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THE EFFECT OF ND-YAG LASER SURFACE TREATMENT ON MECHANICAL PROPERTIES OF CARBURIZING STEEL AISI 1006

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Abstract

Traditional surface heat treatment such as induction hardening and recently, laser surface hardening are applied to carbon steels to improve their surface properties, such as micro hardness and wear resistance. Laser surface hardening has a lot of advantages over others methods; such as flexibility, low distortion due to high power density and accuracy. In this work, thermochemical treatment (solid carburizing) by using a mixture of 40% $BaCO_3$, 60% Charcoal was applied to steel type AISI 1006. The carburizing process was followed by the application of ND: YAG laser surface treatment. ND: YAG pulsed laser was applied to modify the surface characteristics of the carburized steel such as microstructure, micro hardness and wear resistance. The laser parameters were energy 0.89 J, 3.6 J, 4 J and 6.3 J, spot diameter as 1.006 mm, 0.649 mm, 0.613 mm and 0.536 mm, pulses duration 1.00, 4.00, 4.47 and 7.05 ms with fixed wavelength of 1064 nm. The laser surface treatment cycles consisted of melting the layer surface, followed by holding and rapid cooling in air medium. Optical microscopy (OM) and scanning electron microscope (SEM) were used to study the microstructures of the melted laser zone and heat affected zones. The wear rates were measured by the pin -on-disk test. The results showed that increase in pulses duration increases the area of the melted and heat affected zones. Increase in laser Pulses duration leads to increasing peak power, power density and depth and size of the melted zone, leading to an increase in the micro hardness. The micro hardness was higher in the melted area at the centre of the laser spot, the highest micro hardness value was (2520.1 HV) at spot diameter 0.539 and energy 9 J with a reduced wear rate for the laser- treated sample of about 67%.

Keywords**:** Carburizing steel, ND: YAG pulsed laser, Pulses duration, Wear resistance.

1. Introduction

Low carbon steels are widely selected in engineering applications, due to their desired metallurgical and mechanical properties; such as microstructure, micro hardness and wear resistance. They are commonly used in buildings, storage tanks and pipeline. There are many techniques of hardening applied on the surface of ferrous materials such as case hardening, flame, carburizing, nitrating, and carbonitriding. This requires a refinishing surface because of the significant thermal distortion of the parts. For some applications which require specific surface engineering, Light Amplification by Stimulated Emission of Radiation (Laser) beam has gained attraction for engineering the metal surface to modify the properties of metals and alloys. The laser beam is used as a heat source for modification of the structure and physical characteristics of the material. The classification of different surface engineering technologies by using a laser beam depends on the laser parameters, and different physical changes in the surface, as indicated by previous researches [1]. LASER is an advanced process used in several engineering applications for the modification of surface properties of pipe fitting, internal combustion parts, valves and pressure containing parts [2]. The wear resistance of the metal surface after laser application is also improved through an increased hardness of the texture surface [3].

Shahad et al. [4] studied the effect of different ND:-YAG laser parameters such as laser energy, pulse duration on the microstructure, wear and micro hardness of surface grey cast iron. The results showed that increasing laser energy led to an increase in the area of the melted and heat - affected zones, because of the formation of marten site and irregular graphite. Their results have also shown that the micro hardness value was increased. The weight losses due to wear rate of the sample after laser treatment was decreased by about (78%) and the roughness decreased by about (27%).

Mahbobur et al. [5] studied the effect of heat treatment (Hardening, Normalizing, full Annealing) on low carbon steel (AISI 1020) specimens heated treated at approximately 950°C for almost 2 hours and then cooled by different quenching media (Water, Air, Ash) the results showed that the hardening provided increased hardness values compared to annealing and normalizing.

Abbas et al. [6] investigated the modification of the surface microstructure and micro hardness of cast iron valves by applying CO_2 pulse wave laser. The investigated laser parameters were energy 1.8 J, 2 J, and 2.5 J, spot diameter 0.87 mm, 0.75 mm and 0.59 mm at fixed wavelength 1064 nm and pulse repetition rate 1-3 pulse/sec. The results have shown that the modification of microstructure occurred by forming irregular graphite. The increase in laser energy resulted an increase in the micro hardness of the heat affected and laser melted zones.

