POLITECNICO MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

EXECUTIVE SUMMARY OF THE THESIS

Numerical Evaluation of Thermo-Mechanical Residual Stress Induced During Cold Spray Additive Manufacturing

TESI MAGISTRALE IN MECHANICAL ENGINEERING – INGEGNERIA MECCANICA

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ACADEMIC YEAR: 2020-2022

1. Introduction

In cold gas dynamic spraying (CGDS) process, also referred to as cold spray, particles are accelerated towards a substrate by a preheated compressed carrier gas. Due to insignificant heating of impacting particles, many unfavorable effects commonly caused by high temperature like recrystallization and oxidation are avoided. Besides cold spray, deposits are commonly characterized with compressive residual stresses due to the nature of the referred technology. The peculiarity of the cold spray process is the presence of two contradictory factors affecting the residual stress state by induction of compressive stresses due to high impacting velocity and the simultaneous opposing annealing effect due to exposure to the heated gas. The mechanisms potentially influencing the added up residual stress in cold spray deposits include quenching the sprayed material due to high cooling rate, temperature gradient in multi-pass deposition processes, the effect of thermal mismatch between the coating and substrate materials, and the peening effect due to the plastic deformation of particles impacting the substrate.

2. Developing numerical method to predict residual stress prediction in 2D

A detailed numerical model was developed to predict the induced residual stress in cold spray deposited layer, starting from simulations made in the case of other thermal spray technologies and adapting them for the specific case of cold spray deposition. The methodology is divided in two main steps of ''Explicit Particle Impact Analysis'' and ''Implicit Layer Deposition Analysis''.

In the 1st step, a 2D axisymmetric single particle impact model, with defined particle size, velocity and temperature of the substrate and particle, has been considered.

From the explicit single particle impact analysis, the radial and axial stresses right below the point of impact of particle would be extracted to be used as the stress field that has to be recreated after the deposition of each layer; layer thicknesses would be considered equal to the splat height extracted from the single particle impact analysis.

Then in the 2nd step, to input the peening stress while modelling the layer build-up, with an iterative corrective approach, the peening stress would be induced in the assembly of one layer and substrate. Later, the same method would be used iteratively to induce the effect of addition of subsequent layers to the assembly of layer-substrate.

On the other hand, to consider the contribution of the thermal stresses, the knowledge of thermal field evolution during the layer deposition is necessary. Hence, a heat transfer analysis is conducted to obtain the thermal field by considering the heat flux of the impinging gas, duration of heat flux input during addition of each layer, the initial temperature of assembly and the effect of radiation and convection between the part and environment. This analysis provides us with the thermal field history during the layer deposition process. Using these results, a coupled thermo-mechanical analysis can be conducted to measure the residual stress induced by thermal expansion mismatch and other thermal effects.

2.1. Single particle impact analysis

A two-dimensional axisymmetric finite element (FE) model of a stainless steel 316 (SS316) particle impacting on a cylindrical SS316 substrate is developed. The particle impact is analyzed as a coupled thermal–displacement phenomenon under high strain rates.

The temperature of the particle remains below its melting point during spraying. Thus, the impact, deformation and cooling stages are in solid state [1] . The model considers 90% of the kinetic energy being transformed into heat [2], with the remainder of the energy being dissipated as plastic deformation and rebound kinetic energy[3]

The response of the impacting particle and the underlying substrate under such loading conditions is strongly affected by the strain, strain rate, temperature, and microstructure of the material. Therefore, an appropriate constitutive equation for definition of the material properties is essential for modelling such processes. The proposed constitutive relation by Johnson and Cook (J-C) is widely used in numerical models involving high strain rates and temperatures [1] . J-C parameters of SS 316 are listed in Table 1.

Table 1_ J-C parameters of SS 316 [1]

Johnson–Cook parameters	
Yield stress [MPa]	388
Strain hardening coefficient [MPa]	1901
Strain rate sensitivity	0.02494
Thermal softening parameter	0.6567
Strain hardening exponent	0.8722
Transition temperature [K]	298
Melting temperature [K]	1643
Reference plastic strain rate [1/s]	1e-5

Bulk material thermomechanical properties were considered both for the particle and substrates, due to unavailability of properties specifically for atomized powders.

Cylindrical substrate dimensions are 1.5 mm radius and 1.5 mm height. These substrate dimensions were considered to avoid edge effects compared to the particle’s dimensions.

