Simulation and validation of residual stress generation at an interface of a Direct Energy Deposited (DED) Inconel 718 with a wrought substrate of the same alloy

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Abstract. Repair and remanufacturing applications demand precise control of additive manufacturing (AM) technology to prolong part lifespan, optimizing microstructure, mechanical properties, and residual stresses at the interface and in the deposited material. Direct Energy Deposition (DED) is an AM technology that offers the advantages of relatively large build volumes at high speeds, less material waste, and control of microstructure through the control of cooling rates and hence residual stresses, which is an often-overlooked parameter. Research on the effect of a laser-based AM process parameters on the residual stress behaviour in the substrate-deposit interface is limited. The interface region, between the substrate and the deposited material, is characterized by the presence of the fusion zone (FZ), partial melted zone (PMZ) and the heat affected zone (HAZ) which experience transient thermal histories resulting in thermal induced stresses and plastic strain gradients which will generate significant residual stresses at equilibrium conditions. In this study, Inconel 718 was utilized as a work material for both the substrate and deposit due its extensive use in the aerospace sector. Three blocks of Inconel 718 material were deposited by Direct Energy Deposition (DED) using three different laser powers, 550W, 750W and 950W, respectively onto Alloy 718 substrates. A coupled thermo-mechanical transient finite element (FE) model was developed to correlate residual stress behaviour to the process parameters. The contour method and X-ray Diffraction (XRD) were utilized to experimentally benchmark and calibrate the model as per the measured stresses. The as-deposited simulated residual stress profile and behaviour agreed strongly with the contour method results. Validation of the models allowed the further investigation of the residual stress field throughout the laser metal deposition and fully describe the effect of laser power on the magnitude of residual stresses.

Introduction

INCONEL 718, a nickel-based superalloy, is engineered to withstand extreme conditions, providing exceptional mechanical strength in challenging environments. With superior properties at elevated temperatures (up to 650ºC), including corrosion and oxidation resistance, as well as high resistance to creep and fatigue, it's widely utilized in aero-engine components and gas turbine disks[1]. Its remarkable mechanical performance stems from its refined microstructure and precipitation strengthening developed during solid solution and subsequent heat treatments.
Additive manufacturing (AM), notably Direct Energy Deposition (DED), has advanced significantly, optimizing process parameters for repair and remanufacturing purposes [2]. DED, derived from powder injection laser cladding and rapid prototyping, employs a localized heat source to create a molten pool on the substrate surface[3, 4]. The solidification of the molten pool, together with the cyclic local thermal expansion due to the heat input and the accumulated heat and subsequent contraction during cooling, lead to non-uniform plastic deformation and residual stress [5]. Residual stress fields in direct energy deposition have gained increased attention in recent years. Limited but growing research explores the correlation between process parameters and residual stress in laser metal-deposited components through experimental [6-8] or modelling approaches [9-11].

Methodology

DED of ten-layered IN718 solid blocks were deposited onto a IN718 substrate using a Nd:YAG fiber laser Fiber Laser operated with constant process parameters where the laser power varied from 550W to 750W to 950W for each of the three trials..
The as-deposited residual stresses were evaluated using the contour method and X-Ray diffraction.
The contour method offers the axial stress component, aligned with the deposition track, by sectioning each block using Electrical Discharge Machining (EDM) at a specified mid-width/length plane of interest. The release of stresses lead to deformation of the cut surface which can be captured through surface scanning and used for the back-calculation of the as-deposited residual stresses within the component prior to cutting. XRD measurements were carried out at the plane of the cut, in both directions, to complement the contour method measurements and provide higher resolution data at the interface. Then, a thermo-mechanical finite

element (FE) model was developed in Simufact® Welding to simulate and further investigate the residual stress evolution during the LMD process, which would be experimentally calibrated with the contour results by analysing the residual stress behaviour and magnitudes.

Results and Discussion

Figure 1a presents the bulk residual stresses obtained using the contour method, i.e. (axial stresses in the normal direction to the plane of cut). Figure 1b presents a comparison between the predictions of the FE model and contour measurements obtained for the 950W trial, at the location indicated by the dashed black line in Figure 1a. The observed stress profiles between simulated and experimental results were consistent through the thickness of the part, though peak values were different. Overall, as demonstrated by both FEA and the contour method, the interface (the region of interest), the tensile stresses remain relatively low comparative to the maximum stress experienced in the top layers of the deposited block, this was demonstrated by both the contour method and FEA model. However, a more in-depth analysis of the residual stresses in the bulk component is required.

