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Temperature Field of Repetitive Laser Pulse Irradiation and Its Effect on Laser Surface Hardening

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Abstract. Analytical expressions for the temperature rise in a semi-infinite workpiece due to the heating with CW and repetitive laser pulse irradiation have been derived. It has been shown that the soaking time at a temperature above the phase transformation temperature, on which the homogeneity of microstructure and the depth of hardening depend, can be increased by heating with repetitive laser pulses. Experimental results of surface hardening of high-carbon steel with repetitive laser pulses showed higher depth of hardening and better microstructure homogeneity compared to those with continuous wave laser.

Introduction

Laser surface hardening process though established as one of the industrial applications of high power lasers, is still being investigated for developing a better understanding of the effects of various experimental parameters on the surface hardness characteristics, microstructure and residual stress, and also to establish predictive models of the process.

In laser surface hardening process the laser power density and the interaction time have to be so controlled that the material up to a desired depth is heated to a temperature above the phase transformation temperature Ac1 without melting the surface and the temperature is held beyond Ac1 for enough time for the austenite phase to get homogenised. This has been achieved either by using a pulsed laser or a continuous wave (CW) laser scanned over the surface and the input energy density has been optimised by controlling the pulse duration or the dwell time of the laser beam for maximum hardness and maximum hardness depth [1-4]. Recently, several authors have reported better surface characteristics in laser surface modification process with the repetitive laser pulse irradiation than with CW laser [4, 5]. Miokovic et al. have reported increase in the depth of hardened zone with the increase of number of heating and cooling cycles in spot hardening and also with the increase of minimum temperature of the work-piece [4]. Parvathavarthini et al developed a novel technique for generating a sensitization resistant microstructure in type 316(N) stainless steel weld metal by laser remelting with modulated CO2 laser beam [5]. This improved the immunity against intergranular corrosion significantly. The temperature history for the cyclic laser heating and cooling has been studied numerically as well as analytically [5, 6]. Kalyon and Yilbas derived a solution for the temperature rise including the cooling cycle using a Laplace transformation method and presented the results for two heating cycles [6].

We have extended the analytical solution of 1-D heat conduction in semi-infinite workpiece for the temperature rise as a function of depth and time for repetitive laser pulse (RLP) irradiation and have studied the effect of the pulse on-time (heating cycle), off-time (cooling cycle), and laser peak power on the temperature rise and the soaking time duration for holding the material above the austenization temperature. It is seen that the soaking time duration increases significantly in case of heating with RLPs in comparison to CW laser. This should facilitate better homogenization of microstructure and the increase in the depth of hardening. Laser surface hardening of AISI 1055 steel was carried out with a 2 kW fiber laser in CW and RLP modes. Laser power, scan speed and duty cycle at 100 Hz repetition frequency were optimized using L9 array of Taguchi technique for the maximum microhardness and depth of hardening [7]. The microhardness measurement and the scanning electron microscopic observations revealed more homogeneous microstructure and increased hardening depth in case of RLP irradiation than with CW laser. It has been also experimentally observed that the optimum repetition frequency for the maximum hardness depth depended on the thickness of the specimen. The optimum repetition frequency was higher in relatively thinner specimen.

Analytical Modelling

The basic principle involved in laser transformation hardening process is a three-step process:

(i) Increase in the surface temperature above the characteristic austenization temperature $Ac_1$of steel by high power laser irradiation

(ii) Maintaining the temperature of irradiated material above Ac_1 for enough long time duration for the formation of homogeneous austenitic phase

(iii) Subsequent fast cooling by self quenching for the austenite to martensite phase transformation

For the thermal analysis, it is assumed that the heat is transferred to the metal by a source providing a constant heat flux, the workpiece is semi-infinite and heat conduction is in one dimension. These assumptions are valid if the thermal diffusion length is smaller than the physical dimensions of workpiece and laser beam diameter. The temperature change in the workpiece as a function of time, t and depth, z can be given by the 1-D heat conduction equation (1) [8]

$$\frac{\partial^2 T(z,t)}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T(z,t)}{\partial t} \qquad (1)$$

where α is the thermal diffusivity of the material.