Monterio [7] studied the effect of a laser beam on micro structural and mechanical characterization of gray cast iron. They explained the aim of using laser surface hardening and studied its impact when using Nd: YAG pulsed laser. The results showed an improvement in micro hardness and wear resistance of pearlite gray cast iron that is used in the auto mobile industry.

Abbas et al. [8] studied the “improvement The Corrosion Behaviour and Wear Characteristics of AISI 304 Stainless Steel by Using ND-YAG Laser Surface Treatment”. Laser beam of ND-YAG (neodymium - doped yttrium aluminium garnet Nd: $Y_3Al_5O_{12}$) was carried out with laser parameters of 0.8 mm spot size, 10 mm/sec. travel speed, 2 ms pulse duration, 1-3 Hz pulse repetition rates (frequencies), 1064 nm wavelengths and 4 J fixed energy. They found that the samples treated by laser surface melting have a higher hardness and wear resistance than untreated sample. Also corrosion results shown that the samples treated by laser were higher pitting corrosion resistance than untreated samples.

Osamah et al. [9] studied the effect of ND: YAG pulse laser parameters on drilled hole of glass-fibre FR-4 that has 2 mm thickness, the type of the laser source was JK760TR series laser system that has (0.3-50) ms pulse length, average power of 600 w and maximum repetition rate 5000Hz. Scanning electron microscopy (SEM) was used to determine the focal plane position, number of pulses and pulse shape. Three types of pulse shapes were examined, rectangular, cool down and rump-up. The results showed that the rectangular pulse was more efficient than cool down and rump-up due to ability to produce a hole with less tapering as compared with other types. They have also found that all pulse shapes have the same effect on the material structure. The pulse duration and laser peak power had almost no effect on the edge quality and hole dimension without any defect except hole tapering.

Saleh et al. [10] studied improving the surface hardness and related properties such as wear and erosion resistance for Surface carburizing of a Ti-6Al-4V alloy using laser melting. Two different types of lasers were used a continuous wave CO_2 laser with a maximum power of 3 kW and ND: YAG laser with a maximum power per pulse of 100 W. The results showed that the micro hardness of the surface region has increased significantly after carburizing and the maximum hardness achieved was 800 Hv. The depth of the carburized layer produced by the ND-YAG laser was greater than that produced by the CO_2 laser despite the low power of the ND-YAG laser.

In view of the above, this study aims at improving the mechanical surface properties of carburized steel such as microstructure, hardness and wear resistance after changing the laser parameters (energies and pulses duration).

2. Materials and Methods

2.1. Materials

Low carbon carburizing steel AISI 1006 is used in this study provided by the scientific office with the commercial name class Laber A. [3] the chemical compositions of the specimens used in this work were first determined by Spectroscope type ARL/3460, and the results are shown in Table 1. The mechanical properties of the steel are shown in Table 2.

Table 1. Chemical composition of low carbon steel AISI 1006 [3].

Elements	Actual Value wt.%	Standard Value wt.%
C	0.07	0.08
Si	0.01	-
Mn	0.40	0.25-0.4
P	0.01	0.04
S	0.02	0.05
Cr	0.09	-
Ni	0.07	-
u	0.17	-
Co	0.01	-
Fe	Bal	-

Table 2. The properties of low carbon steel AISI 1006 [3].

