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Effect of specimen thickness on heat treatability in laser transformation hardening

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ABSTRACT

Laser transformation hardening is a versatile technique for enhancing surface hardness, but it has been mostly used for hardening of thick plates in order to secure enough self-quenching effect. Recently, there have been increasing needs for heat treating steel sheets, but the understanding of heat treatability for metal sheets is limited. In this study, we have investigated the effect of specimen thickness on hardening performance in the laser heat treatment of carbon steel using the process map approach recently proposed by Ki and So (2012) [1]. Using a one-dimensional heat conduction model, we have studied how the process map evolves as the specimen thickness decreases. For validation purposes, we have systematically conducted laser heat treatment on AISI 1020 steel specimens using a 3 kW diode laser and constructed surface hardness maps. The experimental results are in good agreement with the theoretical predictions.

1. Introduction

Laser transformation hardening (or laser heat treatment) [2–5] has found a wide variety of applications in various industries because of its unique capability of increasing surface hardness *locally* only where higher hardness is required. Because this technique relies on materials' self-quenching characteristic, it has been employed primarily for thick plates to obtain an enough self-quenching effect. Recently, however, there has been an increasing demand for a method of *locally* hardening not-so-thick plates, including steel sheets, where the cooling capability is questionable. Although the laser heat treatment technology is relatively well established, a laser-based sheet metal hardening technology is yet to be studied. The authors believe, however, that a laser beam has the most potential to achieve the goal because it is a highest-precision intense optical energy available that can be delivered to any location in a very short time.

It is for this reason that we have studied how the laser heat treatment process changes as the thickness of the specimen varies. In order to effectively investigate this problem, in this study the process map approach that was recently proposed by authors [1] has been employed, where carbon diffusion and cooling characteristics are calculated for a wide range of two most important process parameters, i.e., laser intensity and interaction time, and are shown inside the *heat treatable region* that is defined in terms of A_3 and melting temperatures of the given steel. The advantage of this approach is that given the steel type and plate thickness an overall perspective of the laser heat treatment process can be obtained.

In this study, we have studied the effect of specimen thickness on hardening performance in the laser heat treatment of carbon steels by first obtaining the one-dimensional analytical solution for the laser heat treatment process with a variable specimen thickness. We have investigated how the *heat treatable region*, *effective carbon diffusion time* and *effective cooling time* evolve as the thickness of the specimen decreases from 10 cm to 1 mm. This study shows that the heat treatable region moves to the lower laser power side and its area decreases. Also, the amount of carbon diffusion in the austenite phase, which we describe by using the effective carbon diffusion time, increases in such a way that at 1 mm thickness carbon diffusion is large enough for the entire process region that we consider in this study. On the other hand, the cooling performance, which is described by the effective cooling time, decreases drastically so that it becomes the critical factor in the laser heat treatment of carbon steels. To validate the theoretical work, the authors have systematically conducted experiments on AISI 1020 specimens with four different thicknesses (2 cm, 1 cm, 5 mm, and 1.3 mm) using a 3 kW diode laser and the obtained results are in agreement with the theoretical findings.

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2. Mathematical model

Adopting the method proposed in Ref. [1], we will first come up with a laser heat treatment map for sheet carbon steels based on a one-dimensional heat conduction model. In Ref. [1], an analytical solution has been obtained by assuming the specimen is semi-infinite and neglecting heat losses due to convection and radiation heat transfer because in most cases the specimen is much thicker than the heat penetration depth and the laser intensity is much higher than the heat loss rate. In the laser heat treatment of sheet metals, however, the specimen cannot be assumed semi-infinite because the heat penetration depth could be much larger than the specimen thickness. If the specimen is very thin, heat flow is mainly parallel to the surface and the one-dimensional model may be an over-simplification. However, constructing a process map using a three-dimensional model for a wide range of process parameters is computationally too costly, so we will stick to the one-dimensional model approach and will validate our approach using experimental results.

In this study, to account for the thickness effect, we have modeled this problem as a one-dimensional heat conduction problem in the plate thickness direction (thickness L). Assuming that a rectangular beam with a uniform intensity distribution is the heat source, a constant heat flux boundary condition is used at the top boundary, which turns off after the interaction time (t_i), and the bottom boundary is assumed to be insulated. If the initial temperature is T_0, the governing equation and initial/boundary conditions are written mathematically as follows:

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

$$T(z, t = 0) = T_0 \quad (2)$$

$$-k \left.\frac{\partial T}{\partial z}\right|_{z=0} = I_0[H(t) - H(t - t_i)] \quad (3)$$

$$\left.\frac{\partial T}{\partial z}\right|_{z=L} = 0 \quad (4)$$

Here, T, t, z, α, k, I_0, and $H(t)$ are temperature, time, spatial variable in the thickness direction, thermal diffusivity, thermal conductivity, laser intensity, and a unit step function (or Heaviside function) of time, respectively. We have solved Eqs. (1)–(4) analytically using the separation-of-variables method and obtained the following solution:

$$T(z,t) = -\frac{I_0}{k}(H(t) - H(t - t_i))\left(z - \frac{z^2}{2L}\right) + \Phi_0(t) + \sum_{n=1}^{\infty}\Phi_n(t) \times \cos\left(\frac{n\pi z}{L}\right) \quad (5)$$

where

$$\Phi_0(t) = \frac{\alpha I_0}{kL}[tH(t) - (t - t_i)H(t - t_i)] + \frac{LI_0}{3k}[H(t) - H(t - t_i)] \quad (6)$$

$$\Phi_n(t) = -\frac{2LI_0}{kn^2\pi^2}\exp\left(-\frac{\alpha n^2\pi^2 t}{L^2}\right) + \frac{2LI_0}{kn^2\pi^2}H(t - t_i)\exp\left(-\frac{\alpha n^2\pi^2(t - t_i)}{L^2}\right) \quad (7)$$

Although the model is one-dimensional and the energy loss due to convection and radiation are neglected, this analytical solution approach is very useful because it offers all kinds of information on the laser heat treatment process with the plate thickness as a variable. In this study, the first 500 terms are used to terminate the infinite sum in Eq. (5). Note that once the plate thickness (L), interaction time (t_i) and laser intensity (I_0) are specified, the temperature profile at any time and spatial point can be calculated if material properties are available. Table 1 presents the material properties for AISI 1020 used for this study. In this table, A_1, A_3, and nose temperatures are obtained from the Fe–C equilibrium phase diagram in Ref. [6].

Table 1
Material property values used for AISI 1020 (from [6,7]).

Thermal conductivity	50.7 W/m K
Thermal diffusivity	1.32555×10^{-5} m^2/s
Melting temperature	1470 °C
A_1 temperature	727 °C
A_3 temperature	793 °C
Nose temperature	540 °C

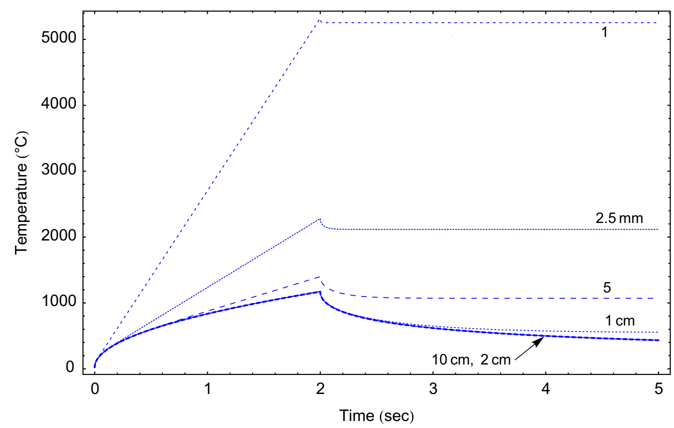

Fig. 1. Surface temperature histories for several different plates thicknesses (I_0 = 1000 W/cm^2, t_i = 2 s).

Fig. 1 shows the surface temperature histories corresponding to six specimen thicknesses (10 cm, 2 cm, 1 cm, 5 mm, 2.5 mm, 1 mm) when the laser intensity is 1000 W/cm^2 and the interaction time is 2 s. All the graphs are plotted using the analytical solution in Eq. (5). When the plate thicknesses are 10 cm and 2 cm, two graphs virtually coincide. However, as the plate thickness decreases, overall the maximum temperature increases and the cooling rate decreases. Note that in this study cooling mechanisms such as radiation and convection heat transfers are neglected, so self-quenching is the only mechanism to cool down the heated specimen. Therefore, if the specimen is not thick enough, the heat supplied by the laser beam cannot be distributed evenly in the thickness direction and temperature will be quickly saturated. This tendency will be aggravated as the plate thickness is reduced further, but we believe that model is still very useful and effective in understanding the effects of plate thickness on the overall heat treatment characteristic for a very wide range of process parameters.

3. Change in heat treatable region

Fig. 2 shows how the heat treatable region changes on the intensity–interaction time diagram, or the $I - t_i$ diagram, as the thickness of the plate decreases from 10 cm to 1 mm. The heat treatable region was defined in [1] using the idea that heat treatment is only possible when the maximum surface temperature during the process lies between the melting temperature and A_3 temperature. In Fig. 2(a)–(f), the upper and lower bounds for the shaded regions are defined by melting and A_3 temperatures, respectively. In this study, interactions time from 0 s to 6 s and absorbed laser intensity from 0 W/cm^2 to 3000 W/cm^2 are considered to construct process maps, which we believe covers most of practically used laser heat treatment parameters. Note that in order to eliminate the complicated energy absorption phenomena from the process map, the intensity values here are actual intensity values absorbed by the specimen.

As seen clearly in Fig. 2, there is virtually no change in the heat treatable region as the thickness decreases from 10 cm to 2 cm.