In case of a laser beam incident on a semi-infinite workpiece surface, the solution of (1) for the temperature distribution can be given by [8]

$$\Delta T(z,t) = 2\frac{I}{k}\sqrt{\alpha t}\, ierfc\left(\frac{z}{2\sqrt{\alpha t}}\right) \qquad (2)$$

where I and k are the absorbed laser power density and the thermal conductivity of material respectively. The temperature decay after the end of laser pulse or dwell time, t_p can be given by [8]

$$\Delta T(z,t) = 2\frac{I}{k}\left[\sqrt{\alpha t}\, ierfc\left(\frac{z}{2\sqrt{\alpha t}}\right) - \sqrt{\alpha(t-t_p)}\, ierfc\left(\frac{z}{2\sqrt{\alpha(t-t_p)}}\right)\right] \qquad (3)$$

In case of the cw laser scanned over the surface, the dwell time, t_p can be given by $t_p = d / v$; where d and v are the laser beam diameter and the scan speed respectively. The above 1-D solutions have been extended for the temperature variation for repetitive laser pulses taking into account the heating by all pulses and cooling between the pulses. The temperature rise due to the laser pulse after the n_{th} pulse can be given by (4)

$$\Delta T_n(z,t)_{heating} =$$
$$2\frac{I}{k}\sqrt{\alpha}[\{\sqrt{t-n(t_p+t_c)}\,ierfc(\frac{z}{2\sqrt{\alpha(t-n(t_p+t_c))}})\}$$
$$+\sum_{n=1}^{n}\{\sqrt{t-(n-1)(t_p+t_c)}\,ierfc(\frac{z}{2\sqrt{\alpha(t-(n-1)(t_p+t_c))}})$$
$$-\sqrt{t-(nt_p+(n-1)t_c)}\,ierfc\frac{z}{2\sqrt{\alpha(t-(nt_p+(n-1)t_c))}}\}] \quad (4)$$

where t_p is the pulse on time and t_c is the pulse off time leading to a cycle time of $t_p + t_c$. The temperature during the cooling cycle after the n_{th} pulse can be given by (5).

$$\Delta T_n(z,t)_{cooling} = 2\frac{I}{k}\sqrt{\alpha}$$
$$[\sum_{n=1}^{n}\{\sqrt{t-(n-1)(t_p+t_c)}\,ierfc(\frac{z}{2\sqrt{\alpha(t-(n-1)(t_p+t_c))}})$$
$$-\sqrt{t-(nt_p+(n-1)t_c)}\,ierfc\frac{z}{2\sqrt{\alpha(t-(nt_p+(n-1)t_c))}}\}] \quad (5)$$

Modeling Results

In order to harden AISI 1055 steel up to 0.5mm depth the absorbed laser power density, I and irradiation time, t_p were estimated using equations (2) and (3) for raising the temperature up to the desired depth above the Ac_1 temperature without melting the surface and the values were 8000 W/cm^2 and 51.5 ms respectively.

Material composition of AISI 1055 steel and its thermo-physical properties were taken as the following:

Composition:
C=0.5-0.6%, Mn= 0.6-0.9%, P= 0.04%, S= 0.04%, Si=0.15-0.3%, Fe= balance.

Therm-physical properties:
Thermal conductivity, k = 52 W/m-K;
Density, ρ = 7865 kg/m^3;
Specific heat, C_p = 472 J/kg-K;
Melting temperature =1773^0K and
Phase transformation temperature=1000^0K.