Micro Hardness HV.	131
Ultimate Strength MPa.	370
Density g/cm^3.	7.85
Poisson Ratio.	0.290
Thermal Conductivity J/kg ^{0}C.	24.3-65.2
Specific Heat J/kg K.	450-2081

2.2. Preparation of specimens

The preparation of the specimens had started by machine cutting, according to the desired test dimensions. For the micro hardness test, the dimensions were diameter of 10 mm and 5 mm height. The sample dimensions for wear tests were diameter of 10 mm with 10 mm height. The samples preparation followed the requirements of ASTME3-11(2017) standard guide for preparation of metallographic specimens. Samples with dimensions of 10 mm × 10 mm with 10 mm were prepared and ground by using silicon carbide paper with different grids 120, 220, 400, 600 and 1200, followed by polishing using special cloth and polishing paste Al_2O_3 solution. The etching solution was formed of 5% HNO_3 and 95% alcohol. The specimens were etched and then washed with distilled water and alcohol to remove any remaining traces of oil on the surface before laser treatment.

2.3. ND: YAG laser system specifications

The specifications of pulsed ND: YAG (neodymium-doped yttrium aluminium garnet; ND: $Y_3Al_5O_{12}$), used in this work, are as follows; with fixed wavelength 1064 nm and pulse duration (50 ms), the frequency (1-100) Hz, the maximum power the of laser beam (7.5 kW). The energy varied from (0.89, 3.6, 4 and 6.30 J) with pulse duration of 1.00, 4.00, 4.47 and 7.05 ms, respectively.

2.4. Hardness test

Hardness Vickers (HV) was carried out by using (Indent machine, produced by England), according to ISO 650-1/2 /2005. All specimens' were prepared with diameters of 10 mm×10 mm height.

3. Thermo Chemical Treatment (Carburizing)

Solid carburization was conducted in a mixture of 40% $BaCo_3$ with 60% Charcoal. After good mixing, the samples were wrapped in stainless steel sheets of stainless steel 304 and immersed it in the mixture. The heat treatment was done by three stages, the first was a heating stage by using the furnace at temperature 900ºC, the second stage was at a holding time of two hours in the furnace to achieve austenite temperature and phase transformation, followed by the third stage; which involved applying a high cooling rate by quenching in water, Fatai et al. [11].

4. Wear Test

The wear test was conducted and the wear rate was computed according to (ASTM-F732-82) specification requirements. The device consists of a rotary electric motor with a speed of 490 rpm attached to a gearbox and shaft. The samples were mounted, as per pin -on-disk principles requirements to measure the wear rate. The applied load was 1000 gm and a sensitive electronic balance was used for measuring the weight of sample before and after the test. The distance of sliding wear was equal to 82 mm and the speed of sliding was equal to 4.2 mm/min. The weight losses at times 10 min, 20 min and 30 min were measured. The samples were weighed before and after the test. The wear rate was calculated from the following equation:

$$WR = (W2\text{-}W1)/S\ t \tag{1}$$

$$SD = S \times t \text{ (mm)} \tag{2}$$

where: *WR*, is the wear rate (gm/mm), *W1*, is the sample mass before wear test (gm), *W2*, is the sample mass after wear test (gm), *SD*, is the distance of sliding wear (mm), *S*, is the speed of sliding (mm/min) and *t* is the time of sliding (min).

5. Results and Discussions.

5.1. Effect of Laser parameters on microstructure

The different parameters investigated in this work are listed in Table 3. It is shown from Table 4 that the ND: YAG laser has fixed wave length 1064 nm, beam diameter 0.6 mm, four different energy values, spot area, pulse duration and cooling in air media. The molten area was found to be affected by the Pulse duration values. An increase in the Pulse duration led to an increase in the laser beam divergence and then an increase in the laser melted and heat affected zones spot area. The spot area of the melted zone after carburizing was increased with increasing the pulse duration, as shown in Table 4.

Table 3. Laser ND-YAG parameters.

