CHAINING OF WELDING AND FINISH TURNING SIMULATIONS FOR AUSTENITIC STAINLESS STEEL COMPONENTS

F.VALIORGUE[*], A.BROSSE[†], J.RECH[*], V.ROBIN[†2], P.GILLES[†2] , J.M. BERGHEAU*

[*]Laboratoire de Tribologie et Dynamique des Systèmes (LTDS)
Ecole Nationale d'Ingénieurs de Saint Etinne
58, rue Jean Parot, 42023 Saint Etienne FRANCE
Frederic.valiorgue@enise.fr

[†]ESI FRANCE (LTDS)
70 rue Robert
69006 Lyon, France
alexandre.brosse@esi-group.com

[†2]AREVA NP
Tour AREVA
92084 Paris La Défense, France alexandre.brosse@esi-group.com
vincent.robin@areva.com

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Abstract. The chaining of manufacturing processes is a major issue for industrials who want to understand and control the quality of their products in order to ensure their in-service integrity (surface integrity, residual stresses, microstructure, metallurgical changes, distortions,…). Historically, welding and machining are among the most studied processes and dedicated approaches of simulation have been developed to provide reliable and relevant results in an industrial context with safety requirements. As the simulation of these two processes seems to be at an operationnal level, the virtual chaining of both must now be applied with a lifetime prediction prospect. This paper will first present a robust method to simulate multipass welding processes that has been validated through an international round robin. Then the dedicated "hybrid method", specifically set up to simulate finish turning, will be subsequently applied to the welding simulation so as to reproduce the final state of the pipe manufacturing and its interaction with previous operations. Final residual stress fields will be presented and compared to intermediary results obtained after welding. The influence of each step on the final results will be highlighted regarding surface integrity and finally ongoing validation works and numerical modeling enhancements will be discussed.

1 INTRODUCTION

Welded components are widely diffused in the mechanical industry. For critical parts such as the ones find in aeronautic or nuclear plants, the knowledge of the final residual stress state is a major issue and requires a deep understanding to master the in-service mechanical behaviour [1]. Research programs have been conducted for a few years on these topics by a lot of industries to rationalize the maintenance schedules or to prolong critical parts' lifetime.

In fact, the final residual stress state is the result of all the thermal, mechanical, metallurgical phenomena occurring during the whole manufacturing process from casting or stamping to finish turning or superfinishing [2]. Every shaping process induces plastic deformations while operating and, at the end of the process, global equilibrium is respected but locally the material can be importantly plastified leading to high levels of residual stresses (tensile or compressive).

In this context, welding residual stresses have been studied experimentally and numerically for thirty years and current results are reliable and employed industrially [3]. Modern computing capabilities allow to simulate wide parts with refined meshes and provide in-depth residual stresses. In contrast with turning residual stresses fields that only affect the top surface material layer, welding operations are prone to generate embedded material affectations with positive or negative signs. The last generation of welding simulation can reproduce multi-fillet strategies applied on wide parts [4].

Turning may be the most studied process in the literature. Since early 50's, researchers are trying to model and understand severe phenomenon occurring around the cutting edge. They commonly use analytical, experimental or numerical approaches to reach local values of stress and temperature fields. Turning is a process involving high level of temperature applied to thin surfaces and generates in most cases tensile residual stresses. Most of the time, these tensile residual stresses generated at the parts surface are undesirable because they can contribute to fatigue failure due to crack propagation or stress corrosion issues. Several types of approaches have been proposed to access these values but only the hybrid method [5], simulating long and stabilized operations is able to predict precisely the turning residual stress fields.

As presented before, both processes have been studied numerically and dedicated methods give reliable results. The main topic of this paper is to present a chained simulation in order to predict the final residual stress fields including turning and welding contribution. It is a next step in virtual machining tools, claimed by industrials.

The first part of the paper will present the two approaches used to model welding and turning and the third part will detail the chaining step. The presented operation is the leveling of a weld fillet of a 304L pipe by a turning operation using tungsten carbide tool coated with TiN. The material is considered stress free before the welding operation.

2 DESCRIPTION OF THE TWO APPROACHES

The mock-up whose simulation is described in this paper was designed and manufactured within the framework of the European Network on Neutron Techniques Standardization for Structural Integrity [6]. This network involves over 35 organizations from industry and promotes the practical application of modern experimental and numerical techniques to problems related to the determination of residual stress and distortion in components. The mock-up issued by the Task Group 4 (TG4), deals with the estimation of residual stress in a 3-pass slot weld deposited on an austenitic stainless steel plate. Initially the mock-up was only concerning welding residual stresses. It is now propose to machine the over thickness bead deposit with finish turning conditions in order to judge the importance of interaction between welding initial state and final surface machining process consequences. Experimental results are compared with welding computation to validate the initial condition before machining. Measurements after machining are not yet available and only computation results obtained after chaining welding with finish turning simulations are presented and discussed.

