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Features of Spot-Matrix Surface Hardening of Low-Carbon Steel Using Pulsed Laser

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Abstract

In this work, results of spot hardening in low-carbon steel by using a pulsed Nd:YAG laser are presented. These results include determination of hardening depth, diameter of hardened spot, aspect ratio and heat-affected zone width with varying laser energy density. In order to determine the effect of irradiation profile on the overall achievable hardness, the profiles of overlapping, adjacent and separated hardened spots are compared and the percent coverage of the workpiece as a function of the laser-hardened spot dimensions.

Keywords: Pulse laser hardening, carbon steel, laser treatment.

خصائص التصليد السطحي بنمط المصفوفة النقطية للفولاذ منخفض الكاربون باستخدام الليزر النبضي

الخلاصة

في هذا البحث، جرى تقديم نتائج عملية لتصليد عينات من الفولاذ منخفض الكاربون بالنمط النقطي باستخدام ليزر النيديميوم-ياك النبضي. تضمنت هذه النتائج تحديد عمق التصليد وقطر البقعة المصلدة والنسبة الباعية وعرض المنطقة المتأثرة حرارياً كدالة لتغير كثافة طاقة الليزر. ومن أجل التعرف على تأثير نمط التشعيع على الصلادة الإجمالية للسطح والتي يمكن تحقيقها، جرى مقارنة الأنماط المحتملة لاستخدام الليزر النبضي في التصليد وهي نمط التراكب ونمط البقع المتجاورة ونمط البقع المنفصلة، كما جرى تحديد النسبة المئوية لتغطية سطح العينة كدالة لأبعاد البقعة المصلدة بالليزر.

1. Introduction

The hardening process of steel depends on the temperature-dependent changes in crystalline structure of the ferrite as well as those in carbon solubility resulted from such changes. The process of phase-transformed hardening can be summarized by [1-5]:

1. heating steel over a range of austenite-forming temperatures for enough time in order to redistribute carbon in the ferrite.
2. cooling rapidly in a manner preventing carbon to leave ferrite lattice to form martensite.
3. final heating in order to increase surface smoothing and ductility of the hardened region.

Hardness of martensite relates totally to the carbon content, so, martensite formed in a AISI1050 steel containing 0.5% carbon without any other elements has the same hardness as same as that of AISI8650 steel containing 0.5% carbon in addition to Cr, Ni and Mo. The role of these

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elements defines a property of steel known as "**hardenability**", which represents the cooling rate required for martensite formation [1, 6-9]. Fig. (1) explains the metallurgical description of laser heat treatment.

In most cases, hardening of the internal part of workpiece is undesired as well as wear and high stress are localized, then only small area is needed to be hardened. However, most of workpiece is often preferred to be tough and ductile that cannot be provided by martensite. Therefore, several techniques for local heating being employed, such as carbonization, flame method, induction and laser [10-14].

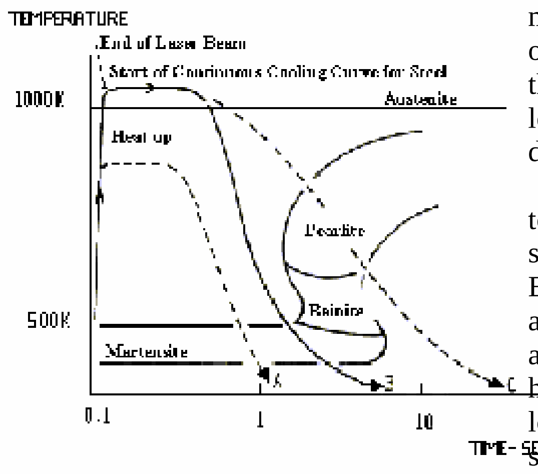


Fig. (1) Metallurgical description of laser heat treatment

Since metals generally are high reflective and opaque to the ultraviolet (UV), visible and infrared (IR) wavelengths, then absorption depth for laser radiation is often limited. In order to overcome high reflectivity, metal surface is usually covered with an antireflection material (coating) to increase the absorption. Graphite, oxides and phosphates are often used for such purpose. All common coating materials have two main limitations in use. First, they need for an additional experimental step (coating). Second, such process requires necessarily controlling thickness of coating in order to obtain a homogeneous effect from heat treatment process. It is so feasible to perform laser treatment without any coatings [15-18].