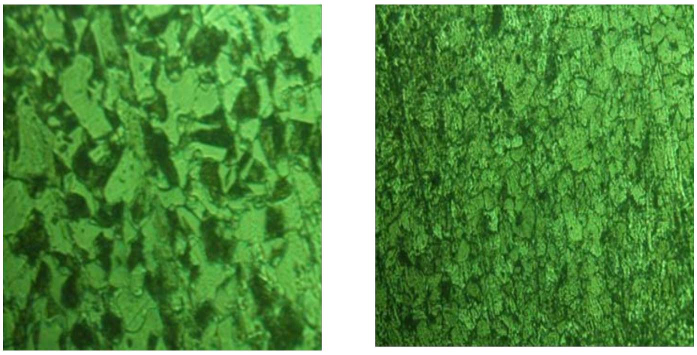
Laser energy *E* (J)	Pulse duration *T* (ms)	Spot area *A* (cm^2)
0.89	1.00	0.00794
3.60	4.00	0.00330
4.00	4.47	0.00293
6.30	7.05	0.00225

Table 4. Effect of energy in melted spot size.

Pulse duration (ms)	Base metal Melted spot size (mm)	After Carburizing melted spot size(mm)
1.00	0.071	0.01
4.00	0.077	0.084
4.47	0.247	0.254
7.05	0.368	1.01

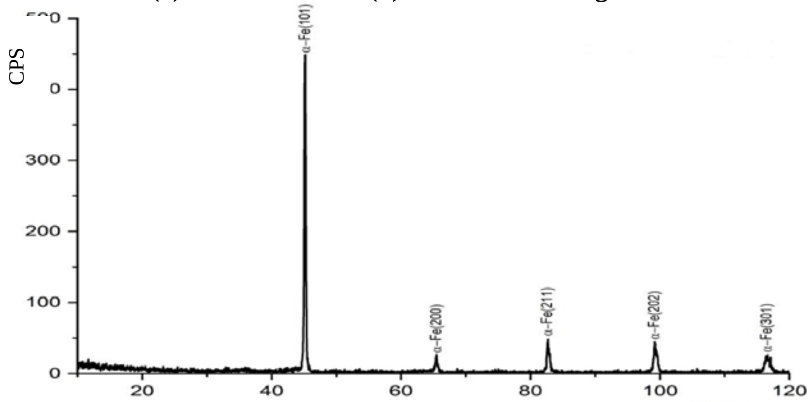
The microstructure of the specimens before and after laser treatment is shown in Fig. 1. Figure 1(a) presents the microstructure of the base metal before any treatment, which consists of a coarse-grained structure of both pearlite and ferrite phases. After the carburizing processes, the microstructure is shown in Fig. 1(b) to consist of fine-grained structure of pearlite and ferrite phases. Figure 2(a) shows the XRD (X-ray Diffraction) analysis, which supports further evidence for the presence of the Alfa -

iron (α -Fe) phase, and the role of the carburizing treatment on carbide formation as shown in Fig. 2(b). Similar findings have been reported earlier [12].

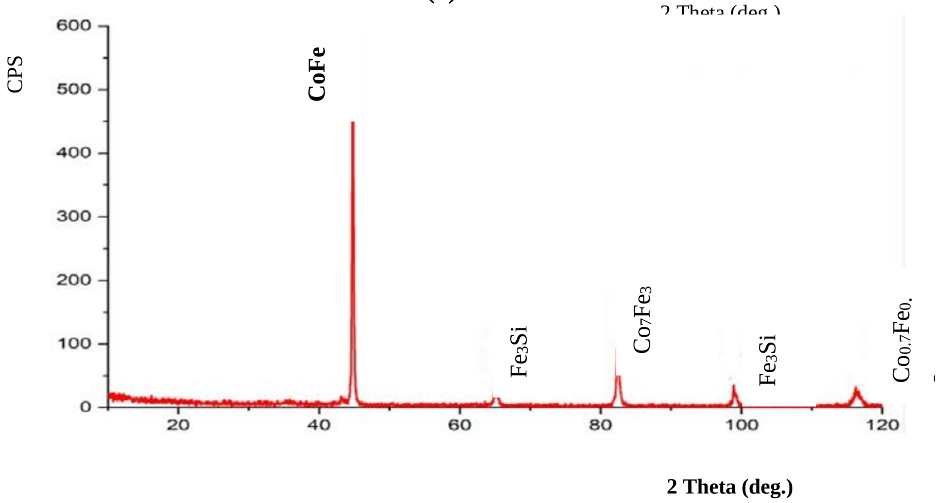


(**a**) (**b**)

Fig. 1. Microstructure of samples.
(a) Base metal and (b) After carburizing 400X.



