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Research Paper

Temperature predictive model of the large pulsed electron beam (LPEB) irradiation on engineering alloys

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HIGHLIGHTS

- The numerical model of large pulsed electron beam irradiation process was developed.
- A mechanism of energy transfer during the irradiation was specified.
- An absorptivity of large pulsed electron beam was numerically investigated.
- Experimental validations of the predictive temperature model were performed.
- The numerical model of molten depths was well matched with the experiments.

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ABSTRACT

The pulsed electron beam irradiation process is a relatively advanced technique for surface modification, including surface hardening, corrosion protection, and wear inhibition. Due to increasing demand for surface modification processes on solid metals, many experimental studies have focused on electron beam irradiation processes. In this study, a three-dimensional numerical model of the large electron beam irradiation with a Gaussian-distributed heat source was developed. To reflect the natural interactions between accelerated electrons and solid substrates, the absorptance of the electron beam was evaluated with considering electron scattering, backscattering, and transmission. Predictions of temperature distributions were validated by measuring molten depths of engineering alloys after the electron beam irradiation. The effects of absorptance on the prediction accuracy of the molten depth were also explored, and the computational results were compared based on constant and calculated absorptance versus depth. The consideration of energy absorbing mechanisms resulted in more accurate predictions of molten depths, as demonstrated by the strong agreement with experimental results.

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1. Introduction

Electron beam surface treatment has found a wide variety of applications in various industries because of its unique local heat-treatment capability and interaction mechanisms between accelerated electrons and materials, enabling reduced surface roughness or increased surface hardness [1,2]. Recently, researchers have focused on corrosion-resistant re-solidified layers induced by large pulsed electron beams (LPEB) [3,4]. Electron beam selective melting has also been developed as an additive manufacturing process [5]. Pulsed electron beam irradiation appears to have great potential as a heat source in such manufacturing processes because of its high energy density and efficiency [6].

Although various studies have investigated experimental approaches and the effects of electron beam surface treatments, a numerical analysis to predict the processing results is still lacking. A simple but highly accurate model of the electron beam irradiation process is essential to allow pre-test performance predictions and post-test performance validation. Additionally, this tool could correctively define the energy density induced by a suitable electron beam source in advance, allowing a recess on a surface to be filled with molten material.

The electron beam irradiation process can be explained by energy transfer, elevation of temperature, melting, and re-solidification mechanisms. Previous studies of heat source modeling have used various methods to describe the heat-diffusion process [7–10]. The beam intensity of an electron beam generally follows a Gaussian distribution. The first heat source modeling of Gaussian-distributed energy was suggested by Pavelic et al. [11]. In the following decades, the Gaussian-distributed heat source

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Nomenclature

ρ	density, kg/m^3
C	specific heat, J/kg K
T	temperature, K
t	time, s
k	thermal conductivity, W/m K
q	heat flux, W/m^2
$I(x,y,z)$	point heat source at (x,y,z), W/m^3
P	maximum power at the beam center, W
$I(x,y)$	incident heat flux, W/m^2; induced by the LPEB irradiation on the top surface
δq	instantaneous point heat input, W
σ	effective radius, m
α	thermal diffusivity, m^2/s
Z	atomic number

model has been advanced and adopted in moving heat source models to predict molten pools. Considering a Gaussian-distributed beam, a 'classical' solution for temperature fields, assuming a semi-infinite body, was proposed [12]. Subsequent studies have tried to specify expanded solutions for a two-dimensional (2D) Gaussian-distributed beam intensity [9] and a finite element model (FEM) solution for transient temperature fields with a three-dimensional (3D) distributed moving heat source [10]. Most recently, Nguyen et al. [13] proposed an analytical solution that can accurately predict transient temperature fields on semi-infinite substrates. This model has been used widely to predict the temperatures in heat transfer processes.

The direct use of another heat source model is not suitable for pulsed electron beams because such models do not describe the natural interactions between accelerated electrons and substrates, such as scattering, backscattering, transmission, and absorption [14]. The processes are difficult to control, measure, and predict because of the extremely short operation time for electron beam surface modification. Thus, many previous models have assumed the energy absorptance of pulsed electron beams to be constant and/or have used experimentally fitted values for simplistic numerical approximations without considering natural interactions [15,16]. Because the interaction between accelerated electrons and substrates is highly dependent on the beam intensity and material, the physical basis of moving heat source models with an assumption of constant absorptance is quite weak for use with pulsed electron beam irradiation processes. Thus, more efforts should be devoted to improve model accuracy following the enhancement of beam intensity.

Although simplified models have been used effectively used to predict molten pools on bulk metallic alloys, it is important to develop an numerical model for electron beam irradiation, specifically reflecting the characteristics of accelerated electrons to replace such impractical concerns. For example, a deburring process of micro-sized burrs using LPEB was reported recently and the melting of micro-sized burrs could be only roughly predicted, without specifying the exact absorptance of electron beams, because the beam intensity of the electron beam used for the process was modified enormously ($\sim$100 mA/cm^2) and the molten layer was extremely thin ($\sim$5 μm) due to the short irradiation time [17].

The major interactions determining the absorptance of electron beams can be divided into three categories: scattering, backscattering, and transmission of electrons [18–20]. During LPEB irradiation of a solid target, the backscattering of electrons is the main cause of energy loss, adversely affecting the efficiency of the beam [21]. The transmission of electrons also induces a loss of energy at the surface layer because they simply pass, without transferring energy [22]. Despite efforts to formulate scattering, backscattering, and transmission of accelerated electrons by series of experiments and theoretical analyses, overall considerations of these interactions to predict the exact energy absorptance of electron beams have yet to be explored.

In this study, a three dimensional temperature prediction model of the electron beam irradiation was developed. Based on the scattering, backscattering, and transmission of electrons, the energy absorptance of the LPEB in the high-intensity range was specified in terms of electron-penetrating depths. With numerical approximations, an investigation was conducted primarily on temperature distributions on the material surface and heat penetration into the material depth to determine the melting zone during the LPEB irradiation period. The predicted results of molten depths were compared, assuming constant absorptance and absorptance corresponding to electron-materials interactions, and the effects of the unique relationships between accelerated electrons and substrates were evaluated. Finally, numerical models for absorptance and temperature prediction induced during LPEB irradiation were validated by direct comparisons of molten depths for metallic alloys, including Al6061T6, SM35C, AISI 304 stainless steel (SS), and copper, and the experimental results of the LPEB irradiation were in good agreement with the numerical results within a specific application range.

2. Numerical modeling

LPEB irradiation can be analyzed theoretically by describing the heat transfer process between the electron beam and the solid substrate. A 3D semi-quantitative transient heat-diffusion equation can be used to analyze the heating process of a substrate under LPEB irradiation.

2.1. Heat diffusion governing equation

The energy transfer and heat diffusion, which is the description of heat transfer in a solid substrate, can be formulated simply using the general heat conduction equation in a 3D Cartesian coordinate system [23]:

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \nabla \cdot q \tag{1}$$

where T is temperature, t is time, ρ is density, C is the specific heat, k is thermal conductivity, and q is heat flux into the target by the LPEB irradiation. This general heat conduction equation directly shows the energy transfer mechanisms of electron beam irradiation with assumptions of no convection. The radiative heat loss also can be ignored due to the extremely short time scale of LPEB pulses and rapid thermal gradient.

The initial and boundary conditions can be expressed as follows:

$$T(x,y,z,0) = T_0 \tag{2}$$

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