From the simulation output, the radial and axial residual stress distributions were measured along the axis of symmetry through the substrate depth, at 400ns after the onset of the impact. This time period is enough to allow for kinetic energy dissipation, particle spreading, substrate deformation and temperature stabilization[1] .

Comparable results were obtained with respect to previous studies [1], as the extracted radial and axial stress profile in the axisymmetric axis of the structure show close correspondence. This can be seen in the Figure 1. It is worth mentioning that even though the Arbitrary Lagrangian Eulerian method (ALE) has been used it proved to be unable to precisely model the jet shape. In the case of high element distortion, the Coupled Eulerian Lagrangian method (CEL) would have been more efficient to capture the jetting phenomenon.

2.2. Peening Stress Prediction

The computational cost of the explicit analysis does not justify modelling the coating process on a particle-by-particle impact basis. Further simplification based on an implicit methodology is required. So, layer by layer deposition for modeling the coating growth was considered.

An iterative corrective approach was adapted to obtain similar radial and axial stresses in the substrate after the addition of the first layer compared to the stress profiles extracted from single particle impact analysis.

The iterative approach included application of the compressive loads and correction of the applied loads to obtain similar stress profiles as single particle impact analysis. The iterative correction of the applied loads will continue till the difference between the area under the target and the imposed stress-depth curves is less than 10%.

Two methods were applied to obtain closer results with respect to the ones reported by Oviedo et al [1], as described below:

1. Substrate: Axial Pressure, Substrate-layers: Radial Pressure Predefined Radial Initial Stress:

In this method to induce the axial stress profiles extracted from single particle analysis, axial pressures are applied in the top 0.2 mm of the substrate. For induction of radial stress, predefined radial stress fields are applied in the substrate. The mentioned predefined stresses are applied in the top 0.2 mm of the substrate and the radial pressure are applied on the right free edge of the substrate to obtain stress profile independent of the radial position in the substrate. Besides, based on the stress evolution in the central node of the particle in the single particle analysis, stress is induced in the added layer representing the first layer of deposited material by axial pressures and predefined initial radial stresses. The representation of the obtained radial stress based on iterative corrective approach and the radial stress profile based on single particle impact analysis are presented in Figure 1.

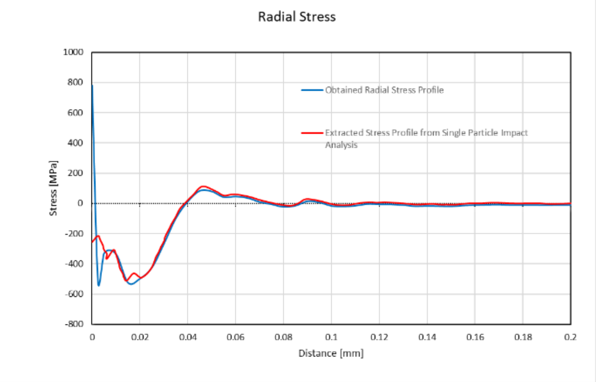

Figure 1_ Comparison of the radial stress profile created after addition of a single layer and the radial stress profile extracted from the single particle impact analysis

Generalization of the loads for 40 layers, the peening stress after addition of 40 layers was obtained. The comparison of the obtained radial stress and the reported radial stress based on Oviedo et al [1] concerning evaluation of induced residual stress during high impact coatings is presented in Figure 2.

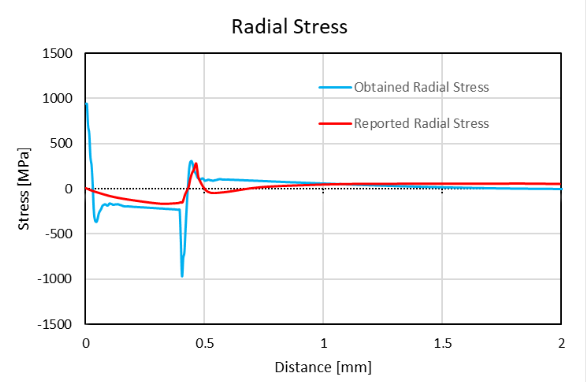

Figure 2_ The comparison of the obtained radial stress and the reported radial stress based on Oviedo et al [1] after addition of 40 layers

2. Substrate-Layers: Predefined Radial Initial Stress

In this method the same iterative corrective approach is used on the applied loads. However, during the layer deposition analysis the two stress components are treated independently and induced by predefined stress fields in the substrate, based on the stress profile from the single particle impact analysis, in conjunction with predefined stress fields assigned to the added layer. The values for the latter stress field are determined based on the stress evolution in the central node of the particle in the single particle impact analysis.

