Hardening Enhancement for Carbon Steel Using High Power CO_2 Laser

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***Abstract*—In this work high power CW CO_2 laser was used to enhance the surface hardness of samples from carbon steel. The irradiation mechanism was in scanning of the samples with different speeds. The effects of laser power, the irradiation scanning speed, sample thickness and carbon contents in the samples were investigated. The results showed considerable enhancement of the hardness with increasing laser power, decreasing scanning speed, decreasing sample thickness and increasing carbon contents. It was concluded that high power CO_2 laser can be used efficiently to enhance the surface hardness of carbon steel.**

Keywords: hardening of carbon steel, CO_2 laser applications, material processing.

1. Introduction

The energy deposition process from a pulsed/continuous wave laser beam into the near-surface regions of a solid involves electronic excitation and de-excitation within an extremely short period of time. The laser–matter interaction within near-surface region achieves extreme heating and cooling rates. This allows the near-surface region to be processed under extreme conditions with little effect on the bulk properties [1]. If the surface being processed reflects too much light energy, the absorbed energy is decreased, the operation efficiency is lowered, and the reflected light may do harm to the optical systems. So reflection and absorption of laser beams is closely related to laser processing.

The overall effect is to convert electronic energy derived from the beam of incident photons into heat. It is this heat that is useful (indeed necessary) in material processing. Depending on the temperature profile, the irradiated material may undergo heating, melting or vaporization [1].

The equation governing absorption of laser energy on the metallic target is given by:

$$I = I_0(1 - R)e^{(-z\sum_i \alpha_i)} \quad (1)$$

where I is the absorbed laser intensity and I_0 is the intensity of the incident laser beam. The fraction of the incident light intensity reflected by the target is given by R. The factor α_i represents the coefficient for the light absorption by the ith process which summed over the different absorption processes occurring at the irradiated surface, and z is the penetration depth of the radiation in the material. In the case of laser hardening the laser intensity must be below the critical value for melting of material.

As the steel is still represent the most important engineering material for most of industries, improving its mechanical properties is very important for both material and manufacturing engineers. Surface hardening treatment is one of those techniques that have been developed for this purpose. For the case-hardening heat treatment processes, such as carbonizing and nitriding, low carbon steel (either straight carbon steel or low-carbon alloy steel) is heated to a specific temperature in the presence of a material (solid, liquid, or gas) which decomposes and deposits more carbon into the surface of a steel. Then, when the part is cooled rapidly, the outer surface or case becomes hard, leaving the inside of the piece soft but very tough. Usually parts become harder than necessary and too brittle for practical use after being hardened. Severe internal stresses are set up during the rapid cooling of the steel. Steel is tempered or annealed after being hardened to relieve the internal stresses and reduce its brittleness. These involve heating the steel to a specified temperature and then permitting the steel to cool [2].

The most important method of surface treatment of metals with lasers has been the surface hardening. High power lasers are used for this purpose. The lasers used most often are the CO_2 laser and Nd:YAG laser, because they provide the highest levels of continuous power [3].

For the steel, when the laser beam irradiates the work piece surface, the surface is heated extremely rapidly and after the laser is switch off, or move away, it is cooled very rapidly due to high thermal conduction, forming a shallow layer of the hardest crystalline structure of steel, marten site. Heating and cooling rates are of the same order ~10^6 K/s [4].

The basic idea of laser hardening is to freeze a mixture of iron and carbon in a met a stable structure, called marten site, which is harder than the phases of iron carbon that are normally present at room temperature [3].

2 The experimental part:

2.1 The laser:

In this work a high power CO_2 laser that emit a wavelength of 10.6µm has been used in order to study the alteration in surface hardness by changing different laser and target parameters.

The specifications of this laser are presented in table 1 below.

Table 1. The CO_2 laser work station technical data

Parameter	Value
Wavelength (λ)	10.6 µm
Power range	0.1 – 1.3 KW
Operating condition	CW mode
Minimum spot size	≈ 100µm
The beam divergence	≤ 3 mrad
Laser head stepping speed	400 mm/min, 10000 mm/min,
Cooling water consumption	3-4 m^3/h
Cooling water pressure	0.2 – 0.4 MPa

2.2 The materials:

The treatment was performed on 20 low carbon steel specimens of 50 mm diameter with thicknesses of: 5, 10, 15 and 20 mm. The chemical structure of these specimens is illustrated in table 2.