2.1 Presentation of the mock-up

The TG4 round robin specimen is a 3-pass slot weld in AISI 316L austenitic stainless steel made using pulsed tungsten inert gas (TIG) welding process. The dimensions of the plate are 194 × 150 × 18 mm. A slot is machined in the middle of the plate. Its dimensions are 80 mm long and 6 mm deep. It is filled with three superimposed weld passes. Figure 1 gives the design plan of the mock-up and Figure 2 is a picture of the plate after filling the slot.

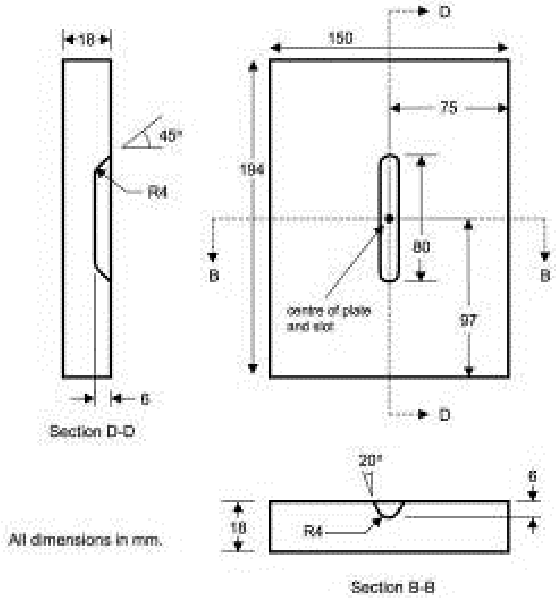

Figure 1: Design plan of the 3-pass slot weld specimen (TG4 mock-up)

Figure 2: Picture of the top surface of the plate after welding

AISI type 316L stainless steel, which is an austenitic stainless steel, was chosen for this study as it is widely used in the nuclear industry for its good resistance to high-temperature creep and corrosion. Moreover, it has a stable austenitic matrix from the ambient temperature to melting point. Thus, during welding and machining processes, no phase transformation occur which will highly simplify the simulation. Table 1 gives the welding process parameters and Figure 3 shows the position of each pass and the position of thermocouples used for heat input calibration.

Table 1: Welding process parameters

	Averaged Energy (kJ/cm)	Travel speed (mm/min)	Bead length (mm)	Interpass Temperature (°C)
Pass 1	17.3	76.2	74	20 +/- 10
Pass 2	15.3	76.2	76	50 +/-10
Pass 3	14.5	76.2	82	50 +/-10

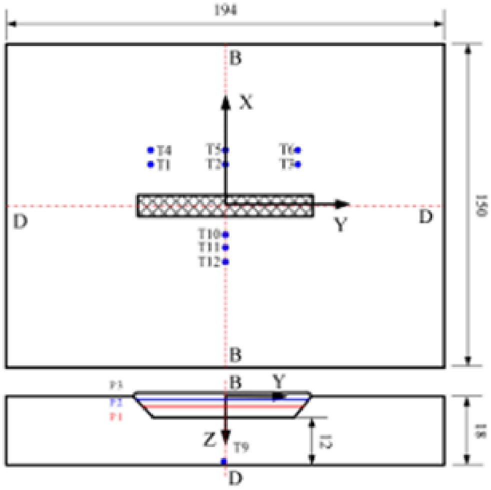

Figure 3: Schematic of the 3-pass slot weld specimen (TG4 mock-up)

2.2 Welding Simulation and Validation of Initial State

Welding simulation is conducted through computational welding mechanics principle using Finite Element Method (FEM) [7]. It consists in solving a thermo-mechanical problem with optionally taking into account phase transformations. As the effect of plastic dissipation on heat transfer and the influence of stresses on metallurgical transformations are not taken into account, the mechanical analysis can be uncoupled from the thermo-metallurgical simulation. The welding simulation is then achieved in two stages. First the heat transfer analysis is performed based on the solution of the classical heat equation at solid state with appropriate boundary conditions. The precise description of the phenomena involved during the energy transfer from the welding device to the work piece is not taken into account (i.e. arc, plasma and weld pool interactions). Indeed, through a calibration procedure using the recordings of thermocouples or the dimensions of the weld pool and the heat affected zone, the heat input can be simply represented by a volumetric heat source with a Gaussian distribution in every direction to model medium energy welding processes with added material. The mechanical state is thus computed in a second stage using the temperatures and optionally the phase fractions previously calculated. The mechanical analysis is based on the momentum balance equation where inertial effects are neglected as detailed in [4].