The representation of the obtained radial stress based on iterative corrective approach through use of this method and the radial stress profile from single particle impact analysis is presented in Figure 3.

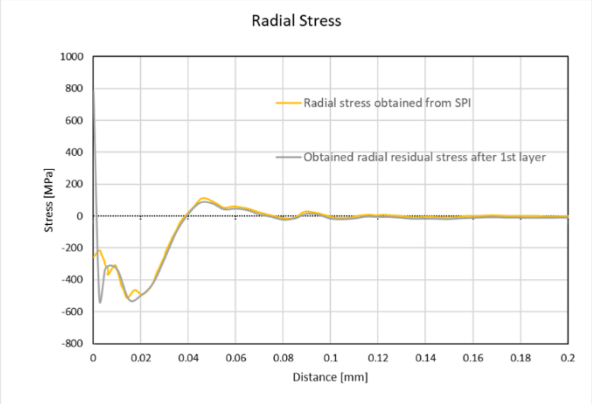

Figure 3_ Comparison of the extracted radial stress from single particle impact (SPI) analysis and the obtained radial residual stress after addition of the first layer

Then by generalization of the loads for 40 layers, the peening stress after addition of 40 layers was obtained. Comparison of the obtained radial stress and the reported radial stress based on Oviedo et al [1] is presented in Figure 4.

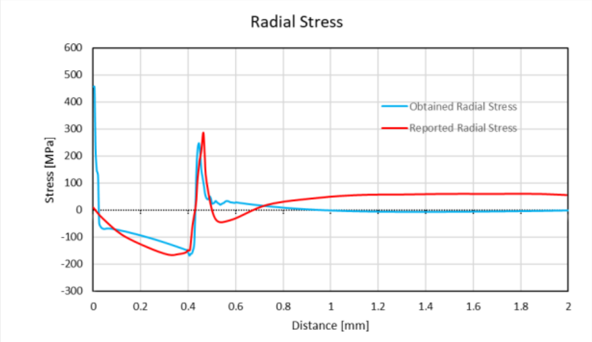

Figure 4_ The comparison of the obtained radial stress and the reported radial stress based on Oviedo et al after addition of 40 layers

2.3. Thermal Stresses

The thermal stresses generated during coating deposition were predicted using a nonlinear, sequentially coupled, thermomechanical FE analysis performed in two stages. To obtain the thermal field, the effect of convection and radiation is considered.

In the first stage, a heat transfer analysis was performed to obtain the thermal history of the specimen. The time-dependent temperature distribution was repeatedly applied for each layer to accumulate the final residual stress distribution [1,3].

The comparison of the obtained radial thermal stress and the reported radial thermal stress based on Oviedo et al [1] is presented in Figure 5.

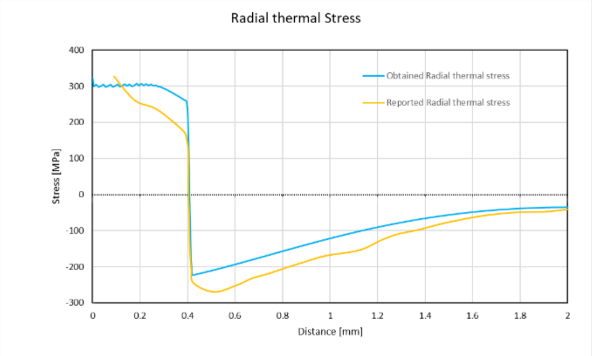

Figure 5_ Representation of the comparison of the obtained radial thermal stress and the reported radial thermal stress based on Oviedo et al after addition of 40 layers [1]

3. Experimental tests

Impact Innovations' cold spray System 5/8 was used to spray the specimens. System's maximum operating pressure and temperature are 50 bar and 1100 °C respectively, . The substrate was made of stainless steel 316, with the nominal dimension of 30×30×5 mm^3, cut from a sheet with the thickness of 5 mm, and simply brushed afterwards with no specific pre-processing. The experimental work consists of deposition of SS316 on substrate of the same material. 1st test was done by deposition of 1 layer, 2nd test with deposition of 2 layers considering bidirectional scanning strategy, the 3rd test, with deposition of 2 layers considering cross-hatching scanning strategy, 4th test, with deposition of 10 layers considering cross-hatching scanning strategy, and 5th test with deposition of 10 layers considering bidirectional scanning strategy.

