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A MULTIOBJECTIVE OPTIMIZATION FRAMEWORK TO OPTIMIZE THE PROCESS PARAMETERS OF ROLLED JOINT

Shyam Kishor Sharma[1], B.K. Mishra[2], I.V. Singh[2], R.K. Sharma[3]

[1] PhD Candidate, Indian Institute of Technology Roorkee, Roorkee, India (shyam_s@me.iitr.ac.in)
[2] Professor, Indian Institute of Technology Roorkee, Roorkee, India
[3] Engineering Directorate, Nuclear Power Corporation of India Limited, Mumbai, India

ABSTRACT

This work presents a parameter optimization study of pressure tube (PT) - end fitting (EF) rolled joint used in pressurized heavy water reactors (PHWRs). In the rolling process of the rolled joint, very high contact pressure and residual stresses are generated. High contact pressure is beneficial for leak tightness, while tensile residual stresses are detrimental as they promote the delayed hydride cracking in the PT. A finite element (FE) model of the rolled joint is modelled to simulate the residual stresses and contact pressure generated after the rolling process. The effect of rolling process parameters such as clearance, coefficient of friction, and percentage wall reduction on the joint's residual stress and contact pressure is analyzed using this FE model. A machine learning (ML) model is trained using the input-output relations obtained from the FE simulations. The neural network obtained from the ML model is used as a fitness function in the multi-objective optimization algorithm, non-dominated sorting genetic algorithm (NSGA-II). The optimized set of process parameters is obtained using this algorithm, which yields the minimum tensile residual stress and maximum contact pressure in the rolled joint. This study will be helpful in deciding the rolling parameters for the rolled joint.

INTRODUCTION

Rolled joints are mechanical joints used in various industries, such as chemical and nuclear power plants. These joints are generally used for joining dissimilar materials that cannot be welded due to the formation of brittle intermetallic compounds (Roy *et al*., 2023). In a pressurized heavy water reactor (PHWR), the rolled joint is used to join the pressure tube (PT) to end fitting (EF) with the help of the rolling process (Singh *et al*., 2019). In the rolling process, the rollers rotate inside the PT (made of Zr-2.5%Nb) and plastically deform it into the EF (made of SS 403 steel). A schematic diagram of the PT-EF rolled joint is shown in Figure 1. In the rolling process, high residual stresses (at the boundaries of PT and EF) and contact pressure (at the interface of PT and EF) are generated in the rolled joint. High contact pressure is beneficial for leak-tightness, while the tensile residual stresses are detrimental as they promote the delayed hydride cracking. Delayed hydride cracking (DHC) is a hydride embrittlement phenomenon (Sharma *et al*., 2018) caused by the migration of hydrogen toward the region of stress concentration due to the tensile stress gradient (Jha *et al*., 2022). For a good rolled joint, there must be high contact pressure and low tensile residual stresses in the joint. The high contact pressure and tensile residual stresses in the rolled joint depend upon several rolling parameters such as clearance, coefficient of friction, percentage wall reduction, etc. In this study, the effect of these parameters on the contact pressure and tensile residual stress is studied. Further using an optimization study, the optimized set of parameters is given for the high contact pressure and low tensile residual stresses.

The parametric and optimization study of PT-EF rolled joint is a less investigated area in the open literature. Some studies have been reported in the literature related to similar joint, tube to tubesheet joint (TTT-joint). Large clearance reduces the contact pressure in the joint while increasing the tensile residual stresses. The effect of the coefficient of friction is studied by Aboodi et al. (2008); the coefficient of friction increases the contact pressure between the joints. Higher the wall reduction of PT results in higher contact pressure and higher tensile residual stresses (Sharma *et al*., 2024). The finite element analysis (FEA) of the PT-EF rolled joint is performed by Sharma et al., (2023). They also investigate the effect of thermal creep on the relaxation of residual stresses and contact pressure.

