Coupled Metallo-thermal Finite Element Model for Prediction of Metallurgical Changes in Laser Cladding Due to Substrate Pre-scanning

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Abstract

Laser cladding provides numerous advantages over the traditional, ad-hoc and imprecise deposition techniques for the repair of critical structural components such as dies and molds used in the cold working industries. In laser cladding, the molten region in the substrate forms an effective dilution zone and significantly, influences the diffusion of heat for the solidification of the deposited clad. Thermal fluctuations produced due to pre-scanning of the substrate can generate various changes in the microstructure of the material and their properties. Finite element modelling is an appropriate way to accurately estimate the transient temperature profile and microstructural changes for the prediction of optimal process parameters. The factors affecting the transient temperature profile are position, laser power, beam diameter, powder feed rate, scanning velocity and pre-scanning strategy. In this study, a sequentially coupled metallo-thermal model is developed wherein the nodal temperatures obtained from the thermal analysis are used to predict the metallurgical transformations using the heat treatment simulation software package DANTE®. DANTE® is a set of user subroutines that link into the ABAQUS/STD solver and considers the transformation kinetics and quantitative property-structure relationships in materials. The material considered is H13 tool steel. This work, demonstrates the capabilities of the metallo-thermal model to understand the influence of pre-scanning of the substrate, on the dilution and residual stresses in a laser cladded sample.

Keywords: Laser cladding, metallo-thermomechanical model, tempering, pre-scanning

1. INTRODUCTION

Laser cladding is a type of deposition technology that utilizes a focused or a defocused high-power laser beam to locally melt a thin surface layer of a substrate and the added materials. It is employed to develop coatings (with thickness of 0.3–2 mm) and repair critical components such as dies and molds [1]. This deposition of the material (similar or dissimilar) on the substrate is accomplished by melting the substrate and deposited material (clad) to form metallurgical bond with minimum dilution at the interface [2]. H13 is a commonly utilized tool steel for the die material for casting, forming and plastic molding applications. Fatigue and wear are the primary causes of damage in the components manufactured using H13 tool steel. This demands for immediate *in-situ* repair or replacement of these components. Intuitively, cost effective approach would be precise repairs rather than the total replacement. One such approach, which offers suitable, precise and economical repair of damaged structures, is laser cladding. In the past, laser cladding based repair of airplane parts, tool components, and extrusion/molding dies were conducted using alloys such as IN-625 [3], Stellite 6 [4] and CPM 9V [5, 6]. For a better interface physically and better integrity, using a material, similar alloy powder as the substrate is favored in laser cladding in repair applications [5]. To warrant, minimum distortion, delamination, and defects in the clad zone and dilution zone, the study of the process parameters is necessary.

For optimum properties, dilution and perfect bonding of the clad on the substrate, pre-scanning treatment schedule may be necessary to achieve the desired strength, toughness and adherence for desired performance [2]. To achieve this knowledge, the experimental methods are though helpful are time consuming and expensive [5]. Numerical simulations such as Finite Element Modelling has proven to be an effective approach to understand the complex physics of the process and optimize the process parameters [7]. Several authors have started with thermal modeling to estimate the temperatures and microstructure evolution in the laser cladding process [5]. It is also used to calculate the clad geometry. Thermo-mechanical model on the other hand are developed to quantify the residual stress. These estimates can be employed to assess the clad integrity by calculating the stress induced deformation and cracking [8]. Whereas, metallo-thermomechanical models can predict the effect of process parameters on the microstructure on the deposited clad layer, the effected substrate zone, and the resulting distribution of properties [9]. They combine a heat transfer model allowing the evolution of temperature in the part to be calculated, solidification theory to predict the solidification microstructure and kinetic models for all the solid-state phase transformations that can occur in the material [5]. If the material properties are to be calculated, quantitative microstructure–property relationships are also required. Heat treatment simulation software package DANTE® is an excellent material database, which covers low and medium carbon steels [10].

