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A STRATEGY FOR THE NUMERICAL SIMULATION OF METAL DEPOSITION AND MULTI-PASS WELDING PROCESSES

N. Dialami [*], M. Chiumenti [*], C. Agelet de Saracibar[†] and M. Cervera [†]

[*] International Center for Numerical Methods in Engineering (CIMNE)
Universidad Politécnica de Cataluña
Campus Norte UPC, 08034 Barcelona, Spain
e-mail: narges@cimne.upc.edu, Michele@cimne.upc.edu

[†] ETS Ingenieros de Caminos, Canales y Puertos
Edificio C1, Campus Norte UPC
Gran Capitán s/n, 08034 Barcelona, Spain
e-mail: agelet@cimne.upc.edu, cervera@cimne.upc.edu

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Summary. In this work a numerical model is developed to accurately predict temperature evolution and distortions associated to the successive welding layers deposited during the multi-pass welding and metal deposition processes (MD).

1 INTRODUCTION

The aim of this work is predicting accurately the temperature evolution, residual stresses and distortions, by coupling the heat transfer analysis with the mechanical field due to the successive welding layers deposited during the process.
A fully coupled thermo-mechanical analysis is performed simulating buildup of different layers of filler material on a substrate including the phase-change phenomena in terms of latent heat release and thermal shrinkage effects. The thermal problem including the solidification evolution is expressed as a function of enthalpy variable. The thermal boundary conditions combine heat convection and radiation to dissipate heat through the boundaries. In order to solve the mechanical problem, linear momentum balance equation with the incompressibility constraint is considered [1].

The material behavior is expressed by the thermo-elasto-visco-plastic constitutive model including isotropic hardening and thermal softening. A smooth transition from liquid-like phase to solid including thermal shrinkage is considered.

The simulation of the MD process is based on an ad-hoc Finite Element *activation methodology* which it is able to reproduce the deposition of the melted material along the predefined welding path by new elements generation. Such amounts of element are switched on at each time step based on the *born-dead elements* strategy. At each pass a new layer is deposited on the previous substrate allowing the fabrication of the desired geometry [4]. In the proposed simulation stabilized mixed U/P linear tetrahedral elements and Q1/P0 hexahedral elements have been utilized.

2 COMPUTATIONAL MODEL

The local form of the quasi-static linear momentum balance and energy balance governing equations can be written as

$$\nabla.\boldsymbol{\sigma} + \boldsymbol{b} = 0 \qquad (1)$$
$$C\dot{\Theta} + \dot{L}(\Theta) = -\nabla \cdot \mathbf{q} + \dot{R} + \dot{D}$$

where σ is the stress tensor and $\boldsymbol{b}$ is the force vector. It is important to point out that the MD process induces extremely high temperature gradients along the welding path in the heat-affected zone, which can provoke temperature overshoots that can spoil the solution. The problem has been avoided adopting a nodal integration rule, which stabilizes the solution introducing a small diffusivity.

In this work thermo-elasto-visco-plastic constitutive model, which includes both isotropic hardening and thermal softening is considered. The definition of temperature dependent material properties allows a gradual contraction of von Mises yield-surface when the temperature increases until a purely viscous (Norton-Hoff) model is recovered when liquid-like behavior must be simulated [2, 3].

In the formulation $C(\Theta)$ is the (temperature dependent) heat capacity coefficient and $\dot{L}(\Theta)$ is the rate of latent heat released during the solidification process. The heat flux per unit of surface **q** is computed as a function of the temperature gradient through the Fourier's law as:

$$\mathbf{q} = -k\,\nabla\Theta \qquad (2)$$

where $k(\Theta)$ is the (temperature dependent) heat conductivity. Heat radiation and heat convection fluxes at the boundary interface are also considered. The welding arc power is defined by

$$\dot{R} = \eta \cdot VI - C\left(\Theta_{liq} - \Theta_{ref}\right)/\Delta t \qquad (3)$$

that η is the welding efficiency, the arc voltage, V and the welding current, I. The dissipation rate per unit of volume $\dot{D}$ can be neglected if compared to the larger heat source amount $\dot{R}$ generated by the thermal gradient between the melted material and the component. The reference material in this work is the INCONEL-718 super-alloy. Assuming that there is no solid state diffusion during the solidification and using the Scheil rule, the solid volume fraction function is given by

$$f_S(\Theta) = 1 - \left[\frac{\Theta_F - \Theta}{\Theta_F - \Theta_L}\right]^{\left(\frac{1}{n-1}\right)} \qquad (4)$$

where $n = C_S/C_L$ is the partition coefficient that is the ratio between the concentration of the solid and the concentration of the liquid at equilibrium which are defined as

$$C_L(\Theta) = C_0\left[\frac{\Theta_F - \Theta}{\Theta_F - \Theta_L}\right]; \quad C_S(\Theta) = C_0\left[\frac{\Theta_F - \Theta}{\Theta_F - \Theta_S}\right] \tag{5}$$

where Θ_F is the fusion temperature.

3 NUMERICAL EXAMPLES

To prove the accuracy of the proposed method, an industrial example using INCONEL-718 is considered to predict both the temperature evolution and the distortion of the structure. The experimental setting is shown in Figure 1 and the finite element model discretized with 54,862 hexahedral elements and 34,012 nodes is indicated in Figure 2. The MD process is defined by the deposition of 10 layers on a rectangular supporting steel sheet of 12 mm thickness.

