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# Thermoviscoelastic dynamic response for a rectangular steel plate under laser processing

Hong-Liang Dai [a,b,c,*], Zhen-Qiu Zheng [a,b,c], Wei-Li Xu [b], Hai-Bo Liu [a,c], Ai-Hui Luo [b]

[a] State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China
[b] State Key Laboratory of Development and Application Technology of Automotive Steels (Baosteel Group), Shanghai Baoshan 201900, China
[c] Key Laboratory of Advanced Design and Simulation Technology for Special Equipments Ministry of Education, Hunan University, Changsha 410082, China

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ABSTRACT

The thermoviscoelastic dynamic response of a simply supported rectangular steel plate under laser processing is studied in this paper. Three-dimensional transient temperature field of the laser processing thermoviscoelastic rectangular steel plate is solved by the method of separation of variables. Meanwhile, based on von Karman nonlinear strain–displacement relationships and classical thin plate theory, a list of nonlinear dynamic equilibrium equations for a rectangular thermoviscoelastic steel plate are deduced. Then the entire problem is solved by utilizing the Newmark method and the iterative method. Finally, numerical results show that laser moving speed, laser power density and thickness-to-length ratio have a great influence on the thermoviscoelastic response of the rectangular DP980 steel plate.
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## 1. Introduction

In recent years, many new types of advanced high strength steels (AHSSs), including dual phase (DP) steels that exhibit excellent combination of high strength, good ability of resistance to deformation and fine weldability, are being produced by steel manufacturers, which contributes to reduction of the vehicular weight in response to such environmental issues as air pollution, fuel economy and high energy cost. Before practical application, the DP steels plates are often processed into various shapes and sizes of specimens with laser processing techniques due to their ability to generate a highly concentrated thermal energy.

Through the separation of variable method, Stephenson et al. [1] developed a transient, three-dimensional analytical model for predicting the cutting tool temperature. Using a disk heat source with a pseudo-Gaussian heat intensity distribution in a semi-infinite steel workpiece of finite width, Komanduri and Hou [2] obtained a general solution for the laser surface hardening process. Considering the phase change problem of steels, Yilbas et al. [3–5] investigated the surface temperature profile, the magnitude of recoil pressure and depth of resulting plastic region inside the substrate. Roberts et al. [6] used an innovative simulation technique known as element birth and death, modeled the three-dimensional temperature field in multiple layers in a powder bed. Winczek [7] presented a model of computation of temperature field in a half-infinite body caused by heat source with changeable direction of motion. Fang et al. [8] studied effect of laser power on the cladding temperature field and the heat affected zone. The eigenstrain modeling method developed and deformation fields were analyzed elastically using the simulated eigenstrain as initial strain by Hu and Grandhi [9]. Jiang and Dai [10] obtained the analytical solutions for three-dimensional steady and transient heat conduction problems of a double-layer plate with a local heat source.

In terms of the laser processing on DP steels problems, mechanical properties and temperature field of High strength DP980 steel have been studied [11,12]. Farabi et al. [13] gave an investigation to evaluate the microstructural change and mechanical properties of laser welded dissimilar DP600/DP980 steel joints. Sreenivasan et al. [14] investigated effect of laser welding on the formability of laser butt welded blanks of the DP980 steel in comparison with the base metal. Xia et al. [15] presented a comparative study of formability of diode laser welds in DP980 and HSLA steels. Ni et al. [16] analyzed strengthening behavior of laser hybrid welding for microalloyed steel. Hea et al. [17] fabricated a novel central hollow laser cladding technique to improve the high-temperature wear resistance of austenitic stainless steel. Cao et al. [18] adopted hybrid fiber laser-Arc welding of thick section HSLA steel. Amano and Rohatgi [19] gave the laser engineered net shaping process for SAE 4140 low alloy steel. Laser gas assisted melting of HSLA

* Corresponding author at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China.
*E-mail address:* hldai520@sina.com (H.-L. Dai).

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steel surface pre-prepared to contain 5% B4C particles in a 40 μm thick carbon film prior to laser treatment process was carried out by Yilbas et al. [20]. By the state-space method, Jiang and Dai [21] investigated the effect of laser processing on three-dimensional thermodynamic analysis for a HSLA rectangular steel plate.

Recently, many researchers investigated the viscoelastic behaviors on the plate structures. Based on the thin-plate theory and the two-dimensional viscoelastic differential constitutive relation, Wang and Wang [22] analyzed transverse vibration characteristics of a viscoelastic plate containing multiple all-over part-through cracks. According to the integral type constitutive relation of linear coupled thermoviscoelasticity, Zhang and Xing [23] studied the vibration analysis of linear coupled thermoviscoelastic thin plates. Based on Reddy's layerwise theory, Hu and Wang [24] investigated the free vibration and transverse stresses of viscoelastic laminated plates. Gales [25] investigated the time-harmonic vibrations for homogeneous and an isotropic thermo-viscoelastic mixtures. Using the analog equation method, Katsikadelis and Babouskos [26] investigated the post-buckling response of thin plates made of linear viscoelastic materials. Based on the variation principle of a uniqueness theorem, El-Karamany [27] established the two-temperature linear an isotropic and in homogeneous micropolar thermoviscoelastic solid. Based on the classical thin plate theory and the Mindlin plate theory, Kaloerov and Parshikova [28] proposed a method to solve a thermoviscoelastic problem for multiply connected anisotropic plates. Based on the thermoviscoelastic theory and the classic plate theory, thermoviscoelastic behavior of a circular plate made from HSLA steel material was investigated by Dai et al. [29]. Based on von Karman nonlinear strain–displacement relationships and classical thin plate theory, thermoviscoelastic dynamic response for a composite material thin narrow strip were analyzed by Dai et al. [30]; and then they [31] investigated the thermoviscoelastic response for a thin narrow composite strip with transverse matrix cracking which was solved by the finite difference method, the Newmark method, the Newton–Cotes method and the iterative method synthetically. However, as far as we know, the thermoviscoelastic dynamic behavior of a rectangular steel plate under laser processing has not been presented in the literature.