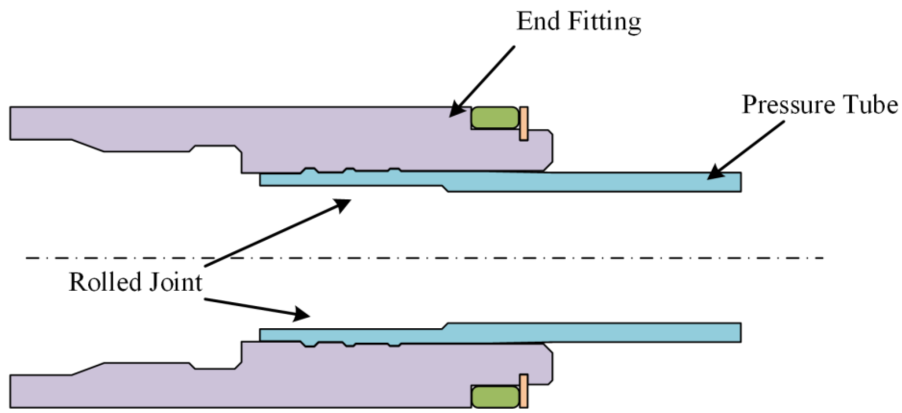

Figure 1. A Schematic Diagram of Pressure Tube-End Fitting Rolled Joint used in a PHWR.

After analysing the recent literature review, certain shortcomings are addressed in this paper. The works of current study are given below.

- An axisymmetric FE model of the PT-EF rolled joint is modelled to find the residual stresses and contact pressure in the joint.
- A parametric study is performed to find the effect of clearance, coefficient of friction, and percentage wall reduction on the residual stresses and contact pressure of the rolled joint.
- An artificial neural network (ANN) model is trained based on the FE simulations to find the value of outputs at any arbitrary sets of rolling parameters.
- A genetic algorithm (GA) based multiobjective optimization of the rolling parameters is done using this ANN model.

SIMULATION DETAILS

An axisymmetric FE model of the PT-EF rolled joint is shown in Figure 2. The inner diameter and thickness of the PT are 83 mm and 3.3 mm respectively. The thickness of EF is 26.5 mm and a clearance of 0.05 mm is given between the PT and EF. The materials of both PT (Zr-2.5%Nb) and EF (SS-403) are assumed to be isotropic and homogeneous in nature. The outer diameter of the EF is fixed in the radial direction and the lower end of EF is fixed in the axial direction. A radial displacement of 0.5 mm is given to the roller, while the roller is fixed in the axial direction. The value of radial displacement (u_r) can be given according to the desired percentage wall reduction ($\%WR$) as per given relation in Eq. (1).

$$u_r = \left(\frac{\%WR * T}{100}\right) + c \tag{1}$$

where, T is the thickness of the PT and c is the clearance between the PT and EF.

There are two contact pairs defined in the FE simulations; one is between the PT-EF and the other one between the roller and PT. The coefficient of friction between the PT and EF is 0.2 and between the roller and PT is 0.1. The quadratic elements are taken for the meshing of the whole FE model of the rolled joint. The PT is meshed denser as compared to the EF and roller. The Young modulus and Poisson ratio of the PT are taken as 96.54 GPa and 0.34, respectively. The Young modulus and Poisson ratio for the EF are 200 GPa and 0.3, respectively. The yield strengths of the PT and EF are 580 MPa and 680 MPa respectively. The linear hardening model is taken for both materials.