Using the above equations the variation in temperature at the surface and 0.5mm depth for CW laser and RLP heating are plotted in figs.1a and b respectively. Laser power density of $8000W/cm^2$ is taken for both cases. For RLP, the laser on- and off- time of 5ms and 10ms respectively have been taken. From figs 1a and 1b it is seen that the average heating and cooling rates have considerably slowed down in case of RLP irradiation compared to those in CW laser case, and the soaking time for the former case has significantly increased. The cooling rate and the soaking time for RLP heating were about 2000^0K/s and 200 ms respectively and the parameters for CW heating were 8000^0K/s and 25 ms respectively.

Fig.2 shows the dependence of soaking time on laser pulse off-time (cooling time) for different pulse on-time (heating time). This indicates that the soaking time increases with the decrease of laser pulse on-time and increase of pulse off-time.

Experimental Results & Discussion

In order to study the effect of RLP irradiation on the surface hardening, experiment was carried out on AISI 1055 steel using a 2kW fiber laser (YLR 2000) which can be operated in both CW and modulated power modes at modulation frequency ranging from 1 to 1000 Hz with the duty cycle variable in 5-100% range. The specimens of AISI 1055 steel were of 30x12x10mms size and these were coated with black permanent marker to increase the absorptivity of laser power. The laser beam diameter on the specimen was kept 3mm through out the experiment. In order to study the effect of laser power, scan speed, and modulation frequencies on the micro-hardness and depth of hardening, first the experimental range of laser and duty cycle variable in 5-100% range. The specimens of AISI 1055 steel were of 30x12x10mms size and these were coated with black permanent marker to increase the absorptivity of laser power. The laser beam diameter on the specimen was kept 3mm through out the experiment. In order to study the effect of laser power, scan speed, and modulation frequencies on the micro-hardness and depth of hardening, first the experimental range of laser and

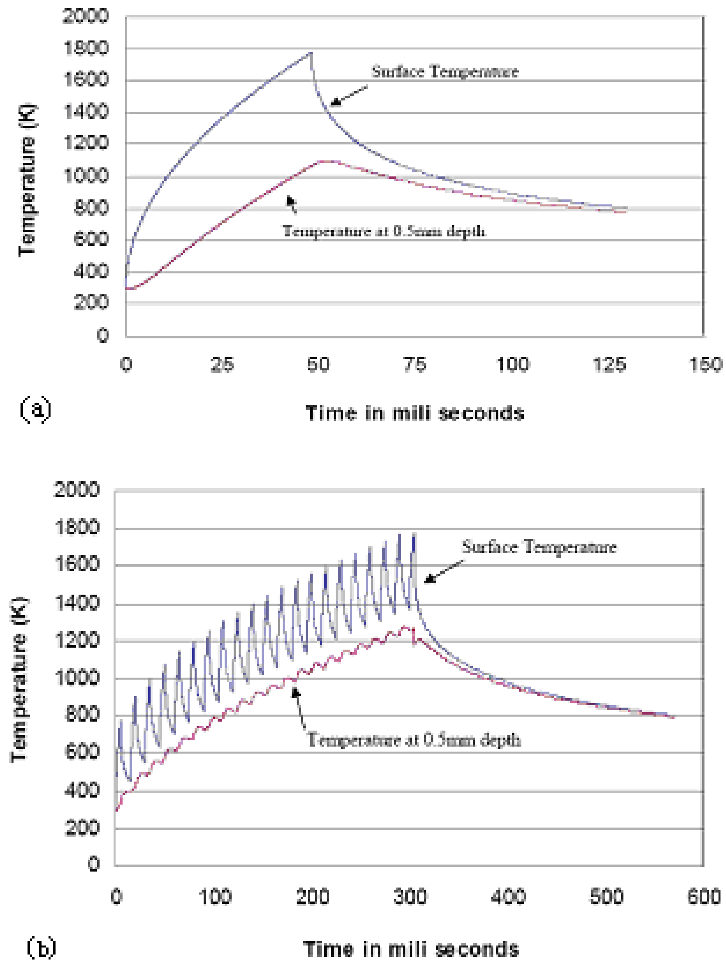

Figure 1. Temperature variation at the surface and at 0.5mm depth with (a) CW laser irradiation, (b) RLP irradiation