Residual stress measurements were performed using AST X-Stress 3000 portable X-ray diffractometer. In depth measurements were performed via layer-by-layer electropolishing using Struers LectroPol-5 on a circular area with a diameter of 1 cm² using an electrolytic solution of 94% CH_3COOH, 6% $HClO_4$ at a voltage of 20V. A Mitutoyo micrometer (IDCH0530/05060) precisely quantified the quantity of material removed at each step. After measurement process, in order to take into consideration, the stress relaxation effect due to layer removal in electropolishing, the results were corrected based on Moore Evan's Theory. [4]

The measured radial residual stresses in the samples are presented in Figure 6.

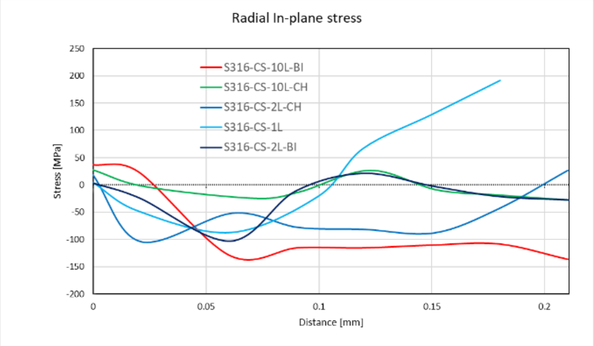

Figure 6_ experimentally measured radial residual stress in the samples

4. Comparing simulation results with experiments

The process gas temperature was 700°C, with a pressure of 35 bar. The powders with the mean diameter size of 30 micron are fed to the system by amass rate of 20 gr/min.

Following the procedure described in the section on Single particle impact analysis, the peening stress profile in the axisymmetric axis of the substrate was extracted.

Thermal stresses were also estimated using the method mentioned in section Thermal Stresses.

Following the methods described in section Peening Stress Prediction, the radial peening stress was obtained.

The total radial residual stresses with consideration of both peening and thermal stresses based on the method 1 is represented in Figure 7.

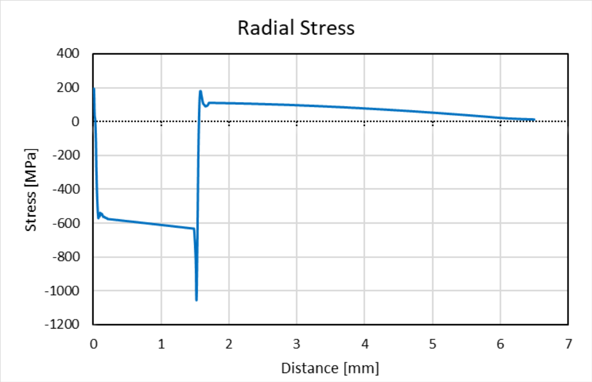

Figure 7_ The total radial residual stress with consideration of peening and thermal stresses with method 1 after addition of 1.5mm of deposited SS316

The total radial residual stress with consideration of both peening and thermal stresses following the method 2 is represented in Figure 8.

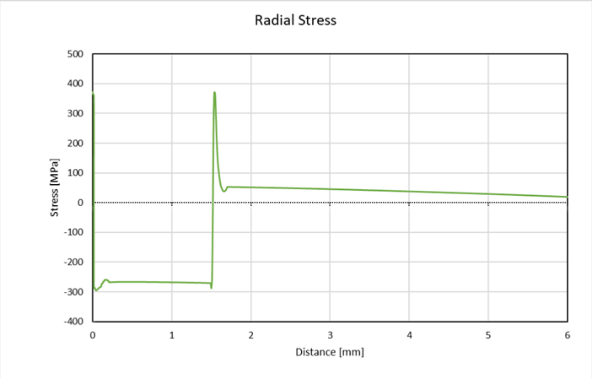

Figure 8_ The total radial residual stress with consideration of thermal stress with method 2 after addition of 1.5mm of deposited SS316

In the same manner described in the second method, peening stresses and total stresses in the radial direction for the 1- layer test and 2-layer bidirectional tests are obtained. Based on the thickness of the added layers and the thickness of the particle in the single particle impact analysis, the mentioned experimental tests are modeled in order by addition of 13 and 23 layers on the substrate.