Due to the symmetry of the structure and process, one half of the plate is modeled as shown in Figure 4. The mesh is finer in the heat affected and plastically deformed zone.

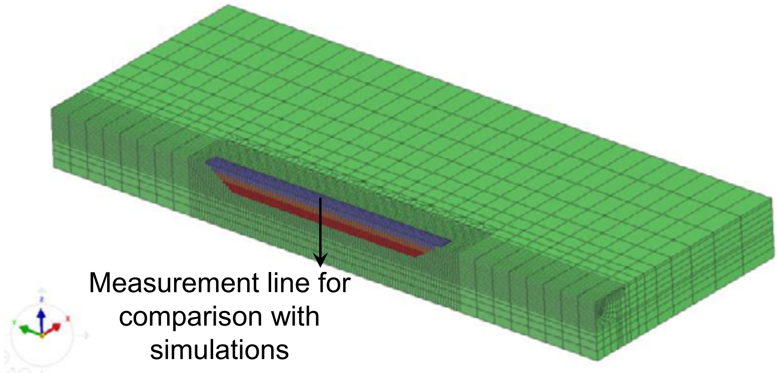

Figure 4: FEM mesh of TG4 specimen

Figure 5 shows the comparison of the third weld bead fusion line between macrographic section and simulation results. The predicted fusion area is very close to the one observed experimentally. More detailed results are given in reference [8]. Furthermore figure 6 gives the comparison of temperature evolution during welding between recordings of thermocouples and computational results. The overall temperature response over time is in excellent agreement with the experimental results which validates the heat input calibration.

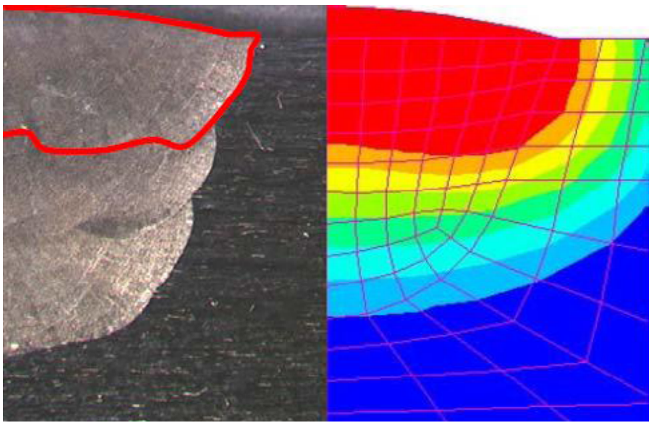

Figure 5: Comparison between macrographic section and simulation of third bead fusion line

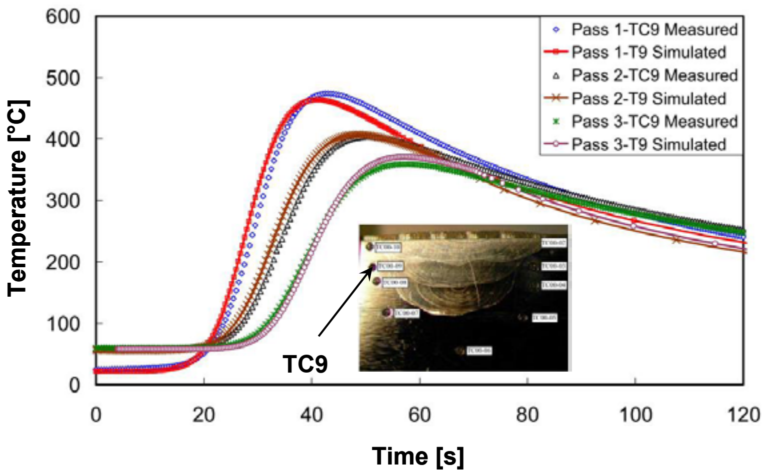

Figure 6: Comparison of temperature evolution at thermocouple TC9 position between recordings and simulation results

Concerning mechanical computation, a specific work has been done to improve the material behavior description. Indeed, to accurately predict welding residual stresses, an advanced material constitutive model considering cyclic strain hardening and recovery effects has been developed to simulate the thermo-elastic plastic behavior of the structure during welding. This model is detailed in [9]. Non-linear kinematic hardening is combined with isotropic hardening in order to properly describe the cyclic tests performed on tensile specimens. For instance, at 30°C; the best agreement between measurements and hardening models is found when mixed hardening is considered with thirty percents of isotropic hardening (see Figure 7 [8]).

