

Laser transformation hardening on rod-shaped carbon steel by Gaussian beam

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Abstract: Laser transformation hardening(LTH) is one of the laser surface modification processes. The surface hardening of rod-shaped carbon steel (SM45C) was performed by lathe-based laser composite processor with Gaussian-beam optical head. The LTH characteristics by dominant processes, longitudinal and depth directional hardness distributions and behaviors of phase transformation in hardened zones were examined. Especially, two concepts of circumferential speed and theoretical overlap rate were applied. When laser power increased or circumferential speed decreased, the surface hardening depth gradually increases due to the increased heat input. Moreover, the longitudinal hardness distribution particularly shows periodicity of repetitive increase and decrease, which results from tempering effect by overlap. Finally, the feasibility of laser transformation hardening is verified by using the beam with Gaussian intensity distribution.

Key words: surface modification; laser transformation hardening; Gaussian-beam optical head; circumferential speed; tempering

1 Introduction

The results of laser transformation hardening(LTH) process are affected by properties of thermal conductivity, power density distribution of laser thermal source, and shapes and mass of materials[1–4]. Generally, conventional research on LTH process has been carried out limitedly on plain specimen by using the beam with uniform power distribution and particular shapes like rectangular[5–9]. This study focuses on the surface hardening of a rod-shaped specimen and uses a Nd:YAG laser, which has relatively higher metallic absorptivity than CO₂ laser, as thermal source. The objectives are to examine the LTH characteristics by dominant process parameters, longitudinal and depth-directional hardness distribution and behaviors of phase transformation in hardened zones, and finally to investigate the feasibility of LTH process by using the circular Gaussian beam.

2 Experimental

The medium carbon steel SM45C was used as a

specimen, and its carbon content was 0.45% (mass fraction). Experimental setup was composed of a 4 kW-Class CW Nd:YAG laser, a 6-axis control robot and a small size lathe. A scheme of the experimental setup is illustrated in Fig.1. A beam moved on the specimen rotated by the lathe, and at the same time the shield gas was sprayed onto the surface processed at a specific angle and distance from a beam-proceeding direction. In this experiment, the optical head with Gaussian circular beam was applied, and the laser power, beam traveling speed and rotating speed (r/min) were proposed as dominant process parameters. Additionally, as the process used a lathe as a rotating device, the concepts of circumferential speed and theoretical overlap rate were applied to set parameters and these can be expressed in Eqs.(1) and (2), respectively:

$$v_{\text{circ}}/(\text{mm} \cdot \text{min}^{-1}) = N \sqrt{(3.14 D_r)^2 + \left(\frac{l_b}{N}\right)^2} \quad (1)$$

$$R_t/\% = \frac{D_b - \frac{l_b}{N}}{D_b} \times 100\% \quad (2)$$

where v_{circ} is the circumferential speed, R_t is the

theoretical overlap rate, D_r is the rod diameter, D_b is the beam diameter, N is the rotating speed, and l_b is the beam traveling speed.

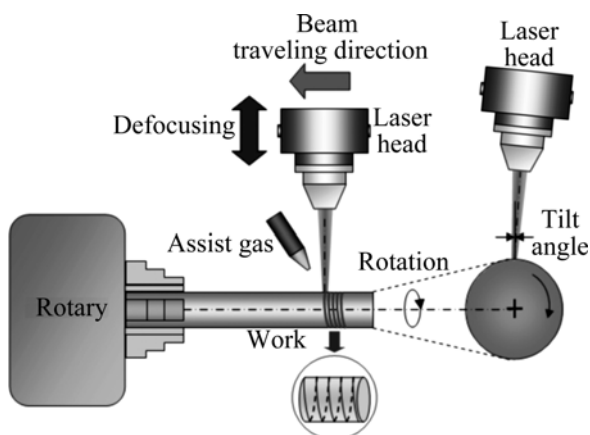


Fig.1 Schematic of experimental setup

3 Results and discussion

3.1 Effects of parameters on heat treatment

The heat input irradiated on the material is affected by beam diameter(D_b), laser power(P_L), rotating speed (N) and beam traveling speed(v_b). Figs.2, 3 and 4 show the surface and cross-sectional images of hardened zone by changing each process parameter. As laser power increases and circumferential speed decreases, the heat input increases; thus, the surface hardening depth gradually increases.

