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

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صهر طبقة سطحية للصلب الكربوني باستخدام الليزر:
الجزء الثاني: تأثير طاقة شعاع الليزر على ملامح البنية الميكروسكوبية والصلادة السطحية

ملخص باللغة العربية:

لصلادة السطح لها تأثير مهم على مقاومة البري الميكانيكي للمواد المختلفة. لذا يعزز التحسن في صلادة السطح مقاومة البري للمواد. تهدف هذه الدراسة إلى تحسين صلادة سطح الصلب الكربوني من خلال صهر طبقة سطحية بتطبيق الليزر في شروط مناسبة. تعد طاقة مرور شعاع الليزر من العوامل الرئيسية التي تؤثر على خصائص المنطقة المعالجة. في هذه الدراسة، تم اختيار ثلاثة شروط مختلفة من طاقة شعاع الليزر (١٨٠٠، ١٥٠٠، و ١٢٠٠ وات) بسرعة ثابتة لمرور الشعاع عند ١٠٠٠ ملم / دقيقة لدراسة تأثير طاقة شعاع الليزر. أجريت جميع التجارب في وجود النتروجين للحماية واستخدم بضغط ومعدل تدفق ٠,٥ بار و ٢٧ لتر / دقيقة، على التوالي. كان طول مسافة التركيز ١٠ مم. وقد تم فحص بنية الطبقة السطحية للعينات المعالجة باستخدام المجهر الضوئي والمجهر الإلكتروني الماسح. أجريت قياسات صلادة أيضا من خلال سمك العينات المعالجة بالليزر. في كل ظروف المعالجة حدث صهر وتصلد لمنطقة سطحية للصلب المعالج. طاقة الليزر ١٨٠٠ وات أنتجت أعمق منطقة معالجة (حوالي ١,٧ مم). وعلاوة على ذلك، فإن زيادة طاقة الليزر، تسبب زيادة طفيفة في عرض المنطقة المعالجة. في المناطق القريبة من السطح الحر، لوحظ تكون كمية كبيرة من المارتنزيت عند إجراء المعالجة بطاقة شعاع كبيرة (١٨٠٠ وات)، في حين لوحظ تكون مارتنزيت أبري أطول عند تطبيق المعالجة بطاقة شعاع أقل (١٢٠٠وات). لطاقة الشعاع ١٨٠٠ وات، تنتج بنية من البيانايات في حبوب الفريت في مناطق أوسع وفي مناطق تقترب من السطح. من ناحية أخرى، فإن تطبيق المعالجة بطاقة أقل للشعاع أدت إلى صلادة سطحية أعلى من التي حصلنا عليها في حالة تطبيق المعالجة بطاقة شعاع أكبر. مساحات المناطق المتأثرة بالحرارة زادت بزيادة طاقة شعاع الليزر. على أية حال، كانت المناطق المتأثرة بالحرارة تتألف من برليت متحلل جزئيا في حبوب الفريت. أخيرا، 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.

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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 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 were chosen to study the effect of laser beam power. All of the experimental works were done with Nitrogen shielding gas used at pressure and a flow rate of 0.5 bar and 27 l/min, respectively, and a focusing distance of 10 mm. The resulting laser-treated specimens were investigated macro- and microscopically scale using optical and scanning electron microscope (SEM). Hardness measurements were also carried out through the thickness of the laser treated specimens. In all process conditions, the laser treated-areas resulted in melted and solidified zones on the surface of the steel. The laser power of 1800 W resulted 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 increased. 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 on higher power.

The heat affected zones (HAZ) were increased by increasing the laser beam power. In all conditions, the heat affected zones 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, Failure of engineering components, 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. As described by some researchers [1], in some cases, the conventional surface engineering (CSE) techniques such as carbonizing, nitriding, etc. are applied. These treatments depend on the workpiece material. Coating using the chemical vapor deposition (CVD), physical vapor deposition (PVD) and thermo reactive deposition and diffusion (TRD) improves the wear resistance, only under appropriate conditions [1]. 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 [2]. One of the most important methods in improving the surface properties of materials is the laser surface engineering [3]. 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, etc. 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 [4].