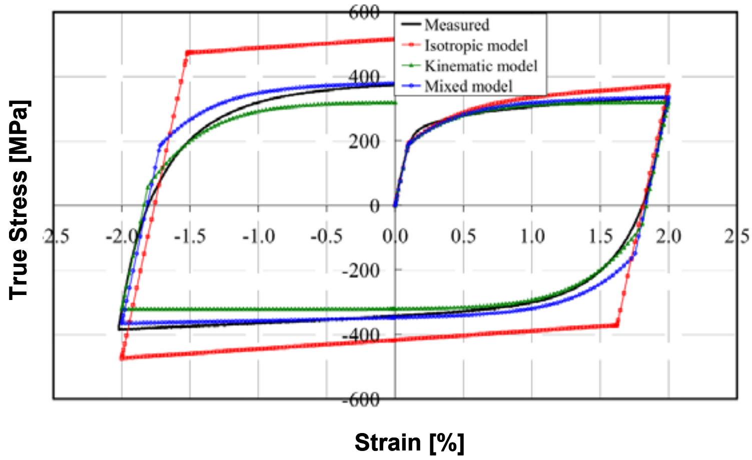

Figure 7: AISI 316L stress vs. strain curves considering different strain hardening models (measurements are performed at 30°C)

Many measurements were performed to evaluate the residual stresses in the mock-up and some of them were selected for comparisons with numerical results according three criteria related to their reliability:

- balanced transverse residual stresses,
- low through thickness oriented stresses,

- repeatability of the results.

Longitudinal stress profiles obtained by simulation in the middle of the weld through the thickness (see plotting line in Figure 4) are in good agreements with the measurements as shown in Figure 8. Numerical transverse stresses fits also with experimental determinations (see Figure 9).

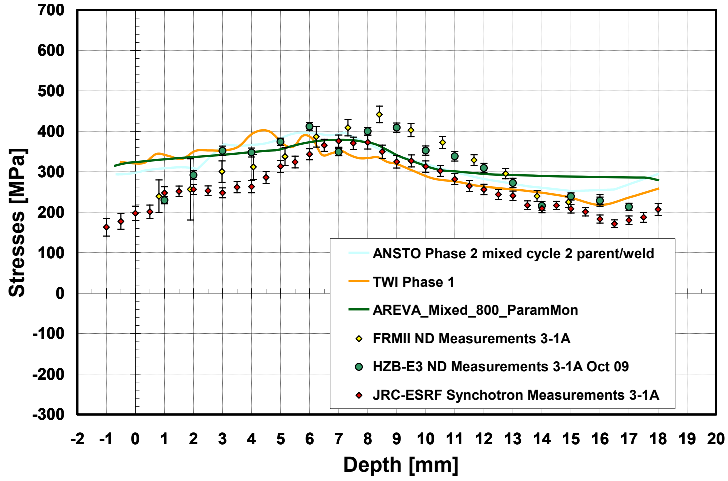

Figure 7: Longitudinal stresses through the thickness

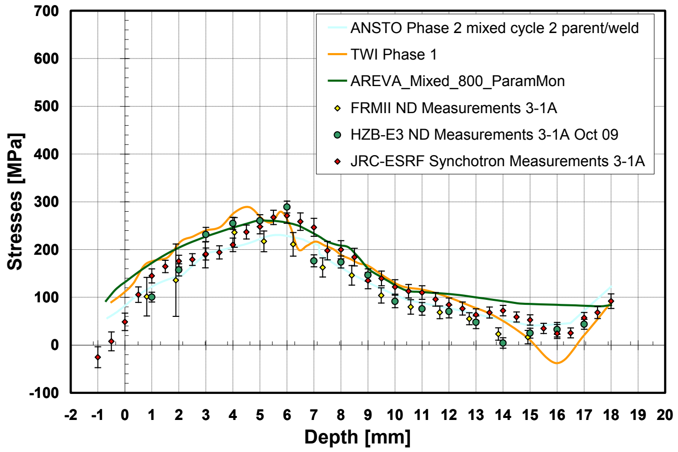

Figure 8: Transversal stresses through the thickness

Finally, at 1 mm under the bead surface, where the finish turning is supposed to have no effect [10], [11], AREVA's computation gives about 300 MPa for longitudinal stress and 120 MPa for transverse stress. These values will be compared with surface stress profiles found after machining simulation in order to understand the nature of interactions between initial welding residual state and final machining effects on surface. Figure 10 show the cutting tool position before trimming the excess bead over the plate reference top surface.