Success of surface hardening is determined mainly by controlling energy transfer rate to the workpiece. The transferred energy must be high enough to raise temperature of the area required to be hardened to the austenitic point with keeping heat flow to the neighbored regions. This heating should not melt surface or material. In case of laser treatment, only surface is heated that limits thermal gradient to an acceptable level, hence maximum hardening depth [14, 19-25].

In some applications, it is desirable to form a complete hardened layer of surface by laser beam scanning. Engine pistons and hard-friction parts are examples. If it is required to treat a surface in order to obtain overall hardened area that is not subjected to localized-friction loading, then surface area can be hardened as a matrix of laser-irradiated spots without any overlap among them. In other words, the pulsed laser is used to create a uniform distribution of transformation-hardened spots to cover only a certain percentage of the surface area. Due to reduced coverage, considerably less energy input to the workpiece is required, which allows surface hardening of thin and intricate parts without distortion. This technique also reduces cost of process and enables mass production of such parts [2, 9, 15, 18, 23, 26-28].

In this work, results of spot hardening of low-carbon steel by pulsed Nd:YAG laser are presented and discussed to achieve matrix spot laser-irradiated hardening. Advantages of such technique compared to overlapped pulses were described.

2. Experiment

Experimental procedure of this work includes sample preparation, laser system and accessories instruments. Samples of disk shape were 15mm-diameter and 3mm-thickness low-carbon steel. The chemical composition of these samples is shown in Table (1).

Table (1) Chemical composition of sample used in this work

C	Si	Mn	P
0.1-0.17	0.5-0.35	0.4-0.7	0.035
S	Cr	Ni	Fe
0.035	0.55-0.95	2.25-2.75	balance

A pulsed 1.06 m Nd:YAG laser with 10ms pulse duration, 4.2J maximum pulse energy and 2mrad Gaussian mode (TEM_{00}) divergence was used. Laser beam was focused using a 20cm-focal length lens in order to obtain maximum power density of about 2.78MW/cm^2. The sample was placed on a moving table in x- and y-direction. A Metallux-Leitz optical microscope was used to introduce dimensions and structure of treated regions. Fig. (2) shows the experimental set-up of this work. The Vickers hardness (H_v) of samples was measured using a Universal research Microscope MeF2 microhardness tester.

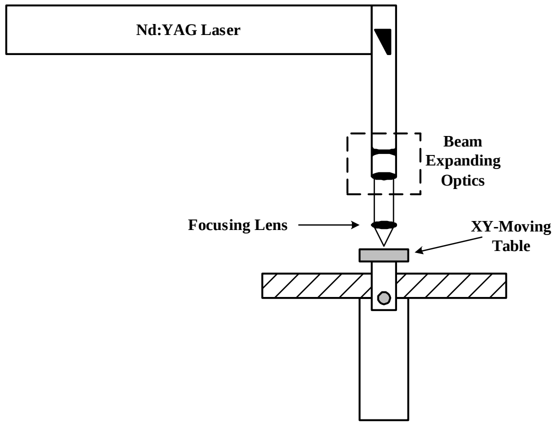


Fig. (2) Experimental set-up of this work

3. Results and Discussion

Samples were placed at the focal length of focusing lens and irradiated in air. Several samples were irradiated at different energy densities and Fig. (3) explains the section of laser-irradiated spot at the minimum energy density (457.57J/cm^2). As can be shown, the configuration of treated region is a uniform half-circle, which is resulted from the uniform distribution of Gaussian laser beam. Using the fundamental mode of laser beam provides an advantage that is easy to control beam parameters, hence controlling dimensions of the formed region [24]. Dimensions of treated region can be measured with good accuracy by optical microscope. Fig. (4) shows schematically the main three dimensions of treated spot.

