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MODELING OF THE DIRECTED ENERGY DEPOSITION PROCESS TO OBTAIN RESIDUAL STRESS STATES OF SIMPLIFIED TRACKS

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Abstract. *Direct energy deposition (DED) is an additive manufacturing process that utilizes a concentrated energy source to melt material while simultaneously depositing it through a nozzle. In this scenario, the surface integrity state plays a key role in determining the mechanical behavior of the part. Thus, the present study developed a DED model process using the finite element method to address the residual stress state in the substrate induced by the additive process. The model was developed through Simufact Welding software. Heat source, boundary conditions, sample geometry, meshing and trajectory were modeled to obtain a simulation setup. Specimens' profiles were measured to understand the effects of parametrization. Experimental evaluation was conducted by comparing the residual stresses numerically obtained against single-tracks DED samples. Model and samples showed a common behavior, which was tensile residual stress over the deposition area, whereas compressive stresses are present at the edges of the substrate. Assessment of the residual stress state showed that the combination of parameters associated with higher linear energy density leads to greater tensile stress. Thus, the DED simulation model was developed, and its results were consistent with experimental assessed values, providing the required validation for further implementation of it.*

Keywords: *Laser direct energy deposition, Finite element method, Residual stresses*

1. INTRODUCTION

Additive manufacturing (AM) appears as an alternative manufacturing possibility in which complex geometries are no longer an obstacle for the designer. AM can be generally defined as a process in which the product is manufactured by adding layers of material, controlled via computer numerical control (CNC). Thus, in an additive manufacturing process, there is increased design flexibility for the product and no raw material waste in the form of chips (Gibson et al., 2015).

Among the different existing AM processes, directed energy deposition (DED) method "stands out for its versatility in depositing both conductive and non-conductive materials, since it is directly based on the melt and deposition principle" (Kumar et al., 2021). Within DED, dense energy sources are used, such as laser or electron beam, in order to input enough heat to melt metallic materials. According to Ahn (2021), capabilities of the process are repair, restoration, remanufacturing (3R), porous coating, tailored materials, tailored structures, and thermal management.

Repetitions passing of the heat source, through the layers, leads to the so-called 'Thermal Cycling' effects. Such effects are related to the localized temperature increase and high cooling rates, which promote thermomechanical interactions to the part and influence on its final integrity state (Thompson et al., 2015). Addressing DED thermomechanical interactions by means of a numerical model might be challenging. Several approaches can be found on literature (Denlinger and Michaleris, 2016; Mukherjee et al., 2018; Song et al., 2020). Most of them neglects the deformation strain induced by solid state phase transformation, due to lack of material characterization.

The current work presents a conservative approach to model and validation of laser directed energy deposition (L-DED), focusing on thermal effects. Within this approach, a single-layer deposition is investigated, while different levels of heat input are employed. Thus, residual stresses are assessed for each level, seeking to comprehend such influence and, in future works, develop the model to repair applications.

2. OBJECTIVE

Prediction of a residual stress state can be accomplished by a well-calibrated simulation model. This paper aims to evaluate the influence of process parameters on residual stress distribution through the finite element method, in a directed energy deposition process. Such numerical evaluation was based on an experimental investigation of DED deposited tracks. The state of integrity of these specimens may indicate whether the conditions of the applied parameters were appropriate or not, since residual stress is correlated to crack nucleation.

3. METHODOLOGY

The work was developed in two stages: numerical modeling and experimental measurements. For the simulations, the thermal modeling, mesh refinement, boundary conditions and geometry design were addressed. For the experimental part, specimens were deposited from a previously defined processing window. Residual stress state and topography were assessed on the manufactured samples.

The definition of used material was driven by 3R application of L-DED process (Ahn, 2021). AISI D2 is a commonly used material for tooling industry (Cora and Koç, 2009), high demands of its application lead to large number of fracture occurrences. AISI D2 steel has M7C3 carbides in its structure. The elongation of these carbides and their high hardness end up generating a low edge stability. This low stability hinders the atomization process of the material to generate its metallic powder for deposition (Bombac et al., 2013). In addition, 420S stainless steel powder is a high carbon (C), high chromium (Cr) material used to repair drive shafts and couples (Ravi et al., 2013). So, AISI D2 and 420S were defined for substrate and deposition, respectively.

