Title:
Residual Stress Modelling of Junction Structures using Powder Injection Laser Cladding of Martensitic Stainless Steel on low Alloyed Carbon Steel Substrate

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Introduction:
Laser cladding is an additive manufacturing (AM) technique that is used broadly to create new parts or repairing existing parts. During laser cladding layers of material are deposited and fused using a powder feedstock and laser power, respectively. The cyclic rapid heating and solidification of the deposited material during the laser cladding process leads to the formation of residual stress, which results in distortion of the part and substrate.

As with other AM processes, in laser cladding the 3D part is sliced into 2D layers and tool path strategies are developed to build the part. Unlike machining, the tool path strategy is an important factor in mechanical properties and surface quality of the built part [1], [2]. For bead deposition AM processes such as laser cladding, both the profile and the mechanical properties of junctions are affected by the tool path deposition strategy.

Shi et al. [3] proposed a Euler path planning algorithm that made a continuous path to produce multimode and multi-trajectory data. J.R Honnige et al [4] investigated the effect of vertical inter-pass rolling and thermalstress relieving on Ti-6Al-4V intersections produced by wire + arc additive manufacturing. Thermal stress-relieving significantly reduced the residual stress in the intersection structure. Inter-pass rolling improved the grain refinement of the intersection. G. Venturini et al [5] classified cross features into multiple types and used single path deposition strategy via a developed CAM software to create each structure with the aim of minimizing the geometrical errors. Han et al. [6] utilized three different scanning strategies to build samples and discovered that the flatness and surface roughness of a square-framed scanning strategy are better than the zig-zag patterns.

Runsheng Li et al [7] proposed a novel path strategy for intersections in wire arc additive manufacturing. Their proposed End Lateral Extension method eliminates the tightened defects at an intersection, and improved the tensile properties of junctions. Much research work has been done on the performance of different path strategies for printing intersecting structures. The abovementioned studies suggested and applied different path strategies for cross structures. They mostly discussed the impact on the geometry and the profile. There are limited studies investigating the mechanical properties of intersections.

Main ideas:
This research evaluates the residual stress and the hardness in laser cladding for generating higher quality junctions with respect to the movement direction of the nozzle or deposition direction. Several scenarios are explored. Junction structures with three joints, four joints and five joints with different path deposition directions have been considered for this study as showed in Fig 1.

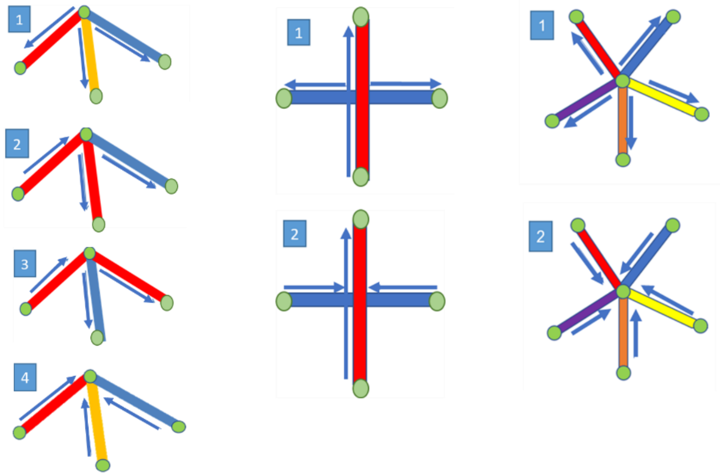

Fig. 1: Junction structures and deposition sequences (red deposited first then blue), and the deposition directions.

Numerical Simulation

Three unique junction structures were considered, and numerical simulations were developed for each one incorporating different path scenarios. The single bead single layer deposition of martensitic stainless steel on low alloyed carbon steel is studied for each configuration. To model the laser cladding process, three software packages were used. The computer aided design software SOLIDWORKS was used to create the junctions' structure and the substrate. The created components were then imported into the HYPERMESH package to generate the appropriate mesh for the finite element analysis (FEA). A fine mesh was generated for beads and the substrate. Following generating the mesh the file was imported into the simulation software package, SYSWELD. Using the SYSWELD software, the laser cladding scanning strategy was defined by selecting the start and stop points of laser movement within the bead and the substrate. In order to simulate the laser cladding process a Gaussian heat source distribution was applied along the scanning path. The Gaussian heat source is demonstrated in Fig. 2 and defined by equations 1 to 3 [8].

