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Laser pulse heating of steel mixing with WC particles in a irradiated region

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ABSTRACT

Laser pulse heating of steel mixing with tungsten carbide (WC) particles is carried out. Temperature field in the irradiated region is simulated in line with the experimental conditions. In the analysis, a laser pulse parameter is introduced, which defines the laser pulse intensity distribution at the irradiated surface. The influence of the laser parameter on the melt pool size and the maximum temperature increase in the irradiated region is examined. Surface temperature predictions are compared with the experimental data. In addition, the distribution of WC particles and their re-locations in the treated layer, due to combination of the natural convection and Marangoni currents, are predicted. The findings are compared to the experimental data. It is found that surface temperature predictions agree well with the experimental data. The dislocated WC particles form a streamlining in the near region of the melt pool wall, which agree with the experimental findings. The Gaussian distribution of the laser pulse intensity results in the maximum peak temperature and the maximum flow velocity inside the melt pool. In this case, the melt pool depth becomes the largest as compared to those corresponding to other laser pulse intensity distributions at the irradiated surface.

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1. Introduction

Laser sintering offers considerable advantages over the conventional methods because of precision of operation, short processing time, local treatment, and low cost. In laser sintering process, high power lasers are used and the irradiated surface undergoes the melting during the heating cycle of the treatment. In order to achieve high power intensity at the surface and control the phase change process in the irradiated region, laser repetitive pulses are favorable during the processing. Laser beam intensity distribution is, in general, Gaussian at the irradiated surface, which gives rise to attainment of the peak power intensity at the irradiated spot center. This in turn causes local evaporation of the surface where the peak intensity is high. To avoid excessive evaporation of the surface during the laser sintering, the laser power setting and overlapping of the irradiated spots at the surface needs to be precisely controlled. In addition, excessive heating at the surface causes melt over flow and formation of high temperature gradients in the surface region. Excess melt flow results in poor surface roughness and high temperature gradient while causing thermal stress formations in the treated region. This lowers quality of sintering and limits the practical applications of the resulting end product. Although proper selection of laser sintering parameters is possible through the experimental data, it requires extensive efforts to finalize the selection process. In addition, laser pulse heating involves with localized temperature rise in a short duration; therefore, experimental study for the laser heating process becomes expensive because of the requirements of the state-of-the-art equipment. On the other hand, simulation studies provide physical insight of the processes, which take place during the laser-workpiece interaction. However, due to the limitations in computational power, the assumptions need to be made describing the physical process. Consequently, a care must be taken to describe accurately the laser interaction process in terms of modeling while incorporating some useful and necessary assumptions to reduce the computational efforts and the cost.

Considerable research studies were carried out to examine laser heating process with presence of particles. Laser heating of dust clusters was investigated by Thomsen et al. [1]. They showed that the laser scanning pattern had a major influence on both the velocity distribution function and the stationary structure of the clusters. Furthermore, the heating effect was found to be enhanced when the laser spots move with slightly higher frequencies than the trap frequency. Investigation of multi-component powder in selective laser sintering was carried out by Zhang et al. [2]. They indicated that with the increase of scanning time, the overall

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Nomenclature

a	Gaussian parameter
Cp	specific heat at constant pressure (J/kg K)
E	volumetric energy gain (J/m^3)
h	enthalpy (J/kg)
h_t	heat transfer coefficient at the free surface (W/m^2 K)
ΔH	enthalpy increase (J/kg)
k	thermal conductivity (W/m K)
L	latent heat of melting (J/kg)
r	radial direction (r – axis, m)
r_f	surface reflectivity
S_o	volumetric heat source (W/m^3)
T	temperature (K)
T_0	ambient temperature (K)
t	time (s)
u	velocity in the radial direction (m/s)
v	velocity in the axial direction (m/s)
$\vec{v}_{liq}$	liquid front velocity (m/s)
I_0	laser peak intensity (W/m^2)
p	pressure (Pa)
z	axial direction (z – axis, m)