However, for the three process parameters, little change in the hardening depth was found especially by changing beam traveling speed, because the processing speed with the change of beam traveling speed is almost consistent, which also makes the heat input almost constant (see Fig.3). When the output was 2.0 kW or

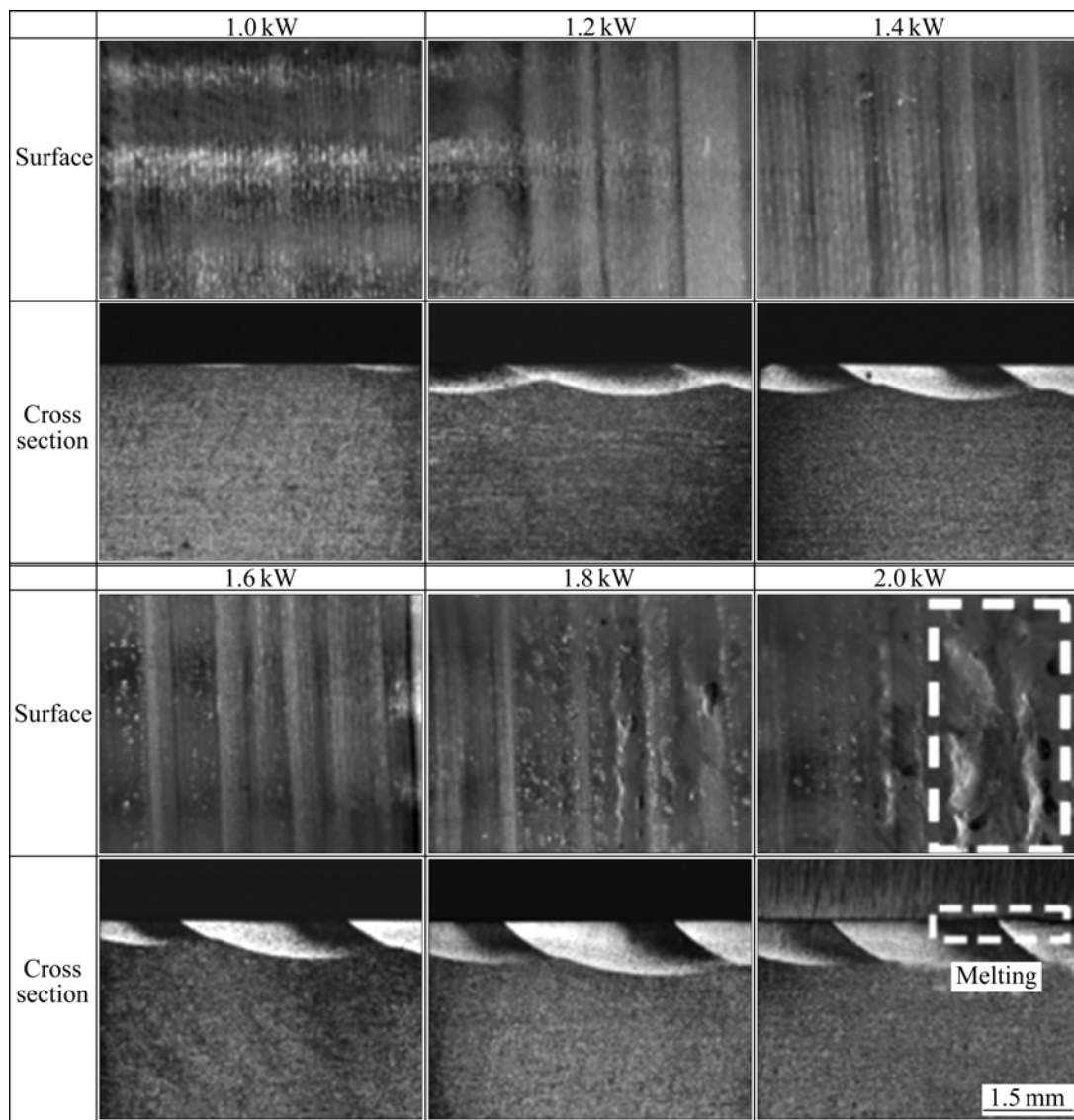