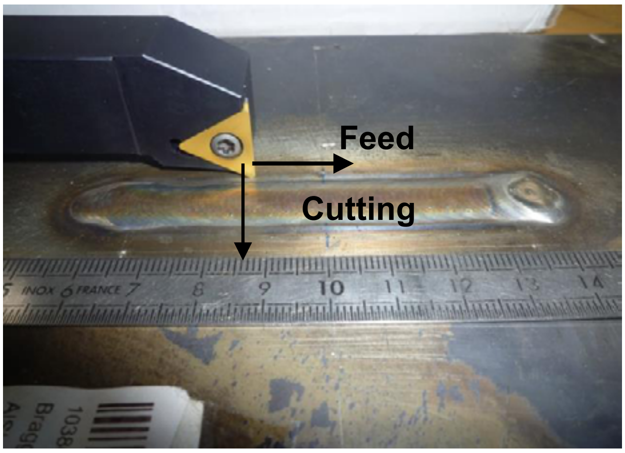

Figure 9: Position of the cutting tool before removing the excess of bead under finish turning conditions

2.3 Turning Simulation: Hybrid approach

The prediction of residual stresses generated in turning is based on the hybrid approach. It is a dedicated method developed by the LTDS\ENISE based on equivalent thermomechanical loadings applications onto the final surface of the parts. It is divided on two main steps:

1. Thermomechanical loadings caracterisation
2. Thermomechanical loadings application

The thermomechanical loadings are obtained through instrumented 3D turning test (figure 11).

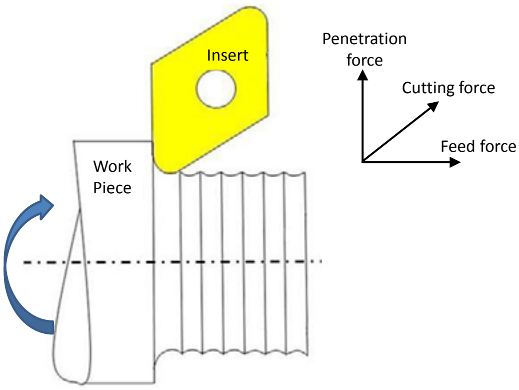

Figure11: 3D instrumented cutting tests

This set up allows measuring the typical contact lengths and cutting forces in all directions (figure 12).

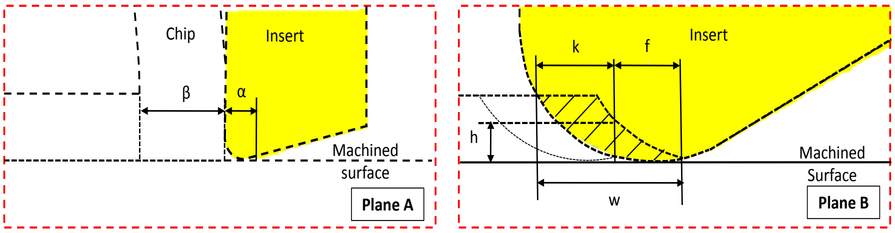

Figure 12: Characterized local contact lengths

Thanks to a homemade post treatment, these experimental values are converted to heat flow densities and local pressures. These data are then applied onto the corresponding mesh, respecting the real timing and global machining strategy (figure 13).

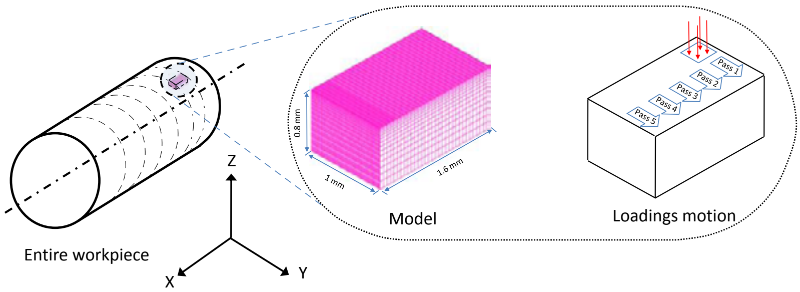

Figure 13: Application strategy of equivalent loadings

All the details of the method are presented in [5]. In this paper, the hybrid method was applied to finish turning of 304L. The figure 14 below, presents the residual stress fields obtained thanks to the method.

