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Numerical modeling and experimental validation of focused surface heating using near-infrared rays with an elliptical reflector

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ABSTRACT

Focused surface heating (or focused heating) using near-infrared (NIR) rays with an elliptical reflector has been widely used in industrial fields. Under ideal conditions, an elliptical reflector can gather NIR heat flux from an NIR heat source by reflection to a focus point. Under engineered conditions, however, NIR heat flux is distributed out of the focus point, being not negligible. Therefore, a thermal model that considers the distribution of heat flux is required to simulate focused NIR heating using an elliptical reflector. However, there has been little study on thermal models that consider the heat flux distribution for the analysis of focused NIR heating using an elliptical reflector. A numerical model is proposed for the simulation of focused heating and the physical meaning of the proposed model is discussed in this paper. Finite element analyses of transient heat transfer using the proposed model were conducted and compared with experimental results of heating dual phase (DP) 980 steel in several conditions. The result comparisons have validated the practical applicability of the proposed numerical model.

1. Introduction

Elliptical reflectors have been used in engineering fields, because of the characteristic to condense wave from a focus of an elliptical reflector onto a target [1]. In the medical field, condensed acoustic pulse by elliptical reflectors has been used to destroy kidney stone [2]. In the optical field, elliptical reflectors have been used to guide light [3,4]. In other industry areas where heating is required, focused surface heating (or focused heating) using a radiant heat source with an elliptical reflector has been widely used [5–8]. In the focused heating, radiant energy emitted from a focus of an elliptical reflector is condensed on a very narrow area by reflection [9]. A near-infrared (NIR) lamp is usually used as a radiant heat source, and well described other papers [10,11]. Recently, the local heating process that heats only plastic deformation areas by using an NIR lamp with an elliptical reflector was proposed to reduce springback in the V-bending process for advanced high-strength steels by Lee et al. [12]. In the aforementioned paper, the focused NIR heating substantially eliminated springback in the V-bending process of dual-phase (DP) 980 steel, reducing the heat-affected zone (HAZ). The NIR heating device, which consists of an NIR lamp and an elliptical heating reflector (together called as an elliptical heating device), used in the paper is described in Fig. 1.

Under ideal conditions, an elliptical reflector reflects all NIR energy emitted from an NIR lamp to the target focus point [13], as shown in Fig. 1. There are two main ideal conditions for an elliptical reflector to gather all the reflected NIR rays to a point. First, the NIR heat source is a point and located perfectly at a focus of an elliptical reflector. Second, all the NIR rays should pass through a specular reflection from the elliptical reflector. In engineered conditions, however, an NIR lamp takes a volume, and some NIR rays are emitted directly to target without any reflection. Additionally, diffuse reflection occurs slightly on the elliptical reflector. These conditions make the NIR heat flux be distributed out of the target point, and the heat flux distribution has a considerable effect on transient heat transfer in focused NIR heating. Sun et al. [14] measured a heat flux distribution generated by a radiant heat source with an elliptical reflector, and the measured heat flux distribution showed a form of normal distribution (or Gaussian distribution). However, numerical models that consider the distribution of NIR heat flux have not been properly studied. An attempt to predict a distribution of energy flux using a ray-tracking code did not provide an acceptable prediction [15].

In this work, a numerical model for the analysis of transient heat transfer in focused heating by an NIR lamp employing an elliptical reflector is proposed. The proposed model is based on

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Nomenclature

C_p specific heat capacity (J/kg · K)
dA small area of NIR heat flux incident (m^2)
f_g heat generation (W/m^3)
f_l focal length of elliptical reflector (m)
$f(x)$ normal distribution function for describing $\Phi_{reflected}(x)$ (m^{-1})
h convection coefficient ($W/m^2 \cdot K$)
I_0 irradiance of the lamp (W/m): defined as radiant power of the lamp per unit length
k_{ij} thermal conductivity (W/m · K)
m central point of heating (m)
N_a shape function
$\hat{n}_i$ unit normal vector to the i surface
$q_{direct}(x)$ heat flux incident on a surface of a heated object without any reflection (W/m^2)
$q_{reflected}(x)$ heat flux condensed on a surface of a heated object by an elliptical reflector (W/m^2)
T temperature of the heated object (K)
T_∞ ambient temperature (K)
$\Phi_{total}(x)$ absorbed total heat flux (W/m^2) (=Φ_q)
$\Phi_{direct}(x)$ direct radiation (W/m^2): absorbed NIR heat flux from $q_{direct}(x)$
$\Phi_{reflected}(x)$ reflected radiation (W/m^2): absorbed NIR heat flux from $q_{reflected}(x)$
$\Phi_{repeated}(x)$ repeated radiation (W/m^2): absorbed NIR heat flux from the heat flux that is reflected infinitely between a heated object and an elliptical reflector
w width in which $\Phi_{reflected}(x)$ is distributed (m)