Hardness of treated regions was measured along the distance from surface (z-axis), as shown in Fig. (5). The hardness decreases with depth, which is attributed to the thermal properties of workpiece resisting more heat conduction from the laser pulse incidence spot inside the bulk.

In order to introduce the parameters of laser-treated region, the hardening depth, the diameter of hardened spot and the heat-affected zone width were measured as functions of incident laser energy density. Moreover, to determine the quality of such process, the aspect ratio of the hardened region was determined as a function of energy density. As shown in Fig. (6), the hardening depth (d) increases continuously with increasing energy density due to the increasing thermal input causing more heat been transferred to the bulk. Hence, penetration depth of the laser pulse will be deeper and the thermal effect is continual inside.

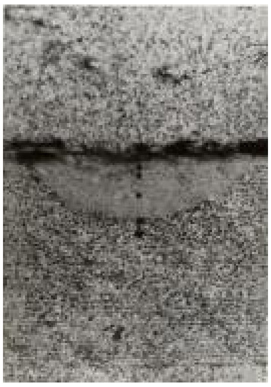


Fig. (3) Cross-sectional microscope photograph of the laser-treated spot at the minimum laser energy density 457.57J/cm^2

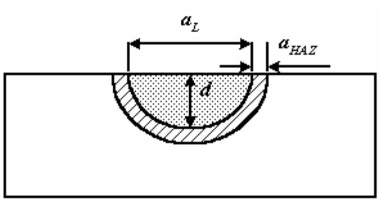


Fig. (4) Dimensions of the laser-hardened spot

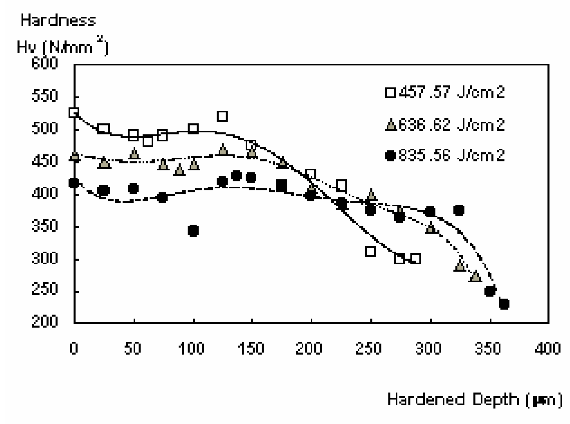


Fig. (5) Hardness of the laser-treated spot along the distance from surface of workpiece at three different energy densities (457.57, 636.62, 835.56)J/cm^2

Accordingly, the diameter of hardened spot (a_L) is also increased with increasing laser energy density due to the effect of thermal conduction in lateral direction and the results are shown in Fig. (7). In some laser applications such as drilling and cutting, the diameter of hardened spot is desirable to be as small as possible in order to induce heat to penetrate deeper inside the workpiece. So, increasing this diameter in such applications should be avoided when it may waste the absorbed energy to widen the crater. While in laser surface hardening, such effect might be useful for the process itself to cover larger area of the surface required being hardened. But such performance shouldn't reduce beam energy density suitable for hardening requirement.

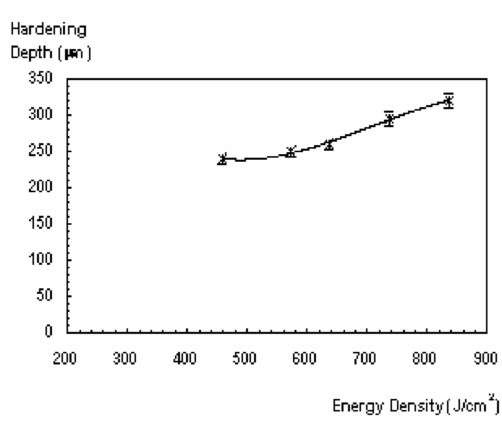


Fig. (6) The hardening depth (d) as a function of laser energy density (E/A)