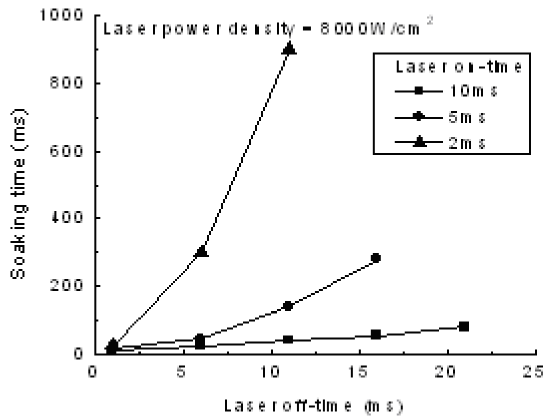

Figure 2. Variations of soaking time with laser pulse off-time for different laser pulse on-time

For CW case, three levels of laser power 600W, 700W and 800W and three levels of scan speed 1m/min, 1.1 m/min and 1.2 m/min were selected. And, for repetitive pulsed mode operation, the repetition pulse rate was kept constant at 100Hz and the three levels of laser power, scan speed and duty cycle were 1000W, 1200W and 1400W; 600mm/min, 700mm/min and 800mm/min, and 10%, 30% and 50% respectively. These parameters were optimized using Taguchi technique for the maximum microhardness and depth of hardening. Maximum depth of hardness was resulted with 800W laser power and 1.1m/min scan speed in CW laser hardening and, with 1400W laser power, 600mm/min scan speed and 50% duty cycle in RLP hardening. Fig.3a shows the variation of microhardness along the depth for both modes of laser hardening. Maximum depth of hardness was 0.36mm in case of RLP irradiation, which was 20% more than that in CW laser hardening process. However, this was less than the designed hardness depth of 0.5 mm, which could be due to the increase in phase transformation temperatures, Ac_1 and Ac_3, for the start and finish of austenite formation at high heating rates [2].

Fig.3b shows the variation of microhardness transverse to the laser scan at the surface.

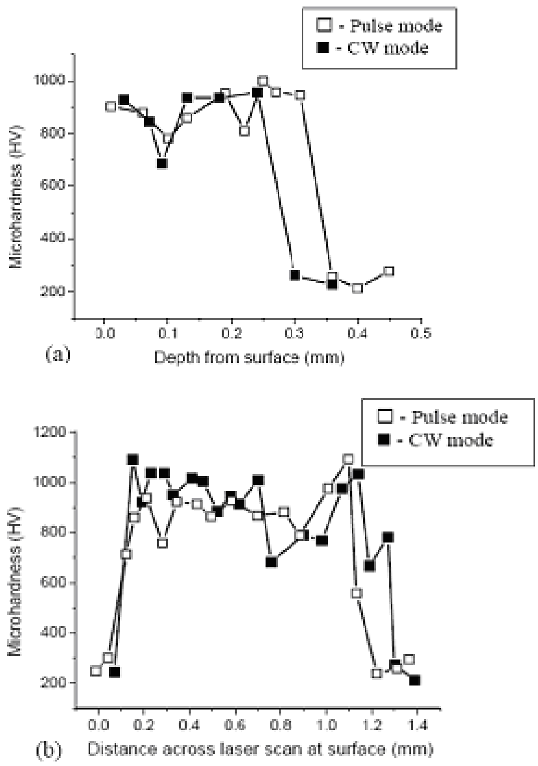

Figure 3. Variation of microhardness for CW and RLP hardening
(a) along the depth from surface (b) across the width of laser scan

The width of hardened zone at the top surface was almost the same for both modes of hardening. The maximum average microhardness realized in both cases was about 900HV.