Greek symbols
α half of open angle of entrance of elliptical reflector (°)
β half of corresponding sector angle of elliptical reflector blocked by the filament of lamp (°)
γ reflectivity of reflector
ε emissivity
μ absorptivity
ρ density (kg/m^3)
σ standard deviation of $f(x)$ (m)
σ_{sb} Stefan–Boltzmann constant (5.67×10^{-8} $W/m^2 \cdot K^4$)

the normal distribution function (or the Gaussian distribution function) for describing the heat flux distribution made by an elliptical reflector. Also the method of determining the standard deviation of the normal distribution is proposed and discussed. In simulation of focused ion beam, the normal distribution function has been often used for modeling of beam profile [16,17]. For validation of the proposed model, it was implemented in a finite element (FE) code, which was made using a Fortran program (Intel Parallel Studio XE). The code considers temperature-dependent thermal properties. Simulated results were compared to the experimental results of heating DP 980 sheet in several conditions. The results have validated the practical applicability of the proposed numerical model for focused NIR heating using an elliptical reflector.

2. Formulation of the numerical model

2.1. Transient heat transfer

The differential equation for transient heat transfer can be written as Eq. (1) [18,19]

$$\rho C_p \dot{T} = (k_{ij} T_{,j})_{,i} + f_g, \quad (1)$$

$$k_{ij}\frac{\partial T}{\partial \hat{n}_q} = \Phi_q \quad \text{on } \Gamma_q$$

(Boundary surface absorbing external heat flux),

$$-k_{ij}\frac{\partial T}{\partial \hat{n}_a} = h(T - T_\infty) + \sigma_{sb}\varepsilon(T^4 - T_\infty^4) \quad \text{on } \Gamma_a$$

(Boundary surface in contact with air),

where ρ is density, C_p is specific heat capacity, k_{ij} is thermal conductivity, T is temperature, f_g is heat generation. The term Φ_q means heat flux on Γ_q with $\partial\hat{n}_q$ which is the outward unit normal vector on Γ_q, and $\partial\hat{n}_a$ is the outward unit normal vector on Γ_a. Both $\partial T/\partial\hat{n}_q$ and $\partial T/\partial\hat{n}_a$ are the normal derivatives of temperature on respective boundary surfaces. h means convection coefficient, σ_{sb} is the Stefan–Boltzmann constant (5.67×10^{-8} $W/m^2 \cdot K^4$), T_∞ is ambient temperature, and ε is emissivity of material. Eq. (1) can be integrated by part, after being multiplied by test function (δT). It can be then rewritten in the weak form by using the divergence theorem. i.e.,

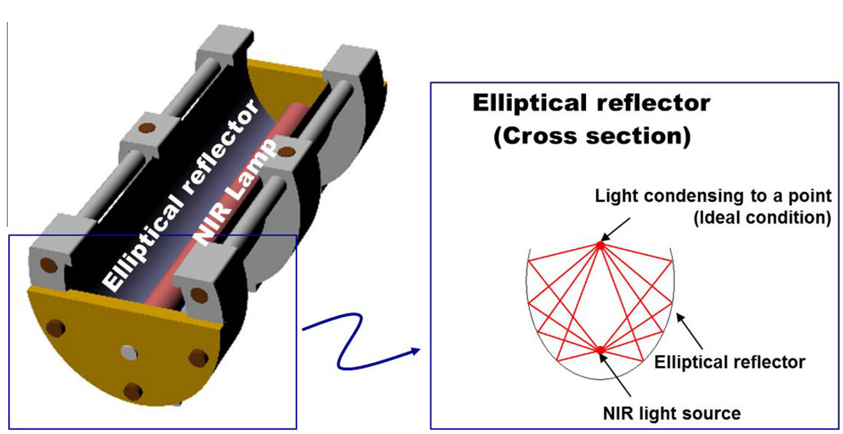

Fig. 1. Elliptical heating device.