3.1 Numerical procedure

In order to replicate DED manufacturing conditions to reach residual stresses of deposited parts, a numerical model was developed. The finite element (FE) model was created using *Simufact Welding* software from *Hexagon*. In general, deposition modeling consists in defining the geometry (substrate and deposition), material properties, mesh creation, trajectory definition, linking the trajectory to the mesh, and modeling the heat source and process properties. Figure 1 presents a definition flowchart to build the simulation model.

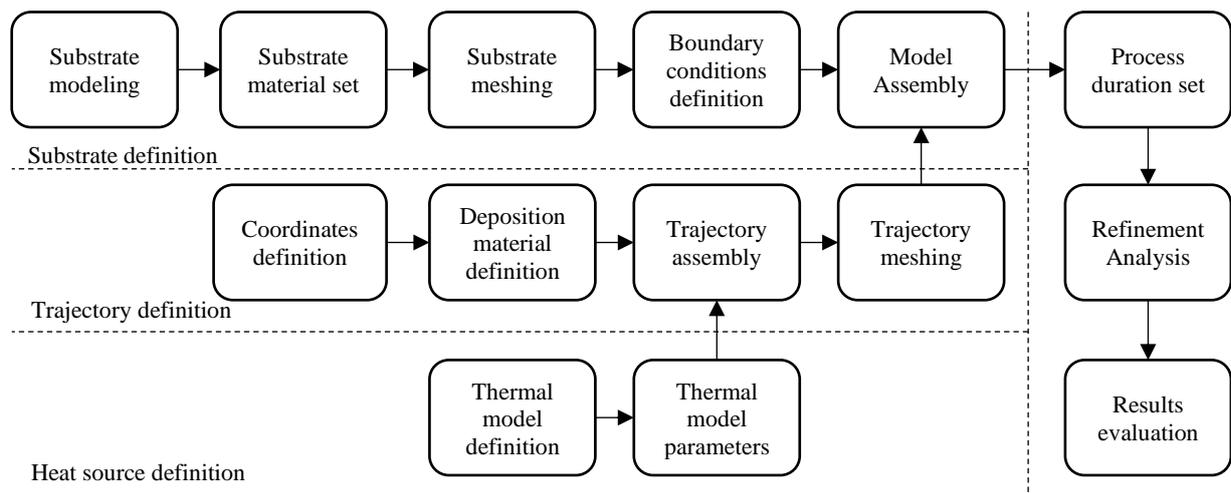


Figure 1. Flowchart of defining a model for DED. Three main routes are highlighted: part modeling, trajectory modeling, and thermal modeling.

The initial substrate geometry was defined based on welding references (Wimpory et al., 2009) with dimension of 17×120×180 mm. Its mesh was refined until an absolute variation of about 9.78% on the equivalent stress. The mesh was composed hexahedral elements (hex) of 2 mm, with eight nodes and eight integration points. Each node of this element has three mechanical degrees of freedom (DoF) and one thermal DoF. Regarding the material properties, the software

library lacks the material AISI D2, so an alternative approach was chosen, in which three chemically or mechanically similar steels were used: 316L, S690 and 16MnCr5.

Since during deposition the substrate is resting on the machine table, a geometric bearing boundary condition was modeled. Through this condition, a geometry identical to the substrate was positioned immediately below it. The contact between both parts applies to the process a displacement constraint in the Z axis and rotation constraints in the X and Y axis. Friction condition is numerically applied at the contact between the substrate and the boundary condition, which prevents inaccurate movements.

The trajectory followed by the laser beam was manually set by defining coordinates on the working area. This approach was chosen since the effects of a single-track is investigated, so there was no complex trajectory. The length of this layer was 60 mm and its cross-section profile, obtained nominally from previous experiments, was 0.5×1.5 mm (height × width). Considering the available library of the software, the definition of the material was done by similarity of mechanical properties, so S690 was selected. For the deposition mesh, one element/depth and two elements/width of the layer were used. Therefore, a Voxel mesh with 0.5 mm hexahedral elements was defined.

Simufact Welding software presents two possible thermal source models: Goldak's double ellipsoid and volumetric conical. The conical model was chosen since it best represents dense energy sources, such as a laser (Kik, 2020). A laser intensity diagram was used to evaluate the geometry and heat distribution of the source. This yields a base diameter of 1.206 mm, with an intermediate Gaussian (M) distribution, and an upper diameter of 1 mm. As nozzle-substrate distance, a conventional value of 1 mm was considered (Gibson et al., 2015). Figure 2 reports all the modeling performed and presents the final model.

