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An experimental–numerical investigation of heat distribution and stress field in single- and multi-track laser cladding by a high-power direct diode laser

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ABSTRACT

High-power direct diode laser (HPDDL) cladding offers several advantages in the laser surface modification and repair of high-value parts. The wider beam and uniform energy distribution in the direct diode laser provide a smooth heating and cooling cycle during the cladding process. Subsequently, lower dimensional distortion and thermally-induced stress occur during the process. In this paper, temperature evolution and molten pool dimensions as well as stress-and-strain fields were studied by utilizing experimental and numerical methods. A three-dimensional (3D) transient uncoupled thermo-elastic–plastic model was developed to simulate a thermal process during the single- and multi-track laser cladding and the thermally-induced residual stress in the laser cladding. The effect of latent heat and phase transformations are considered in the thermal analysis. The numerical results were validated by experimentally-measured values, and the maximum prediction error was 3.5%. The experimental results were collected by in-situ monitoring techniques (e.g., thermocouples and a high-speed CCD camera). The level of residual stresses at the cladded surfaces were measured by an X-ray diffractometer. In addition, the effect of scanning speed on the thermal and stress evolution was quantitatively discussed.

1. Introduction

Laser cladding (LC) has been widely used as a surface modification technique in advanced manufacturing. Fabrication of the protective coatings by materials with enhanced mechanical and physical properties as well as repair of the worn-out parts are the main objectives of this process. The development of laser cladding has offered distinct advantages such as high hardness, a narrow heat-affected zone (HAZ), minimal dilution, good controllability, few microscopic flaws, and high bonding strength. However in laser cladding, mechanical stress is one of the inevitable consequences of highly concentrated laser energy input. Rapid heating and solidification during the process is one of the sources for residual stresses in the deposited material at room temperature. During the cladding process, a high stress region is formed around the molten area that may contribute to plastic deformation and consequently dimensional distortion in the cladded parts. As a consequence, residual stresses resulting from inhomogeneous permanent deformation between clad and substrate are generated in the cladded parts. The presence of high tensile stress in the coating layer at room temperature has a crucial effect on crack sensitivity, decreasing the component life expectancy and leaving the fabricated parts prone to premature failure [1].Therefore, it is essential to study thermal distribution and the thermally-induced stress field during the LC process.

Thus far, several studies have been carried out on the experimental measurements and numerical modeling of the thermal and mechanical behaviors, distortion, and crack propagation of the fabricated parts by laser cladding. One of the first calculations in thermo-mechanical field for laser cladding as a two-dimensional (2D) and axisymmetric finite-element (FE) model was published by Chin et al. [2]. Deus and Mazumder [3] developed a 2D FE model based on longitudinal mid-plane for simulating the temperature and stress-and-strain field. For modeling the plasticity behavior in the model, the von Mises criterion was used. The results show that the highest absolute values for longitudinal stresses are located at the interface zone between the substrate and the clad. Nickel et al. [4] studied the effect of the deposition pattern in laser-layered manufacturing on the stresses and deflection of fabricated parts. They developed a 3D FE model in ABAQUS and studied different scanning patterns on plate-and-beam-shaped substrates. The residual stress is not measured in their study; however, the measured and calculated strain shows a good agreement. Dai and Shaw [5] developed a 3D model in ANSYS

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Nomenclature

C_P	specific heat (J/kg °C)
E	Young's modulus (Gpa)
$f(x,y,z)$	bead shape function
F	yield function
G	hardening function
$hconv$	coefficient of free convection (W/m^2 °C)
h_l	lumped heat transfer coefficient (W/m^2 °C)
H	height of deposited layer (mm)
H_m	middle position of inclined molten surface
k	thermal conduction (W/m °C)
K	hardening parameter
L	length of laser spot (mm)
LP	laser power (W)
$\dot{m}$	powder flow rate (g/s)
n	normal vector of surface
q	heat density (W/m^3)
t	time (s)
T	temperature (°C)
T_0	ambient temperature (°C)
T_m	melting temperature (°C)
w	width of laser spot(mm)
x,y,z	Cartesian coordinate