The surface of metals can be modified by the application of one or more of suitable laser surface treatments [5,6,7]. The laser surface melting (LSM), laser surface alloying (LSA), and laser surface cladding (LSC), are examples of the suitable treatments which can be applied for surface modification [8]. Some of the advantages of these surface treatments include flexibility and the possibility of treating small areas, leaving the others parts unaffected [3]. In laser surface melting (LSM, 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 and cooling rates in the region of 104-108 ºK/s can be obtained. This can result in non equilibrium microstructures which may confer substantial increases in hardness and wear resistance, the application areas which have received utmost attention, particularly for steels, cast irons and alumineum alloys. In general the non equilibrium surface microstructures produced result in finer, more uniform structures with superior homogeneity compared with conventional surfaces. Laser surface melting produces an increase of the hardness, toughness and wear resistance of the material surface in a very short time [9,10]. This is done using a focused or near focused beam [10]. The surface to be melted is shrouded by an inert gas [10].The melted surface layer is followed by subsequent rapid solidification [11]. Using this treatment, the following can be obtained [10]: little thermal penetration, resulting in little distortion, process flexibility, due to software control, and possibilities of automation. The laser surface melting was used as a modifying treatment in different cases such as cast iron [12,13], carbon steels [14], high carbon steels [13], tool steels [11,15], stainless steels [16]. So, materials that do not harden through martensitic transformation, such as cast iron, titanium, tool steels, etc can be hardened by application of the laser surface melting [10]. A combined treatment of the conventional laser surface melting and water-quenching was proposed and applied to alloy and high speed steels [17]. An appreciable increase in surface hardness was obtained by the application of conventional laser surface melting treatment [17]. Higher improvement in surface hardness was achieved by the application of the combined treatment [17]. The LSA technique works on the principle of mixing an alloying element in the melt pool of the substrate created by the laser beam. The laser surface alloying process [18-21] is better than the conventional surface treatments. However, the laser surface alloying for steels has shortcomings of thin surface-hardened layer and obvious overlapping phenomenon [22]. The laser cladding (laser coating) is an advanced coating technology for improving surface properties of various components and equipment. In this process, only a thin surface layer of the workpiece melts together with the additive material to form a coating. Laser cladding and surface restoration of tool steel has begun to change the way we service dies and molds [23]. In addition, the coating by laser cladding should offer wear resistance to that offered by solid tungsten carbide, but at lower cost and with fewer design complications [24]. As described in [25], the main features and advantages of the laser surface alloying / cladding treatments are: 1. Moderate to rapid solidification rates resulting in fine homogeneous structures, 2. Desired coating depth with dilution, 3. Minimal distortion with low HAZ, 4. Controlled thermal profiles and shape, 5. Good surface finish, 6. Selective alloying/cladding, 7. Minimal wastage of costly alloying material, 8. Precise control of alloy geometry, 9. Extremely versatile, 10. Excellent metallurgical bonding, 11. Reduced porosity, 12. Excellent coating homogeneity, 13. High deposition efficiency, and 14. Faster processing rates.

As reported in [5], 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 [5]. The modification can be improved by controlling the treatment parameters. The power and travelling speed of laser beam are the 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. Experimental work:

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 (a). The mechanical properties of the base metal are tabulated in table (2). The laser machine operated at powers of 1200, 1500 and 1800 W, at a fixed travelling speed of 1000 mm/min. The focusing distance was 10 mm. The pressure and flow rate of N_2 gas: 0.5 bar and 27 l/min., 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.

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

Chemical compositions%									
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.