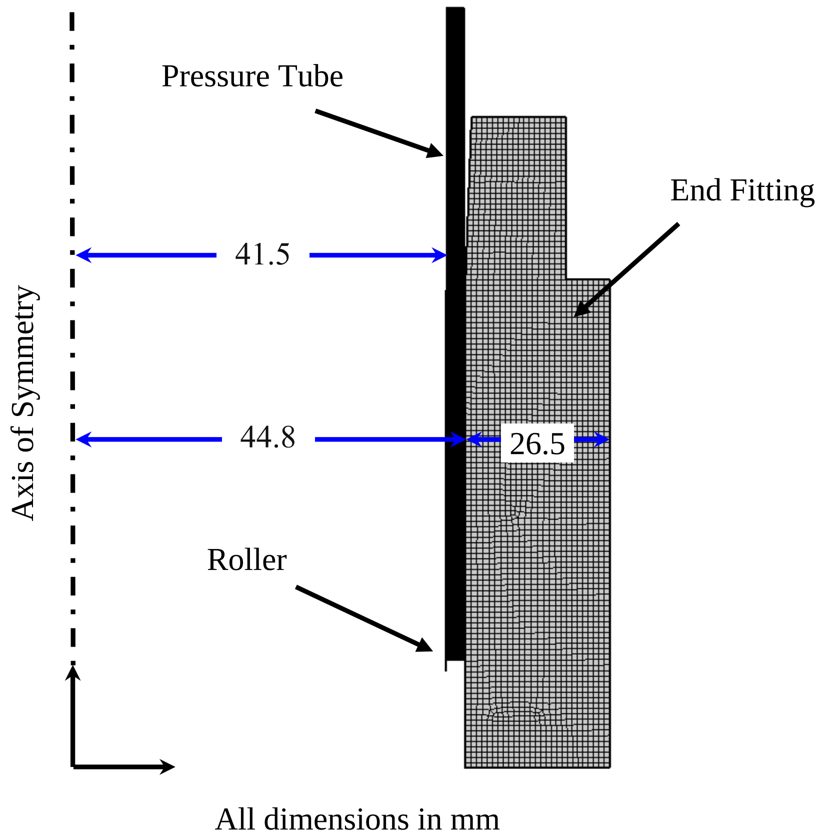

Figure 2. A Finite Element Model of Pressure Tube-End Fitting Rolled Joint used in a PHWR.

RESULTS AND DISCUSSION

In this section the outcomes from the simulations of the rolled joint FE model are presented. In the subsequent sub-sections, the model validation, ANN model, and results obtained from the optimization study are discussed.

Finite Element Model Validation

As the details given in the previous section, the FE simulations are performed on the axisymmetric FE model of the rolled joint. All the FE simulations and parametric studies are executed using the COMSOL-Multiphysics software (COMSOL-6.2, 2024). The equivalent residual stress at the pressure tube inner diameter (PTID) and contact pressure at the interface of the PT-EF are compared with a previous study by Singh *et al*. (2019). This comparison is given in Figure 3; a good correlation is obtained between the simulation results and the literature findings. A variation of residual hoop stress in the rolled joint and at the PTID is given in Figure 4. It is observed that in the rolling region (region of direct contact with roller), high compressive residual hoop stress is generated; this region is called rolled region. Near the rolled region, tensile residual hoop stress is generated, and this region is known as the transition region. This tensile residual stress is detrimental to the delayed hydride cracking. In the next sections, the effect of different rolling parameters on the tensile residual hoop stress and contact pressure are analyzed.

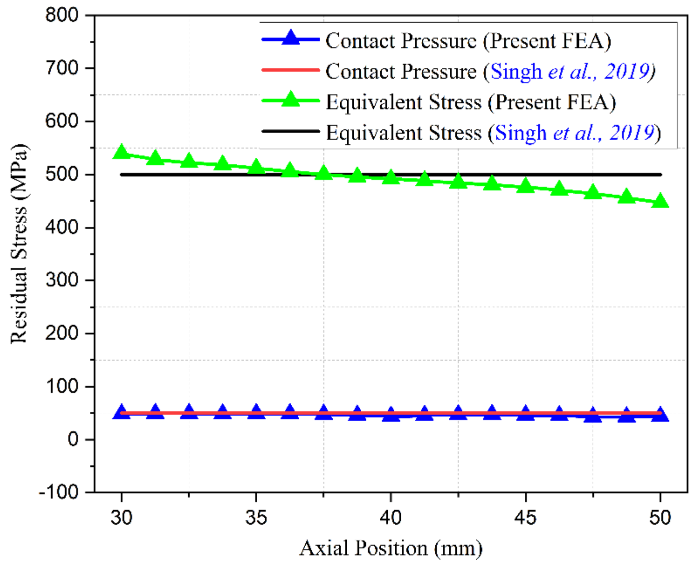

Figure 3. A comparison of the residual equivalent stress (at the inner diameter of PT) and contact pressure (at the interface of PT-EF) with the literature findings.

