Modeling Residual Stresses in Arc Welding

F. Roger*,1 and A. Traidia1,2
1ENSTA Paristech, 2AREVA NP, NTCW-F
*Corresponding author: ENSTA Paristech UME, Chemin de la Hunière 91120 Palaiseau, France, frederic.roger@ensta.fr

Abstract: The prediction of the mechanical behavior of assemblies during arc welding requires the knowledge of thermal history of the components and the constitutive behavior of the materials. Comsol can simulate thermal and structural interactions, but it needs to evaluate the time evolution of internal variables like viscoplastic strain and hardening parameters. In the present paper we extend the thermoelastic Comsol model to thermoelastoviscoplasticity using a Chaboche viscoplastic law with non linear kinematic and isotropic hardening with a temperature dependence of the model parameters.

The model is used to describe the residual stresses evolution during the welding of 316L stainless steel.

Keywords: Welding, Viscoplasticity, Stainless steel, Chaboche model.

1. Introduction

Welding simulation permits to evaluate the thermal history, metallurgical state and then the mechanical residual state. Such simulations can help the welder to evaluate the consequences of welding and then to take decisions about the welding parameters. Comsol multiphysics, with its ability to consider coupled CFD and heat transfer PDEs, can describe the weld pool behavior and then the thermal history during fusion and solidification [1]. To predict the mechanical response of the assembly submitted to high thermal gradients, we need to use a non linear behavior constitutive law with viscosity.

Chaboche [2] has developed the theoretical framework for behavior laws at high temperature for aeronautic materials such as Inconel. Such behavior laws are also used for the description of behavior of nuclear materials at high temperature such as stainless steels. In the present paper, as we like to study the mechanical behavior of 316L SS during welding, we select the elasto-viscoplastic model with non linear kinematic and isotropic hardening. This model considers the time evolution of hardening variables and viscoplastic strain.

2. Description of the mechanical behavior law

At the starting of welding, the arc heating leads to thermal gradients and then to a thermal expansion of the assembly. To describe this stage, we need to select an elastic behavior law with temperature dependence of Young modulus and we must subtract the thermal expansion to the total strain. This coupling is easily taken into account in Comsol by activating the thermal expansion option in structural mechanics. However, with the decrease of the yield stress with temperature and the increase of thermal stresses in a clamped assembly, plasticity occurs with incompatible plastic strains. At elevated temperature (half of fusion temperature for example) the material behavior is time dependent and then viscosity must be introduced. Some materials such as stainless steels can exhibit static (thermally activated process) and dynamic hardening recovery, and therefore in the hardening equations we must introduce recall parameters.

The present Chaboche viscoplastic model considers non linear kinematic and isotropic hardening with temperature dependence of the model parameters and dynamic recovery.

$$\dot{\varepsilon}_p = \frac{3}{2}\dot{p}\frac{\sigma' - X'}{J_2(\sigma - X)} \quad (1)$$

$$\dot{p} = \langle \frac{J_2(\sigma - X) - R - k}{K} \rangle^n \quad (2)$$

$$\dot{X} = \frac{2}{3}C\dot{\varepsilon}_p - \gamma X\dot{p} \quad (3)$$

$$R = Q(1 - \exp(-bp)) \quad (4)$$

$$J_2(\sigma - X) = \sqrt{\frac{3}{2}(\sigma' - X'):(\sigma' - X')} \quad (5)$$

K,k,n,C,γ,Q and b are temperature dependent and are listed in the table 1 for 316L stainless steel.

Variable	K(MPa)	K(MPa)	n	C(MPa)
T=293°K	151	82	24	162400
T=873°K	150	6	12	24800

Variable	γ	Q(MPa)	b
T=293°K	2800	60	8
T=873°K	300	80	10

Table 1 : Material parameters for 316L [2]

σ' and X' are the deviators of respectively the tensors σ and X.

Equation 1 describes the time evolution of viscoplastic strain where $\frac{3}{2}\frac{\sigma'-X'}{J_2(\sigma-X)}$ is the direction of viscoplastic flow and $\dot{p}$ is the magnitude of the viscoplastic strain rate.

Equation 2 corresponds to a viscous power law with kinematic hardening X and isotropic hardening R variables. <a> is the positive part of a. K is the drag stress.