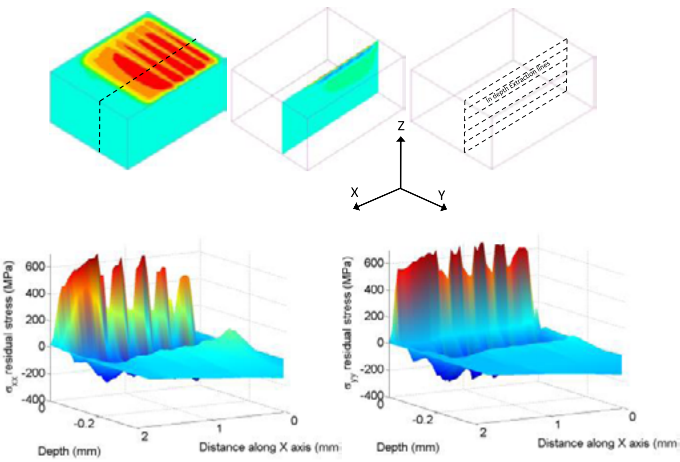

Figure 14 : Residual stress fields after 5 revolutions

These residual stress fields are obtained for steady conditions and the results can be directly compared with the ones obtained experimentally. Concerning the finish turning of 304L, the actual level of precision allows the model to be chained with other process.

3 DESCRIPTION OF THE CHAINING PROCESS SIMULATION

There are two major points to consider in order to chain processes:

- the physics needed for each model
- the dimensions needed for each model

Welding requires the simulation of metallurgical transformations in order to have accurate stresses and the whole structure is often modeled in order to consider global rigidity.

The simulation of turning using the hybrid method is a local approach that considers only a small part of the workpiece. Moreover the effect of machining is expected near the surface and then in order to simulate it using finite element method, the mesh size needs to be very small in this area.
Finally, considering heat rate and maximal temperature attend during turning, the effect of metallurgical transformations can be neglected for the simulation. On the contrary, a dependency with the deformation rate is required.

The next paragraphs will describe the procedure to transfer initial state fields from welding and the way to restart for a machining calculation.

3.1 Residual stress field transfer

Figure 15 shows the difference of models in the case of welding and turning.

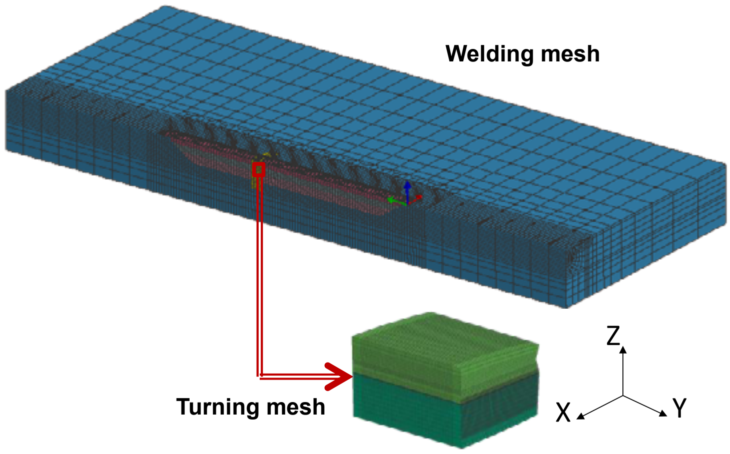

Figure 15 : Difference of meshes

The mesh size for welding is about 1 mm in every direction whereas the machining mesh requires a refinement near the surface until a few micrometers under the surface.
Therefore the number of nodes for turning is about six times the one for welding even if the total dimension of the model is about twenty times smaller than the welding bead length.
For this study the effect of machining is tested on the middle of the welding joint. On this location, the welding has reached a steady state.
Figure 16 presents the residual stresses in relation with the depth of the workpiece at the end of the welding simulation in the local area affected during turning.