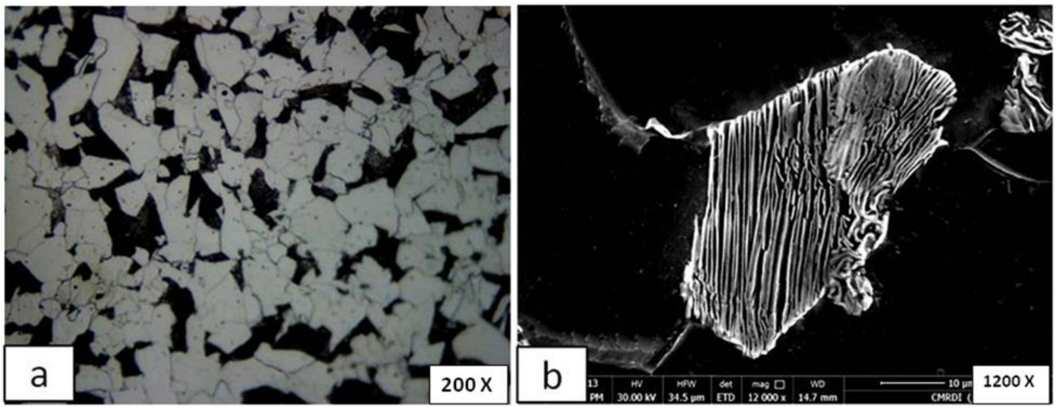

Fig. 1 Microstructure of the untreated steel (a) Optical micrograph showing normal ferrite (white color)- pearlite (dark color)structure, and (b) SEM image showing full laminated pearlite structure with larger magnification.

Table (2) Mechanical properties of the base metal.

Yield Strength, MPa	Ultimate Tensile Strength, MPa	Elongation, %	Hardness, $Hv_{0.1}$
307	417	32	176

3. Results and discussions:

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 Figs. 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, consequently, affects the depth of the treated zone which is reduced to about 1.3 mm. By reducing the laser power to be 1200 W, the resultant treated zone depth was slightly decreased to about 1.2 mm.

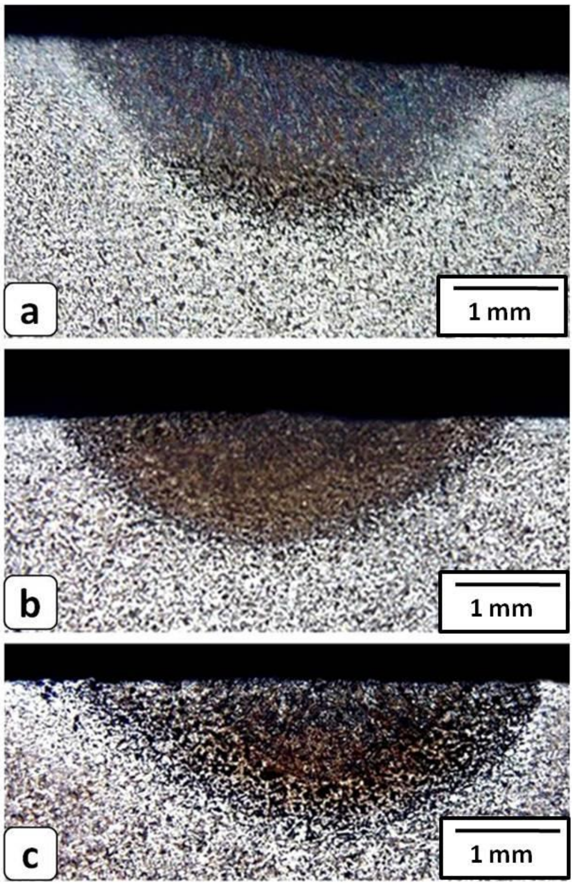

Fig. 2 Optical macrographs for treated zones produced by travelling speed of 100 mm/min. and laser power of a) 1800 W, b) 1500 W , and c) 1200 W.