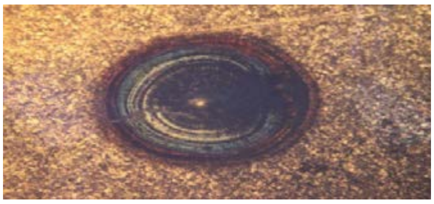
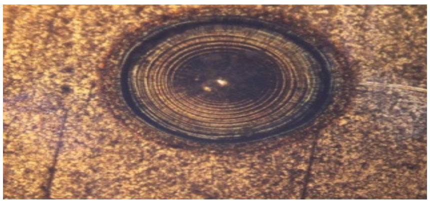
(a)



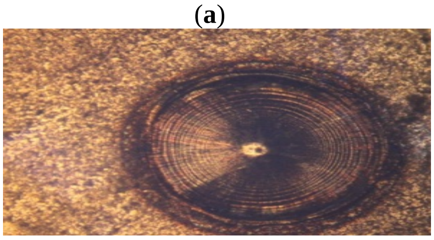
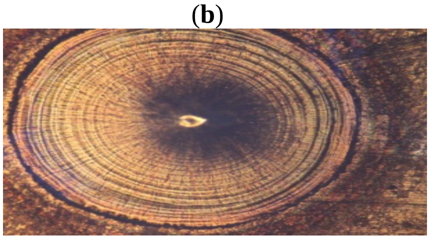
(b)

Fig.2. X-Ray diffraction of specimens.
(a). Ans-received and (b). After carburizing.

The shape of the laser melted pool depended on laser energies values, where energies of 0.89 J and 3.60 J were found to be insufficient to perform laser treatment as shown in Figs. 3(a) and (b) Also we found increase molten area with increase pulse duration and energy as shown in Figs. 3(c) and (d). It was also noted the occurrence of increase melted zone size (MZ) and heat affected zone (HAZ) width with increased laser energies and pulse duration as shows in Fig. 4. The laser interaction with metal surface after carburizing is illustrated in Fig. 5(a), showing incomplete fusion at low laser energy of 0.89 J, while a larger size of the molten zone was associated with the laser energies of 4 J and 6.30 J as shown in Figs. 5(c) and 5(d). This may be attributed to the formation of carbides after carburizing process. These results are in agreement with Kazuhlko [13], because formation of carbides phases in same mechanism phase transformation.

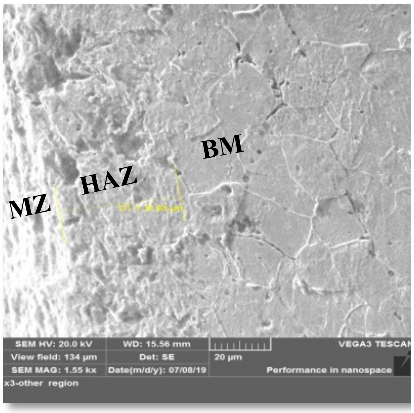



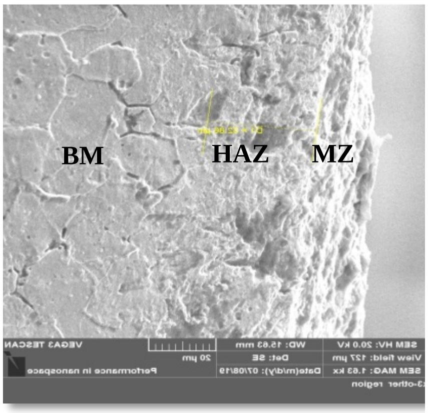
(**a**) (**b**)

(**c**) (**d**)

