A simulation study of stress induced in pressure vessels during plate rolling process

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Abstract - *Finite element simulations were performed for plate rolling process which is a part of pressure vessel manufacturing. The rolling setup consisted of a three-roller assembly and the simulation was performed for the curved plate. The dynamic explicit simulations were performed for four different rolling speeds and residual stresses in each of the cases were analysed. The study shed light on the importance of their assessment during initial stages of pressure vessel design with respect to the resultant hoop and longitudinal stresses.*

Key Words: finite element, pressure vessel, residual stress, rolling

1.INTRODUCTION

Pressure vessel manufacturing often relies on rolled plates to efficiently and cost-effectively form the cylindrical or spherical shells that constitute the vessel's fundamental structure. The process initiates with large steel plates, cut and then expertly shaped into the desired geometries using specialized machinery. This rolling procedure not only imparts strength to the vessel's shell but also ensures uniform distribution of internal pressure. Further fabrication steps, such as welding and component attachment, complete the pressure vessel assembly.

Following cold rolling, plates exhibit residual stresses characterized by inherent mechanical tensions and compressions persisting within the material post-processing. These residual stresses result from the plastic deformation during cold rolling, where compressive surface forces induce tensile stresses within the material's interior. The extent and distribution of these stresses hinge on material properties, process parameters, and initial plate conditions.

Residual stresses can significantly impact material properties, including ductility and dimensional stability, and influence subsequent machining and forming processes. Consequently, understanding, measuring, and mitigating these stresses are paramount for enhancing the quality and reliability of cold-rolled plates in various industrial applications.

The Finite Element Method (FEM) serves as a powerful numerical tool for predicting stress distributions during the cold rolling of metal plates. FEM discretizes the rolled plate into mesh elements, facilitating the simulation of complex mechanical interactions. Material properties, boundary conditions, and process parameters are incorporated into the model to calculate stress and strain distributions within the plate, providing valuable insights into material behavior under rolling forces and geometry.

There have been some attempts at simulations of rolling to evaluate the stresses induced. Mori et al. presented a method for simulating three-dimensional deformation in plate rolling and edge rolling using the rigid-plastic finite-element method and simplified elements were developed. It predicts plate shapes and loads, validated against experiments with aluminium plates. Devarajan et al. presented a study using FEM simulations with varying roll angular velocity and diameter to analyse cold rolling of thick strips. It aimed to determine the impact of roll speed and diameter on contact pressure and residual stress, offering insights for process optimization and product quality improvement. Recently Zhang et al. modelled deformation resistance with big data. The study improves rolling force prediction accuracy by introducing a Backpropagation neural network model based on industrial data and outperforms traditional models, with a maximum error of only 3.86% compared to theoretical models. Although, there have been a few more of these studies, a comprehensive analysis of the rolling for pressure vessel manufacturing is lacking.

In this work, finite element simulations are performed to model the rolling process of plates to formed curved sections of pressure vessels. Dynamic explicit simulations were conducted across four distinct rolling speeds, and the examination of residual stresses in each scenario was carried out. This investigation has highlighted the significance of evaluating these stresses in the early phases of pressure vessel design, particularly in relation to their influence on resultant hoop and longitudinal stresses.

2. Simulations Methodology

In Figure 1, we can observe the schematic of the rolling assembly. This assembly comprises three rollers: rollers 1 and 2, which create the rolling pass, and roller 3, responsible for shaping the plate into the desired curve.

The initial workpiece measured 10mm in thickness, 100mm in width, and 943mm in length. These dimensions were designed to meet the vessel's required specifications of 100mm in length, 8mm in thickness, and 300mm in diameter, with rollers of 160mm in diameter employed in the assembly. The current numerical study was performed on four different rolling speeds viz., 0.4m/s, 0.8m/s, 1.2m/s, 1.6m/s.

The simulation was conducted using Abaqus/Explicit™ with a dynamic-explicit approach. In this setup, the three rollers were treated as rigid bodies, while the workpiece was meshed with hexahedral 8-noded C3D8R linear elements, with 'R' indicating reduced integration points.

The material chosen for the study was SAE1045 steel. The plasticity data was incorporated through the strain and strain rate dependent Johnson cook model at constant temperature. The coefficients were taken from [Murugesan et al.]. Rolling temperature was kept as equal to ambient.