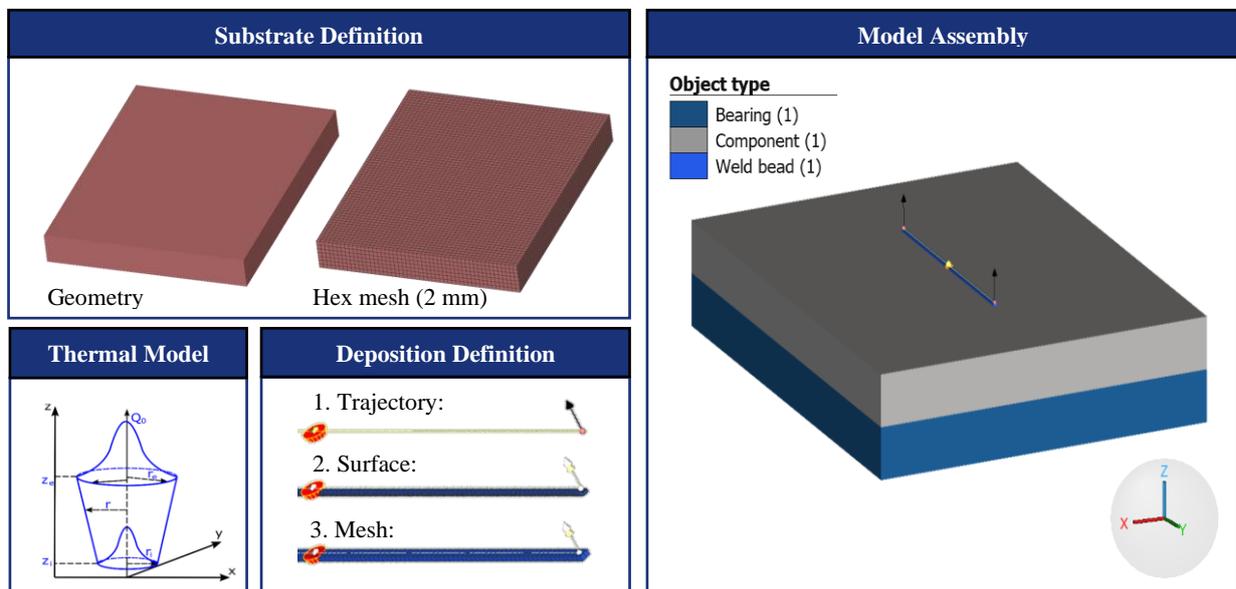


Figure 2. Setup of the DED simulation. Steps to get to the model assembly, going through substrate definition, thermal model, and deposition.

Once the model assembly is defined, it is possible to define the simulation time. The temperature gradient mechanism (TGM) is known for playing a key role in AM residual stresses (Thompson et al., 2015). To make sure that the stress state is indeed residual, the graph of maximum temperature as a function of time is observed (Fig. 3). From the graph, it is possible to see that in one hundred seconds, the substrate is already in equilibrium with the room temperature. Therefore, a simulation time of 150 s was used.

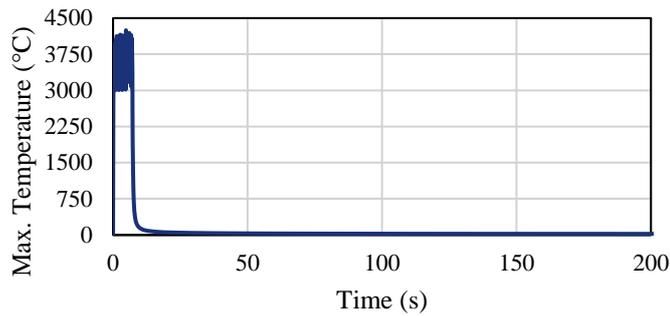


Figure 3. Maximum temperature in the model as a function of time. Method used to evaluate the stress stabilization time.