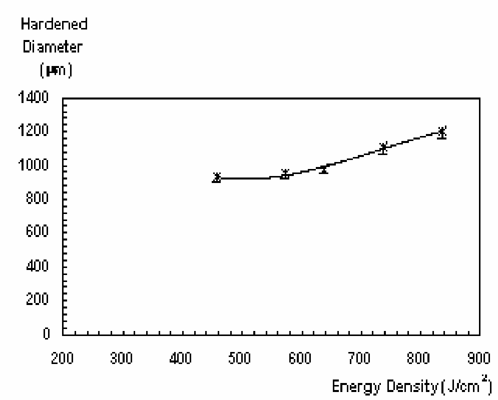


Fig. (7) The diameter of hardened spot (a_L) as a function of laser energy density (E/A)

In order to introduce the quality of laser hardening process, the aspect ratio, shown in Fig. (8), was determined. The quality is increased constantly but some decreasing was observed at about 740J/cm^2 energy density. So, this process is generally qualitative before this value of laser energy density.

The thermal conduction is always supplemented by the formation of heat-affected zone (HAZ) due to the decay of thermal wave propagating in a semi-spherical region surrounding the beam incidence spot. The HAZ may act an important role in surface hardening if the temperature of HAZ reaches a value high enough to induce the phase transformation required in such application. Otherwise, the extension of such region should be avoided as possible to confine heat transfer in the effective region. Measurement of HAZ width as a function of laser energy density is explained in Fig. (9).

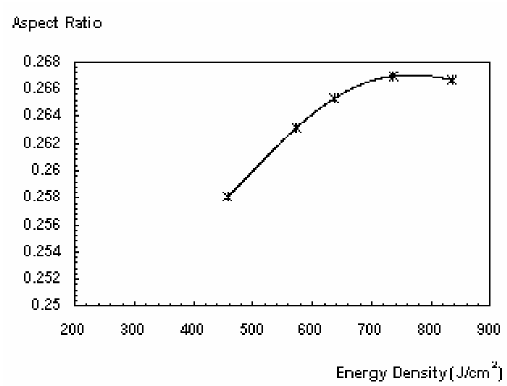


Fig. (8) The aspect ratio (d/a_L) of the hardened spot as a function of laser energy density (E/A)

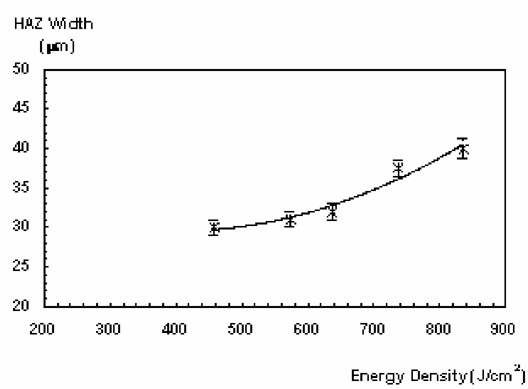
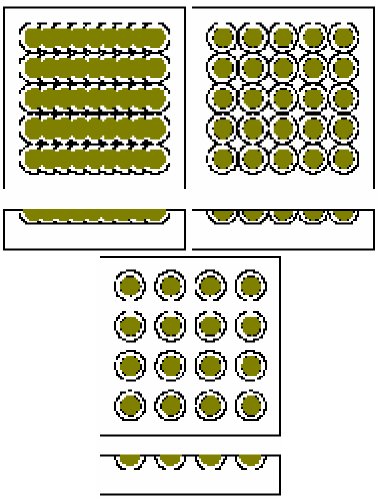


Fig. (9) The HAZ width (a_{HAZ}) in the laser-treated region as a function of laser energy density (E/A)

There are several profiles of surface scanning by laser beam in surface hardening process as shown in Fig. (10). This process can be performed with overlapped spots (0-100%), adjacent spots or separated spots. The first profile (overlapped) (Fig. 10a) requires much pulses than the others since the overlapping pulse supports the former one by a certain percent. Here, overlapping region is subjected to the laser irradiation twice and this is required when the total surface needed to be hardened. Some applications impose the workpiece surface be hardened 100%.