Greek symbols

α	thermal expansion coefficient
δ_{ij}	dirac delta function
Δ	a finite increment
$\Delta\varepsilon$	total strain change in a time step
ε	surface emissivity
$\dot{\varepsilon}_{ij}$	effective strain rate tensor
ε^{th}	thermal strain
ε^{V}	volumetric dilatation due to phase transformation
ε^{tp}	phase transformation induced plastic strain
ε^{e}	elastic strain
ε^{p}	plastic strain
η	absorption coefficient
λ	wave length
ρ	density ((kg/m^3)
σ	Stefan–Boltzmann constant (5.67×10^{-8} W/m^2 K^4)
σ_{ij}	stress in tensor form
Θ	step function
Ω	effective wetting angle
θ	Bragg angle
ψ	side angle
ξk	enhancement convection factor

software for analyzing the temperature and stress field as well as distortion of the components in multi-material laser solid-freeform fabrication. They verified the mismatch of the thermal expansion coefficient between added material and substrate has a direct impact on residual stress and its distortion. Similarly, Labudovic et al. [6] utilized a 3D FE model to simulate the temperature and stress fields in laser deposition of MONEL 400 on AISI 1006 steel. They studied the effect of process parameters on residual stress and found that scanning speed has the main effect on the levels of residual stress. Ghosh and Choi [7] developed a 3D thermokinetic FE model for calculating the temperature history, phase transformation, and stress-and-strain fields during the laser-aided direct metal deposition by Nd–YAG laser. They indicated the phase transformation effects in the residual stress simulation are usually neglected due to the complexity of the numerical simulation. However, if thermal stresses are in the plastic region, the phase transformation term is a determinant in the residual stress level. Zekovic et al. [8] developed a 3D thermo-mechanical FE model to investigate the residual stress in laser direct metal deposition of H13 tool steel by a fiber laser with a different scanning pattern. They showed a one-directional deposition strategy induces lower residual stress than a zig-zag deposition strategy. They showed the straight wall deposited structures are exposed to high tensile residual stresses close to the free edges leading to cracks in the contact zone between the wall and the substrate. Brückner et al. [9] investigated different methods that are suited to reduce residual stress and prevent cracking in laser cladding of hard-phase material. They developed a 3D transient model for a single bead laser cladding to visualize the essential phenomena in stress-and-strain evolution during the process. Based on their study results, the phase transformation, plastic deformation, and process conditions such as heating time and preheating temperature have significant roles in the evolution of residual stress and part distortion. Foroozmehr and Kovacevic [10] studied the effect of the deposition pattern on the final stress distribution in laser powder deposition of AISI 4140 steel on the substrate of the same material by a fiber laser. Their study investigated four different patterns of deposition. Based on the numerical results, a spiral-in pattern caused the highest residual stress and a short-bead pattern led to the lowest residual stress in the coated material. Kong et al. [11] developed an FE thermo elastic–plastic model considering the phase transformation process in the laser treatment of DP980 high-strength steel with a direct diode laser. They found that by increasing the overlap ratio in multi-pass laser hardening, the maximum equivalent residual stress tends to decrease. Ding et al. [12] developed an efficient FE thermomechanical model to predict the residual stress and distortion of workpiece during wire and arc additive manufacturing process with 99% saving in computational time. They found the maximum temperature experienced by the material during the process is the main factor to determine that whether or not residual stresses could be developed in the fabricated part.

There are a number of destructive and non-destructive techniques to quantify the presence of residual stresses. The destructive techniques are measured based on the original stress from the induced displacement for removing the material, such as sectioning, slitting, and hole drilling [13]. Provot et al. [14] used a step-by-step hole drilling technique for measuring the residual stress in WC–Co coating by plasma spraying. They reported the value of the residual stress along the coating thickness has a smooth gradient. However, the obtained value in the hole drilling technique is strongly dependent on the Poisson ratio and modulus of elasticity [15]. Non-destructive methods usually measure some parameter that is related to the stress. The X-ray diffraction technique is a new non-destructive approach that measures the elastic strain of specific atomic lattice planes (*h k l*) [13]. This technique has been widely used because it is non-destructive and has the capability to measure the stress of each individual phase in multiphase metal [16]. Ahmed and Hadfield [17] used the X-ray measurement technique for measuring the residual stress in thermally-sprayed coatings. Because the anisotropy of the coating influenced the measured residual stress, they measured the stresses at three different angles (0°, 45°, 90°) while keeping the measurement point constant. By this method, the effect of anisotropy in the coating was eliminated. Oliveira et al. [18] used the X-ray diffraction technique for measuring the residual stress in CO-based laser