The microstructures of the treated zone after laser power of 1800 W are shown in Figs. 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 ferrite grains even near the free surface. At areas a little bit far from the free surface, mixed acicular martensite and lower bainite appeared in large ferrite grains. Moreover, the results show large heat affected zone due to lower cooling speed.

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 are shown in Figs. 5 and 6. The heat input that generated by laser power of 1500 W reduces the cooling rate and, subsequently, affects macro and microscopically of the resultant 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 resulting 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.

By reducing the laser power to be 1200 W, the resulting treated zone shows some changes, as shown in detail 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, a small plate of fine acicular martensite 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.

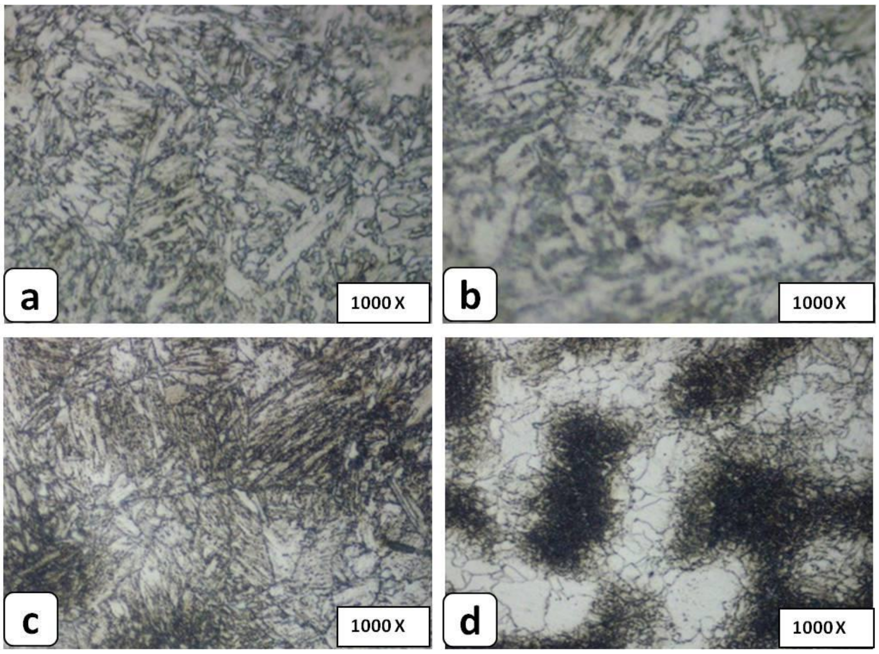

Fig. 3 Optical micrographs for microstructures produced by laser Power of1800 W and travelling Speed of 1000 mm/min, where (a) near the free surface of the treated zone showing mixed martensite and bainite structure in ferrite grains, (b) at the center of the melted and solidified zone showing mixed martensite and bainite structure in ferrite grains, (c) at the end of the melted and solidified zone showing lower bainite structure in ferrite grains, and (d) at the heat affected zone (HAZ) of the treated zone.