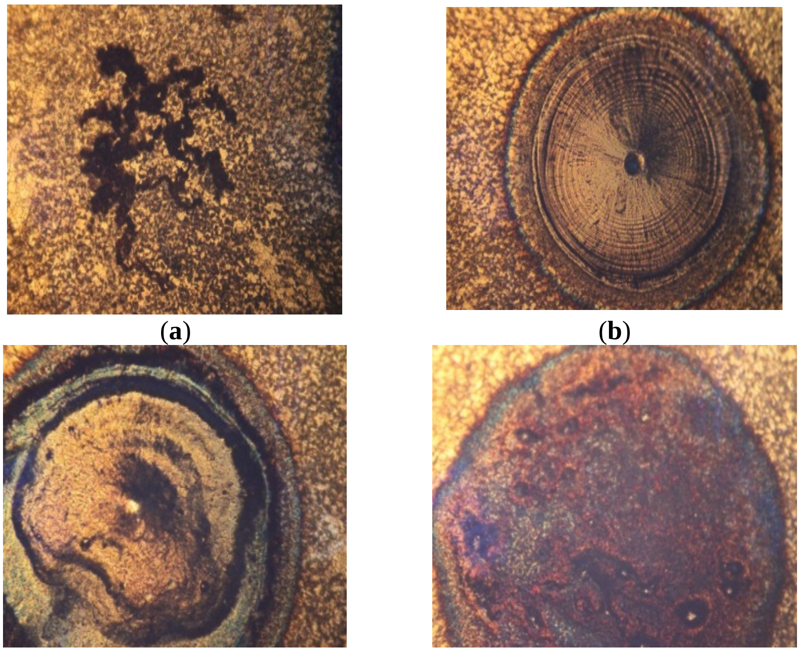
Fig. 4. The molten pool shape of low carbon steel after laser treatment with different energies and pulse duration. (a). 0.89 J with 1ms. (b). 3.6 J with 4 ms. (c). 4 J with 4.47 ms. (d). 6.3 J with 7.05 ms. 100X.





(**a**) (**b**)

Fig. 4. SEM image for laser spot of low carbon steel with different energies and pulse duration. (a). 4 J with 4.47 ms and (b). 6.3 J with 7.05 ms).



(a) (b) (c) (d)

Fig. 5. The molten pool shape of carburizing steel after laser melting for different energies and pulse duration. (a). 0.89 J with 1 ms. (b). 3.6 J with 4 ms. (c). 4 J with 4.47 ms. (d). 6.30 J with7.05 ms. 100X.

5.2. Effect of pulse duration on the micro hardness

Pulse duration is one of the most important laser parameters, the effect of changing the pulse width and power density on the laser surface melting effect is reported in this work. The results of the samples after laser treatment with different pulses durations for as received steel samples were calculated and correlated with the obtained surface melting are shown in Table 5.

It is shown from this table that increases in pulse duration lead to an increase in micro hardness, peak power, power density, energy density and decrease in the spot area. Also, we found increases in micro hardness values due to rapid cooling and carbide formation after the laser surface melting of carburizing steel as shown in Table 6. We found a higher hardness values after laser treatment of carburizing steel (Table 6) compared with a base metal (Table 5), because of carbides formation which had high hardness, these results with high matching with the result of Khansaa and Mohamad et al. [14, 15], because of all results refer to obtained the refine grain size of microstructure.

Table 5. Hardness of base metal with different pulses duration.

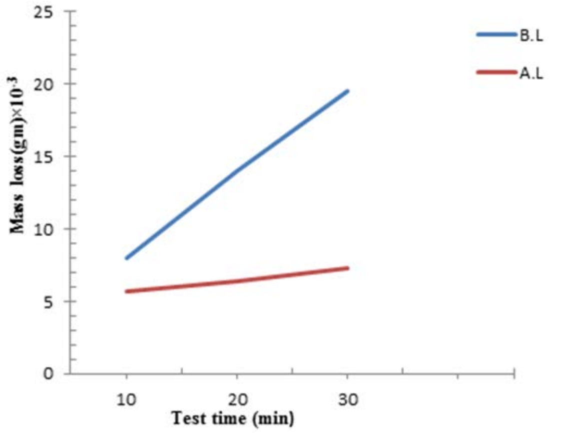
Pulse duration (ms)	1.00	4.00	4.47	7.05
Spot area(cm^2)	0.0079	0.00330	0.00293	0.00225
Peak power (W)	1000	2000	4000	9000
Power density (W/cm^2)	125×10^6	303×10^6	333×10^6	434×10^6
Energy density (kJ)/cm^2	0.126	0.606	1.379	4.01
Hardness (HV)	727.1	751.1	857.6	952.4

Table 6. Hardness of carburizing steel with different pulses duration.

