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A novel numerical method to predict the transient track geometry and thermomechanical effects through in-situ modification of the process parameters in Direct Energy Deposition

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ABSTRACT

Direct Energy Deposition (DED) is being widely used to repair damaged components to increase service life and economical operation. Process parameters including laser power, traverse speed and the mass flowrate of the feedstock material may be adapted in-situ. This allows bespoke repair strategies to be devised to match the variability in the condition of the parts supplied that require repair; however, there are limited modelling techniques that allow the adaptive control within the DED process to be represented. In this study, a novel modelling strategy is presented which allows the DED process to be modelled in a transient state. This allows varying process parameters to be included in the model, to predict the transient track geometry and the associated thermomechanical effects of the process. Here, a single-track deposition of IN718 with a varying cross section has been modelled utilising the proposed approach. The modelling methodology was validated with a corresponding experimental study on a deposition made using a Nd:YAG laser source with a coaxial nozzle. An in-situ modification was generated by variation of the laser power. The track profile was compared against focus variation microscopy images and the thermomechanical portion of the model was validated through in-situ temperature measurements, micrographs and residual stress, obtained from neutron diffraction measurements. A good agreement between the predicted and experimental findings were observed. The track height and width were predicted with a maximum error of 6.5% and 7.6% respectively. The peak temperature and residual stress were predicted within 6.2% and 11.4% respectively. Overall, the modelling method presented will allow complex and bespoke multi parameter repair strategies to be rapidly developed.

1. Introduction

Additive Manufacturing (AM) techniques, such as Direct Energy Deposition (DED), are being used within the advanced manufacturing sector to repair high value components, this removes the need to remanufacture or replace the component, reducing operational costs. Often, DED is utilised over traditional welding techniques due to the high material utilisation ratio, increased accuracy and increased flexibility during manufacture. The nature of the DED process allows for in-situ modifications to the process parameters, which could result in greater control of the track geometry, cooling rates and subsequently the mechanical properties of the component. As not all repair requirements are identical, this type of deposition strategy would inherently allow bespoke and flexible repairs to be implemented. The development of more flexible solutions could also allow the distortion and the evolution of stresses within a component to be controlled during repair, reducing the need for additional processing such as heat treatment or further machining.

The DED process involves a laser source irradiating a metallic substrate to generate a moving melt pool. The feedstock material may be delivered in powder, wire or strip form and conveyed to the work area using a nozzle and an inert gas stream [1]. A moving melt pool is

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generated from the deposition head moving relative to the substrate surface [2], which, coupled with the incoming material forms a raised track. The entire process is controlled through CNC, therefore, in-process modifications can be implemented with ease. When no modification is made to the parameters a steady-state track geometry is formed. Variations in the process parameters will not only lead to a transient geometry being formed, but variations in the temperature fields, which drive the stress condition during solidification, will also occur. Therefore, a tool which allows the prediction of the track profile, thermal field and residual stress evolution, due to process parameter variation, would allow bespoke repair procedures to be developed.

Experimental depositions and numerical predictions of a track geometry with an in-situ parameter variation have not been reported to date. Despite this, predictions of track geometries and the thermomechanical effects of the process, utilising different modelling methods, has received attention within the literature. Early models to determine track profiles were derived empirically across a range of process parameters, often neglecting the physical complexities of the process such as the interaction of the powder feed distribution and the melt pool [3]. An empirical model, presented by Kumar et al. [4], allowed the track height to be derived based on the laser power and the material mass flow rate. Although the time required to predict the track height was minimal, experimental data was required to calibrate the model. This was required to reduce the maximum error between the predicted and experimental height from 50% to 13%. To increase the accuracy of the approach, an empirical statistical model was later used to include more parameters of the process. Davim et al. [5], utilised a similar method, with the final equation being derived using a Multiple Regression Analysis (MRA) model. The track height and width were determined with an error of 7.6% and 6% respectively. Despite the volume of data collected to inform the model, the percentage error for the predicted melt pool depth was 20.1% showing a level of inaccuracy with this approach. The main issue with using empirical/statistical models is the experimental data needed to derive the model. This would not be feasible to design repair strategies as each repair would be bespoke. In addition to this, the empirical approach is limited in providing accurate predictions within the bounds of the process parameters used to define the model. Therefore to enable the effects of in-situ modification to be evaluated for bespoke repair applications, a high number of experiments would be required to enable the correct repair scheme to be designed. As this would be an inefficient approach, leading to a lengthy and costly design process, a generalised modelling method which allows the process to be simulated is therefore required.