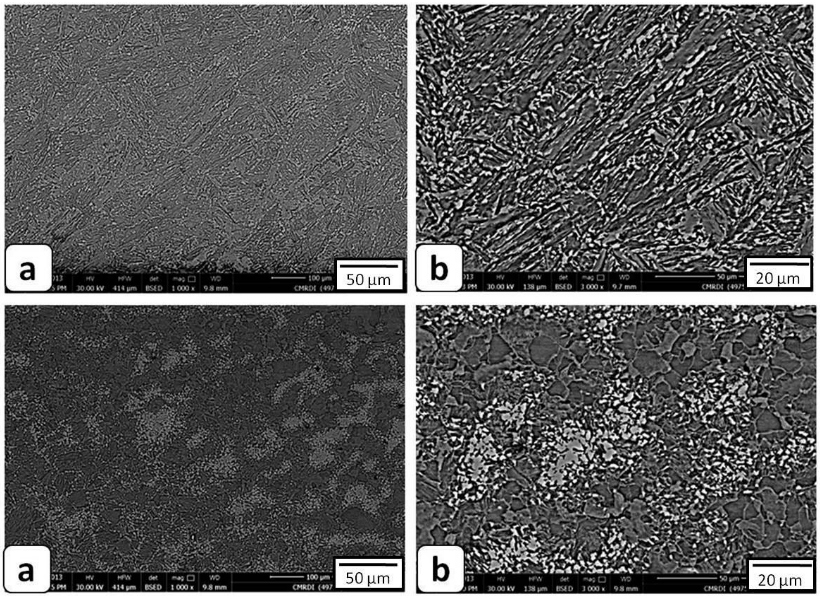

Fig. 4 SEM images of microstructure produced by laser Power of 1800 W and travelling Speed of 1000 mm/min., where (a) & (b)near the free surface of the treated zone showing long acicular martensite structure, and (c) & (d) at the lower part of the treated zone showing Small batches of mixed martensite and bainite inside large grained ferrite structure.

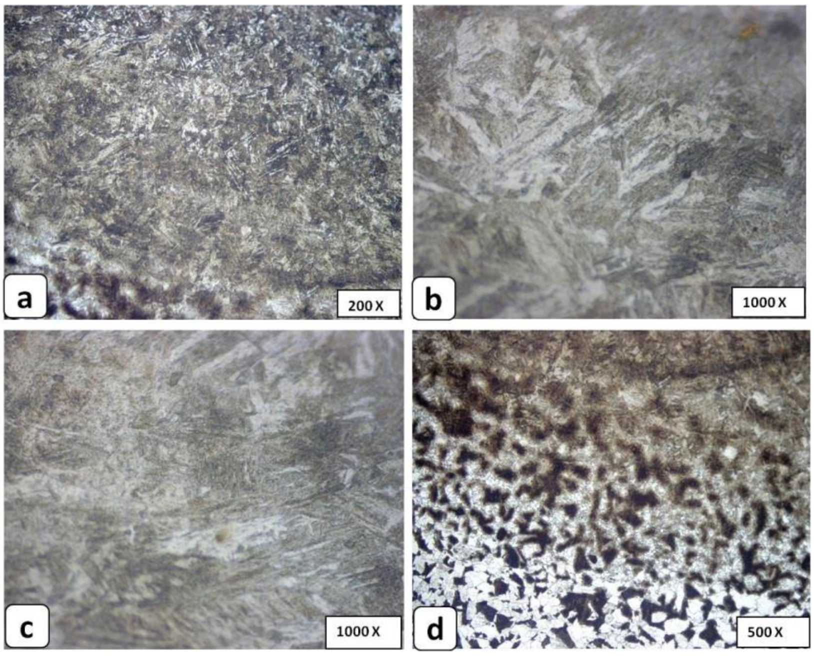

Fig. 5 Optical micrographs for microstructures produced by laser Power of 1500 W and travelling Speed of 1000 mm/min. (a) Low magnified micrograph of the melted and solidified zone, (b) & (c) High magnified micrographs of the melted and solidified zone showing large martensite plates, and (d) Low magnified micrograph at the interface between the laser treated and untreated zones.

