Forming residual stresses effects on the electron beam welding distortions of thick components

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ABSTRACT: The purpose of this study is to evaluate the effects of forming residual stresses on the electron beam welding distortions of thick components building up the ITER vacuum vessel. The deformed shape of a thick plate is obtained by a three point rolling process. The numerical simulation of this process is then performed to evaluate the induced residual stresses. Forming residual stresses are taken into account as initial conditions for the welding simulation of two deformed thick plates. A simulation is finally performed to evaluate the influence of the forming residual stresses on the welding distortions.

Key words: thick plates, rolling, electron beam welding, distortions.

1 INTRODUCTION

Numerical simulations of welding processes have been performed since many years now [1]. Thanks to these simulations, the welding distortions and their influence on the behaviour of the welded components can be investigated.
The manufacturing of the ITER vacuum vessel involves the welding of thick deformed plates (60 mm thickness). These 316L(N) austenitic stainless steel plates are curved using a three point rolling process which induced residual stresses. The deformed plates are then electron beam. The aim of this study is to investigate the influence of the residual stresses induced by the forming process on the welding distortions. For comparison, a simulation on two plates without residual stresses will also be performed.
In the first part, the experimental device and the numerical simulation of the forming process will be described. The simulation requires a mechanical behaviour law for the steel that is identified thanks to an experimental database. In the second part, the welding simulation is described and the influence of the forming residual stresses on the welding distortions is investigated.

2 FORMING OF A THICK PLATE

2.1 *Experimental device*

The dimensions of the plate are 1400 x 1000 x 60 mm^3. It includes over-lengths on both side of the plate for the rolling process. These over-lengths are water-jet cutting after the rolling to obtain the final dimensions and shape of the plate (1000 x 1000 x 60 mm^3). The rolling process consists in the displacement of a plate between three cylinders to obtain a curved deformed shape of this plate (figure 1). The plate is deformed in several passes (displacement from one side to the other) between two fixed cylinders under the plate and the upper movable cylinder that gives the curvature by going down during the displacement of the plate. Furthermore, a load is applied on the upper cylinder by two jacks during the process.
After the rolling, the over-lengths are water-jet cut and four holes are drilled on the plate, also by water-

jet cutting. These operations must be taken into account in the numerical simulation for a better description of the residual stresses distribution at the end of the overall process, i.e. from the forming to welding.

2.2 Mechanical behaviour law

Monotonous tensile tests and cyclic tensile-compression tests have been performed at different temperatures to characterize the behaviour of the 316L(N) austenitic stainless steel [2]. The behaviour of this steel is described by an elastic-plastic model [3] with a non-linear kinematic hardening. The numerical simulations have been carried out using SYSTUS® software. This model is closed to the one proposed by Armstrong-Frederick [4]. The hardening is described by two variables. The first one (1) is a variable of Prager type that depends on the cumulated plastic strain. The second one (2) is a classic Armstrong-Frederick variable. The evolution laws of these variables are:

$$\dot{\underline{\underline{\chi}}}_1 = \frac{2}{3} h_1\left(\varepsilon_{eq}^p\right) \dot{\underline{\underline{\varepsilon}}}^p \quad (1)$$

$$\dot{\underline{\underline{\chi}}}_2 = \frac{2}{3} h_2 \dot{\underline{\underline{\varepsilon}}}^p - k_2 \underline{\underline{\chi}}_2 \dot{\varepsilon}_{eq}^p \quad (2)$$

With $h_1\left(\varepsilon_{eq}^p\right) = \frac{\partial \overline{\sigma_1}}{\partial \varepsilon_{eq}^p}$ (3)

And $\overline{\sigma}\left(\varepsilon_{eq}^p\right) = \overline{\sigma_1}\left(\varepsilon_{eq}^p\right) + \frac{h_2}{k_2}\left(1 - e^{-k_2 \varepsilon_{eq}^p}\right)$ (4)

Where $\overline{\sigma}\left(\varepsilon_{eq}^p\right)$ represents the stress for a monotonous tensile test minus the initial yield stress. This model allows a good description of the monotonous tensile test curve. However, only weak variations of the parameter h_1 with ε_{ep}^p are allowed and the variation of $\overline{\sigma_1}\left(\varepsilon_{eq}^p\right)$ must be nearly linear.

The parameters of this model are identified thanks to SYSTUS® software by an inverse approach based on the least square method. The response of the model is compared to experimental data and the parameters are identified in order to minimize the gap between the numerical results and experiments.

2.3 Numerical Simulation of the process before welding

The forming process is divided into different steps, from the rolling to the drilling of the holes. The methodology used for the simulation is the following: a 2D simulation using plane strain assumption of the rolling process is first performed, the 2D results are then transferred on a 3D mesh of the plate including the holes and the over-lengths. Finally the machining of the over-lengths and the drilling of the holes by water-jet cutting are simulated by decreasing the machined elements stiffness down to zero. This approximation can be used due to the fact that the water-jet cutting process induces no significant thermal effects near the hole.