Fig.2 Surface and cross sectional images of hardened zone with different laser power ($D_b=5.0$ mm; $N=20$ r/min; $v_b=54$ mm/min; $G_s(\text{Ar})=20$ L/min, $v_{\text{circ}}=1.5$ m/min; $R_t=46.0\%$)

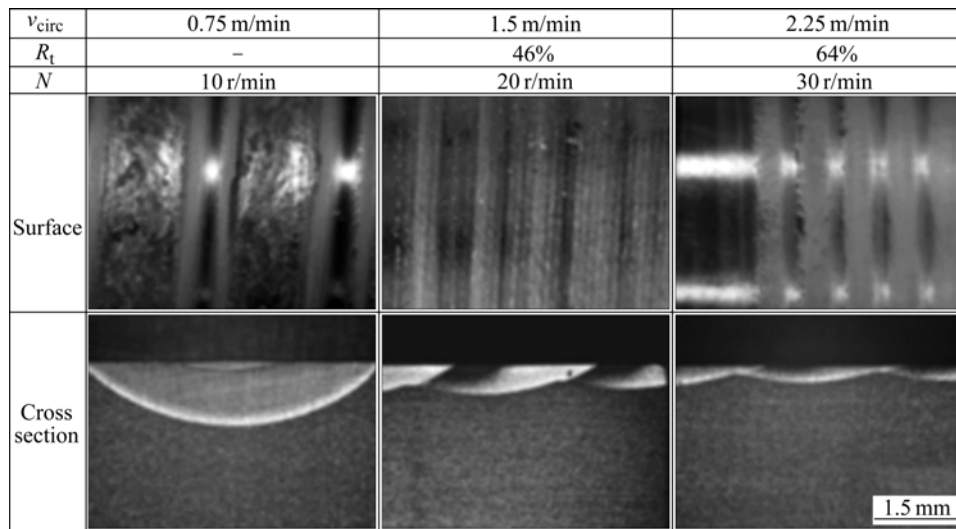


Fig.3 Surface and cross sectional images of hardened zone with different rotating speed ($D_b=50$ mm; $P_L=1.4$ kW; $v_b=54$ mm/min; $G_s=20$ L/min)

