*Proceedings of VAFSEP2004, 6-9 July 2004, Dublin, Ireland*

# LASER SURFACE TREATMENTS OF IRON-BASED SUBSTRATES FOR AUTOMOTIVE APPLICATION

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## ABSTRACT

In the present work laser surface alloying of low carbon steel with carbon has been investigated for automotive application. The laser used was Nd-YAG, having a wavelength of 1.06μm. It was operated at energy levels between 5 – 30 J, pulse duration from 1.5-4msec and beam diameter varied between 1-3mm. As a result of laser treatment at different energy levels and pulse durations, treated layers of varying thickness between 0.03-0.20mm with carbon concentrations exceeding the eutectic point are produced. As a consequence of this treatment, a range of microstructures and microhardness values was obtained. High hardness values were observed in the layers with predominantly martensite structure (650Hv) and relatively low values in region showing austenite microstructure (500Hv) and maximum hardness (850Hv) was found in the layer, which showed large proportion of $Fe_3C$. Surface melting of nodular cast iron by ruby laser (0.69μm wavelength) has been also reported. The presence of retained austenite and martensite was found to be a characteristic feature in most of the treated layers.

*Keywords*: laser, cast iron, heat treatment of steel, physical metallurgy.

## 1 INTRODUCTION

Within the past few years, a considerable interest has developed in the field of surface treatment of materials using high power lasers because of the improvement it produces in the hardness; wear resistance and corrosion resistance of materials. These include transformation hardening [1-3], surface melting [4-5], alloying [6-9], cladding [10], and ceramic/particles injection [11-12]. The main reason for the laser surface melting is 'metallurgical', namely to utilize the benefit of rapid solidification. The quenching rates can be as high as those achieved in other technique such as melt spinning and atomization. On the other hand, laser surface alloying (LSA) is an effective method of surface modification of metals with a variety of alloying elements, for example nickel, chromium, molybdenum, and so on. Many researchers have studied the technique of LSA; an excellent review paper was presented by Draper [9].

In the present study, the laser alloying technique was applied to cheap materials such as low carbon steel and ductile cast iron; microstructure characterization, microhardness measurements, and alloy composition achieved for a range of processing parameters are reported here.

The substrate used was low carbon steel (20x20x3mm) with chemical composition of 0.28%C, 1.25%Mn, 0.04P, 0.05S, Bal Fe and ductile cast iron (40x20x20mm) with chemical composition of 3.6%C, 2.75%Si, 0.6Mn, 0.8%Cr, 0.05%P. 0.13%S, 0.1%Mg, Bal Fe. The samples were prepared through grinding, cleaned with alcohol, and etched with nital to reduce the beam reflectivity and then coated with graphite to a thickness of about 30μm using organic binder (see ref.13). A solid state Nd-YAG laser of 1.06μμm wavelength operated at energies 5-30J, duration pulses 1-4ms is used. The laser beam diameters ranged between 1-3mm, which correspond to energy density levels (E) between 60 to 10 MJ/m$^2$. The laser processing parameters were varied to obtain treated layers of different depths and consequently different carbon concentration. A shielding gas of argon was used to minimize contamination of the treated surface. After laser treatment, transverse sections were cut perpendicular to the laser direction, and standard method of metallography was followed to study the microstructure and measure the depth and microhardness. Carbon content in various alloyed layers was calculated by measuring the dilution of the graphite powder with the molten liquid and compare the results with those values obtained from the optical macrograph of some of the treated layer after annealing.

## 3 RESULTS

### 3.1 Low Carbon Steel Substrate

In previous work [13] it was found that a laser surface melting treatment of this substrate without coating produced structure consisting entirely of massive martensite. In the present work, laser surface melting of the same substrate coated with graphite (thickness 30μm) using the same parameters produced structure consisting of martensite in a matrix of light-etching region interpreted as retained austenite [13]. Fig.1a-c illustrates cross sections of some alloyed layers produced at constant beam diameter (0.8mm), laser beam energy (30J); this give E value of 38MJ/m$^2$ and different pulse durations (between 1 and 4ms). The penetrating depth of the alloyed zone ranged between 0.05 to 0.15mm and the alloyed zone width 0.5±0. 03mm. It is evident that the proportion of the martensite increased with increasing the pulse duration (i.e. with increasing the melted depth).