The scanning electron microscope (SEM) images of the resulting microstructure at different regions of the transverse section in the laser hardened zone were recorded. Fig.4 shows the SEM images of different regions along the depth. SEM microstructure of near the top surface shows the formation of homogeneous martensite plates, fig. 4a. However, the microstructure of material in between the top surface and the boundary of the heat affected zone shows the formation of heterogeneous structure of martensite phases (high carbon plates and low carbon laths), due to relatively slower cooling rate compared to that at the top surface, fig. 4b. At the boundary of hardened zone, microstructure shows the lamellar pearlite in a ferrite (dark) field, fig. 4c.

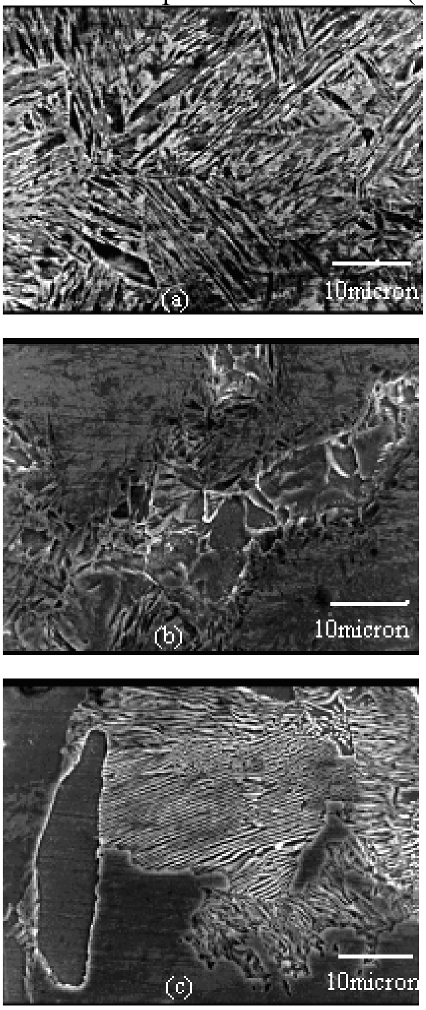

Figure 4. SEM micrographs of CW laser hardened section (a) near the top surface, (b) middle of the hardened zone, (c) near the boundary of hardened and base material

Fig.5 shows the SEM images of different locations in laser hardened region produced by RLP irradiation at the optimum laser processing conditions, i.e. laser peak power=1400W, laser scan speed=600mm/min, pulse repetition rate=100Hz and duty cycle=50%. SEM microstructures in fig 5a and 5b show that the homogeneous martensite laths have resulted along the depth. Comparison of figs. 4b and 5b shows that the microstructure is more uniform in case of RLP treatment than in case of CW laser. Some nodular pearlite islands were also formed in case of RLP process, fig. 5a. At the microstructure at the boundary of laser hardened zone shows the lamellar pearlite in a ferrite field, fig.5c. More homogeneous martensite microstructures in RLP treatment can be attributed to the relatively slower cooling rate and longer soaking time compared to those in CW laser treatment. Moreover, since the high heating rate tends to raise the Ac1 and Ac3 temperatures, heterogeneous martensite phase formation and reduction in the depth of hardening is expected in case of CW laser irradiation with higher heating rate compared to RLP treatment. This has been observed as shown in fig.3a and 4b depicting the depth of hardness and microstructure respectively.