3. Results and Discussions

Figure 2 shows the contour plot of von mises stress at a certain point of time. The case of flat rolling suggest a plane strain compression and rolling, hence only the side view contour is displayed in figure 2. A completely curved plate is not shown as the stresses induced would be the same at all the points on the plate. The drop in stress values after rolling suggest the non-loading condition in the plate. The existent stresses at such locations are the residual stresses.

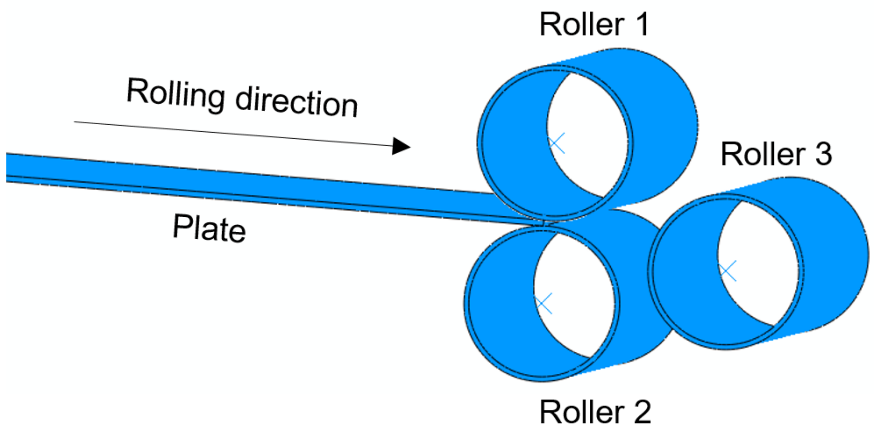

Figure 1 Schematic of rolling setup

Figure 3 displays the von stress evolution with time at a mesh element in the plate for the case where rolling speed was 0.4m/s i.e. 5rad/s angular velocity. Initial low stress values are due to unloaded condition at that element, i.e. that location had not reached the rolling pass. 1mm thickness was each reduced by the top and bottom rollers. This compression and resulting elongation caused the occurrence of peak stress as shown in the graph of figure 3. Later, the drop corresponded to the unloading and the elastic strain relaxation which resulted into the residual stress of 4.42MPa.

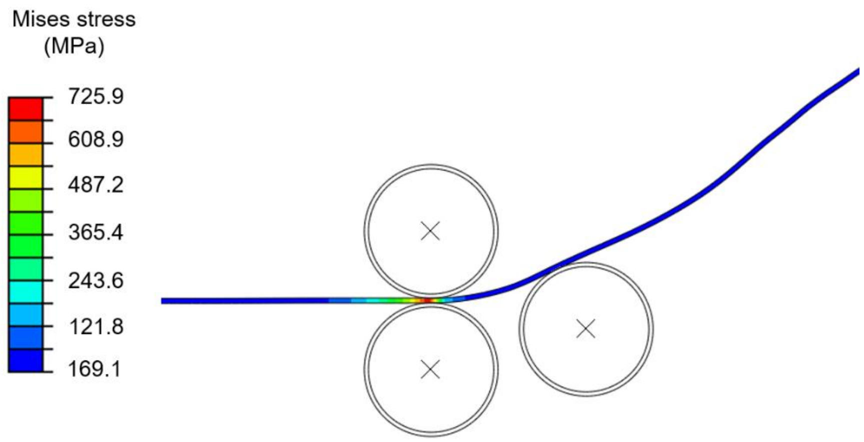

Figure 2 Mises stress contour at rolling speed of 0.4m/s

Similarly, this data was extracted and compiled in table 1 for all the four rolling speeds as shown below. The numerically predicted peak and the residual stresses were found to increase with the rolling speeds. The reason behind this behavior can be attributed to the increase in imparted shear strain rates. The shear forces are acted upon by the rollers during the compression, which also result into the elongation of the workpiece. The shear is acted through the friction and the rolling speed drives the shear strain rate. This strain rate increases the effective stress values. It must be noted that as discussed earlier, the flow stress is also a function of strain rate. Further, due to the increase in stress values developed with increased speeds, the residual stress also increases after the unloading and relaxation.