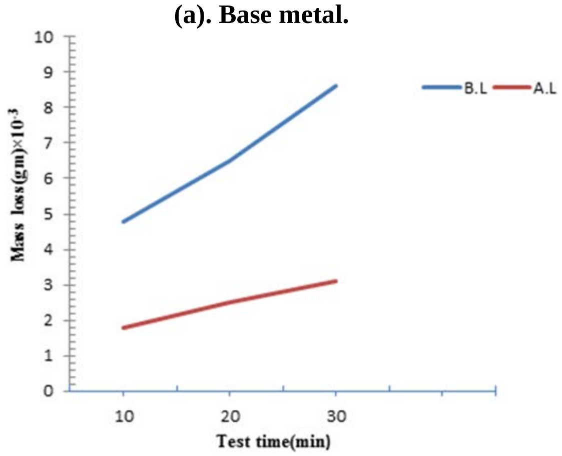
Pulse duration (ms)	1.00	4.00	4.47	7.05
Spot area (cm^2)	0.0095	0.0064	0.0051	0.0038
Peak power (W)	1000	2000	4000	9000
Power density (W/cm^2)	105×10^6	156×10^6	196×10^6	250×10^6
Energy density (kJ)/cm^2	0.105	0.3125	0.801	2.368
Hardness (HV)	1103.1	1110	2397	2520

5.3. Effect of pulse duration on wear characteristic

Major causes of improvement in wear resistance include modified microstructures and higher hardness. The increase in hardness observed in the heat- treated samples is due to the increase in heating generation rate from laser and the consequent rapid cooling. The increase in pulse duration led to an increase in surface hardness which led to the decrease in mass loss by wear, as shown in Figs. 6 and 7.The increase in hardness values led to decreases in wear rate as shown in Fig. 8. These results are in agreement with [16, 17**],** because of all results related with an increase hardness led to decrease in wear rate.

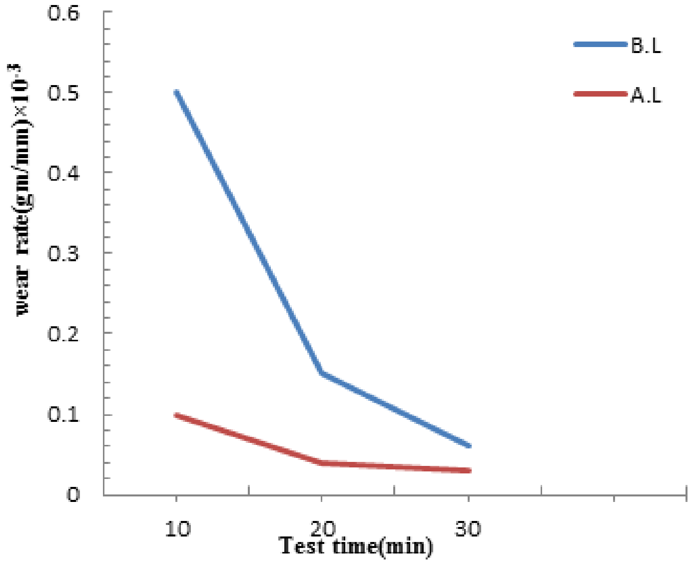


(a). Base metal.