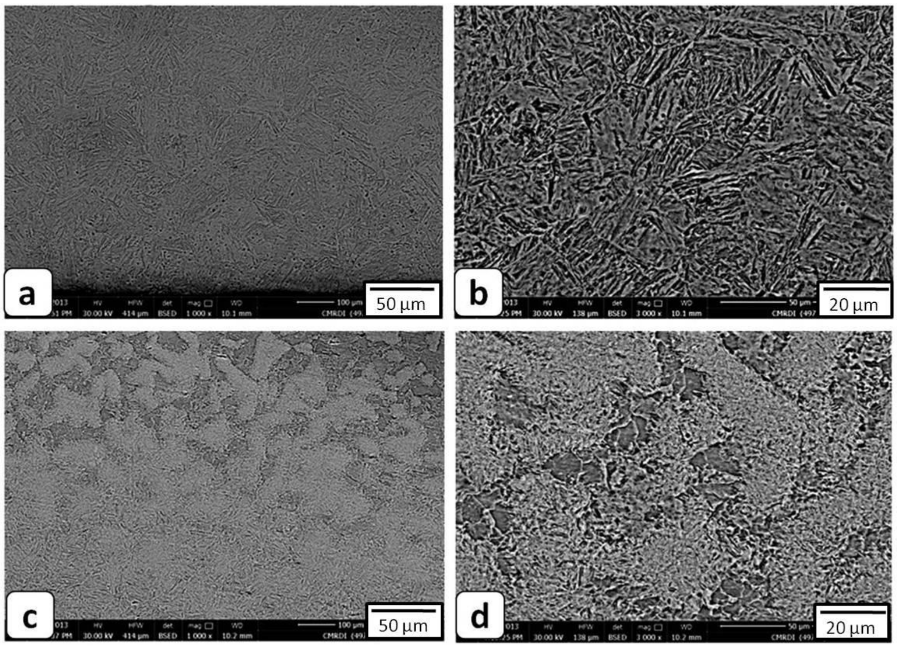

Fig.6 SEM images for microstructure produced by laser Power of 1500 W and travelling Speed of 1000 mm/min. (a) & (b) at areas very near to the free surface showing acicular martensite structure, and (c) & (d) at the end of the treated zone showing Large batches of mixed martensite and bainite inside fine grained ferrite structure

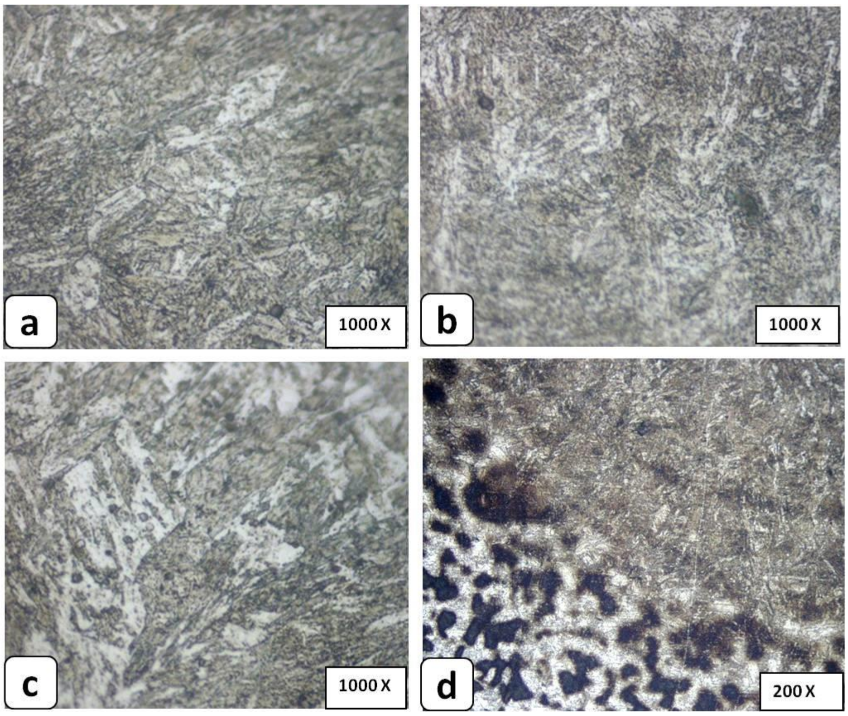

Fig.7 Optical micrographs for microstructures produced by laser power of 1200 W and travelling speed of 1000 mm/min. where, (a) at areas very neat to the free surface) showing large batches or plates of martensite structure, (b) at the center

of the melted and solidified zone showing large batches or plates of martensite structure, (c) at areas near the lower part of the treated zone showing large batches or plates of martensite structure inside ferrite grains, and (d) at the interface between the laser treated and untreated zones.