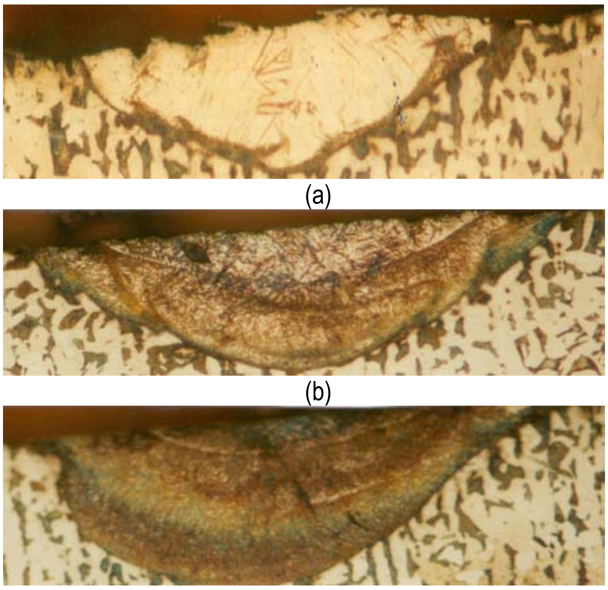
(a)
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Fig. 1: Laser surface alloyed zones produced at E = 38 MJ/m$^2$ and different pulse durations (a) 1.65ms, (b) 2.5 ms, (c) 3.2 ms, Mag. 200X.

Fig.2 a-c shows another series of laser treated zones processed at relatively larger beam diameter (E=17MJ/m$^2$) and similar parameters used in the first series. It is apparent from this figure that increasing the beam diameter led to produce a wide-alloyed zone with large surface to volume ratio and with a little penetration. However, increasing the pulse duration leads to increase in the melted depth and consequently decrease the carbon concentration in the alloyed zone. The microstructure of these layers ranged from predominantly austenite in the zone processed at low pulse duration to a mixture of austenite and martensite in the zone processed at 3.2msec.

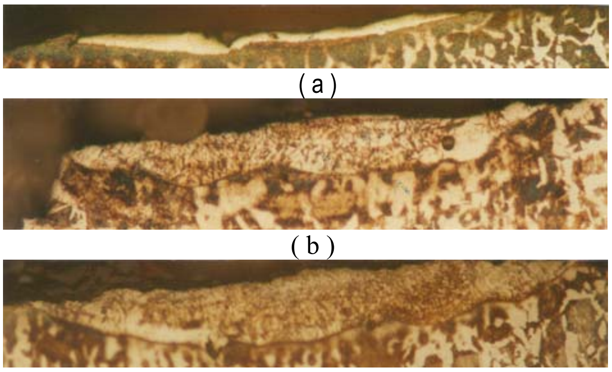
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Fig. 2: Laser surface alloyed zones produced at E = 17 MJ/m$^2$ and different pulse durations (a) 1.65ms, (b) 2.5 ms, (c)

Fig.3 illustrates the variation of the maximum-alloyed zone depth (D) as a function of pulse duration for two different levels of E (MJ/m$^2$). It may be noted that D is measured by optical microscope on the cross-sectioned plane perpendicular to both lasing direction and top surface. The longer pulse duration, the higher D and presumably the lower the carbon content. In the previous research [12] where the alloying elements were fed directly into the laser melted zone, the average composition of the alloyed layer was calculated by measuring the dilution, which is defined as the ratio of the build up area above the substrate surface to the total alloyed zone thickness (which is the summation of the melted area and the build up area) taking into account the differences in the densities, thermo-physical properties, and some losses due evaporation. In the present work an attempt was made to calculate the carbon content in the alloyed layer and compared the results with the value obtained by annealing some the treated layer (at 850 °C for 10 min) to obtain equilibrium structure and estimate the carbon content from the optical macrograph and referring to the Fe-$Fe_3C$ phase diagram. The result of this experiment showed that the carbon content ranged between near eutectoid and hyper- eutectoid; some diffusion of carbon into the heat affected zone to small depth (about 10µm) and formation of near eutectoid structure at the interface has been observed. Also some decarburization might occur even the annealing time is short. Measurements were made on mid position of the treated depth. Fig.4 presents the effect of pulse duration on the calculated carbon content and compared it with the estimated values, which were taken from the optical macrograph. Although the two curves showed the same trend but the calculated values are higher than estimated by 60%. The estimated carbon content using E 38MJ/$m^2$ is 1.5%, 1.8% and 3.2% for pulse duration's 1.65, 2.5, and 3.3 respectively, (Fig.4)