3.2 Experimental procedure

The DED specimens were manufactured with a *PRECO SL8600* equipment, equipped with a CO₂ laser operating at 10.6 μm wavelength. This machine has a working volume of 787×1200×2438 mm, and load capacity of 454 kg. Among L-DED parameters, power of the laser, scan speed and feed rate are major parameters affecting the bead formation (Ahn, 2021). In order to explore different heat inputs and its effects on residual stress states, scan speed and laser power were varied. Both parameters influence the so-called linear energy density (unit: joules per millimeter) incident on the bodies. Thus, according to the equipment capabilities, the following processing window was proposed in Table 1.

Table 1. Experimental parameters variation proposed for the present work.

#	Laser power (W)	Scan speed (mm/min)	Replicates
1	500	500	3
2	500	800	3
3	1100	500	3
4	1100	800	3
Total samples			12

The substrate geometry was initially defined according to welding references (Wimpory et al., 2009), so that residual stress gradients would be majorly absorbed along its dimensions. Aiming to reduce the amount of raw material needed, the substrate sizes were optimized according to simulation model.

The topography of single-tracks was evaluated aiming to correlate profile variation with previously selected parameters. For this purpose, the assessment was conducted with an *Alicona Infinite Focus G5+*, an optical profilometer capable of evaluating micro and nanometric scales. A magnification of 10× showed suitable resolution for the tracks' profiles, with its focal length of 17.5 mm and measurement area of 1.62×1.62 mm.

The residual stress state was evaluated through X-ray diffraction, by means of the $\cos(\alpha)$ method (Tanaka, 2019). The equipment used for this purpose was the *Pulstec μ-X360n*, with a collimator of diameter equal to 2 mm and chrome (Cr) radiation, which is capable of measuring αFe (211) and γFe (311) phases. The setup included the definition of a diffraction angle of 156.4°, exposure time of 50 s, diffraction plane (2, 1, 1), body-centered cubic (BCC) crystal structure, interplanar distance of 1.17 and Fitting Lorentz peak analysis method. The residual stresses were assessed perpendicular to the deposition, covering the area thermomechanically affected by the deposition. Figure 4 presents all the experimental methods used in the present work.

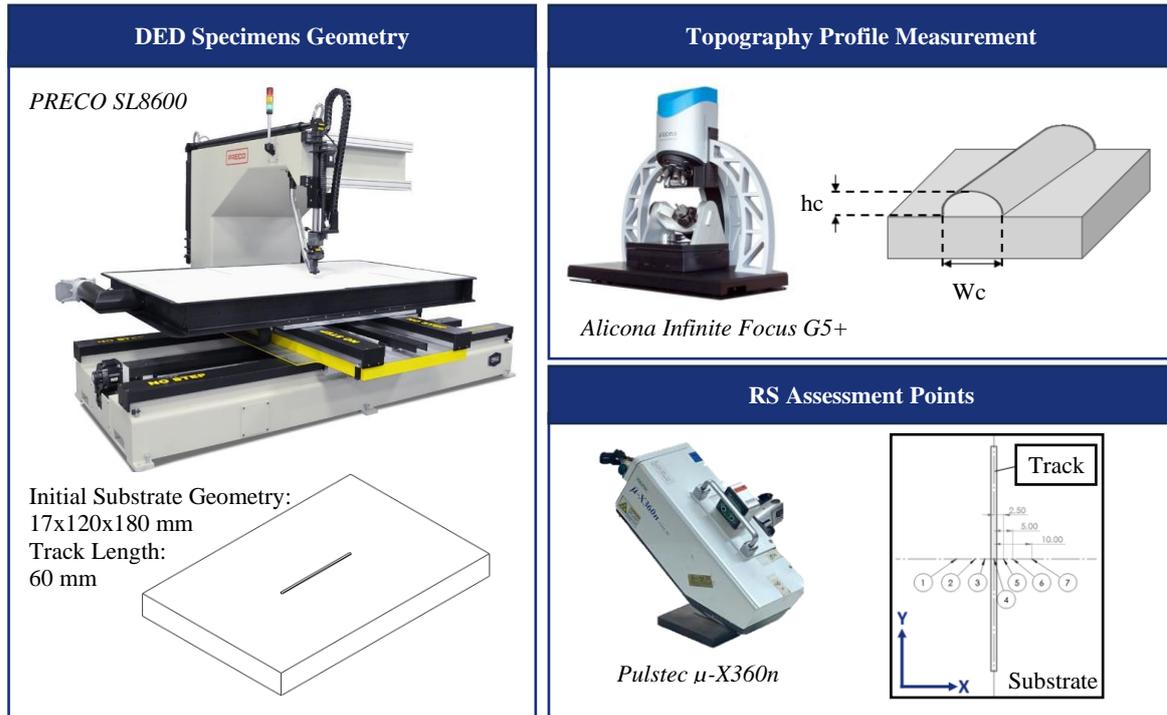


Figure 4. Experimental Techniques: DED samples deposition, topography profile investigation and residual stress (RS) assessment.