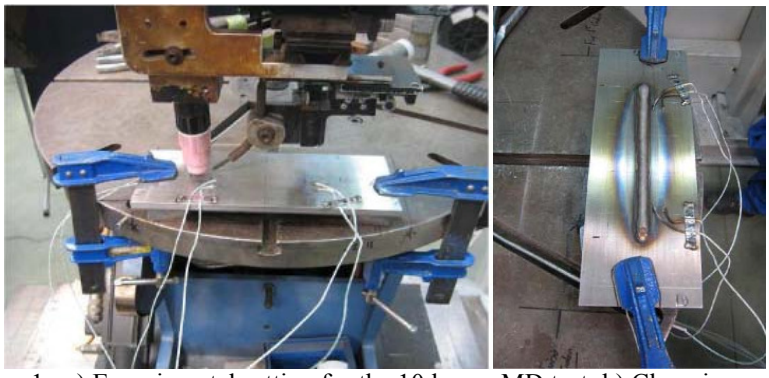

Figure- 1: a) Experimental setting for the 10 layers MD test; b) Clamping system;

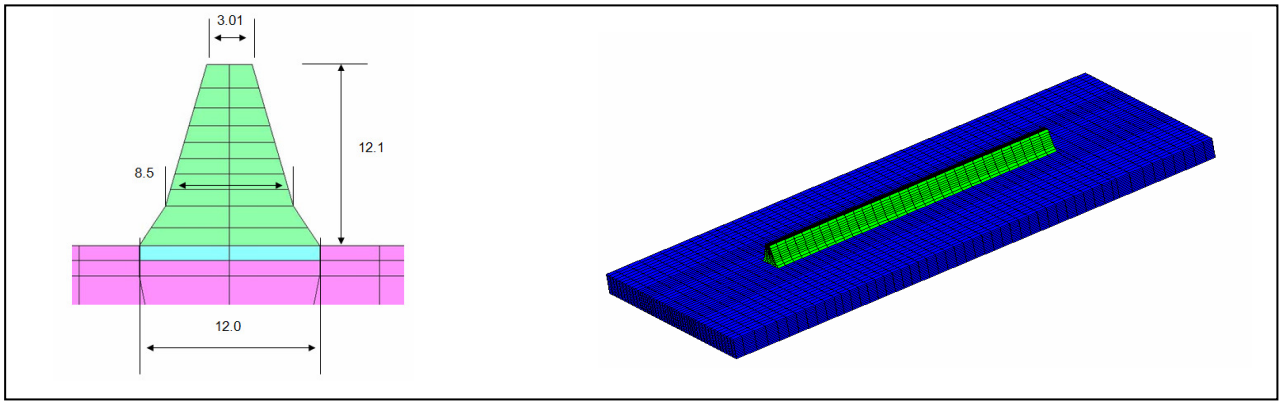

Figure- 2: a) Cross section for the 10-layers MD process; b) used FE mesh

Figures 3 compare the numerical and experimental results for the temperature evolution at different locations of the thermocouples. A very good agreement between the experimental and numerical results can be seen.

Figure 6 shows the Z-displacement field achieved by the analysis after the cooling phase and the comparison between the experimental and numerical results obtained for the deformation at two transversal sections.

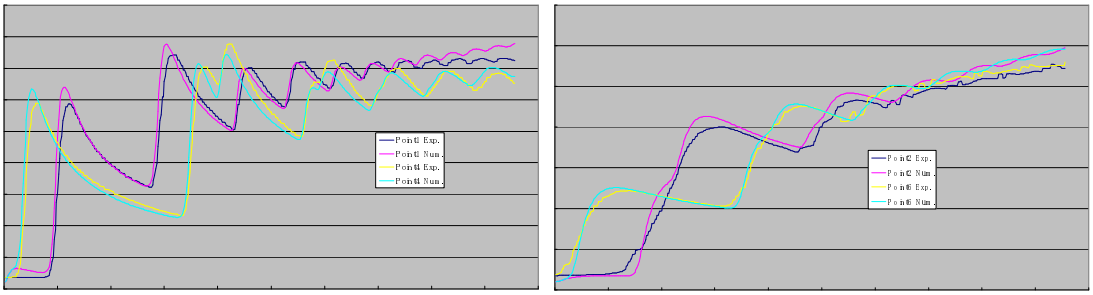

Figure - 3: experimental and numerical results for the temperature evolution at different thermocouples

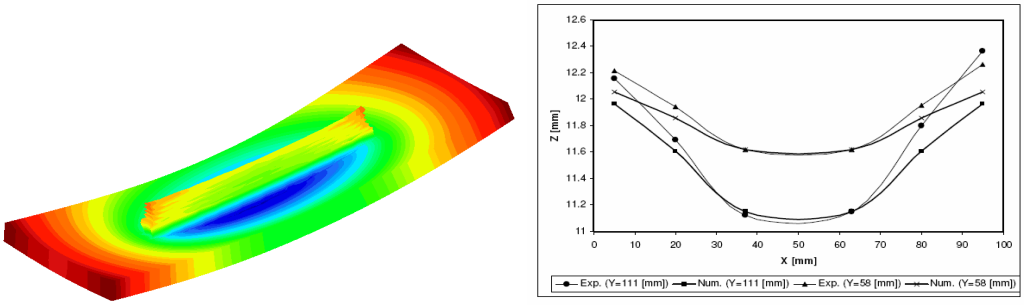

Figure 6: a) Deformed geometry; b) experimental and numerical deformation results at transversal sections

4 CONCLUSIONS

This work presents the strategy adopted for the numerical simulation of the MD processes. A coupled thermo-mechanical analysis for both the energy and momentum balance equations is presented. The activation procedure to simulate de metal deposition along the welding path is also presented and studied in detail. The accuracy of the mentioned method is validated by comparing the thermal and mechanical results with experiment.

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