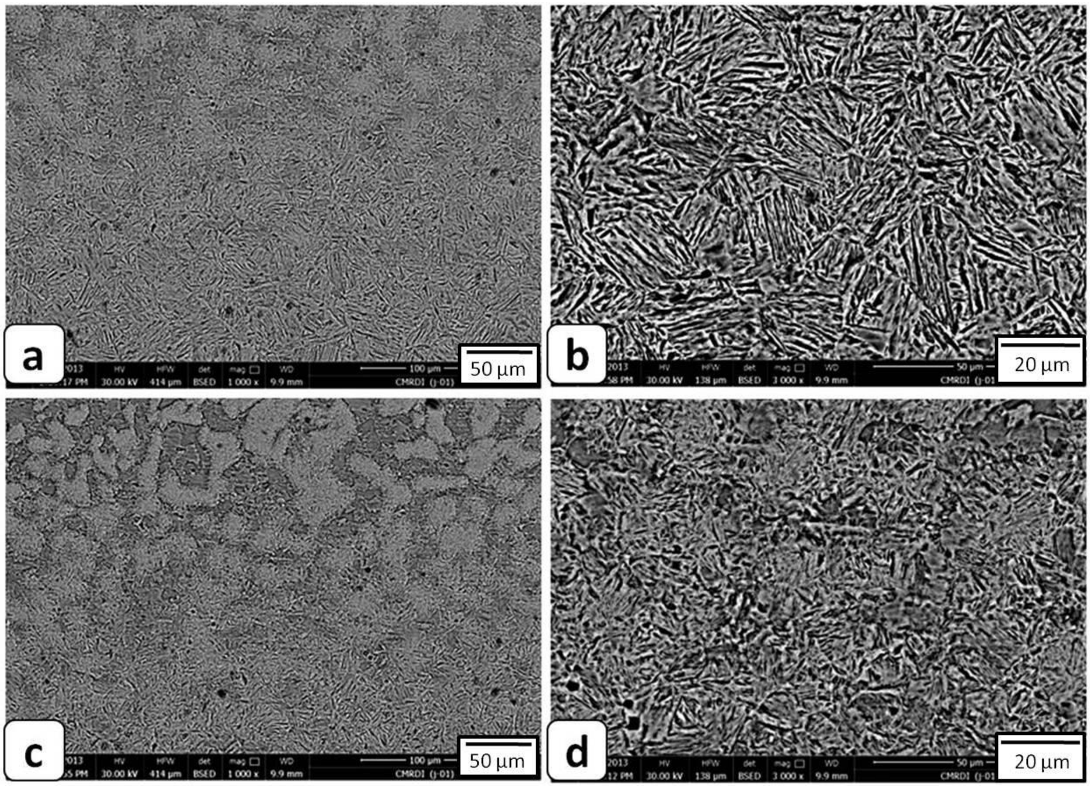

Figure 6: SEM images for microstructure of laser treated zone by laser Power of 800 W and travelling Speed of 1000 mm/min. (a) & (b) at area very near to the free surface showing acicular martensite structure, and (c) & (d) at the center of the laser treated zone showing islands of bainite structure in ferrite grains.

The results of laser-treated areas produced by travelling speed of 500 mm/min were shown in Figs. 7 and 8. For such a slow travelling speed, the depth of the laser-treated zone became about 1.2 mm which is the maximum depth between the 3 conditions due to the largest heat input per unit area associated 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 Figs. 7 and 8. Moreover, these martensite structures with its features appeared in deeper areas. The slower travelling speed of 500 mm/min gives 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. Below this zone, bainite structure appeared as shown in Figs. 8 e and 8 f. This is mainly due to the slow cooling rate in these deeper areas.

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 laser beam 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 width, which depends mainly on the focus length. On the other hand, the travelling speed has a reverse effect of the amount and 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 where the amount of heat input is smaller and dissipates faster. 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.