Table 2. The steel targets chemical structure

Target code /element	C%	Si%	Mn%	Cr%	Mo%	Ti%	Fe%	others
S1	0.96	0.22	2.09	0.32	0.001	0.015	96.2	0.194
S2	1.56	0.25	0.32	0.26	0.073	0.013	97.2	0.324
S3	1.4	0.28	0.31	0.26	0.032	0.018	97.4	0.140
S4	2.44	0.67	0.33	11.3	0.39	0.001	83.0	1.869
S5	2.34	0.78	0.35	11.5	0.41	0.001	82.1	2.519
S6	2.34	0.78	0.35	11.5	0.41	0.001	82.1	2.519
S7	1.56	0.25	0.32	0.26	0.073	0.013	97.2	0.324
S8	1.4	0.21	0.28	0.24	0.061	0.008	97.5	0.302
S9	1.59	0.28	0.34	0.28	0.034	0.015	97.2	0.161
S10	0.25	0.25	0.68	0.92	0.001	0.018	97.7	0.181
S11	1.4	0.21	0.28	0.24	0.061	0.008	97.5	0.302
S12	2.13	0.68	0.33	11.3	0.39	0.001	83.0	2.269

A portable advanced Brinell tester was used in this work to measure the hardness of each sample before and after laser irradiation. This type of Brinell hardness tester has a pen like loading device that can easily be hold by hand and used in applying a shock load onto the identer carbide ball (1mm). The loading device has been connected with a built-in microprocessor which has already programmed in order to display a direct digital reading of surface hardness [5].

In order to perform the surface treatment, the specimens had been named and grouped into four groups as follows:

Group (1): This includes the samples S1, S2 and S3 which have a 5 mm thickness. This group was treated with the laser powers 100 W, 250 W and 300 W, respectively at 10000 mm/min scanning speed.

Group (2): This group includes the samples S4, S5 and S6 which are also of 5mm thickness but treated with a 250 W laser power using scanning speeds of 10000 mm/min, 20000 mm/min and 40000 mm/min.

Group (3): This includes the samples S7, S8 and S9. They have thicknesses of 10, 15 and 20 mm, respectively. This group also was treated with a 250 W laser power at 10000 mm/min scanning speed.

Group (4): This includes the samples S10, S11 and S12.They all have 5mm thickness and also they have a considerable difference in carbon content. It was treated with a 250 W laser power using scanning speed of 10000 mm/min.

2.3 The procedure:

Before treating the samples, the surface of each sample had been grinded with a surface grinding machine because the hardness tester measurements are very sensitive to the surface roughness. But on the other hand, this of course increased the surface reflectivity and diminished the coupling of the laser into the target. The hardness of the grinded surface was then tested by the Brinell tester.

Each sample in the four groups was irradiated with the CO_2 laser. The irradiation parameters were different for each group. The scanning were performed by moving the CNC laser head a cross the sample surface in straight laser beam paths. The laser power and the scanning speed had been reset for each group of samples.

After finishing the scanning process, the resulted surface hardness along the scanning paths was measured using the Brinell hardness tester. The measured hardness values were recorded for each sample and then the enhancement in hardness was calculated by subtracting the original hardness from that measured after the laser treatment and the average values were taken.

3. Results and discussion:

In this section, the results of surface hardness of steel specimens before and after treatment using TEA CO_2 are tabulated. The study was targeted the influence of laser power, laser scanning speed, carbon content and target thickness' on the resulted hardness.

The initial hardness of the targets before laser treatment is listed in table 3 bellow (two readings were recorded i&ii).

Table 3. The target Hardness before CO_2 laser treatment

Group	sample	Hardness reading (HB)	
		i	ii
1	S1	172	177
	S2	196	194
	S3	189	193
2	S4	208	204
	S5	233	224
	S6	235	233
3	S7	192	194
	S8	179	177
	S9	187	187
4	S10	160	161
	S11	124	126
	S12	189	193

3.1 Effect of laser power:

Table 4, and its graphical relation in figure 1, indicates the hardness and the change in hardness after the treatment with different laser powers. The hardness increased slightly as the laser power increased. This is limited by the melting temperature of the target which is the critical point for the maximum power that can be used in surface hardening. Another possible limitation is the risk of damaging the coupling lenses by the reflected portion of the laser beam which may be reaches about 80%.