In the present study, a coupled metallo-thermomechanical model has been developed. This model is used to study the laser cladding of AISI H13 tool steel powder on the substrate of same alloy. The influence of pre-scanning of the substrate on the clad integrity is studied. Finally, the mechanical property of the clad zone in terms of micro-hardness was assessed using heat treatment simulation software package DANTE® [10].

2. PROCESS MODELING

2.1 Physical description

Laser Cladding with powder injection is a processing technique used for deposition of powdered material in a controlled manner onto a surface of a substrate material. A laser beam is focused and scanned along a substrate surface as a desired powder is

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injected into it [1]. This creates a molten pool of the clad material which solidifies and bonds with the substrate. The schematic for powder injection laser cladding is shown in Fig. 1.1.

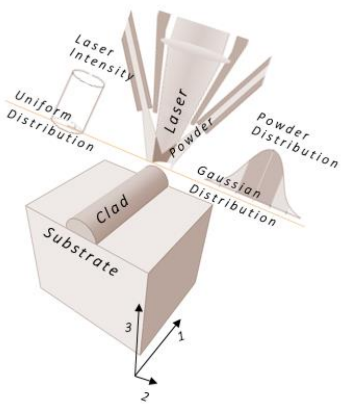


Fig. 1. Schematic of laser cladding process

2.2 Methodology

To understand the complex process, mechanics of laser cladding a coupled numerical model was developed to capture the thermal, mechanical and metallurgical phenomena involved in the process. The three dimensional metallo-thermomechanical models developed in this respect incorporate the following phenomena:

- Uniform moving heat source with element activation technique: Inactive element method and attenuation of laser power due to laser-powder interaction
- Identifying the dilution and HAZ;
- Microstructural evolution in the clad and the substrate;
- Residual stresses generation incorporating thermal strain as well as strain developed due to volume dilation due to change of phase;

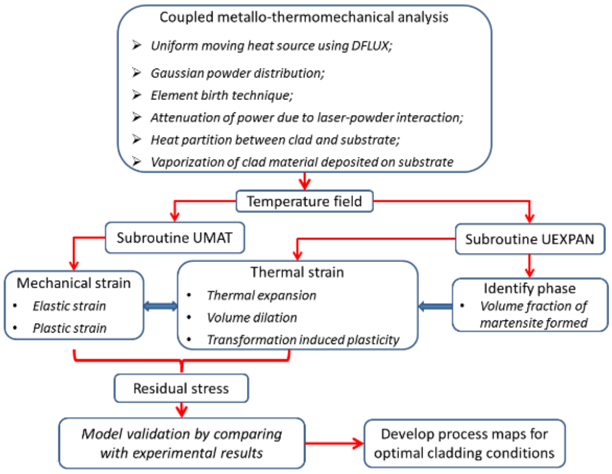


Fig. 2. Methodology of 3D metallo-thermomechanical analysis [4]

The methodology for three dimensional metallo-thermomechanical analysis of laser cladding process is illustrated in Fig. 2. The uniform moving heat source is modelled using the user defined subroutine DFLUX [4]. The coupled metallo-thermomechanical analysis predicts the transient temperature field and the initial stresses developed due to differential thermal expansion and contraction. Based on the transient temperature field the phase fractions are identified using the kinetic model in UEXPAN subroutine. Accordingly, the volume fraction of martensite formed in the computational domain is calculated using the kinetic model. The mechanical components of strain, elastic and plastic part are calculated using user defined subroutine UMAT [3]. Note that the subroutine UEXPAN is used to calculate the following components of thermal strain:

- Strain due to differential thermal expansion and contraction
- Volume dilation due to phase change from austenite to martensite
- Transformation induced plasticity.

Apart from calculating the strain components, the initial melt pool dimensions and dilution zone are calculated based on the temperature field.

2.3 Model assumptions

The following assumptions were made about the process for developing the thermal model:

- Clad elements, which reach the vaporization temperature, are assigned higher value of thermal conductivity
- Fluid flow effect on final clad shape and residual stress profile was neglected [3-4].
- For residual stress analysis elasto-plastic behavior with temperature dependent yield stress, with Johnson-Cook Model [5].
- Creep (time dependent deformation) effects are also neglected.