Analytical models have recently been used to allow for a more flexible modelling approach, as the methodology is no longer bound by a range of process parameters. An early model presented by Picasso et al. [6] determined the parameters required to fabricate a deposition of a prescribed height through solving a series of analytical expressions. An iterative solution procedure was utilised to reassess the thermal field through recalculation of the power absorbed by the workpiece. The power loss and interaction between the laser beam, substrate and powder particles were considered at each iteration. The solution procedure was terminated when the relative change between the absorbed power, laser velocity and the powder mass flow rate was less than a prescribed value. A major drawback of this approach was that the track height had to be predefined, therefore, no assessment could be made on how the process parameters affected the deposition geometry. A simplified approach presented by Pinkerton and Li [7], modelled the geometry of a moving melt pool and the subsequent deposition track through an energy and mass balance. The laser process was simplified by assuming that the heat source and track profile could be represented as a point source and a circular arc respectively. The approach was relatively simple and was not computationally demanding, therefore providing a quick prediction of the track geometry. The model was used to assess the effect of the laser power on the steady-state track width and height, with a maximum error of 11.1% and 38.9% respectively; therefore, the validity of the approach has to be assessed when analysing the effects of the process parameters on the deposition geometry. A hybrid model of a numerical and analytical approach was presented by Ahsan and Pinkerton [8], which determined the track height, utilising a fully-coupled mass-enthalpy balance. Similar to Picasso et al. [6], the thermal field was reassessed to include the power losses associated with the process. An analytical temperature field, solved through numerical integration, was used to determine the melt pool geometry. The track profile was calculated from analysing the interaction between an analytical representation of the powder flux distribution and the predicted melt pool geometry. The model was verified experimentally, with a maximum error of 8.4%, 3% and 20% for the peak temperature, track width and height respectively. Through representing the key physics of the process, a more accurate representation of the track profile was determined. For most analytical models, the time required to determine a solution is minimal, as the models are not computationally demanding as a discretised domain is not required. Therefore, when designing bespoke repair strategies and evaluating the effects of the process parameters on the track geometry, these models are beneficial. However, as a quasi-static solution of the thermal field is calculated, the time dependent history of the process is neglected; therefore, the effect of in-situ parameter modifications cannot be evaluated using analytical models. Also, when determining an analytical thermal field, the geometry is often simplified to an infinite plate. Therefore, no real assessment of the repair strategy can be made with these methods using the true component geometry. It should be noted that analytical modelling to predict residual stresses are very limited for DED; however, a model presented by Tamanna et al. [9] predicted the residual stress for laser cladding using a one-dimensional model. The model was used to evaluate the effects of preheating the substrate at different temperatures on the final residual stress field. No experimental validation of the proposed methodology was completed and only a one-dimensional representation of the stress field could be predicted. Therefore, evaluation of the thermomechanical effects for the entire component would not be possible utilising this approach.

Numerical models of the DED process tend to focus on calculating the thermal histories and thermal distributions of the final part. In some cases these types of models are used to predict track geometries and can be extended to predict residual stress fields. Early numerical models applied the heat flux to an unchanging surface, however, the inclusion of material deposition can be incorporated through element manipulation techniques [10]. Numerical models using computational fluid dynamics (CFD) have been used to predict the physical phenomena from the deposition head to the melt pool dynamics, with some of these models allowing the formation of the track to be included [11,12]. However, as CFD cannot be used to predict the thermomechanical effects of the process, a review of these methodologies will not be included. Therefore, the focus will be on the finite element method, specifically to predict the track geometry and the thermomechanical effects of the process. A three dimensional model for DED, utilising both an analytical and numerical approach was derived by Labudovic and Kovacevic [13]. An analytical model based on Green's function was used to determine the thermal field of the process and this was compared to the FE simulation. A numerical model to determine the residual stress field for a wall structure was also presented, in an attempt to determine a feedback control to reduce residual stresses during the deposition. Experimental data for both the thermal and mechanical portions of the model were used to validate the approach, with the use of a high speed camera and x-ray diffraction data. Although a good agreement was present between the experimental data and the modelling method, a square track geometry was used for the FE model which does not reflect the true track geometry. The interaction between the powder feed and melt pool were not included; therefore, a prediction of the track profile was not possible. Utilising this methodology, a bespoke repair solution could not be designed, as a true representation of the track geometry was not included in the model; also, as the powder feed was not included, in-situ variation of the process parameters could not be incorporated with this approach. A model was