The hardness increased exponentially with the increasing in the laser power which can be attributed to the effect of the high power laser on the crystalline structure of the steel [6, 7].

Table 4. Surface hardness corresponding to different CO_2 laser power

Sample no.	Carbon content (%)	Sample thickness (mm)	CO_2 laser Power (Watt)	Scanning speed (mm/min)	Hardness reading (HB)		Average Change in hardness (ΔHB)
					I	II	[(I-i)+(II-ii)]/2
S1	0.96	5	100	10000	205	197	26
S2	1.56	5	250	10000	222	222	27
S3	1.4	5	300	10000	218	224	30

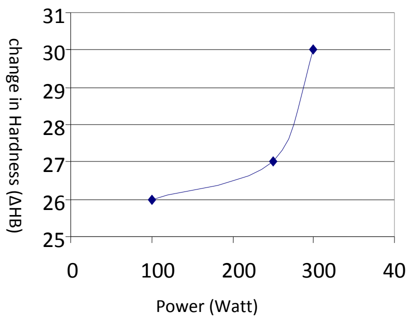

Figure 1. Influence of increasing laser power on surface hardness

3 . 2 Effect of the laser scanning speed:

Table 5, and its graphical representation in figure 2, proves that increasing the scanning speed of the laser led to shortage in activation energy required for phase change to take place to a considerable depth. So the change in hardness was clearly better at low scanning speed. The amount of reflected power may play the main role in determining the suitable scanning speed for the surface hardening. The economical scanning speed is depending on the hardness required, laser power, beam shape and complicity of the surface [8, 9].

Table 5. The resulted surface hardness with different laser scanning speeds

Sample no.	Carbon content (%)	Sample thickness (mm)	CO_2 laser Power (Watt)	Scanning speed (mm/min)	Hardness reading (HB)		Average Change in hardness (ΔHB)
					I	II	[(I-i)+(II-ii)]/2
S4	2.44	5	250	10000	277	271	73
S5	2.34	5	250	20000	250	254	23
S6	2.34	5	250	40000	252	251	16

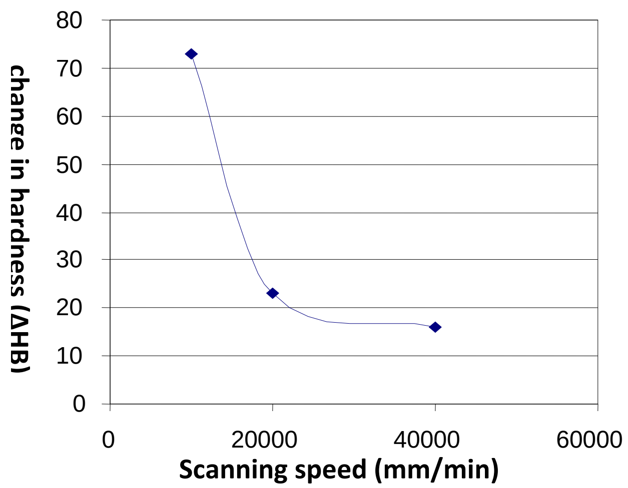

Figure 2. Influence of increasing the scanning speed on surface hardness

3. 3 Effect of sample thickness:

Table 6, and its graphical relation in figure 3, shows that when the thickness increased, the enhancement in hardness is decreased. This may be due to the influence of the thickness on the rate of sudden cooling. Thinner specimens have higher rate of heat dissipation by convection than that for thicker ones.

Table 6. The resulted surface hardness, for different target thickness

Sample no.	Carbon content (%)	Sample thickness (mm)	CO_2 laser Power (Watt)	Scanning speed (mm/min)	Hardness reading (HRC)		Average Change in hardness (ΔHB)
					I	II	[(I-i)+(II-ii)]/2
S7	1.56	10	250	10000	222	222	26
S8	1.4	15	250	10000	192	193	19
S9	1.59	20	250	10000	204	201	15