Equation 3 describes the evolution of kinematic hardening with a back term for dynamic recovery.

Equation 4 is a function that describes the saturation of isotropic hardening with cumulated viscoplastic strain. Q is then the value of saturation.

J_2 is the second invariant of the deviator of σ defined in equation 5.

3. Application to the arc spot welding simulation of a 316Lss disk.

The elastoviscoplastic Chaboche model (EVP) is applied to simulate the arc spot welding heating of a 316Lss disk. As the disk and the heating are axisymmetric, the computational domain is chosen 2D axisymmetric.

3.1 Heat transfer simulation

The thermal properties of 316L are temperature dependent. The arc heating is a heat flux boundary condition with a Gaussian distribution at the top surface of the disk. The heat distribution is given by the following equation:

$$Q = Q_{max} \exp\left(-3\frac{r^2}{b^2}\right) \quad (6)$$

Where Q_{max} is the maximum heat flux at the center of the arc and b the arc radius (5mm).

The heat flux is progressively increased in order to improve the convergence, then it is maintained constant during 1s and finally decreases linearly with time. This time evolution is shown in figure 1.

At r=0, we have an axisymmetry boundary condition. For the other sides of the disk, we have convective heat transfer with air, we have chosen a high value for convective coefficient to reduce the cooling time (h=15W/m^2°K). Figure 1 shows the computational domain and summarizes the boundary conditions.

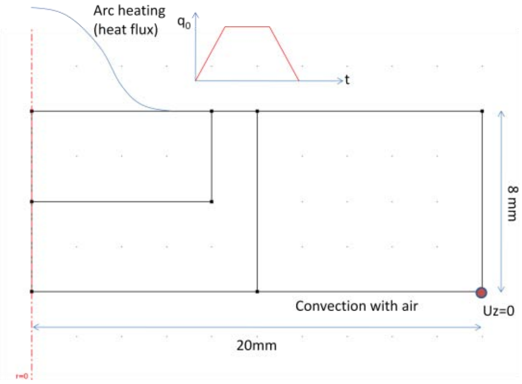

Figure 1. Computational domain and boundary conditions.

The figure 2 shows the thermal history of the top center point under the arc. The shape of this distribution is representative of a typical welding thermal cycle.

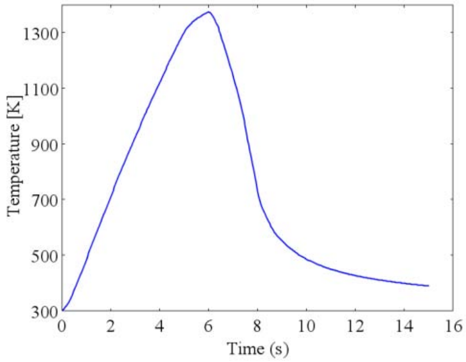

Figure 2. Thermal cycle at the top center point.

The maximum temperature is about 1400°K. The figure 3 shows the maximum temperature field distribution.

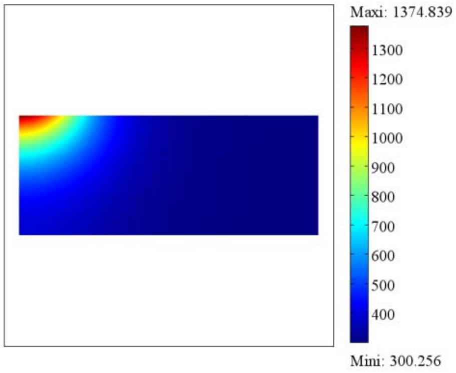

Figure 3. Thermal field at t=6s.

3.2 Mechanical behavior of the disk

The bottom right point of the domain is fixed in the vertical direction z to avoid rigid body displacement. The non homogeneous high gradients in the weld zone leads to inelastic strains and then to residual stresses. The figure 4 shows the accumulated plastic strain distribution after cooling (t=15s).