The thermomechanical model concurs with contour measurements, illustrating a low stress region at the bottom of the substrate transitioning to a highly compressive region below the deposited material, reaching a peak at approximately 4mm below the interface. Both simulation and experimental methods identify the transition from peak compression to a relatively low tensile region towards the fusion line (~ -0.5mm) with a subtle stress pivot at the substrate/deposit nominal interface (0mm). Within the deposited region, the tensile stresses rose across the height of the build reaching a maximum in the FE model at around +2.8mm which is not captured in the contour method. Nevertheless, both the FE model and Contour method were in good agreement with regards to the stress assessment.

The magnitude of experimentally measured compressive stresses at the substrate interface were under-predicted by approx.30% and the maximum tensile stress in the deposited region were underpredicted by approx. 24%. Tensile stresses were observed within the deposit, with the maximum tensile stress occurring near the deposited blocks' terminus and a minimum around its midpoint. In this configuration, the substrate central regions experience compressive stresses due to compensatory tensile stresses experienced by the deposited bonded material. During the cooling phase, conduction primarily influences material shrinkage, with lesser impacts from convection and radiation. The clamps at the substrate's lower extremity also act as heat sinks. After deposition, the cessation of the beam causes rapid cooling at the peripheries and the clamped regions, leading to more substantial shrinkage along the deposit's free edges where heat is dissipated in the environment. This results in tensile stresses at the free surfaces and compressive stresses at the substrate bulk centre, with greater shrinkage and stress at the centre compared to the surfaces.

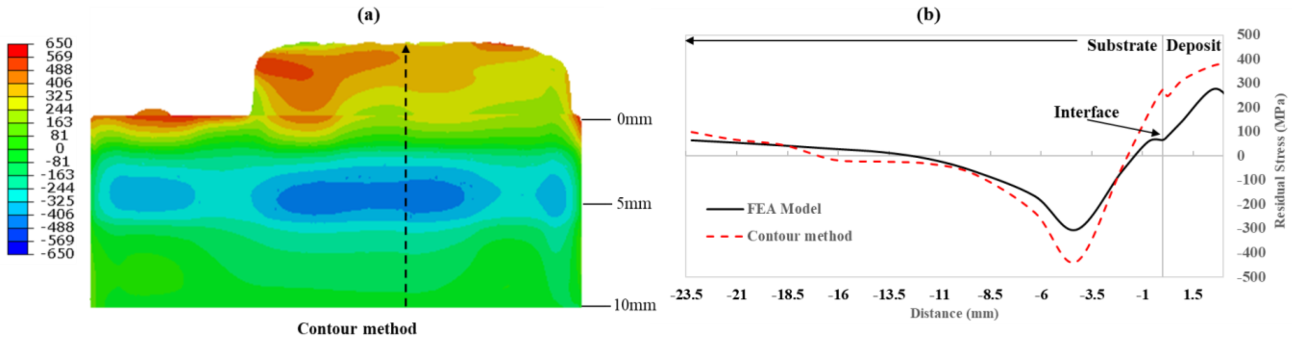

Figure 1 Residual stress measurement of the 950W specimen cross section using (a) the contour method and (b) comparing the experimental data from the contour method vs the FEA model.

Conclusion

Additive manufacturing induces intricate residual stress fields within the substrate and the deposited material, primarily stemming from thermal gradients, rapid cooling rates due to heat conduction and convection, moving heat sources, and solidification of molten material. Contour method revealed the RS field in all three specimens where, upon equilibrium, a large compressive band existed in the top-third of the substrate compensating for the tensile region band across the deposited region. A relatively low axial stress component was measured at the interface region which agreed with the simulated results. The thermal-mechanical coupled FEA was experimentally calibrated with the contour results. The RS distribution across the substrate and deposited region agreed well with the contour results, however discretion in the magnitudes was observed and this was likely to several influencing factors such as melt-pool dynamics, modelling approach and the mechanical properties of the additively manufactured material.

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