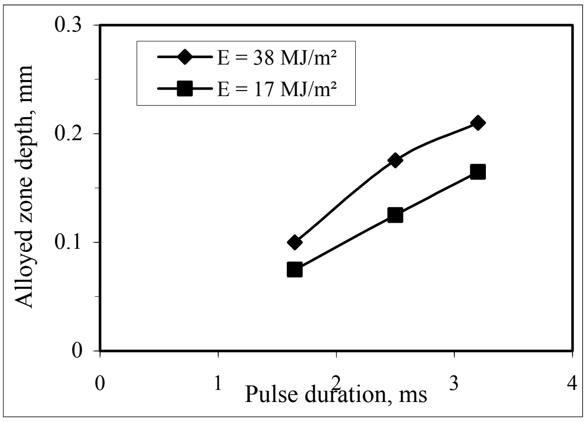


Fig. 3: Alloyed zone depth verses pulse duration at different energy levels.

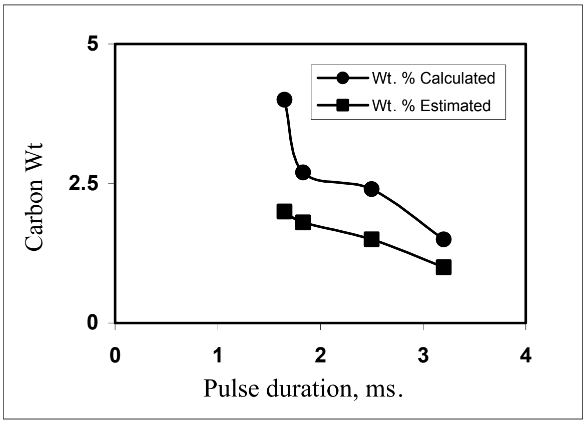
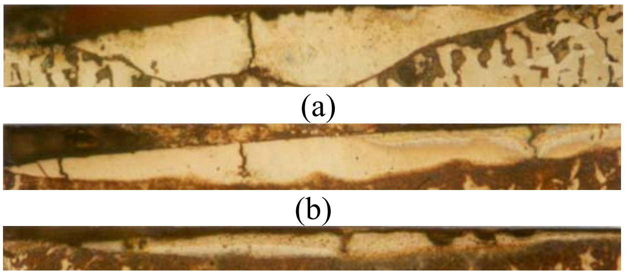


Fig. 4:Effect of pulse duration on the composition of alloyed zone.

In order to increase the extent of alloying and introducing high amounts of carbon into the alloyed zone, another experiment was carried out for a given pulse duration and different E. The resultant structural features are illustrated in Fig.5 Examination of the microstructure of Fig.5a at high magnification revealed a dendritic structure and interdendritic region. Such a microstructure resembles a white cast iron where these dendrite are of austenite extended upward from the base of the melt zone; the interdendritic region contain fine lamella eutectic originated from the liquid → $Fe_3C$ + austenite; or it might be possible that the structure is $Fe_3C$ + ferrite or martensite + austenite. The alloyed layer composition seems to inter the range of cast iron. Fig.5b, is a very wide and thin showed hypereutectic structure, comprises primary $Fe_3C$ in a eutectic structure. The proportion of the primary $Fe_3C$ is estimated to be more than 50% and carbon content of about 6%. Extensive porosity and cracking were seen in this series especially in the hyper eutectic. West et al [6] have carried out similar investigation during laser surface alloying of S135 steel with carbon. They used five successive cycles of graphite painting and laser melting to obtain the hyper eutectic level. From this result it can be concluded that carbon concentration in the alloyed zone is directly proportional to the laser beam diameter for a given E and inversely proportional to the pulse duration for a given beam diameter. Further more, increasing the E leads to increase the dilution and consequently decease the average carbon content in the alloyed layer.