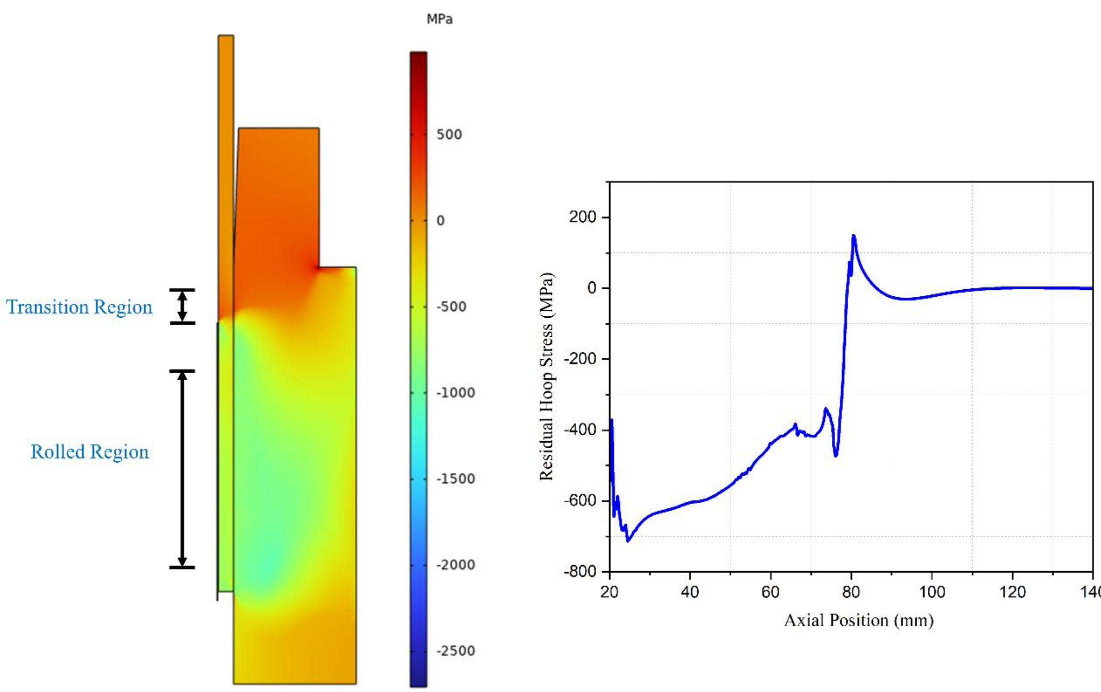

Figure 4. The residual hoop stress plot in the PT-EF rolled joint and a variation of residual hoop stress at the inner diameter of PT along the length of the PT.

Parametric Study

In this section, the effect of different rolling parameters (clearance, percentage wall reduction, coefficient of friction) on the rolled joint's contact pressure and residual stresses is analyzed. In the following paragraphs, the contact pressure means the average contact pressure at the interface of PT and EF in the rolled region, while residual hoop stress represents the maximum tensile residual hoop stress at the inner diameter of the PT.

Initial clearance between the PT and EF plays an important role in the values of the residual stresses generated after the rolling process. The effect of clearance on the contact pressure and residual hoop stress is shown in Figure 5. As the clearance increases, the contact pressure between the PT and EF decreases and the residual hoop stress increases. With low clearance, the material of PT experiences high localized plastic deformation in the rolled region, which increases the contact pressure. High clearance results in less plastic deformation in the rolled region; due to that, more elongation and more tensile stresses are generated in the transition region.