2.4 Governing equations and boundary conditions

In a coupled thermomechanical finite element analysis of laser cladding the values of nodal temperature obtained after thermal analysis of Uniform moving heat laser source are used as input to calculate the mechanical response particularly the residual stresses developed. Transient heat conduction equation for a homogeneous, isotropic material is used as the basic governing equation for thermal analysis, which is given as [11]:

$$\rho C_p\left(\frac{\partial T}{\partial t}+U_i\,\nabla T\right)=\nabla(K\,\nabla T)+H \tag{1}$$

where ρ, Cp and K refers to density, specific heat and thermal conductivity respectively of material; T and t refer to the temperature and time variables respectively. Ui is the speed of the moving heat source in x direction and H is the volumetric heat generation.

The coupled metallo-thermomechanical FE predicts the transient temperature field from thermal analysis and the initial thermal stresses developed due to differential thermal expansion from stress analysis. Accordingly, the kinetic model for the transformation of pearlite to austenite used here is based upon the original work of Ashby and Easterling [7]. For a small increment, the incremental linear strain tensor can be divided into elastic ($d\epsilon_{ij}^{e}$) and plastic ($d\epsilon_{ij}^{p}$) components as [4]:

$$d\epsilon_{ij}=d\epsilon_{ij}^{e}+d\epsilon_{ij}^{p}+d\epsilon_{ij}^{th} \tag{2}$$

In the metallo-thermomechanical, analysis of the process the effect of metallurgical transformations on total strain is considered.

2.5 Numerical formulation

At every instant of time, the surface heat flux is applied using the DFLUX subroutine in ABAQUS®. The DFLUX subroutine updates the local co-ordinate definition to simulate the effect of heat source moving forward during deposition. Thereafter, the values of elemental temperatures were retrieved using the variable TEMP through the subroutine UEXPAN. A user defined field variable was used in UEXPAN subroutine and was assigned numerical values corresponding to the various identified regions. As the effect of Marangoni on the transient stress field is neglected. Therefore, it is important to ensure that the elements that exceed melting temperature do not contribute to the stress field. Accordingly, one way to achieve this is to render the defined element set as mechanically inactive till the elemental temperature is higher than the melting temperature.

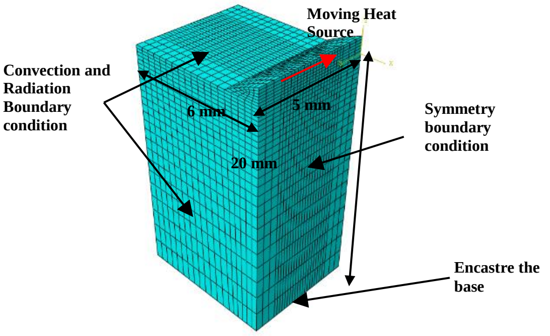


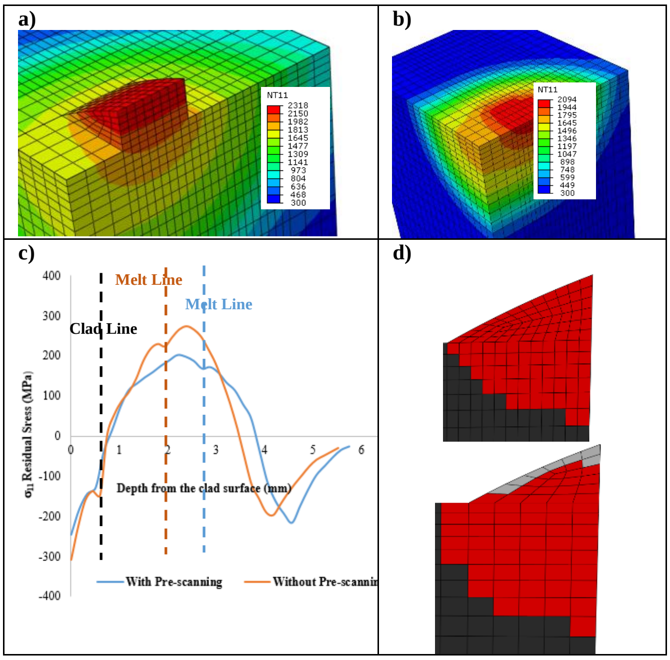
Fig. 3. Representation of computational geometry along with loading and boundary conditions