4. RESULTS AND DISCUSSION

A method for optimizing the substrate geometry based on the stress gradient in each direction was proposed. Such analysis was conducted by simulating the highest expected gradient, which was 1100 W and 500 mm/min. That condition presents the highest heat input of the proposed parameters window, in J/mm. An isometric view of the equivalent stress with cross-section cut on X-axis, due to symmetry, is shown in Fig. 5. Following the simulation cartesian reference, residual stresses were plotted.

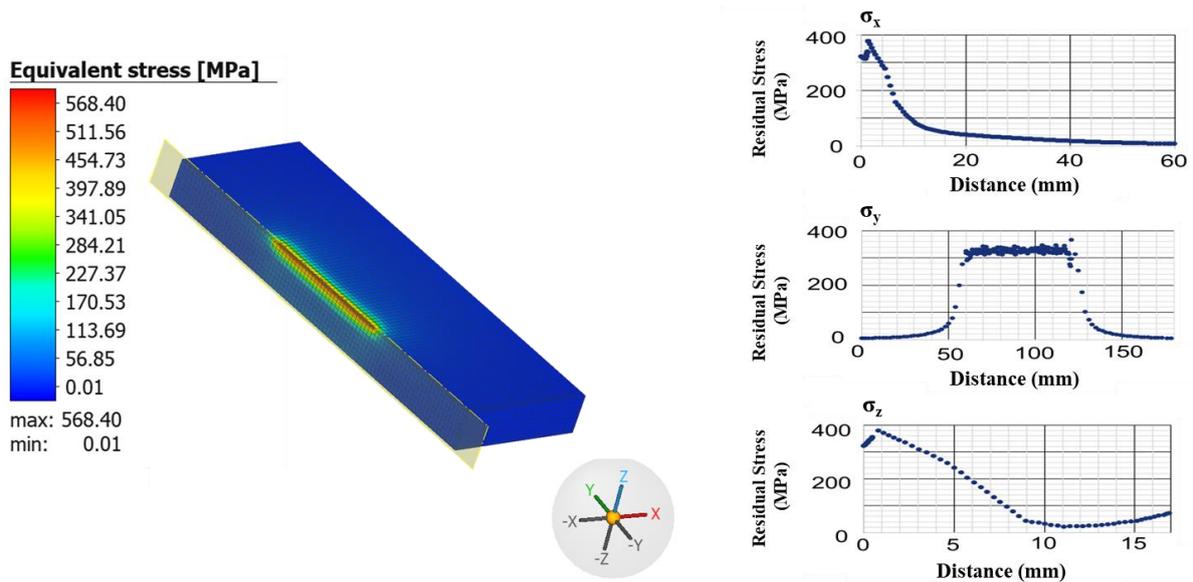


Figure 5. Equivalent residual stress in the initial 17×120×180 mm geometry at the set time of 150 s.

The highest equivalent stress levels were induced across the deposition area. Through the stress analysis, it is possible to observe that in all directions, there were clearances between the gradients and the edges of the substrate, allowing a reduction in the dimensions of the substrate. Therefore, the geometry was optimized to 15×100×125 mm.

To evaluate the influence of the parameters on the profile of each track, geometric evaluation was performed. Figure 6 shows the result of the optical profilometry evaluation. It is noticeable the presence of partial-molten particles on all tracks' surfaces, which is inherent to the DED process. Svetlizky (2021) points out that the percentage of unmelted powder can reach 80%, indicating the need for studies focused on optimizing material efficiency in DED.