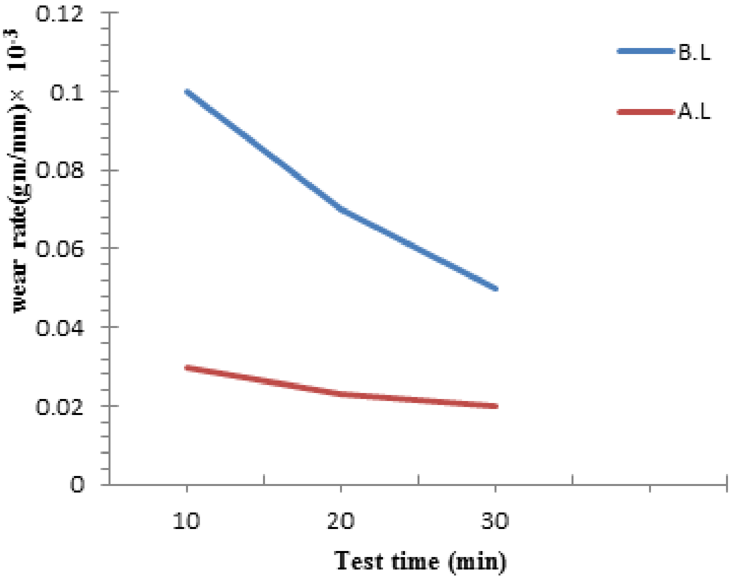


(b). Carburizing steel.

Fig. 6. The relationship between the mass loss and the period time.
(a). Base metal and (b). Carburizing steel before laser (BL) and after laser (AL).

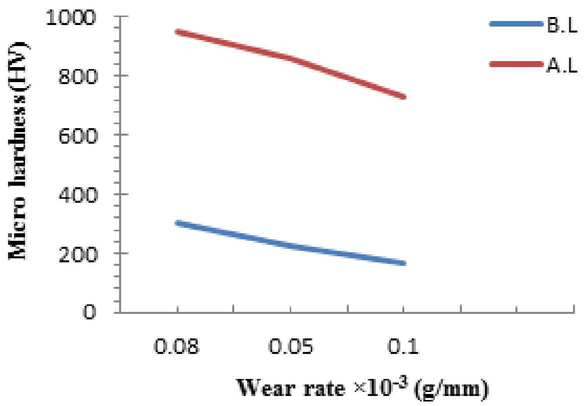


(a). Base metal.

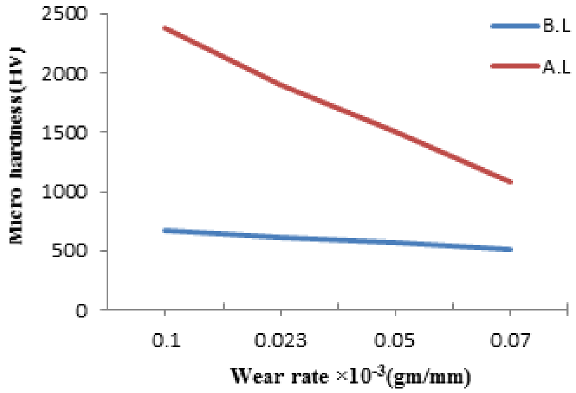


(b). Carburizing steel.

Fig. 7. The relationship between the wear rate and the period time. (a). Base metal and (b). Carburizing steel before laser (BL) and after laser (AL) with 7.05 ms pulse duration.



(a). Base metal.



(b). Carburizing steel.

Fig. 8. Effect of the surface hardening on the wear rate.
(a). Base metal and (b). Carburizing steel before laser (BL) and after laser (AL) with 7.05 ms pulse duration.

6. Conclusion

A combined thermochemical treatment by using solid carburizing and LASER treatment has improved the mechanical properties of low carbon steel surface by increasing the micro hardness and decreasing the wear rate. The increase in the LASER pulse duration led to increased area of melted and heat-affected zones. This work has illustrated that increase in laser Pulses duration leads to the formation of martensitic phase in low carbon steel and iron carbide phase in carburizing steel after laser treatment which effects to increases in micro hardness, peak power, power density, and the depth and size of the molten zone as well as wear resistance. Also we noted an increase in laser energy and pulse duration lead to increase size of meted and heat-affected zones.

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