Technical Notes

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Computational Simulation of Laser Heat Processing of Materials

Vijaya Shankar* and Daniel Gnanamuthu†
Rockwell International Science Center
Thousand Oaks, California

Introduction

LASER surface hardening of materials (especially iron base alloys) through solid-state phase transformations is of considerable manufacturing interest in enhancing their resistance to surface wear and thereby prolonging the service life of components that usually undergo severe abrasion and fatigue. Recent improvements in the development of high-power, continuous-wave CO_2 laser beams that provide uniform power intensities over a large cross-sectional area make the laser surface heat treatment a viable and an economical process.

Laser heat treating is accomplished by sweeping a workpiece at controlled speeds under a laser beam, as shown in Fig. 1. The painted surface, after absorbing the beam during laser beam irradiation, is heated to elevated temperatures localized only to those exposed surface areas. Thus, steep temperature gradients are set up extending from the surface into the substrate. After heat conduction from the work surface into the substrate, a finite volume of the substrate is heated above the austenitizing temperature range for small time intervals and subsequently cooled at rapid enough rates to yield martensite, forming a self-quenched, heat-treated stripe along the surface. Dimensions of the heat-treated stripe, i.e., case width and case depth, are controlled by absorbed laser beam power density, beam size, and travel speed.

To study the effectiveness and feasibility of laser surface hardening of engineering materials, a systematic experimental-*cum*-computational simulation of the heat treatment process has been conducted. Experiments were performed with AISI 4140 steel plates as workpieces and a continuous-wave CO_2 laser beam with an elliptical cross-section as a heat source.

A computational model simulating the laser heat treatment process has been developed using the three-dimensional, time-dependent heat equation subject to appropriate boundary conditions. The solution technique is based on Newton iteration applied to a triple approximate factorized form of the equation.[1] The method is implicit and time accurate. For simulation of finite-length workpieces with a finite laser beam dwell time, maintenance of time accuracy in the numerical formulation is of paramount importance.

The validation of the results from the computational simulation with experimental data suffers from the following uncertainties: 1) an estimate of the precise cross-sectional shape of the laser beam before contact with the workpiece surface; 2) variations in power intensity over the beam cross-sectional area; 3) laser absorptivity factor; and 4) precise estimate of the transformation temperature and the required critical heating and cooling rates for structural transformation. In spite of these uncertainties, the results from the computational simulation of the present study compared well with a wide range of experimental data. The paper presents results for a finite length AISI 4140 steel plate having a rectangular cross section.

An extension of this work to include surface melting is presented in Shankar and Gnanamuthu,[2] which solves the incompressible Naiver-Stokes equations to account for convection induced by surface tension.

Numerical Formulation

In Fig. 1, the coordinate system (t',x',y',z') is fixed to the workpiece that is undergoing a motion. The energy balance equation in this coordinate system can be written as

$$q_{t'}+E_{x'}+F_{y'}+G_{z'}=0 \tag{1}$$

where

$$q=\rho H,\quad E=\kappa\frac{\partial T}{\partial x'},\quad F=\kappa\frac{\partial T}{\partial y'},\quad G=\kappa\frac{\partial T}{\partial z'}$$

and ρ is the density of the workpiece, κ is the thermal conductivity, H is the enthalpy given by C_pT where C_p is the specific heat of the material and T is the temperature. For treatment of arbitrary shaped workpieces undergoing complex motion, a coordinate transformation of the form

$$\tau=t'$$
$$\xi=\xi(x',y',z',t');\quad \eta=\eta(x',y',z',t');\quad \zeta=\zeta(x',y',z',t') \tag{2}$$

is necessary. After the transformation, Eq. (1) can be written in the form

$$\bar{q}_\tau+\bar{E}_\xi+\bar{F}_\eta+\bar{G}_\zeta=0 \tag{3}$$

where $\bar{q}$, $\bar{E}$, $\bar{F}$, and $\bar{G}$ are expressible in terms of q, E, F, G, and transformation metrics.[1]

Assuming no surface melting, Eq. (3) can be written as

$$R(T)=0 \tag{4}$$

where T is the temperature distribution in the workpiece at a given time level n, and R is the discretized functional representation of Eq. (3). The solution procedure is as follows: Say, we know the temperature distribution T^n at the nth time level, and we want to compute T^{n+1} at the next time level while the laser beam or the workpiece is in motion. A Newton iteration can be initiated to solve Eq. (4) by linearizing the equation about a known neighborhood state T^*

$$R(T^*)+\left(\frac{\partial R}{\partial T}\right)^*(T-T^*)=0 \tag{5}$$

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*Manager, Computational Fluid Dynamics. Associate Fellow AIAA.

†Member Technical Staff, Metals Processing Department.

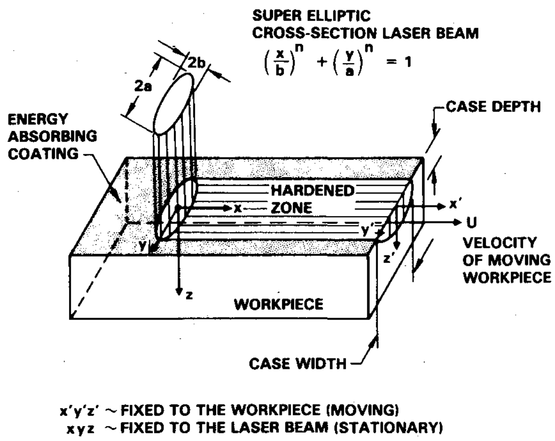

Fig. 1 Laser heat processing of a workpiece.