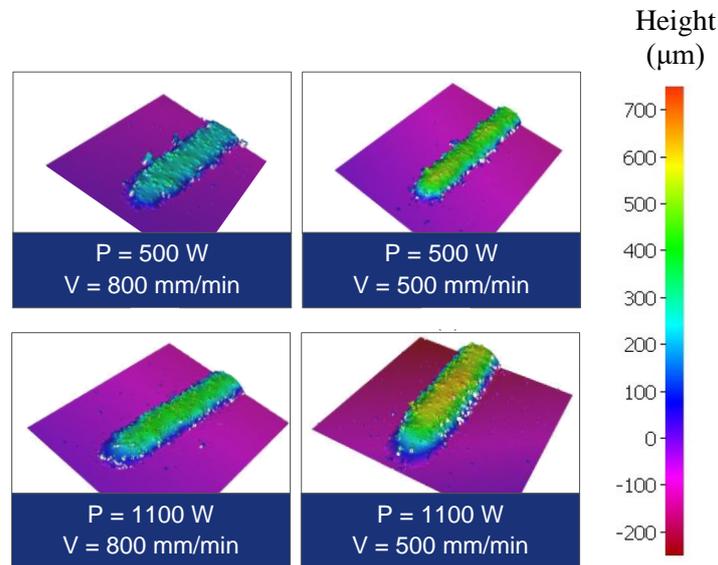


Figure 6. Edge surfaces of each parameter combination by optical profilometry.

Figure 7 presents the profile width and height measurements conducted on the deposited tracks, according to reference shown in Fig. 4. It is possible to observe increasing the linear density of the laser beam also increases the cross-sectional area of the profiles. Since the powder feed was constant in the experiment, it is possible to correlate the direct increase in heat input with the percentage of molten powder, thus generating such an increase in cross section.

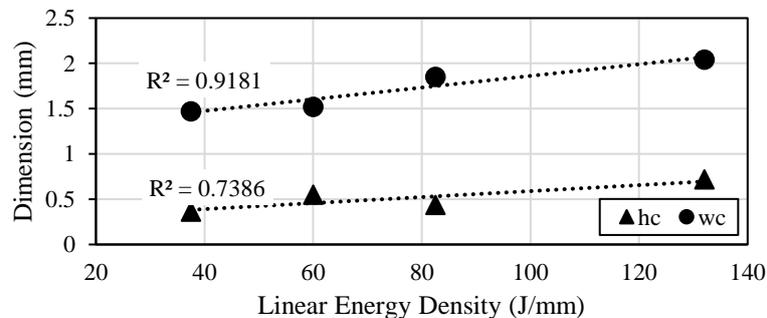


Figure 7. Specimens profile measurements by optical profilometry.

The residual stress was evaluated transverse to the direction of the deposition, in the central area of the substrate, as shown in Fig. 4. Residual stresses obtained numerically and experimentally, for each parameter condition, are shown in Fig. 8.