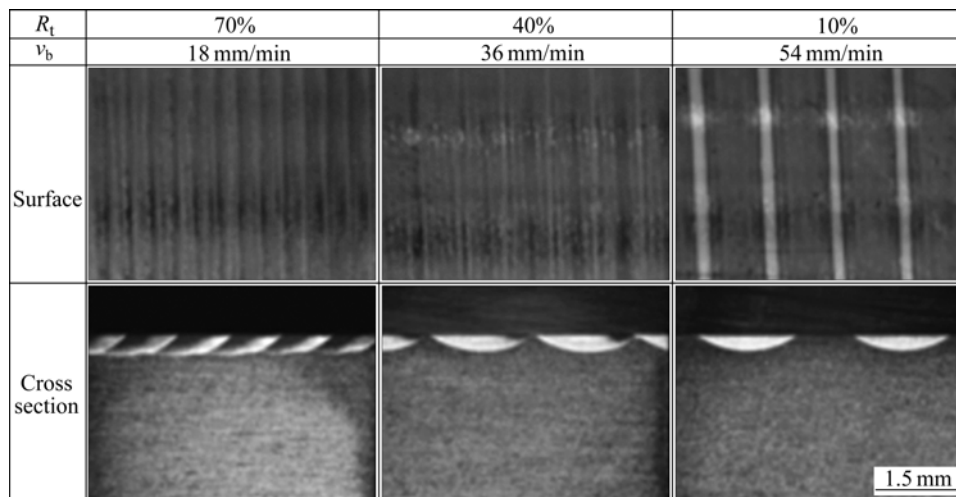


Fig.4 Surface and cross sectional images of hardened zone with different beam traveling speeds ($D_b=2.8$ mm; $P_L=0.5$ kW; $N=20$ r/min; $G_s=20$ L/min)

higher (see Fig.2) and the rotating speed was 10 r/min or lower (see Fig.3), surface melting caused by overheating is observed. Especially, the rotating speed and beam traveling speed have correlations with overlap rate, which means that as the rotating speed increases and the beam traveling speed decreases, the overlap rate increases.

Moreover, when a rod was treated with heat, unlike a case when a specimen was processed on work table, it is rotated while fixed on a lathe and irradiated with laser, and due to this processing characteristic, it is more likely to accumulate heat inside the specimen. Fig.5 shows that the hardening depth, width and overlap length gradually increase as the number of hardening tracks increases.

3.2 Hardness distribution in hardened zone

The longitudinal and depth-directional hardness

distributions of the hardened zone were measured at intervals of 300 and 150 μm , respectively, by using micro beaker hardness tester (see Fig.6(a)). As shown in Fig.6(b), the longitudinal hardness distribution shows the periodicity that the hardness repeatedly increases and decreases, which results from tempering by overlapping. Especially, the depth-directional hardness distribution was measured at two points. Those are the highest and lowest points of the longitudinal hardness distribution. The depth-directional hardness at the highest point shows a typical tendency that it gradually decreases, as the depth becomes deeper. On the contrary, the hardness at the lowest point slightly increases and then decreases again. This phenomenon at the lowest point is caused by different distances from the overlap interface, which varies by the depth. In other words, this phenomenon can