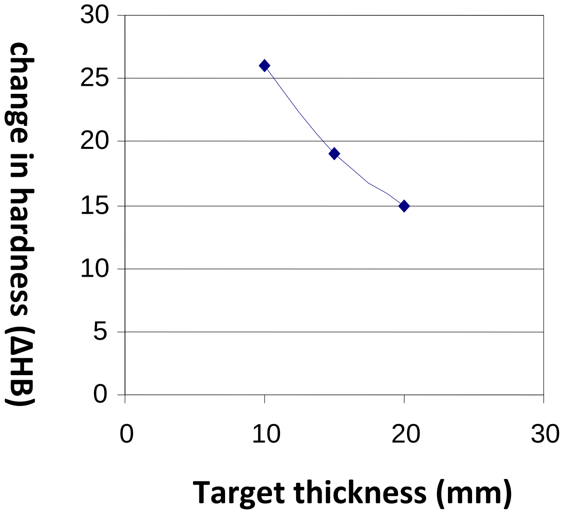

Figure 3. Influence of the Target thickness' on the resulted surface hardness

3. 4 Effect of carbon contents:

As in conventional surface heat treatment processes, the higher the carbon content the more possibility for getting a harder surface in steel [10]. The very interesting result is that for low carbon steel specimen, which is normally classified in conventional methods as non-hardenable steel (mild steel), the recognized improvement in hardness of those specimens, showed that laser was able to enhance the surface hardness for mild and structural steel. Table 7 and figure 4 show that the hardness for different carbon content steel irradiated by 250 W increased with the increment of carbon content. The relation is linear up to the conditions of the experiments and this is in a good agreement with the theoretical approach.

Table 7. The resulted surface hardness for different sample carbon contents

Sample no.	Sample thickness (mm)	Carbon content (%)	CO_2 laser Power (Watt)	Scanning speed (mm/min)	Hardness reading (HB)		Average change in hardness (ΔHB)
					I	II	
S10	5	0.25	250	10000	177	178	16
S11	5	1.4	250	10000	149	149	24
S12	5	2.13	250	10000	218	224	30

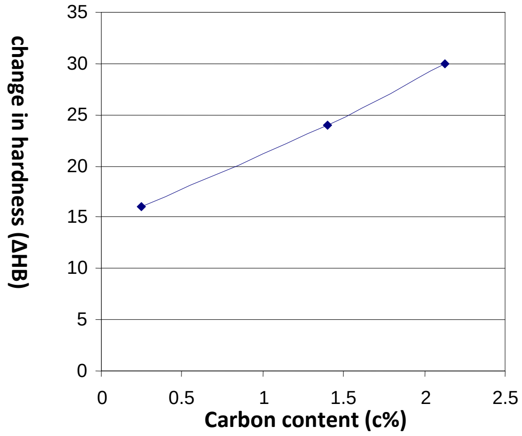

Figure 4. Influence of the carbon within the Target on the resulted surface hardness

4 . Conclusions:

The usage of high power CO_2 laser in surface hardening of carbon steel targets showed encouraging results that can be used as a guide for treating steel parts that may require selective and shallow surface hardening. The results showed that the treatment gave a considerable enhancement in hardness for the steel samples. The improvement in hardness increased with the increment of laser power, the decrease in samples thickness; decrease in the laser scanning speed and with the increment of carbon contents.

References:

1 - Dutta JM and Manna I., Laser processing of materials, vol. 28, Parts 3 & 4, Sadhana – India, 2003.

2 - William TS, Laser Fundamentals, Cambridge University Press, UK, 1999.

3 - Raymond AH., Engineering Metallurgy, fifth edition, Edward Arnold – UK, 1983.

4 - Ready JF, Industrial Application of lasers, 2nd edition, Academic Press, USA, 1997.

5 - www.hardness testers.com/brinell-conversion-10mm.htm (retrieved may 2012).

6 - Oros C., "Laser surface hardening", Journal of Optoelectronics and Advanced Materials; vol. 6, no. 1, pp. 33-39, 2004.

7 - Lee JH, Jang JH, Joo BD, Son YM, Moon YH., "Laser surface hardening of AISI H13 tool steel", Trans. Nonferrous Met. Soc. China, vol. 19, pp. 917−920, 2008.

8 - Khan S., Salam I. and Ahmed K., "Laser Surface Hardening of GCr15 Bearing Steel Ring", Key engineering materials, vol. 4 no. 2, pp. 130-136, 2010.

9 - Gupta N., Nataraj N., and Pani AK., "On the optimal control problem of laser surface hardening", International journal of numerical analysis and modeling, vol. 7, no. 4, pp. 667–680, 2010.

10 - Çalik A., “Effect of cooling rate on hardness and microstructure of AISI 1020, AISI 1040 and AISI 1060 Steels”, International Journal of Physical Sciences, vol. 4, no. 9, pp. 514-518, 2009.