Greek symbols

α	thermal diffusivity of the molten material (m^2/s)
β	laser pulse parameter
β_E	volumetric thermal expansion coefficient (1/K)
β_f	liquid fraction
δ	absorption coefficient (1/m)
ρ	density of material (kg/m^3)
σ_T	temperature coefficient of surface tension (N/m K)

temperature of the substrate and the particles was gradually rising; in which case, the heat-affected zone was increasing and the asymmetric temperature distribution became visible in the laser irradiated layer. Laser short-pulse heating and influence of spatial distribution of absorption coefficient on temperature field was examined in silicon film by Mansoor and Yilbas [3]. The findings revealed that electron temperature attained the highest for the case of high absorption coefficient located in the surface region of the silicon film. As the high absorption region moved inside the film, electron and lattice temperatures became low. Investigation of effect of gas flow and powder transport on laser direct metal deposition process was carried out by Kovalev et al. [4]. They demonstrated that the particles might overheat in between the nozzle and substrate; the overheating depended on the trajectories by which particles moved, on their size, and time of their retention in the laser-irradiation region. Analytical model for the geometrical characteristics of the laser sintered surfaces was introduced by Ioannou et al. [5]. They formulate the heating problem under the assumption that the maximum temperature remained below the melting point in the irradiated region and the energy lost due to conduction in the metal substrate was very small. Laser induced metallurgical changes in the re-solidified zone of W-Cu composite powder system was studied by Dai et al. [6]. They demonstrated that as the angle of attractive force and pressure was acute angle, tungsten particles formed a small-scaled rim structure and the rearrangement rate was limited, accordingly tending to form segregation structure. Otherwise, tungsten particles formed large-scale rim structure and the re-arrangement was efficient, contributing to the formation of homogeneously distributed structure. The thermal history of the multiple laser deposited layers was examined by Amine et al. [7]. They simplified the heating problem after assuming that the deposit geometry was known prior to the simulations; this would affect the temperature and stress fields developed during heating cycle. Thermal transport during coaxial laser direct deposition process was investigated by Wen and Shin [8]. In the model study, they introduced mass source term into the continuity equation, which considered the rate of the gas phase being replaced by the deposited material due to the moving interface during the phase change process. The study on laser melting of stainless steel 316L metal powders was carried out by Antony et al. [9]. They presented the effect of process parameters such as laser power, scanning speed, and beam size on the characteristics of the melt zone geometry and ball formation. Laser treatment of dual matrix cast iron with presence of WC particles at the surface was studied by Yilbas et al. [10]. They showed that laser treated layer consisted of a dense region composing of fine grains and WC particles, and then followed dendritic and featherlike structures below the dense layer and the heat affected zone. Low temperature nanoparticle sintering was carried out by Kumpulainen et al. [11]. They indicated that laser sintering enabled short sintering times and selective sintering, which made it possible to avoid printed structures containing fragile active components. Effects of post-heat treatment on microstructure and properties of laser cladded composite coatings on titanium alloy were examined by Li et al. [12]. They demonstrated that the post-heat treatment could decrease the residual stress and increased the fracture toughness of the coatings. High power direct diode laser cladding was investigated by Liu et al. [13]. They introduced an optical monitoring system consisting of a high-speed CCD camera, a pyrometer, and an infrared camera to analyze the mass and heat transfer in the cladding section.

Although laser interaction of surfaces was studied earlier [10], the main focus was to examine metallurgical changes in the laser treated region, and temperature field and particle distribution in the irradiated region were left for the future study. In the present study, laser heating of solid surface with presence of hard particles (WC) in the irradiated region is considered. Temperature distribution and particle dynamics in the melt are studied numerically. The findings of the particle distribution are compared with the experimental data. In the numerical simulations, phase change and melt flow in the irradiated region is incorporated and the absorption of the laser beam is modeled using the Lambert's law. The boundary conditions of the solution domain are set according to the experimental conditions. The study is extended to include the effect of laser pulse intensity distribution at the irradiated spot center on temperature field in the irradiated region. Laser pulse parameter is defined as β, which describes the exponential distribution of the pulse intensity at the surface. In this case, $\beta=0$ corresponds to Gaussian intensity distribution at the irradiated surface.

2. Heating analysis

Laser pulse heating of steel mixing with WC particles is considered. The heat transfer equation in relation to the laser pulse heating process can be written as:

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