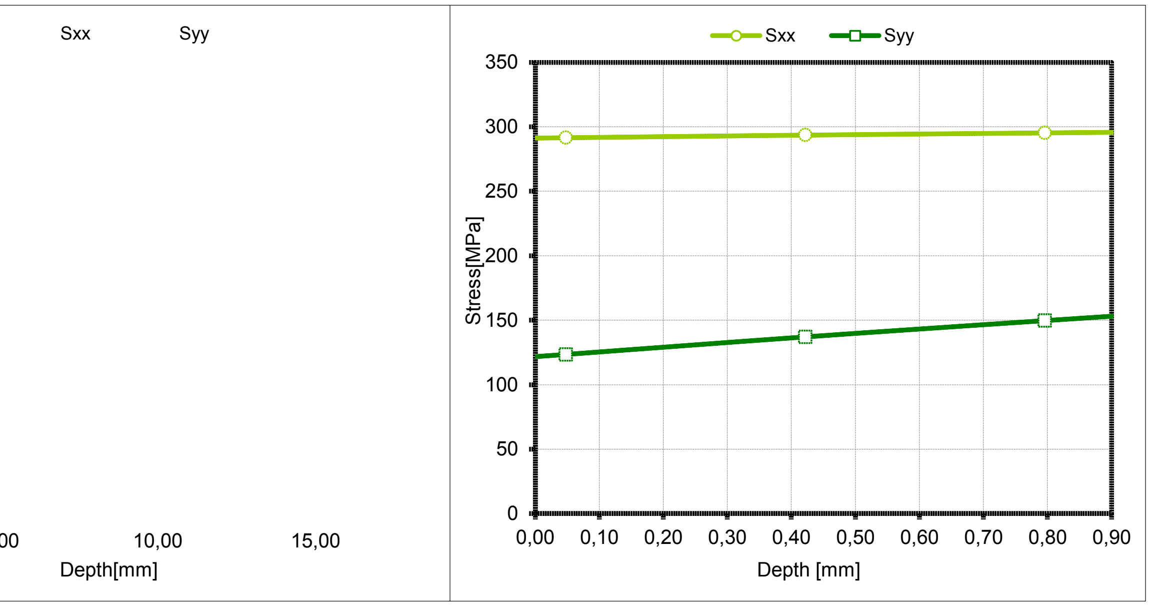

Figure 16 : In depth stresses from welding

One can see that the residuals stresses from welding are almost constants near the surface area.

3.2 Initial state for machining simulation

Since all the calculations are performed assuming the small displacement hypothesis, only plastic deformation and hardening variables are required for transportation.

The procedure to restart from a welding simulation is as follows:

- Transport from welding model to local model including buildup from welding
- Balancing of the results
- Buildup removal
- Balancing of results
- Machining simulation

Figure 17 shows the Von Mises stress on the local mesh for machining.

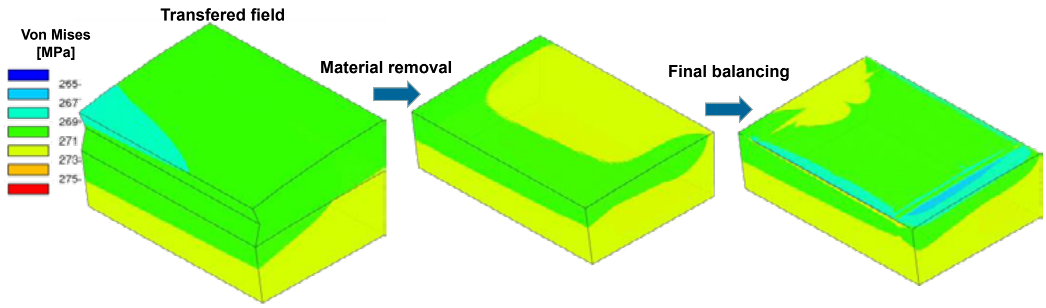

Figure 17 : Initial step obtention step for machining

Finally, the machining simulation is performed with the following conditions :

- Cutting speed : Vc = 100 m/min
- depth of cut : 0,3 mm

- feed per pass : f = 0,3 mm/rev-1

As described in previous paragraph, the simulations of five passes are made on the local model such as shown on figure 18.

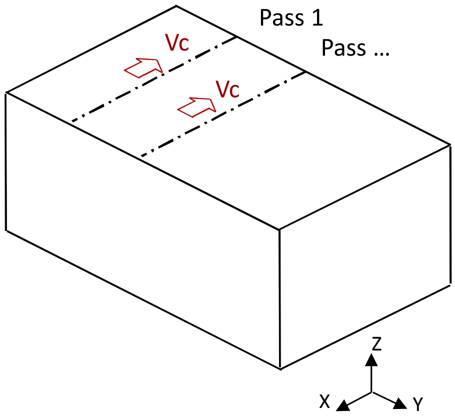

Figure 18 : Local machining simulation

Since welding need simulation of metallurgical transformation, the initial state for machining is dependent of each metallurgical phase. In order to chain simulations the same materials laws are kept and a dependency to the plastic strain deformation is added.