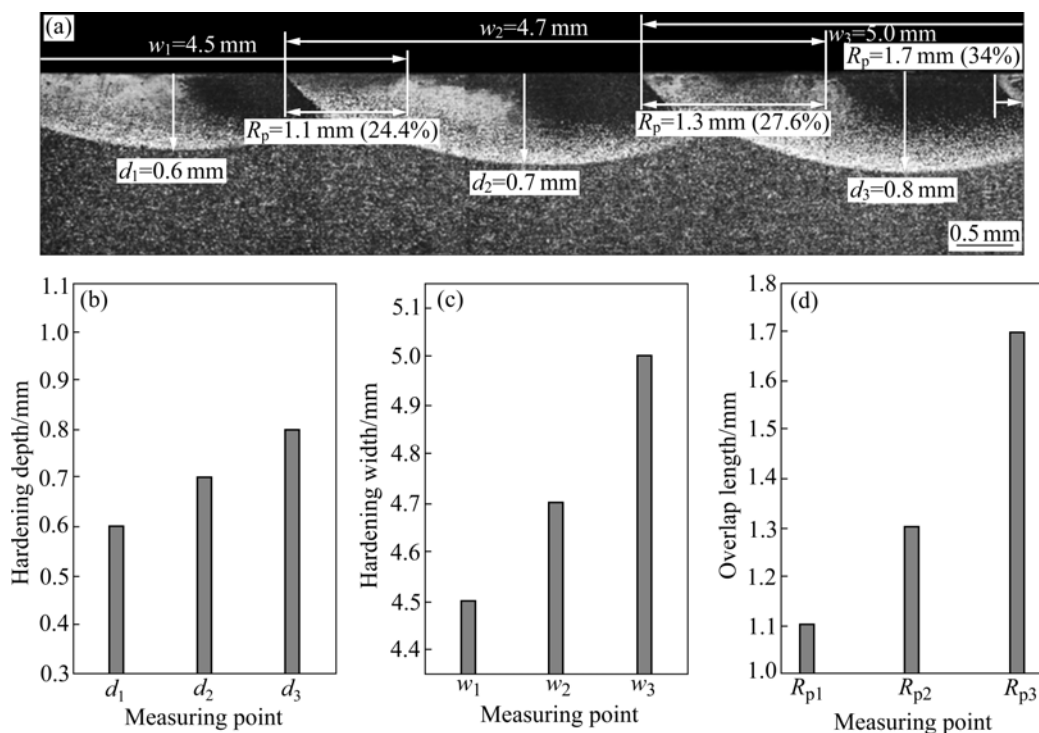


Fig.5 Effect of heat deposition on hardening depth, width and overlap length: (a) Cross section image; (b–d) Measured values of each hardened track

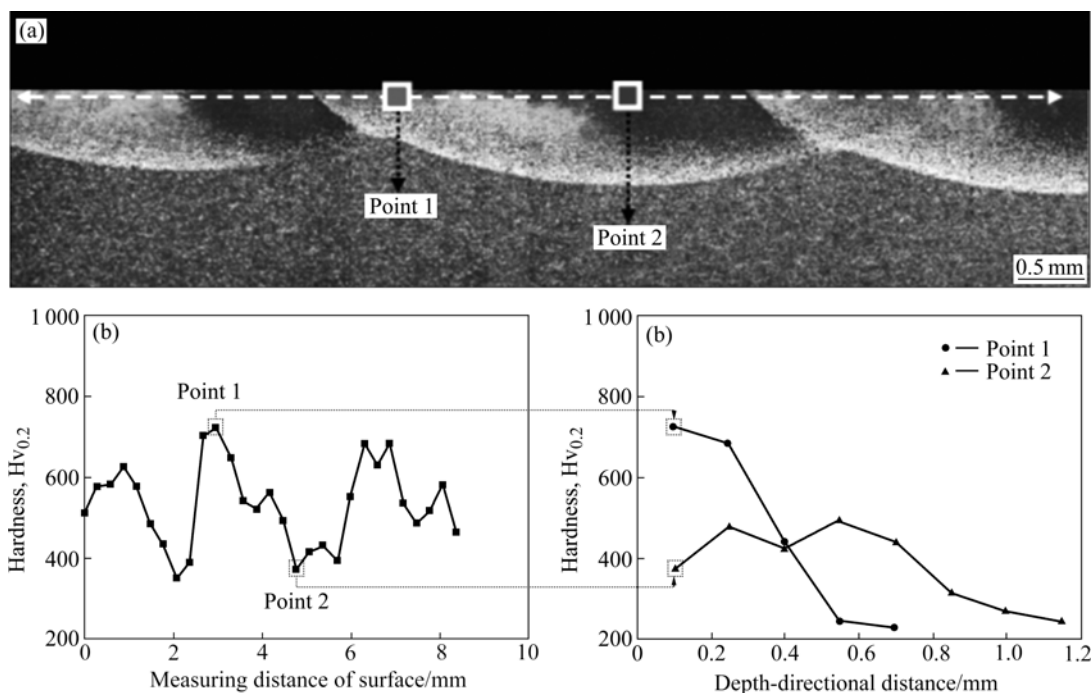


Fig.6 Hardness distribution of hardened zone: (a) Cross sectional image; (b) Longitudinal hardness distribution; (c) Depth-directional hardness distribution

be explained by the fact that as the distance from the overlap interface increases in depth, the back tempering effect diminishes, slightly increasing the hardness.