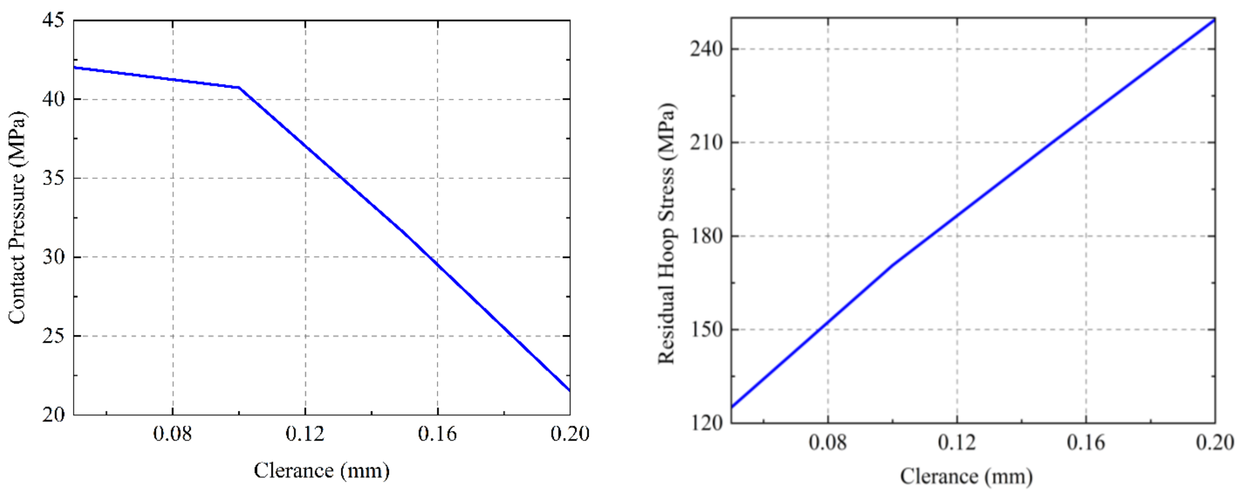

Figure 5. Variation of contact pressure and tensile residual hoop stress with change in clearance.

Percentage wall reduction of the PT is directly related to the radial displacement given to the roller as given in Eq. (1). As percentage wall reduction increases, the PT deforms more plastically inside the EF, resulting in more contact pressure in the rolled region. For a fixed value of clearance (0.05 mm) and coefficient of friction (0.2), as the percentage wall reduction increases, more extrusion of the PT in the transition region happens. This results in an increase in tensile residual hoop stress with an increase in the percentage wall reduction. These variations in contact pressure and residual hoop stress with the percentage wall reduction are shown in Figure 6.

Friction between the PT and EF is another important parameter, which puts an additional degree of freedom in contact between the PT and EF. A high value of the coefficient of friction (High friction) results in restricted movement of the PT in the axial direction relative to the EF. Due to that, less tension forces are generated in the PT in the transition region, which results in less tensile residual hoop stress with an increase in the coefficient of friction. On the other hand, higher friction results in a more confined area and more localized plastic deformation in the rolled region. Due to that, contact pressure increases with an increase in the value of the coefficient of friction between PT and EF. The variation of contact pressure and residual hoop stress with the change in coefficient of friction is shown in Figure 7.