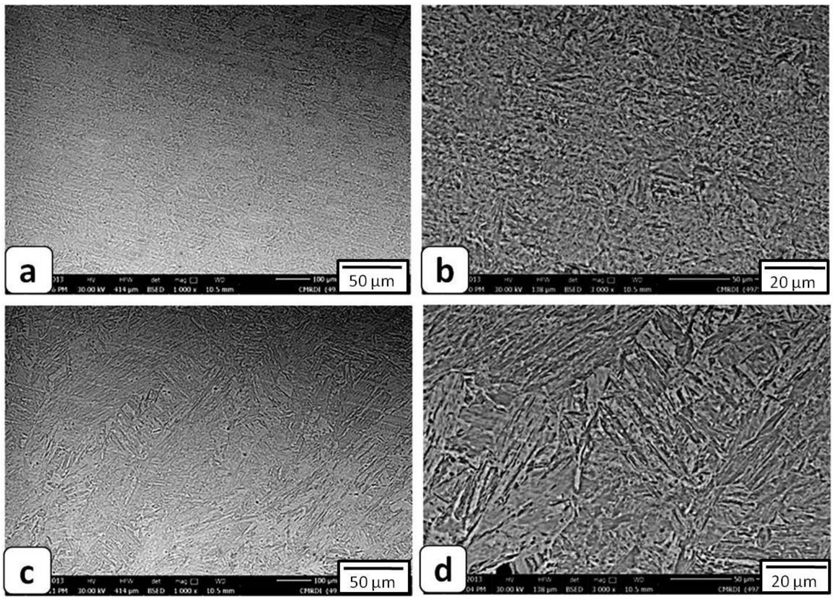

Fig. 8 SEM images for microstructure produced by laser power of 1200 W and travelling speed of 1000 mm/min. where (a) & (b) at areas very near to the free surface showing fine acicular full martensite structure, and (c) & (d) at the center of treated zone showing large plates of martensite structure.

Generally speaking, these results show that the laser power has a great effect on the macro and microstructure. As the laser power increases, the depth of melted zone also increases. This is due to the higher power that penetrates deeper distance inside the materials. On the other hand, the higher power deceases to some extent the cooling rate after solidification. In consequence, the relatively slow cooling rate (of higher power) decreases the amount of formed martensite and gives the bainite structure and ferrite grains to appear in large areas as clearly shown in the previous micrographs.

3. 2. Effect of laser treatment on surface hardness:

The hardness data is obtained through the micro-hardness tester. Hardness on the top surface and the cross sectional region of X52 carbon steel in the as-received condition and after laser hardening has been taken for the vickers load of 0.1 kg. The average value of hardness for the untreated base material is 176 $HV_{0.1}$. The properties of surface and subsurface layer are affected by the microstructural features and both of the types and percentages of alloying elements in the different constituents. The rapid cooling after laser surface melting (up to 10^6 °K/s [11]) leads to the formation of amorphous structure for the surface or nanostructure which improves the surface properties. In all cases of 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 surface hardness. Generally, the wear, corrosion and fatigue failure resistances can be increased by strengthening the surface layer.

The power of the laser beam is one of the main factors in LSM which alter the depth and width of melted and heat-affected zones to obtain desired surface properties. The results indicated that this process parameter has a significant effect on the microstructural features and hardness of surface and subsurface layers. The effect of laser power on hardness values is shown in Fig. (9). It is clear that the hardness of the free surface or its neighbor shows higher values at lower laser power. For example, the power of 1800 W reaches a hardness of only 350 HV, while that of 1200 W can achieve a hardness of 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 higher hardness appeared to a deeper depth inside the materials (Compare the plot of hardness of 1800 W and that of 1500 W).