The 2D simulation of the rolling is performed in plane strain conditions and finite displacements with sliding contacts between the plate and the cylinder. The mesh of the plate is composed of four-node quadrilateral linear elements with 4 integration points (12 elements through the thickness). To take into account the contact with the cylinders, the plate skin is meshed by 1D linear elements with 2 integrations points.

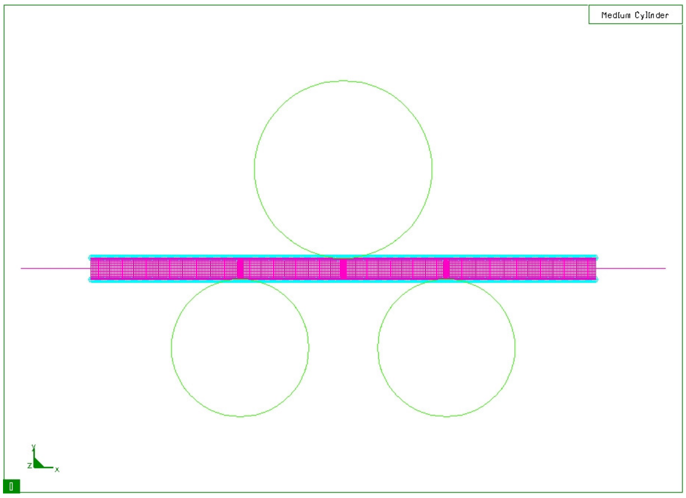

Fig. 1. Mesh of the plate and solid rigid cylinders.

To validate the use of linear elements, the numerical simulation of a three point bending test on this geometry has been performed with linear and quadratic elements (same size of elements for the two simulations). The two simulations highlight the same results. Consequently, linear elements have been used for the simulation in order to decrease the calculation time. Concerning the boundary conditions, the two lower cylinders are constrained in the X and Y directions and the upper cylinder can only move in the Y direction. The displacement of the plate is performed thanks to a spring type 1D element at each extremity of the plate.

The results of the rolling simulation show that the stresses are low in the over-lengths and that they are concentrated on the central part of the plate (between the two lower cylinders). The results also give information about the deformation mode of the plate. In the final state, a bending profile can be observed with the apparition of the neutral fibber. This fibber is the separation between two domains within the plate: compression in the upper part and tension in the lower part.

The next step of the simulation is the transfer of the 2D results on a 3D model for the simulation of the machining and drilling, which are 3D processes. The 3D model includes the mesh of the holes and of the over-lengths. After this operation, a balance of the plate is performed to consider the edge effects.

The influence of the machining and drilling can be estimated in term of stress distribution and changes of the deformed shape of the plate. The results show that the machining has negligible effects on the residual stresses but, even if the variations of displacement are weak, this operation gives a saddle shape of the deformed shape of the plate. Regarding the drilling of the four holes, this step only has a little effect on the stress distribution near the holes (relaxation of 20 MPa for the σ_{11} stress). Figure 2 gives the distribution of the σ_{11} stress at the end of the forming process.

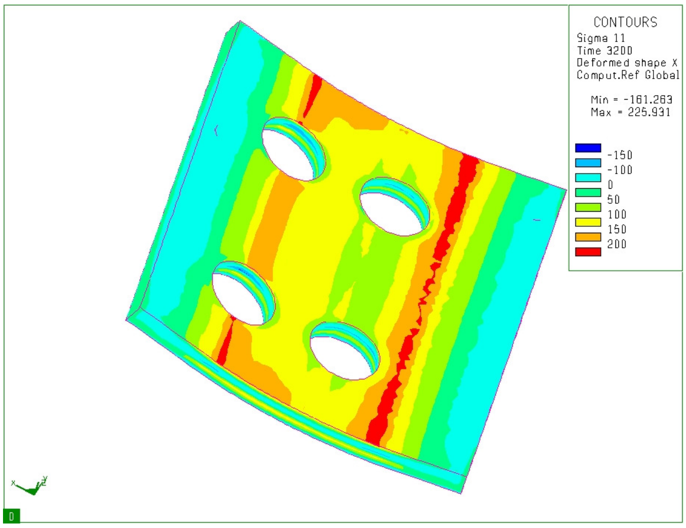

Fig. 2. Sigma 11 distribution at the end of the forming process.

3 INFLUENCE OF RESIDUAL STRESSES ON THE WELDING DISTORTIONS

Forming residual stresses are taken into account as initial conditions for the welding simulation of two deformed thick plates. Welding process which involves complex physical phenomena [5] leads to residual stresses in the welded region and global distortions along the components that may have negative effects on the welded structure behaviour in term of strength and displacement margin. Numerical simulations of residual stresses and distortions due to a welding operation need to accurately take into account the interactions between heat transfer, metallurgical transformations and subsequent mechanics loading. In the present investigation, the 316L(N) austenitic stainless steel does not exhibit any phase transformation so the simulation is simplified. The welding simulation could be performed to evaluate the influence of the forming residual stresses on the welding distortions using a local/global approach similar to the one commonly employed to access welding distortions of large assembly [6] but due to the size of the model and its geometry, a classical approach is used [7]. In order to study the influence of forming residual stresses, two simulations are performed: the first on a plate without residual stresses and the second one on a deformed shape with residual stresses. The welding simulations are performed using SYSWELD® software.