(a)

(b)

(c)

Fig.5: Laser surface alloyed zones produced at different E exhibiting high carbon concentration (a) 26.5 MJ/$m^2$, (b) 11 MJ/$m^2$, (c) 7 MJ/$m^2$, Mag.200X.

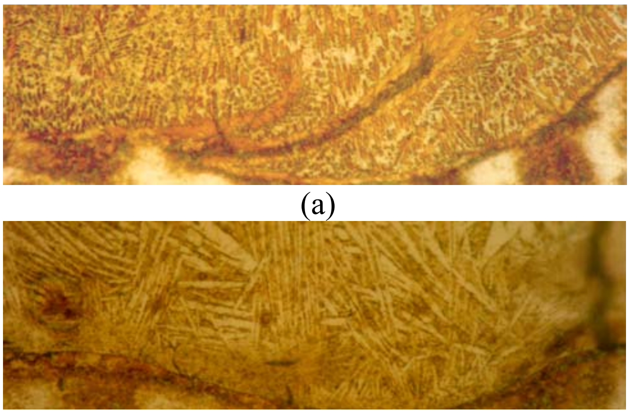

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Fig.6: Laser alloyed zone of fig.5 at high magnification, Mag.1000X.

Microhardness measurement across the alloyed zone of different treated specimens measured at the mid-depth of the alloyed zone (mean of 5 readings) showed a considerable increase in the level of microhardness (800Hv) as compared with the substrate (150Hv); the presence of austenite has led to a decrease in the hardness (to 550Hv). However the alloyed layer, which showed hypereutectic structure, showed a high level of hardness (850Hv) compared with the hypoeutectic-alloyed layer (650Hv). Fig. 7 presents the variation of average level of microhardness ($Hv_{av}$) as a function of calculated carbon contents for the range of E used. The mechanism of hardening can be attributed to the solution of carbon, martensite formation, and refinement of structure and also to the large proportion of cementite.

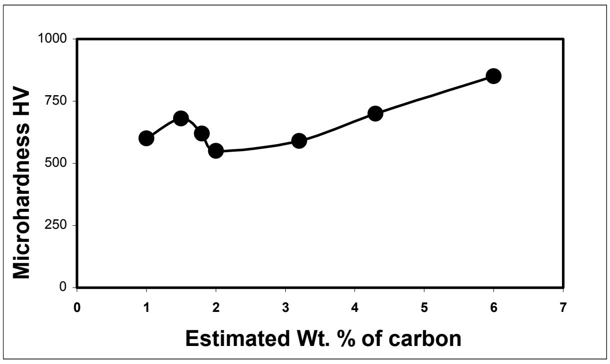

Fig. 7: Effect of carbon content on the average microhardness of the alloyed zone.

## 3.2 Ductile Cast Iron

The starting microstructure of the as received ductile cast iron consists of graphite nodules surrounded by ferrite and small amount of a pearlite. The average hardness was about 150Hv. After surface melting by ruby laser operated at 4100 volt and 2mm-beam diameter, the microstructure has change considerably as shown in Fig.8. The width of the melted layer is about 0.8 mm and the depth is about 0.05mm. It is evident that the graphite nodules had completely dissolved in the molten ferrous materials during treatment and rapid-self quenching had suppressed the re-formation of nodular in favor of the formation of white iron. In the region at the bottom of the melt layer, only partial dissolution occurred and the graphite nodules although become smaller have been retained. The melted zone was comprised of a mixture of retained austenite (of 500Hv) and coarse martensite plates (650Hv). Eutectic structure was not observed even at high magnification. The lower part of the melt showed graphite nodules surrounded by ledoburite protruding from the outer melt layer. This combination is a common feature at the irregular melt interface, and indicated that as the melt layer encroached into the substrate, it was the material in the vicinity of the graphite, which melt initially. This occurs because carbon enrichment near the graphite nodules locally lowers the melting point of the ferrous material. These features were observed previously at large depth during fusion welding of the same material using TIG welding [13].