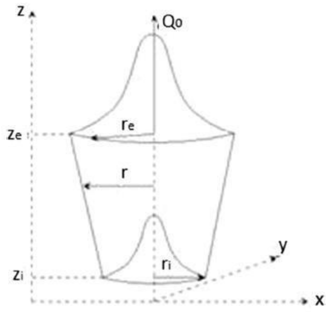

Fig. 2: The Gaussian heat source schematic [8].

$$F = Q_0 * e^{\left(\frac{r^2}{r_0^2}\right)} \tag{1}$$

$$r = (x^2 + y^2)^{1/2} \tag{2}$$

$$r_0 = r_e - (r_e - r_i) * (z_e - z)/(z_e - z_i) \tag{3}$$

F is the source intensity, Q0 is the maximum source intensity, re is the keyhole top radius at z=ze, and ri is the keyhole bottom radius at z=zi. The laser penetration depth was adjusted to 1.5 times of each layer. The parameters used in simulation are reported in Table 1.

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Process parameter	Value
Heat source	beam
Velocity (mm/sec)	10
Energy (J/mm)	90
Efficiency (Percentage)	100

Tab. 1: Process parameters used in the simulation.

The substrate was clamped at four corners in the back of the plate using rigid boundary conditions. Succeeding the build process, the part is air cooled to the room temperature via convective, conductive and radiative heat transfer. The element activation and deactivation method was used in SYSWELD to model the layer-by-layer deposition of material. In this method all elements are generated prior to the simulation starting, however the elements are not activated until the laser beam reaches to that element. Moving the laser beam along the deposition direction, the elements become activated along the path. The material properties of low alloyed carbon steel as a function of temperature are defined in Fig. 2.

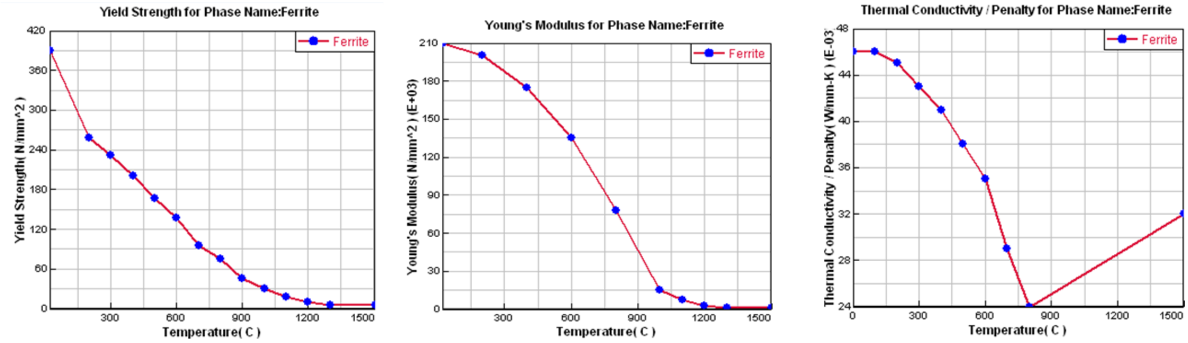

Fig. 3: Yield strength curve, Young's Modulus temperature dependent and thermal conductivity properties of low alloyed carbon steel WS355J2G3.

Fig. 3 illustrates a schematic of SYSWELD building process. The meshed structure, the thermal map and the melt pool generated by laser. The Simulations was run on a double core on a computer with 32 GB of RAM. The time needed to complete each simulation scenario was around 18 hours.