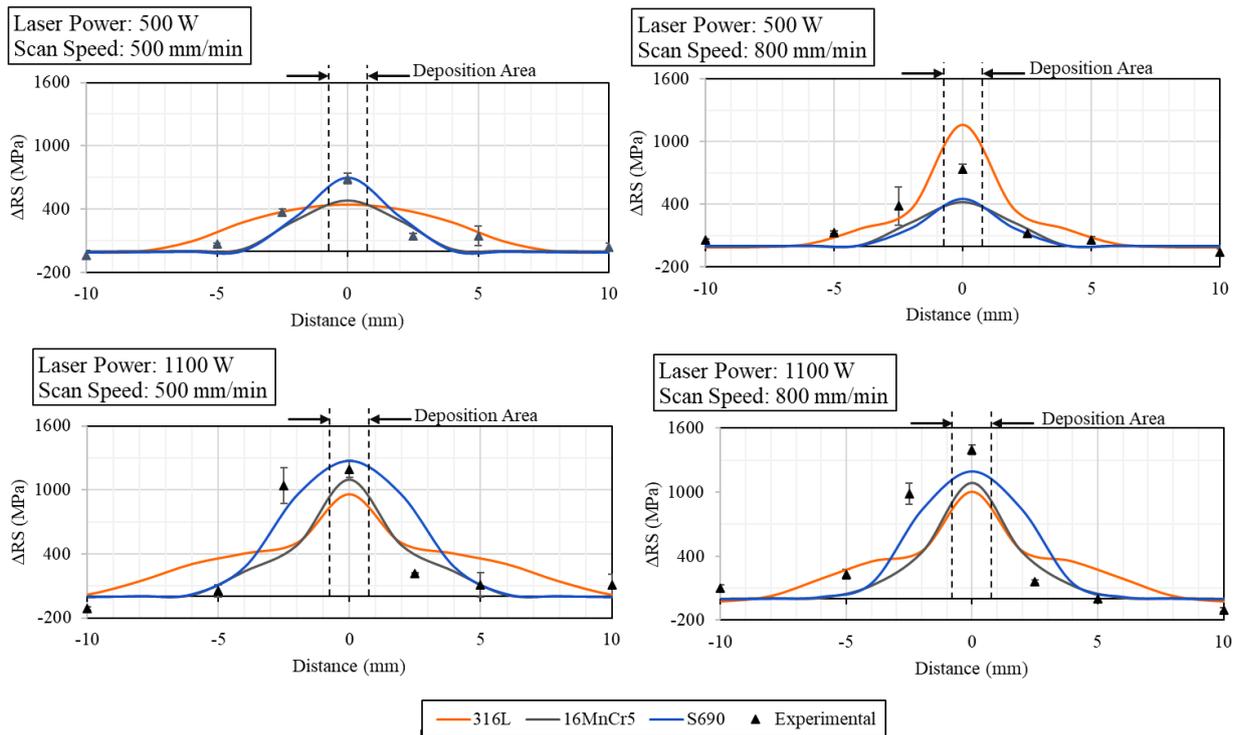


Figure 8. Residual stress comparison between the numerical model, for each material used, and the experimental assessment. A residual stress delta was used considering the variation from the measured point to the endpoint. The deposition area has been highlighted.

The transverse width of the deposition, corresponding to approximately 1.5 mm, has been highlighted. According to Zinn and Scholtes (2002), in welding when the amount of incident heat on the system is increased, the stress tends to be more tensile in the melting pool region and more compressive around the edges. This same behavior was observed in the experimental results presented in Figure 8. When the energy density increased across parameters, the stress became increasingly more tensile in the deposition region.

It was observed a divergence between the numerical model and the experimental results. When the stress was measured at one edge of the substrate, in a region where it should not be influenced by the deposition, the result was of the order of 1000 MPa compressive. Thus, experimental data showed a shift of the same magnitude from those seen in simulation, and therefore it was necessary to present the graphs as the ΔRS related to the average stress at the edges.

The main hypothesis to explain this behavior would be the manufacturing chain of the substrate. Rego (2016) shows the influence of the manufacturing chain on the residual stress state of a part. Thus, the compressive stress seen at the edge may be a result of the manufacturing process undergone by the part, since it did not undergo stress relief before deposition. Other possibilities that would explain such variation would be the phase transformation and the material used. It is known that phase transformation can induce changes in the macroscopic stress state through volumetric and displacive effects on grain boundaries (Zinn and Scholtes, 2002). For simplification purposes, and considering the available material properties, structural transformation effects were not considered in the present simulation. Finally, the change of the material used in the experiment to the material of the simulation cannot be discarded as the source of divergence of the results.

5. CONCLUSION

This work aimed to model the DED process by applying a finite element simulation method. So, the single-track geometry was chosen to simplify the analysis and reduce the number of variables. The choice proved to be effective, since studies could be performed with the specimens, using less material in the deposition.

Regarding the topography of the tracks, a variation in the profile was noticed as a function of the amount of heat introduced into the system. A four times increase in the amount of heat, represented a variation of 38.4% in the width and 98.6% in the height of the layer. Thus, considering the concept of near net shape (NNS) (Thompson et al., 2015), it is noted the need for optimization of parameters specifically aimed at the part to be designed. These optimizations should

be previously performed using the predictive simulation model, to determine the representative dimensions of the layer to be used, which are reflected in the integrity condition of the part.

Regarding the residual stress state, the sensitivity of the influence of each parameter could be revealed. The increase of the linear energy density is responsible for the increase of the tensile stress in the deposition area. In the window of parameters adopted, the definition of laser power ended up generating a greater influence on the residual stresses state when compared to scan speed. Finally, those influences could be numerically verified using the proposed model. Once this tool was validated, it may be applied in future applications such as repair and fabrication of parts by L-DED.

6. ACKNOWLEDGEMENT

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