The 3D forming simulation has shown little effects of the drilling of the holes on the deformed shape of the plate. As a consequence, only the 2D forming results taking into account the influence of the machining of the over-lengths will be taken as initial conditions for the welding. A first approach is to use a 2D model for the welding simulation and to consider generalized plane strain assumption. This approach has already been validated for tubular structure [8]. Furthermore, the welding simulation is performed on the middle of the plate where the stresses are maximal and only a half of plate is meshed for symmetry reasons (500 x 60 mm²). Two-dimensional linear elements are used and the mesh is refined under the heat source (middle of the plate). Regarding the boundary conditions, the nodes along the weld line are constrained in the Ux direction (symmetrical conditions) and a node at the extremity of the plate is constrained in the Uy direction to stabilize the structure.

The simulation is performed using an electron beam welding process. The first step of the process is the heat input-fitting source. The fitting is validated thanks to a comparison between numerical results on a plane plate 60 mm thick with experimental results (molten zone size, temperature distribution). The welding simulation can then be performed using this heat source. Figure 3 shows the thermal state at the end of the heating. The molten zone is well defined and a difference of width of the molten zone between the upper and lower skins of the plate is also found numerically.

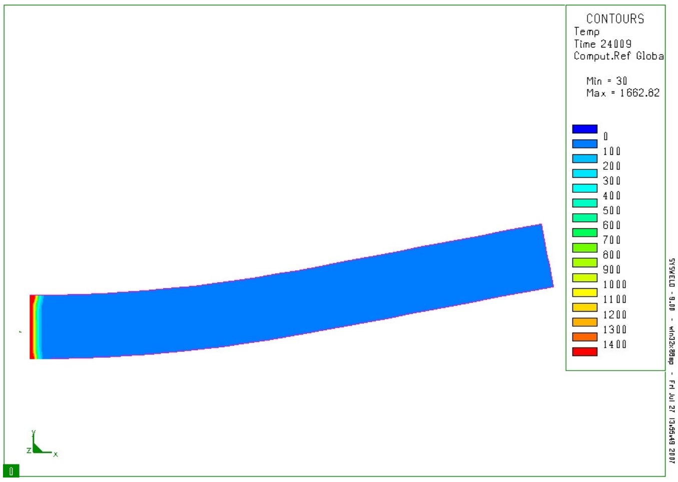

Fig. 3. Thermal state at the end of the heating.

The results of the two simulations (with and without residual stresses) are compared in term of displacements. During the welding, for the two simulations, the plate tends to move towards the convex side. It means that the plate is on flexion.

In term of displacements, the distribution of the Ux and Uy components are identical between the two simulations. The maximum difference of Ux displacement is of the order of 0.02 mm at the extremity of the plate and also in the molten zone. The maximum difference of the Uy displacement is of the order of 0.16 mm and is located in the molten zone (figure 4). There is no variation of the Uy displacement at the extremity of the plate.

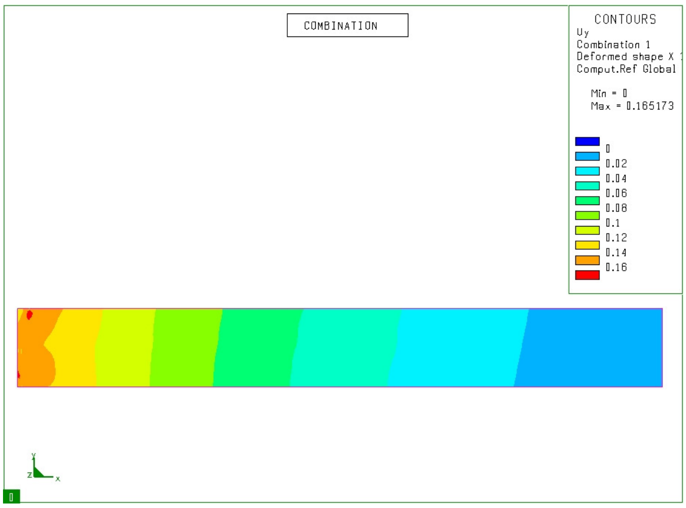

Fig. 4. Difference of UY displacements between the two welding simulation.

To conclude this part, the results show that forming residual stresses have a negligible effect on the distortions induced by the welding process.

4 CONCLUSION

Forming residual stresses effects on the welding distortions have been investigated on this paper. The first step was the simulation of the forming process of a thick plate to estimate the residual stresses induced by the forming. Then, the second step was the electron beam welding simulation of two thick plates taking into account the forming residual stresses. The results show a little influence of the residual stresses due to the forming on the welding distortions.

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