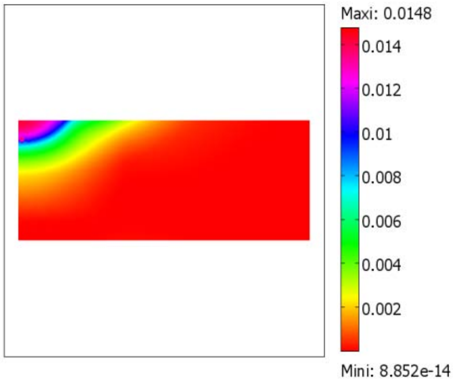

Figure 4. Accumulated plastic strain after cooling.

The maximum accumulated plastic strain is 1.48% at the top surface. This high value is the consequence of a high thermal gradient in this area. In the welding heat affected zone this value falls to 0.4%.

The figure 5 shows the radial and azimuthal residual stresses after cooling. The variation of the sign of stresses along the thickness leads to a bending of the disk after cooling. The figure 6 shows the resulting distortions of the disk with the associated Von Mises stress field.

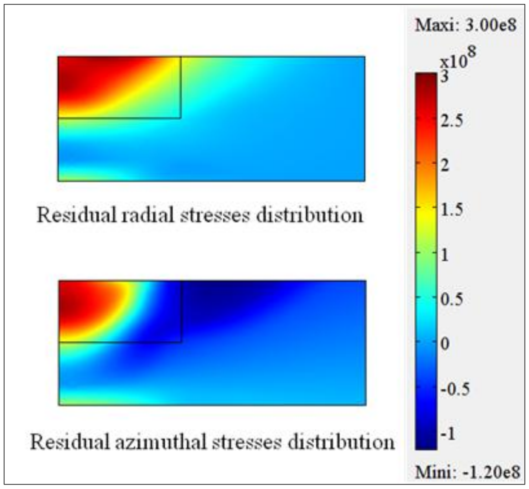

Figure 5. Residual stresses after welding

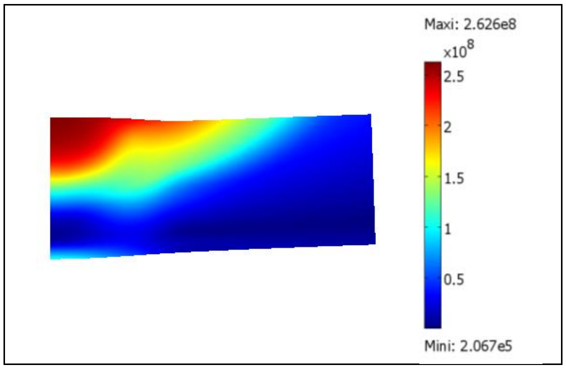

Figure 6. Von Mises stress field and distortions

The maximum Von Mises stress is 262 MPa in the welded zone. This high value is due to high temperatures and gradients in the weld and the associated hardening during welding.

In welding, in the weld pool, hardening variables are reset with the fluid phase, therefore we have to add reset terms in the model for the fusion zone.

4. Use of comsol multiphysics

Heat transfer and elasticity are solved using the corresponding Comsol modules in 2D axial symmetry.

Equations 1-3 of the Chaboche's model are non linear Ordinary Differential Equations solved for each node of the mesh. For this type of equation, we need the General Form in Comsol PDEs mode. This mode is only available in 2D. However, we can choose this mode because the flux terms are set to zero. d_a (time derivative coefficient) is set to 1.

The whole system of non linear equations is complex. The critical stage is the convergence of isotropic hardening. Indeed, the power law (equation 2) and the viscoplastic flow conditions (J_2>R+k) lead to difficulties in the initialization of the simulation. Moreover, the power law can give very high values. The initialization of each term of source contribution in the ODEs must be controlled.

5. Conclusions

The elastoviscoplastic Chaboche model with non linear kinematic and isotropic hardening has been implemented in Comsol. As its parameters are temperature dependent the model can simulate the behavior of metallic structures submitted to thermomechanic loadings. Welding, which produces high thermal loading is a good application to test the model.

Simulations show a realistic plastic strain distribution after welding and the predicted bending distortion is close to the geometry observed during spot welding experiments. In the future, the thermomechanical model will be coupled to our Comsol Welding CFD model of the weld pool [1]. The whole simulation, including arc modeling, will give us the possibility to study the consequence of the welding parameters on the residual stresses and distortions.

6. References

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