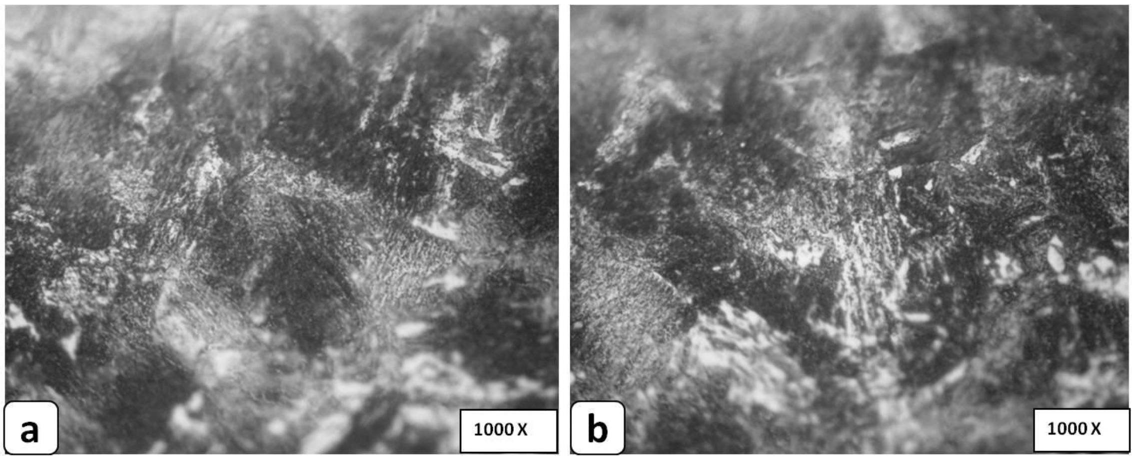

Figure 7: Optical micrographs of laser treated zone by laser Power of 800 W and travelling Speed of 500 mm/min., (a) high magnified micrograph of the melted and solidified zone (very neat to the free surface) showing large batches or plates of martensite structure, and (b) high magnified micrograph at the center of the melted and solidified zone showing large batches or plates of martensite structure.