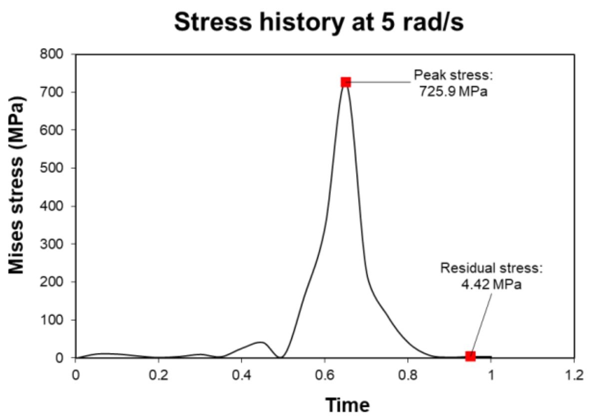

Figure 3 Mises stress history at 0.4m/s (5 rad/s)

The residual stresses at every rolling speeds are plotted in figure 4. The residual stress values are not significant enough with respect to the yield strengths. However, these values shed light on their importance while designing the pressure vessels. The residual stress components get added up to the stresses due to internal pressure (hoop, longitudinal and radial stress, where radial stresses are usually lesser than other two). The resultant hoop and longitudinal would ultimately depend on the residual manufacturing stresses and more importantly on the internal pressure and wall thickness. It's hence important to initially asses the residual stresses especially in the cases of weaker material, thinner walls or comparable internal pressure.

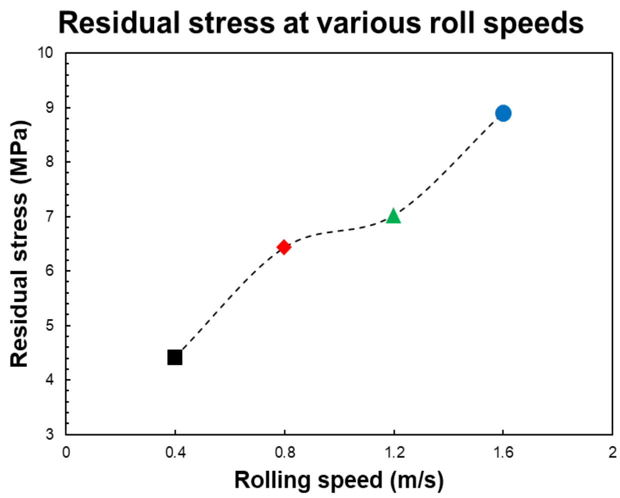

Figure 4 Residual stress at different rolling speeds

Table 1 below outlines the peak stress and residual stress obtained at different rolling speeds.

Speed (m/s)	peak stress (MPa)	residual stress (MPa)
0.4	725.9	4.42
0.8	730.7	6.43
1.2	741.6	7.02
1.6	745.8	8.9

4. Conclusion

The simulations aimed to evaluate the development of residual stresses in the context of plate rolling for pressure vessel fabrication. The findings, as summarized in Table 1, indicate a notable escalation in residual stress magnitude corresponding to increased rolling surface speeds. This observed trend can be attributed to heightened shear stresses associated with greater rolling velocities.

Although the final stress values are not of substantial concern in comparison to the material's yield strength, they do underscore their potential impact on resultant hoop and longitudinal stresses within the vessel. This influence, in turn, hinges on factors like internal pressure levels and the considered wall thicknesses. Consequently, this study underscores the necessity of an initial assessment of residual stresses during the manufacturing process when designing pressure vessels.

References

1. Devarajan, K., K. Prakash Marimuthu, and Ajith Ramesh. "FEM analysis of effect of rolling parameters on cold rolling process." *Bonfring International Journal of Industrial Engineering and Management Science* 2.1 (2012): 35.

2. Mori, K., and K. Osakada. "Simulation of three-dimensional deformation in rolling by the finite-element method." *International Journal of Mechanical Sciences* 26.9-10 (1984): 515-525.

3. Murugesan, Mohanraj, and Dong Won Jung. "Johnson Cook material and failure model parameters estimation of AISI-1045 medium carbon steel for metal forming applications." *Materials* 12.4 (2019): 609.

4. Zhang, Shun Hu, Li Zhi Che, and Xin Ying Liu. "Modelling of deformation resistance with big data and its application in the prediction of rolling force of thick plate." *Mathematical Problems in Engineering* 2021 (2021): 1-10.