3.3 Characteristics of phase transformation

The phase transformation depends on the

temperature gradient and varies with the depth and distance from the overlap interface, and this is caused by the difference in thermal cycle. The images of regional microstructure in the hardened zone are shown in Fig.7. The matrix is SM45C, a hypoeutectoid steel with 0.45% carbon content, and its base structure is composed of

pearlite and ferrite in the approximate ratio of 6:4 as shown in Fig.7④. In the vicinity of the surface, most of the matrix is transformed into martensite phase (Fig.7①). As the depth increases, the rate of remaining austenite in the martensite phase increases (Fig.7②), and this contributes a gradual degradation of the hardness in depth. The structure mixed with austenite and ferrite is observed in the interface between the hardened zone and the matrix (Fig.7③)[9–11]. The martensite phase in the region of Fig.7⑤ is transformed into troostite or sorbite (fine pearlite) phase by the diffusion of supersaturated carbon within the martensite structure (BCT: Body Centered Tetragonal), which results from the tempering effect. As shown in Fig.7⑥, a tempering zone and an adjacent hardened zone are separated by the overlap interface. It is expected that the structure of this region would be more complex due to relatively slow thermal cycle.

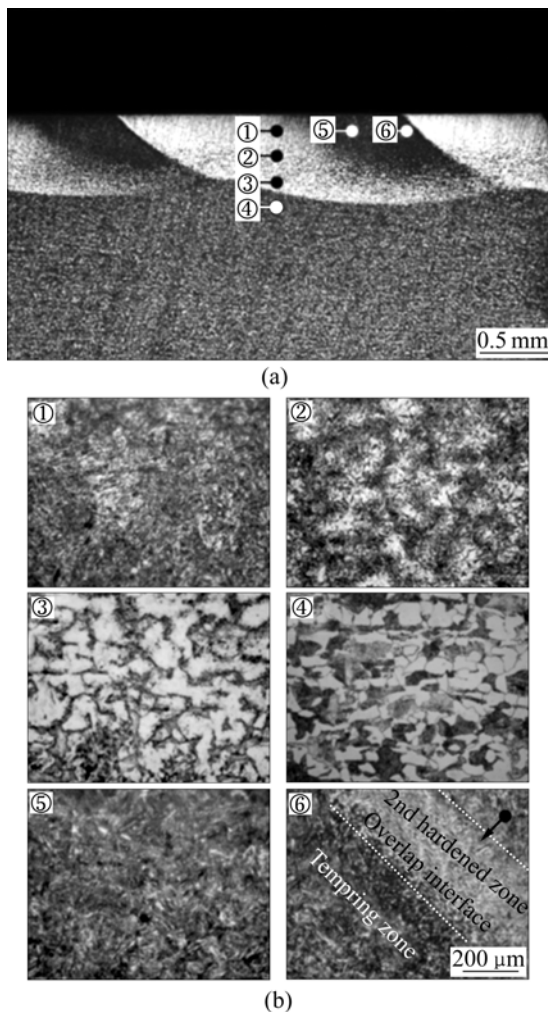


Fig.7 Regional microstructures in hardened zone: ① Hardened zone(upper); ② Hardened zone(lower); ③ Interface (matrix/hardened zone); ④ Matrix; ⑤ Tempering zone; ⑥ Overlap interface

4 Conclusions

This paper discussed several issues including LTH mechanism, hardening characteristics by dominant process parameters, and the hardness distribution and phase transformation in the hardened zone. Hardening characteristics such as depth and width are related to heat input that is applied to the surface of specimen. The heat input depends on laser power, rotating speed of specimen and beam traveling speed. The hardness distribution was measured in longitudinal and depth directions on the cross section of the hardened zone. The longitudinal distribution indicates periodicity that the hardness repeatedly rises and falls, which results from the back tempering effect by overlap. The depth-directional hardness distribution expresses different tendencies at the highest and lowest points of the longitudinal hardness distribution. Several phases on the hardened zone are observed through an optical microscope, and this is attributed to the difference in the thermal cycle caused by temperature gradient. Finally, the feasibility of laser transformation hardening is verified by using the beam with Gaussian intensity distribution.

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