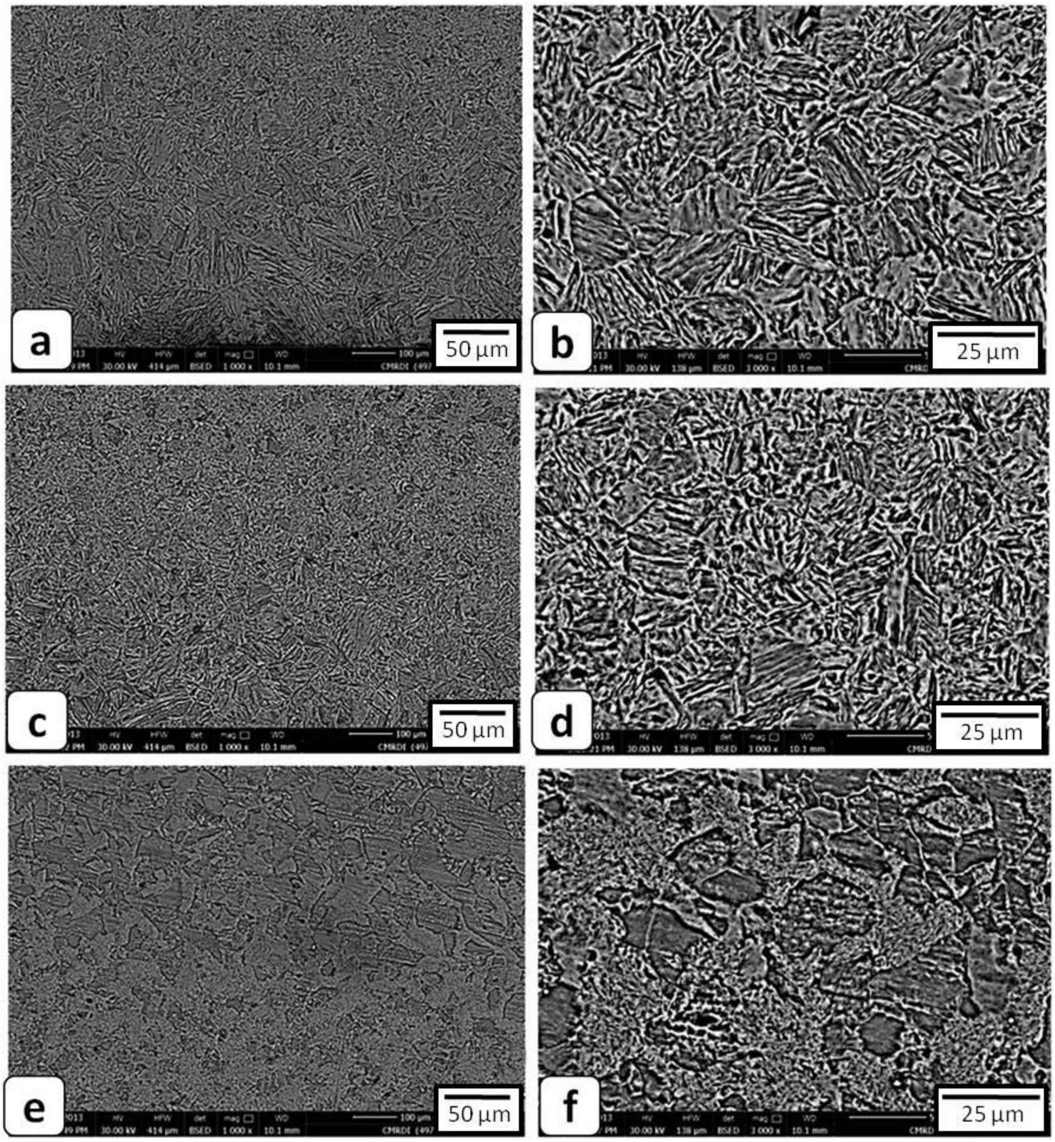

Figure 8 SEM images of the laser treated zone by laser Power of 800 W and travelling Speed of 500 mm/min. (a) & (b) at areas very near to the free surface showing fine acicular martensite structure, (c) &(d) at the center of the treated zone showing acicular martensite structure, and (e) & (f) at the end of the laser-treated zone showing bainite structure in ferrite grains.

3. 2. Effect of treatment at different speeds on surface hardness:

The hardness of the base material is in the range of 173–183 $HV_{0.1}$ (the average value is 176.4 $HV_{0.1}$) which indicates a uniform surface hardness of the base material. To obtain high surface hardness range, LSM (laser surface melting) can be used for localized heating and melting. The microstructural features affect the properties. Generally, in the laser surface melting process, cooling rates up to 106 K/s are obtained (compared to less than 100 K/s in conventional solidification during a casting [31]. This leads to the formation of amorphous structure for the surface or nanostructure which improves the properties of the surface layer. Some investigators [32,33] reported that, non-equilibrium solidification takes place due to the rapid cooling rate after the laser surface melting. Accordingly, the solid solubility limit of alloying elements can be extended beyond the equilibrium phase diagram. Further, metastable phases may result from the application of laser surface melting [32,33]. In the present study, refined structures with modified martensitic structure resulted in the melted and solidified zone due to the application of the laser surface melting treatment. This structure improves the hardness and strength of the surface layers which are important requirements for improving wear, corrosion and fatigue failure resistances.

Figure (9) shows the effect of travel speed on hardness profile beneath the surface for the steel (X52) for the power 800 W. It was accordingly clear that the travelling speed affects hardness in two different ways. The first one is the hardness value at or near the free surface. The hardness at or near the free surface is higher at the higher travelling speed. For example it shows about 480 HV at 1500 mm/min, while it shows only less than 400 HV at travelling speed of 500 mm/min. 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 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.