In Figure 9 in order radial thermal stresses, radial peening stresses and radial total stresses after addition of 13, 23 and 82 layers are represented. Obviously based on Figure 9, the stress relaxation effect is noticeable after consideration of the thermal effect.

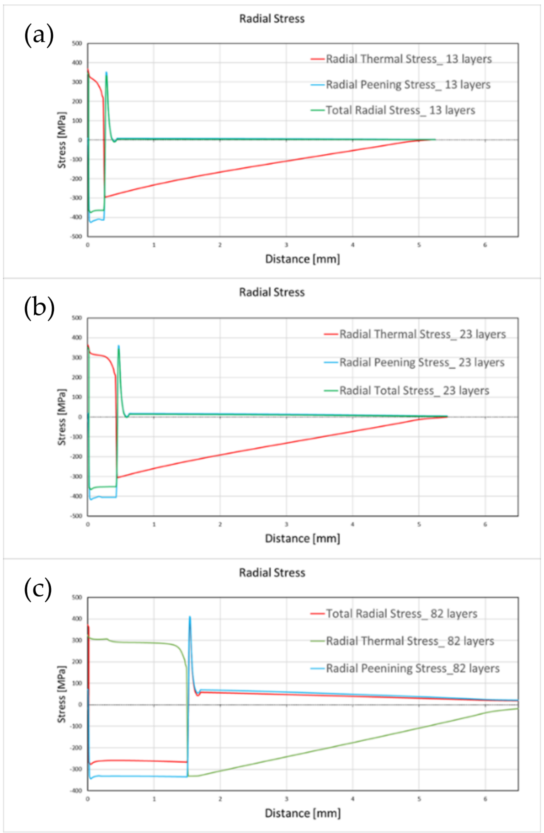

Figure 9_ Representation of the radial thermal stresses, radial peening stresses, and radial total stresses after addition of (a): 13 layers, (b): 23 layers and (c): 82 layers

It should be mentioned that even though the amplitude of the stresses' change by addition of the layers, the radial thermal stresses, radial peening stresses, and radial total stresses for all the models including 13, 23, and 82 layers follow the same trends.

5. Conclusions

In the current work, a multi-step finite element model was developed to estimate the residual stresses generated in the deposit and substrate during cold spray additive manufacturing. The model considers the contribution of two major features in developmentt of residual stresses; these are the peening effect caused by multiple subsequent impacts with high kinetic energy, and the effect of exposure to heated gas that can cause partial stress relaxation during the spray process. Compariosn of the results with available models develpped for other thermal spray technologies showed a very good match. However, when considerably increasing the number of the layers to reach the high deposit thickness that resembles the application of cold spray for AM applications, the results showed less quantitative agreement with the experimentally measured data, despite correctly predicting the evolution trend of the stresses. Future work can include:

- The usage of multiple particle impact analysis as the first step of the process for the acquisition of the peening stress as the number of layers increases.
- The usage of better generalization method for addition of the layers. Instead of addition of the initially obtained corrected loads over and over, based on the multi particle impact analysis, an extrapolation can be obtained to be used in the generalization phase by checking the trend of stress after the successive impact of particles. Since the addition of stress will probably not be constant as considered in this project and a multitude of papers concentrating on evaluation of residual stresses during high velocity impact techniques.
- The use of temperature dependent heat transfer coefficient during process for better acquisition of the thermal stress.
- In this project due to unavailability of the Johnson-cook parameters and thermomechanical properties of stainless-steel powder in the literature, the deposited material is treated the same as the bulk material. These simplifications contribute to error in the obtained results. The Mechanical behavior of the deposited material should be considered different from the bulk material of the substrate to have more realistic results.

6. References

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7. Acknowledgements

I would like to express my special thanks of gratitude to my family, especially to my dearest, my father, who has recently passed away. The great man undoubtedly unconditionally supported us during our lives. I would remember the sweet memories of my father till the moment I breathe. My father is gone, but his memories are alive. I hope he rest in peace. I am extremely grateful to pay my special regards to Dr. Sara Bagherifard, my thesis supervisor, Amir Ardeshiri Lordejani and Professor Mario Guagliano my thesis co-supervisors, for their invaluable advice, continuous support, and encouraging spirit. I would also like to thank Giuseppe Ghilardi, and Ludovica Rovatti, for their great contribution during experimental phase of the thesis.