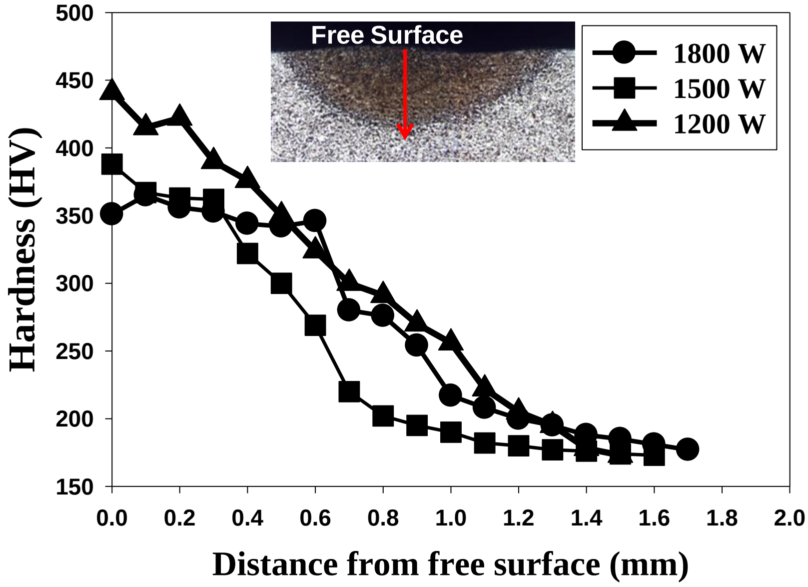

Fig. (9) Effect of processing power on hardness along depth of the zones treated at the travelling speed of 1000 mm/min.

The maximum hardness of the laser surface melted and solidified zones was increased to 441, 388 and 356 $HV_{0.1}$ with improvements of 150, 119.96 and 101.8 % in cases of 1200, 1500 and 1800 W respectively. The enhancement in hardness can mainly be attributed to the effect of the produced fine martensitic structure. It was observed that a finer microstructure and a higher hardness were achieved with low accepted power. The observations show a higher hardness near the free surface. 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. If it is well known (and for a long time) that quenching improves the mechanical properties of steels, laser treatment confirms and strengthens this results , owing to the large quenching rates induced by such treatments. These are due to rapid solidification processes. In the laser surface melted and solidified zone, martensitic structure is produced 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. It is assumed that 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 to complete decomposition of the pearlite. The result is partial decomposition of pearlite**.** Therefore, there is an increase in hardness in this zone but with value lower than that in the melted and solidified zone. Generally, 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 of the base metal. Moderate hardness in the transition zone was obtained due to the ferrite-partially decomposed pearlite structure produced in the HAZ. As a result, the hardness distribution shown in Fig. (9) was obtained. All observations of the present study showed that, crack-free melted and solidified zones of high hardness can be obtained by laser surface melting.

4. Conclusions:

The surface of grade X52 steel was laser treated with different powers (1800, 1500, and 1200 W). The resultant laser treated specimens were investigated in macro- and microscopical 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 the used powers 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 of the experimental conditions, while some bainite structure in ferrite grains are detected in its lower part.
3. The laser power of 1800 W causes the deepest value of the laser treated zone (about 1.7 mm).
4. By increasing the laser power, the width of the treated zone was slightly increased.
5. Near the free surface: Large martensite plates were observed at higher laser power (1800 W), while longer acicular martensite was observed at lower laser power (1200 W)

6. 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.
7. The lower laser power shows higher hardness on the free surface than that of higher power.
8. The heat-affected zone (HAZ) areas were increased by increasing the laser power.
9. In all conditions, the heat-affected zone areas were composed of partially decomposed pearlite in ferrite grains.
10. The microstructure of the base metal far from the laser-treated areas shows normal ferrite-sound pearlite microstructure.

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