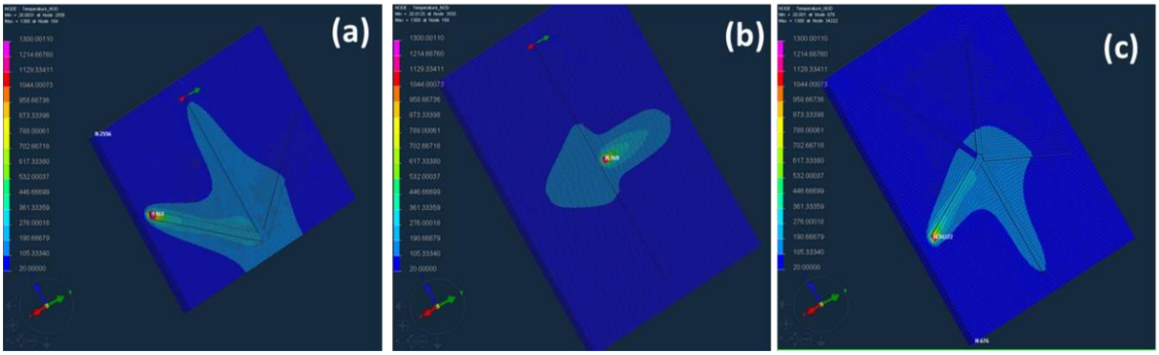

Fig. 4: The temperature profile of the junction structures showing a) three, b) four and c) five joints configuration.

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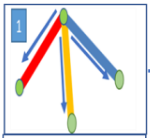
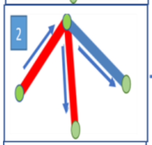
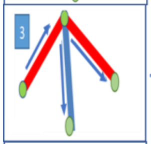
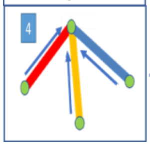
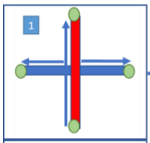
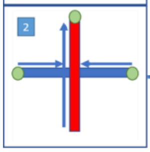
Results and discussion:

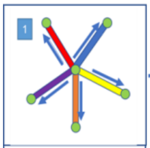
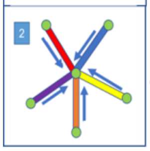
The results for this thermo-mechanical finite element analysis are shown in Tables 2,3 and 4. The residual stresses in three principal directions are summarized. It can be seen that the deposition order has an influence on the junctions' resulting residual stresses, especially the compressive stress values.

Junction structure	XX (MPa)		YY (MPa)		ZZ (MPa)	
	max	558.7	max	255.2	max	655.32
	min	-733.66	min	-454.8	min	-802.7
	max	793.5	max	1414.41	max	905.34
	min	-1774.09	min	-1329.56	min	-1877.06
	max	559.56	max	306.45	max	640.83
	min	-992.35	min	-483.52	min	-911.18
	min	572.37	max	713.26	max	643.5
	max	-1738.03	min	-1255.48	min	-1526.6

Tab. 2: Simulated residual stress results for three joints junction.

Junction structure	XX (MPa)		YY (MPa)		ZZ (MPa)	
	max	670.9	max	237.69	max	669
	min	-613.34	min	-412.62	min	-875
	max	718	max	235.96	max	670.27
	min	-744.03	min	-494.2	min	-848.5

Tab. 3: Simulated residual stress results for cross junction set.

Junction structure	XX (MPa)		YY (MPa)		ZZ (MPa)	
	max	539.1	max	250.9	max	567.5
	min	-564.9	min	-374.6	min	-540.9
	max	563.6	max	485.1	max	613.53
	min	-760	min	-613.4	min	-809.09

Tab. 4: Simulated residual stress results for five joints junction set.

Conclusion:

Residual stress was investigated for junction structures using laser cladding. Thermo mechanical simulations were developed using FEA method to assess the effect of deposition direction on formation of residual stress in junction structures. The following conclusions can be achieved from this study:

- Tensile residual stresses were observed close to the base plate and compressive residual stresses in the beads of the junctions for three, four and five joints configuration.
- The tensile residual stresses in the x, y and z directions for the second scenario in the three joint junction structure have the most extreme values compared to the other scenarios. This deposition solution could lead to performance issues in the field.
- Both deposition direction options for the cross structure showed nearly similar thermo mechanical performance; therefore, the configuration is less problematic.
- The second scenario of the five joints junction had the greatest amount of residual stress.

The influence of AM tool path solutions must consider performance conditions. There are significant challenges to managing both the geometry and residual stresses, as localized high stress areas can result with a component consisting of multiple junctions. Multi-layer and heat only passes will be included to determine their influences on the resulting residual stresses.

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