If the laser-hardened spots are separated on the workpiece surface (Fig. 10b), then the hardness is measured exactly at each spot but the unhardened area is definitely a loss in such process. This profile is practical only in those applications requiring only spots of the hardened material such as diagnostic probes and pin-head tools.



(a) (b) (c)

Fig. (10) Profiles of surface hardening using pulsed laser (a) overlapped, (b) touched-HAZ and (c) spot-matrix

The adjacent spots in the third profile (Fig. 10c) is a good solution for some applications those require an overall hardened surface as in low-friction parts and sliding benches. So, we can perform a laser hardening process throughout the irradiation of a matrix of spots on the surface where each spot touches its adjacent at the circumstances of laser incidence spots or at HAZ. If the thermal effect on HAZ is not enough to satisfy the hardening requirement, then HAZ's are overlapped in order to accumulate the thermal effects.

If the thermal effect on HAZ is enough to induce the minimum transformation at the surface, then making each two HAZ regions adjacent. This definitely will cover the surface with maximum hardened spots and transformed regions and minimum unhardened region among the HAZ's. The efficiency of such coverage process can be controlled by the size of laser-hardened spot and HAZ accompanied and the percent coverage is given by [29]:

$$Coverage(\%) = \frac{pa_L^2 + 4pa_L a_{HAZ} + 4pa_{HAZ}^2}{9a_L^2 + 24a_L a_{HAZ} + 16a_{HAZ}^2} \times 100$$

Accordingly, the percent coverage mentioned can be represented as a function of both hardened spot diameter and HAZ width as in Fig. (11). It is clear that maximizing both variables (a_L and a_{HAZ}) doesn't result in a corresponding maximum coverage. So, there is some compromise in values of both parameters should be considered to achieve the maximum allowable coverage. According to the results obtained in this work, the maximum achievable coverage is about 47%. Such process has a potential advantage that the irradiated spot is subjected to minimum stresses resulted from shockwave and heat transfer effects [25].

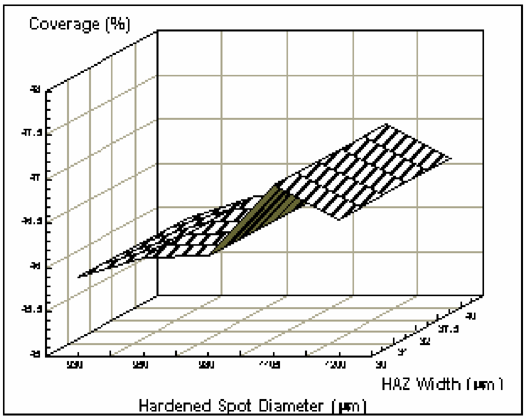


Fig. (11) The percent coverage of laser-hardened surface as a function of both hardened-spot diameter (a_L) and HAZ width (a_{HAZ})

4. Conclusions

In this work, results of spot hardening in low-carbon steel by pulsed Nd:YAG laser are presented. These results included hardening depth, diameter of hardened spot, aspect ratio and heat-affected zone width with varying laser energy density. To determine the effect of irradiation profile on the overall achievable hardness, the profiles of overlapping, adjacent and separated hardened spots are compared and the percent coverage as a function of the laser-hardened spot dimensions. In practice, scanning the workpiece surface with a matrix of laser-hardened spots where their HAZ's are adjacent offers an acceptable solution to maximize the hardened area by a minimum number of laser pulses. The achievable coverage due to our results is about 47% with an overall surface hardness not more less than that achieved in overlapping profile.

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