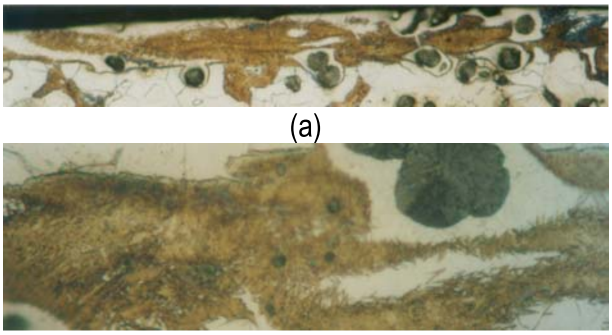
(a)

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Fig.8: Laser melted zone of ductile cast iron, (a) Mag.200X, (b) Mag.1000X.

The result of surface melting of the ductile cast iron is slightly different from those obtained by Sedunov [2] who reported a mixture of austenite and cementite in most of the melted zone using $CO_2$ laser. It should be noted that the number of the graphite nodules dissolved in the molten liquid are a few and this would lead to a lower concentration of carbon in the melted zone.

## 4. DISCUSSION

The result of microstructure examination of the entire surface alloyed layers and surface melting of nodular cast iron showed the presence of both martensite and retained austenite. Evidence of the presence of austenite was made by immersing some of the processed sample in liquid nitrogen for some time and taken out. This processed was repeated many times. Microhardness measurements of the treated zone before and after immersing in the liquid nitrogen showed slight increase in hardness although the microstructure was not change significantly. These results are consistent to those obtained by Ruhl and Cohen [6] who showed that splat-cooled with up to 2wt%C contained both austenite and martensite and also to the work of West and Steen [4] have reported a significant amount of retained austenite in high carbon steel after laser melting. Their results were interpreted as due to the lower Ms temperature with increasing carbon content and cooling rate. A depression of Ms has been observed in certain non-interstitial alloys, e.g. Fe-Cr-C [6]. A part from the possible role of interstitial elements, it has been proposed that the nucleation of martensite be hindered by the refined grain size resulting from rapid solidification. Grains refinement produced by thermo-mechanical treatment and thermal treatments has also been found to be capable of substantially lowering Ms temperature [6]. Thus it appears possible that martensite formation is hindered by the small lateral dimensions of the grains (or cell/dendrite) in laser-melted material. The cellular/dendrite structure of the austenite is interpreted as involving segregation of carbon to the inter-dendritic region (see Fig 6) as a result of rapid solidification. It may be noted that this, together with the finer grain size is likely to contribute significantly to the relatively high hardness of the austenite compared with the conventional austenite.

## 5. CONCLUSIONS

1. The work on laser surface alloying of low carbon steel with carbon produced a range of depths and microstructures. The levels of carbon concentration obtained exceeded the eutectic composition. Large beam diameter favor the production of wide and shallow alloyed zone with high amount of carbon (between 2 and 6wt%) while small beam diameter leads to produce deep and narrow alloyed layer and relatively lower concentration of carbon (1 to 2.5wt%). However, cracks and porosity associated appeared in the sample treated at large beam diameter.

2. The average microhardness of the alloyed layer increased with increasing carbon content but the presence of retained austenite has led to a decrease in the hardness. Large proportions of austenite are formed especially at low E ($MJ/m^2$) and short pulse duration.

3. Laser melting of nodular cast iron produced microstructure consisted of martensite and austenite with average hardness of about 600Hv

## ACKNOWLEDGMENTS

Acknowledgments are made to the laser research centre in Tripoli for their help and permission to use the laser and to General pipes establishment in Benghazi and the great man-made river project in Libya for supplying the materials. Also to Dr Belied S. Kuwairi, the head of mechanical engineering dept. for providing facilities.

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