In this paper, the thermoviscoelastic dynamic response of a rectangular steel plate under laser processing is considered. Separation of variable is used to solve the three-dimensional transient temperature field of a rectangular plate under laser processing. Based on von Karman nonlinear strain–displacement relationships and classical thin plate theory, a list of nonlinear dynamic equilibrium equations for a thermoviscoelastic composite material are deduced. Then the entire problem is solved by utilizing the Newmark method and the iterative method.

## 2. Structural model and solution of temperature field for the rectangular steel plate

A rectangular steel plate with length $a$, width $b$ and thickness $h$, as shown in Fig. 1, is considered. The steel plate is simply supported on four edges; the tiny force of clamp device on steel plate can be simplified as a small uniform distribution force. And the laser processing equipment can be simplified as a laser beam source applied on top surface of plate. Meanwhile, the Cartesian coordinate system $oxyz$ is set on the middle surface ($z = 0$). As the laser progresses with a velocity $u_L$, the heat from the source penetrates further into the steel plate.

Based on two following assumptions

(1) Heat losses by radiation are negligible as compared to the intensity of the incident laser beam.

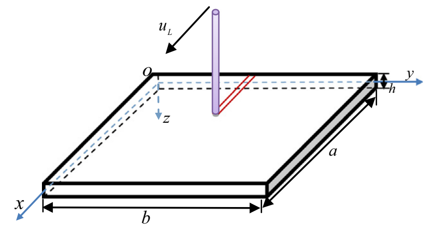


**Fig. 1.** Geometrical configuration of a thermoviscoelastic rectangular steel plate under laser processing.

(2) Thermal properties are considered constant and evaluated at an average temperature. With the above assumptions, the three-dimensional transient state heat conduction equation for the steel plate can be written as

$$c\rho\frac{\partial \Delta T}{\partial t} - k_1\frac{\partial \Delta T^2}{\partial x^2} - k_2\frac{\partial \Delta T^2}{\partial y^2} - k_3\frac{\partial \Delta T^2}{\partial z^2} = g(x,y,z,t) \tag{1}$$

where $\Delta T = T - T_0$ indicates the temperature variation relative to initial temperature, $c$ and $\rho$ represent the plate's specific heat and density, respectively, $k_i(i = 1,2,3)$ are the heat conduction coefficients along $x$, $y$ and $z$ directions, and $g(x,y,z,t)$ is the heat generation expressed as

$$g(x,y,z,t) = g'(x,y,t)\delta\left(z + \frac{h}{2}\right) \tag{2}$$

where $\delta(z + \frac{h}{2})$ is the generalized Dirac delta function.

The heat source term $g(x,y,z,t)$ is considered as a laser beam of temporal continuous wave (CW) and spatially modeled by assuming a spatially uniform plane heat source. The heat flux $g'(x,y,t)$ takes the forms of a rectangular constant energy density [32] as

$$g'(x,y,t) = \begin{cases} \frac{G_0}{4RS} & at\, z = -\frac{h}{2}, u_L t < x < u_L t + 2R, y_0 < y < y_0 + 2S \\ 0 & others \end{cases} \tag{3}$$

here, $G_0$ is the heat flow absorbed by the plate, $R$ and $S$ are the half size of laser beam along $x$ and $y$ directions, respectively, $y_0$ represents the initial position of laser beam along $y$ direction.

The temperature boundary conditions of steel plate can be expressed as

$$\begin{aligned} &T(0,y,z) = T(a,y,z) = T_0 \\ &T(x,0,z) = T(x,b,z) = T_0 \\ &T(x,y,\tfrac{h}{2}) = T_0 \end{aligned} \tag{4}$$

The top surface of steel plate is considered an insulated condition except on the heating zone powered by the laser.

The non-homogeneous heat conduction equation can be solved by assuming $\Delta T(x,y,z,t)$ a series of the eigenfunctions

$$\Delta T(x,y,z,t) = \sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\sum_{k=1}^{\infty}\Theta_{ijk}(t)X_i(x)Y_j(y)Z_k(z) \tag{5}$$

where the eigenfunctions satisfied the temperature boundary conditions have the form as

$$X_i(x) = \sin\frac{i\pi x}{a},\ Y_j(y) = \sin\frac{j\pi y}{b},\ Z_k(z) = \cos\frac{(2k+1)\pi(z + \frac{h}{2})}{2h} \tag{6}$$

The non-homogeneous term $g(x,y,z,t)$ can be expanded in a linear combination of the eigenfunctions

$$g(x,y,z,t) = \sum_{i=1}^{\infty}\sum_{j=1}^{\infty}\sum_{k=1}^{\infty}\phi_{ijk}(t)X_i(x)Y_j(y)Z_k(z) \tag{7}$$

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