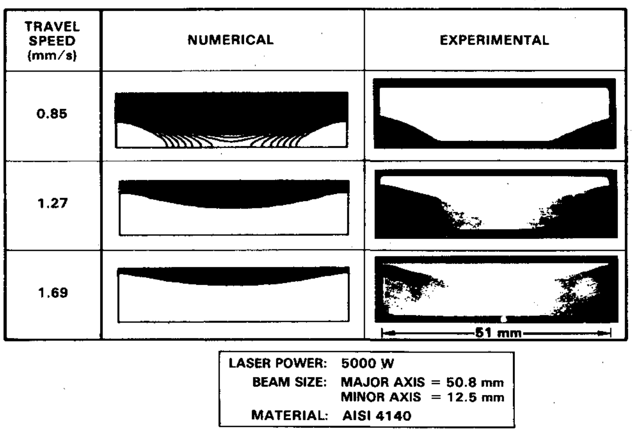

Fig. 2 Cross-sectional views of hardened zone.

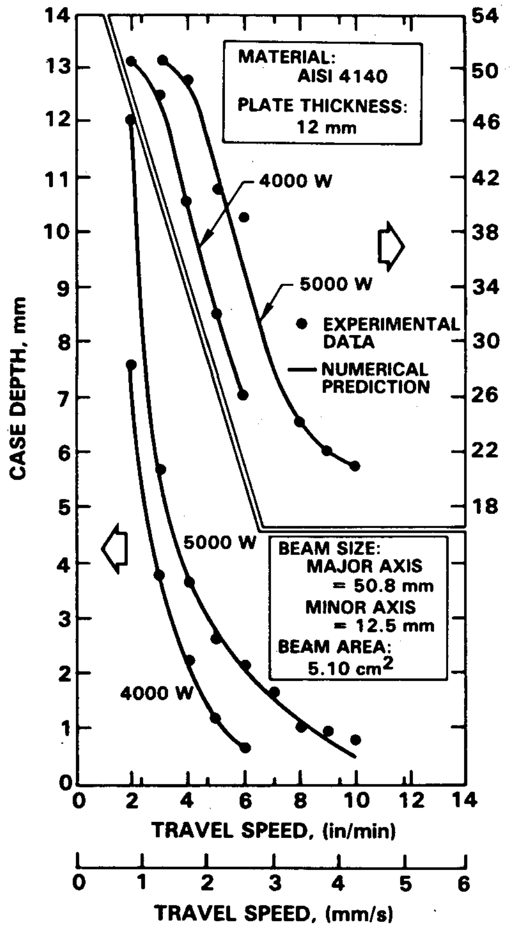

Fig. 3 Case depth and case width as a function of travel speed for various beam powers.

To start the Newton iteration, Eq. (5), initially T^* can be assumed to be T^n.

For a finite length workpiece, computational solution to the heat flow model, Eq. (3), requires boundary conditions along the entire surface of the workpiece. At the top surface of the workpiece, where it is subjected to laser heating, at boundary points directly inside the laser beam cross section, the following condition is applied

$$-\kappa\frac{\partial T}{\partial z}=\frac{Q_0\eta}{A} \tag{6}$$

where Q_0 is the beam power, A is the beam cross-sectional area, and η is the local absorptivity factor taken to be 0.8 for the calculations presented here.

At all boundary points outside of the laser beam, a mixed-type boundary condition equating heat flux due to conduction to surface heat loss due to cooling is applied.[1]

Results

To validate the computational model, a rectangular finite length workpiece (AISI 4140 steel) having dimensions 100 mm long (x), 50 mm wide (y), and 12 mm thick (z) is considered. The workpiece is modeled by a $61\times21\times21$ grid with clustering near the heat source.

A typical calculation for a finite-length workpiece is done in 50 time steps. This means, for a 100-mm-long workpiece undergoing a travel speed of 2 mm/s, the time step used in solving the heat flow equation, Eq. (3), is 1 s. The numerical method being implicit in nature, the solution is stable even for larger Δt's. As Δt is increased, more internal Newton iterations will be required to converge the temperature at each time level for accuracy.

The critical temperature for solid-state phase transformation for AISI 4140 steel is around 723°C. Figure 2 shows the cross-sectional views of the hardened zone profile (the dark zone in the numerical results indicates temperature contours >723°C) for a given laser power (5000 W) and beam size ($a=25.4$ mm, $b=6.25$ mm) at various travel speeds of the workpiece. The hardened zone profiles agree well with the experimental simulation.

Figure 3 shows the case depth and case width of the hardened zone as a function of travel speed of the workpiece and for two different laser beam powers.

Acknowledgments

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References

[1]Shankar, V. and Gnanamuthu, D., "Computational Simulation of Laser Heat Processing of Materials," AIAA Paper 85-0390, Jan. 1985.

[2]Shankar, V. and Gnanamuthu, D., "Computational Simulation of Heat Transfer in Laser Melted Material Flow," AIAA Paper 86-0461, Jan. 1986.