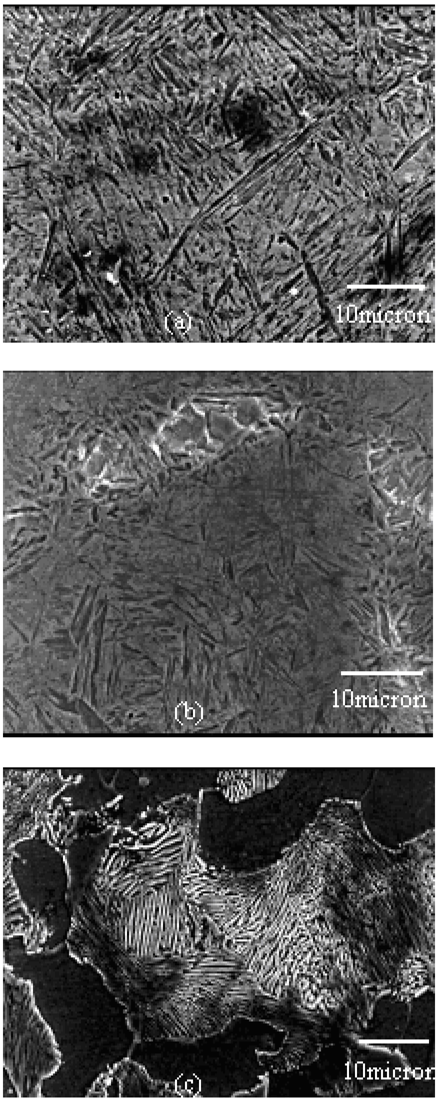

Figure 5. SEM images of RLP surface hardened section (a) near the top surface, (b) middle of the hardened region, (c) near the boundary of hardened and base material

RLP Hardening of Thin Sheet

In thin specimens where the resulting thermal diffusion length for CW laser irradiation is comparable to the thickness of specimen, cooling by self-quenching may not be fast enough for realising phase transformation up to the desired depth. It has been described above that the RLP irradiation tends to increase the depth of hardness and the increase depends on the pulse on-time, off-time and repetition frequency. In order to study the effect of RLP irradiation on thin specimen, surface hardening was performed on 1.5 mm and 5mm thick specimens at 200Hz, 500Hz, and 1000Hz frequencies. Laser power, scan speed and duty cycle were 1400W, 600 mm/min and 30% respectively. Fig. 6 shows the microhardness along the depth at these frequencies. The maximum hardened depth was realised at 1000Hz and 200Hz repetition frequency in 1.5 mm and 5mm thick specimens respectively. For a given scan speed and duty cycle the higher repetition frequency could cause smaller thermal diffusion length than the lower repetition frequency and this could be the reason for the observed different optimum frequencies for two different thicknesses.

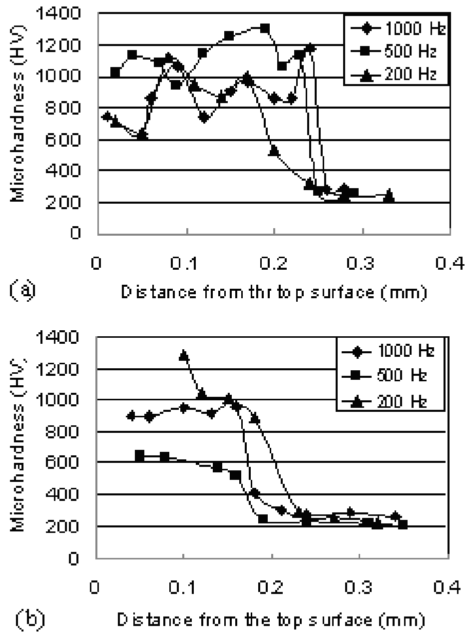

Figure 6. Microhardness along the depth at various modulation frequencies in specimens of thickness (a) 1.5 mm, (b) 5mm

In conclusion, analytical expressions for the variation of temperature during heating and cooling cycles in a semi-infinite workpiece irradiated with repetitive laser pulses have been derived. In case of RLP irradiation the average heating and cooling rates were found to be lower and the soaking time above the phase transformation temperature longer than those for CW laser irradiation. More homogeneous martensite microstructure and deeper hardness depth were realised in AISI 1055 steel by irradiation with RLPs than with CW laser. The optimum repetition frequency of RLP irradiation for maximum depth of hardness depended on the thickness of specimen and this was found to be higher for the thinner specimen. In thin specimen where the heat conduction along the depth is restricted, surface hardening with RLPs at relatively higher frequency could provide larger depth of hardness.

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