For simulation, a half symmetric model with dimension 5 mm (along the deposition) × 6 mm (transverse)× 20 mm (perpendicular to the plane of deposition) has been developed. Three-dimensional, eight nodes thermally coupled brick, trilinear displacement and temperature elements, C3D8T were used. Various mesh sizes were analyzed to identify the optimal mesh size. The total number of elements is 21190. Material properties of the considered material (H13) is presented in the reference [3-5].

3. RESULTS AND DISCUSSION

3.1 Effect of pre-scanning

The time-dependent temperature and stress were calculated for the both non-prescanned and pre-scanned case (Fig. 4(a), Fig (b)). A dilution zone along with residual stresses is presented for both the cases in the Fig. 4 (d). The grey zone indicated in the Fig 4 (d) for the case of the laser cladding with pre-scanning shows the vaporized (burnt off) region which is obtained from utility routine GETVRM via USDFLD user defined subroutine as the model predicts that ~100 µm of top layer is estimated to be vaporized. Whereas the model without pre-scanning has no burnt off region. It should be pointed out that the diagrams of the temporal dependences are related to the respective points from the surface of the clad to the substrate during pre-scanning and deposition. The red color in Fig 4 (d) indicates that the condition of melting of both the clad and base materials. It can be noticed that a proper bonding between the clad and substrate is being obtained. But the dilution in the pre-scanning case is predicted to be higher than the without pre-scanning case which goes with the intuition. The residual stress plots in Fig 4 (c) reveals marked peaks in the substrate and clad for both the cases. The value of tension induced in the substrate estimated with pre-scanning is lower than the without pre-scanning. A similar decrease of the residual stress in the clad region on a pre-scanned substrate can be observed for the considered processing parameters. Same trend of decreasing residual stress can be observed both in clad (compressive) and substrate (tensile) with the increase in the laser power during pre-scan presented in Fig. 5. It is worth noting that the interfacial stresses between the clad and the substrate has not affected much due to the pre-scanning. This means that the clad surface and the substrate reveal a higher cracking susceptibility for the case of without pre-scanning. This is due to the larger temperature gradients in the cladding process without the pre-scanning. The above consideration indicates that conclusions regarding the reducing the cracking susceptibility at the predicted locations can be extrapolated for various process during pre-scanning. In contrast to the stress data, the values of the corresponding temperature peaks are comparable to each other, despite different initial temperatures of the base material.



Process parameters:
Powder feed rate: 5 g/min *Laser power: 2400 W*
Scanning velocity: 270mm/min *Pre-Scan Power: 2400 W*

Fig. 4. (a) Temperature distribution during deposition (b) Temperature distribution during the pre-scanning (c) Residual stress along the transverse direction with and without pre-scanning (d) Dilution zone with without pre-scanning.

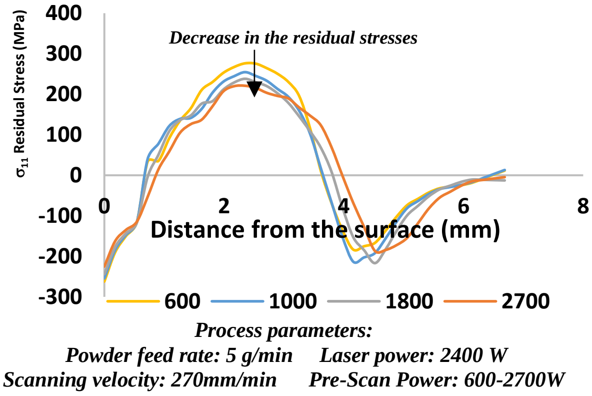


Fig. 5. Residual Stress along the transverse direction with various pre-scanning power

3.2 Thermal Modelling using heat treatment simulation software package DANTE

Though considerable amount of work is done in the development of the thermal modeling of the laser cladding, the thermal model with microstructure dependent of material properties has not been studied much. In this section, the thermal model with microstructure dependent material properties is modeled and demonstrated by using DANTE®. DANTE® models require a comprehensive description of the steels being simulated. The material characterization includes:

- Mechanical Data for each phase as function of temperature, strain rate and alloy content (primarily carbon)
- Thermal Data for each phase as function of temperature and alloy content (primarily carbon)
- Phase Transformation Kinetics Data during heating, cooling and tempering processes

The material database in DANTE® covers low and medium carbon steels. The data required for heat treatment simulation includes thermal properties, phase transformation kinetics, and mechanical properties of each individual phase of the H13 over the range of temperatures and heating/cooling rates for the process. The accuracy of the model is of course directly related to the accuracy of the material data.

DANTE mechanical data includes:

- Elastic properties as a function of temperature;
- Plastic properties as functions of temperature, strain, and strain rate for the phase's austenite, ferrite, pearlite, upper bainite, lower bainite, martensite and tempered martensite;
- Thermal conductivities, latent heats and specific heats for these phases; coefficients of thermal expansion for each phase; transformation introduced plasticity; phase transformation strain data; and
- phase diagram data critical temperatures for equilibrium heat up phase transformation kinetics.

Heat transfer analysis using ABAQUS aided with DANTE using the model discussed in section 2.5 to predict the austenite fraction, martensite fraction and the hardness profile. The contour plots of the temperature, austenite fraction, martensite fraction and hardness values are shown in the Fig 6 and Fig. 7.

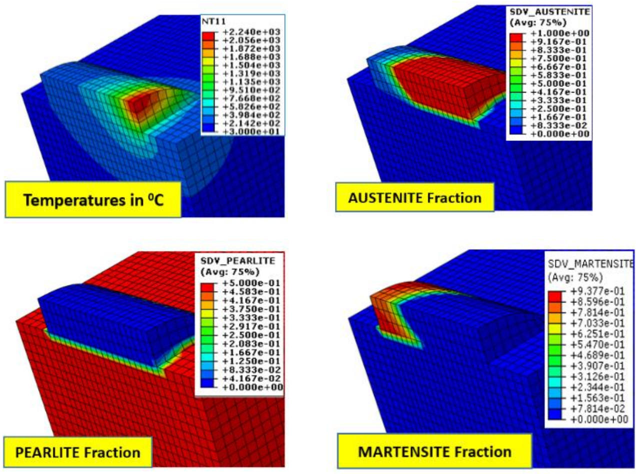


Fig. 6. DANTE Thermal Model Initiation of the cooling

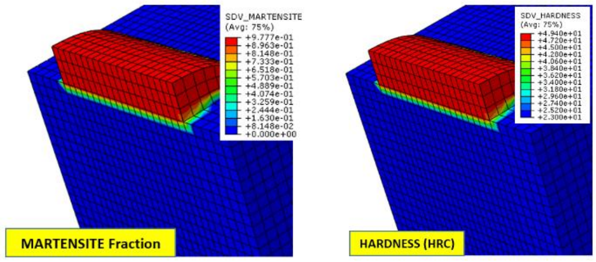


Fig. 7. DANTE Thermal Model Ending of the cooling

It shows the capability of the model to predict the microstructure transformation in the laser cladding process due to the thermal fluctuations.

4. CONCLUSIONS

Time-dependent temperature and residual stress fields induced in laser cladding are estimated using a metallo-thermomechanical model.

For the estimation of the harness and martensitic fraction in the discrete model were obtained by means of DANTE® heat treatment model with an implemented ABAQUS module.

- Results of calculations shows that a pre-scanning of the substrate contributes considerably to the reduction of stresses induced in the clad zone and the substrate. This suggests the improvement in the clad integrity with respect to the cracking susceptibility.
- Results of calculations shows that a pre-scanning of the substrate contributes nothing to reduce the stresses in the interface zone. This suggests no improvement in the clad integrity with respect to the delamination of the clad layer.
- The numerical model with thermo-kinetic model using DANTE® and solutions obtained gave a valuable insight into laser cladding and the estimation of the metallurgical characterization.

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