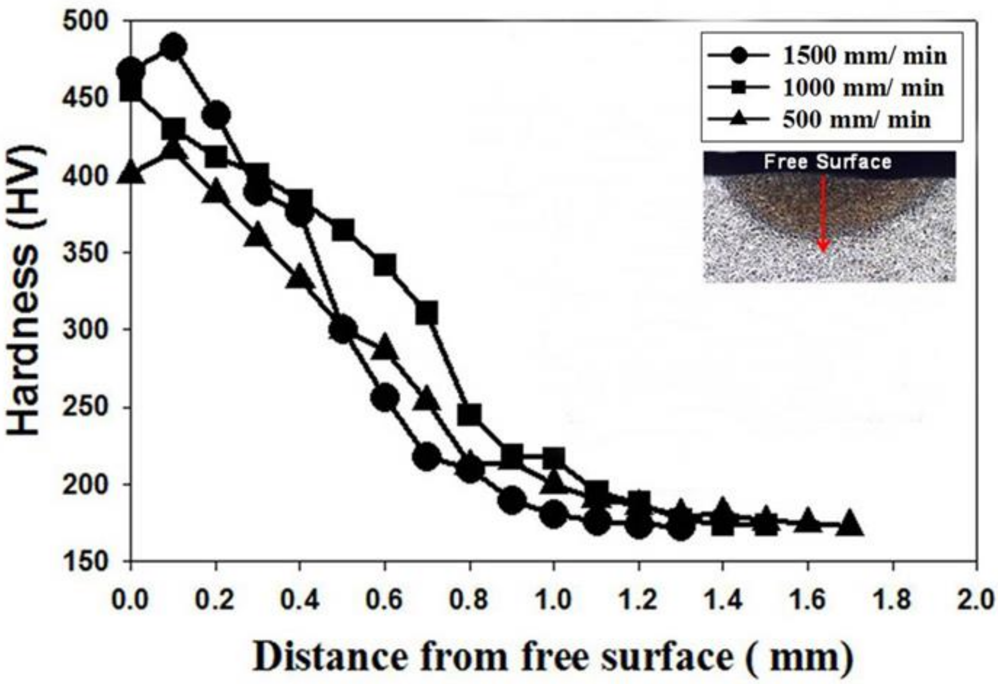

Figure 9 Effect of travelling speed on hardness along depth for the power of 800 W.

The maximum hardness of the laser surface melted and solidified zones of the specimens was increased to 483, 455 and 401 $HV_{0.1}$ with improvements of 173.8, 157.94 and 127.3% in cases of 1500, 1000 and 500 mm/min respectively. These improvements in hardness can mainly be attributed to the effect of the produced fine martensitic structure. As for this microstructure, the increase in hardness corresponds to increase in surface volume fraction of the fine martensite constituents. In cases of high processing 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. This increase corresponds to increase in surface volume fraction of the fine martensite constituents.

It was observed that a finer microstructure and a higher hardness are achievable with higher laser travelling speeds. The observations show a high hardness near the free surface, the thickness of which decreases as the travelling speed increases. This result may be explained by the increase of quenching rate accompanying the speed increase.

The results of hardness measurements are shown in Fig. (9). In the first zone (melted zone), hardness is very high due to the existence of martensitic structure. At the same time, the HAZ 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 106 °K/s during the solidification process. As described above, after the laser surface melting treatment (LSM), martensitic structure is produced in the melted and solidified zone due to the rapid cooling. Solid state transformations occurring in the HAZ of a laser-treated low carbon steel are due to carbon diffusion phenomena as a result, partial decomposition of pearlite 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. The hardness measurements proved that its values for the solidified and heat-affected zones are higher than those for the base metal. The hardness of the ferrite-partially decomposed pearlite structure produced in the HAZ is higher than that of the base metal. Therefore, the produced structure will assist to obtain the moderate hardness in the transition zone. So, the hardness decreases with the depth to reach the value of the base metal in the untreated zone.

4. Conclusions:

The surface of grade X52 steel was laser-treated with different travelling speeds (1500, 1000, and 500 mm/min). The resulted laser treated specimens were investigated in macro- and microscopic 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:

1. The laser-treated areas with all used travelling speeds results in melted and solidified zone on the surface of the steel.
2. 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.
3. By increasing the travelling speed, the depth of the laser treated zone was decreased, while travelling speed has much less significant effect on the laser-treated zone width.
4. The size of the formed martensite plates was increased by decreasing the travelling speed from 1500 mm/min to 500 mm/min. 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 becomes longer, while it shows fine acicular martensite at lower travelling speeds.
5. The depth that full martensite structure can be reached is increased by increasing travelling speed. At lower travelling speed (500 mm/min), large amount of bainite structure is observed at the center of the treated zone up to its lower end.
6. The fast travelling speed (1500 mm/min) shows higher hardness on the free surface than that of slow travelling speed (500 mm/min). On the other hand, the travelling speed has a reverse effect on the depth of this hardness increment; the slower travelling speed gives deeper areas of high hardness than that of fast speed.

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