3.3 Results from chaining

Figure 19 shows results after five passes with and without taking into account the residual stresses from welding.

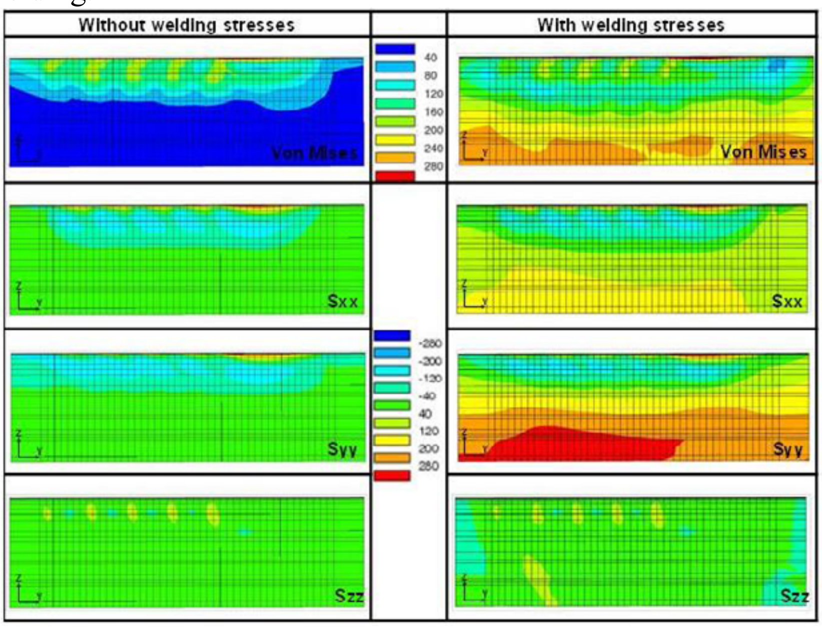

Figure 19 : Results step obtention step for machining

Figure 20 also shows the effects of machining on residuals stresses in relation with the depth of the workpiece.

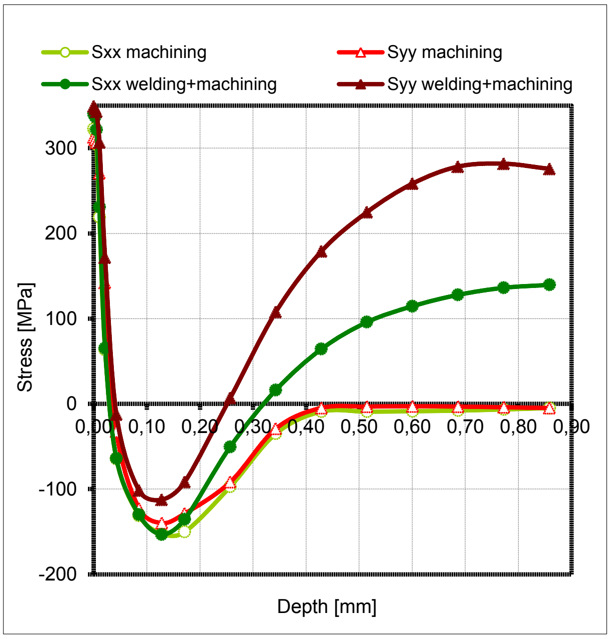

Figure 20 : In depth stresses

With these results one can see the followings:

- Surface residual stresses after machining are not influenced by the welding initial stresses. Both of them are near 300MPa
- The depth affected by turning is around 0.7mm. After this value, residual stresses are the ones generated by welding
- The Syy welding surface residual stress is not significantly modified by turning
- The Sxx surface residual stress is multiplied by two

4 CONCLUSION

This paper presents a chaining simulation of welding and finish turning of a 304L plate. Even if the two types of simulations are widely diffused in the scientific community, chaining both processes remains an issue. The welding simulation uses classical developments conducted since several years while the turning reproduction uses a dedicated approach called “hybrid method”. This kind of simulations, closed to reality are important for fatigue response of the parts. The key point is the method to project the welding results on the turning model.
The results are interesting and turning seems to have an important influence on the surface initial residual stress field. At the end, experimental measurements will be the only way to validate this method.

5 ACKNOWLEDGEMENT

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