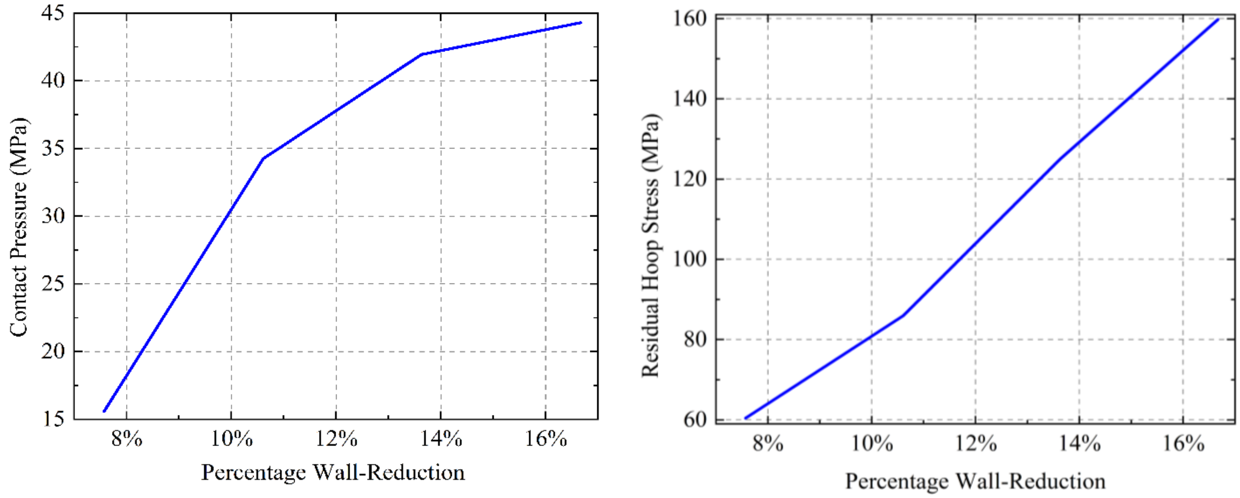

Figure 6. Variation of contact pressure and tensile residual hoop stress with change in percentage wall reduction of PT.

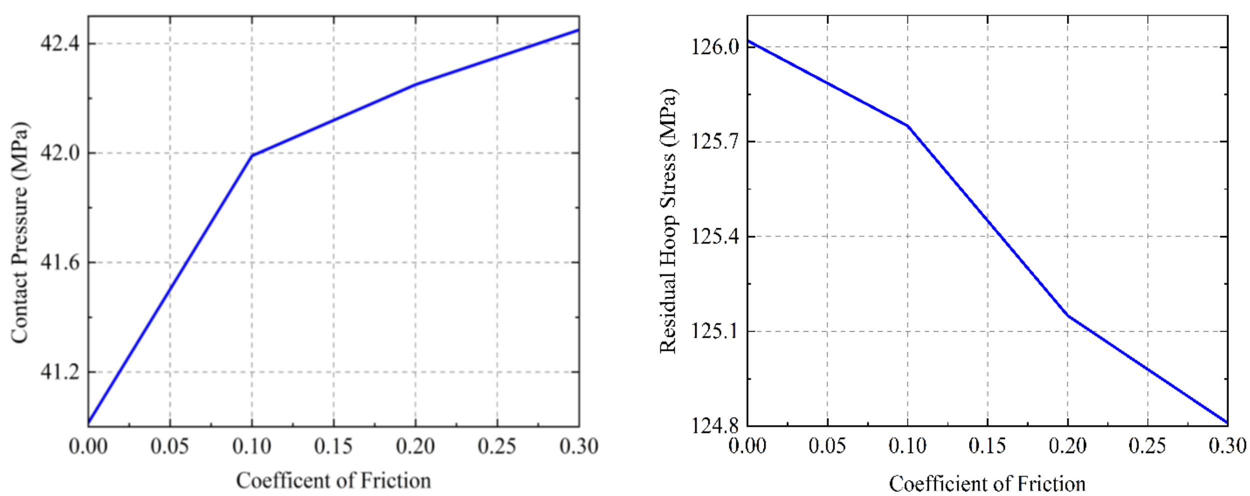

Figure 7. Variation of contact pressure and tensile residual hoop stress with change in coefficient of friction.

Artificial Neural Network and Optimization Study

As already discussed, an artificial neural network (ANN) model is trained based on the FE simulations. This ANN model is used in optimization algorithms as a fitness function to find the outputs at any desired input parameters. There are 125 sets of input (clearance, percentage wall reduction, coefficient of friction) and output (contact pressure and residual hoop stress) formed using the FE simulations. The upper and lower bounds of the input parameters are the same as those taken in the parametric study. Using these data sets an ANN model is trained and validated using the FEA model. For the training of the ANN model Levenberg-Marquardt backpropagation technique is used. After successfully training of the ANN model, the model is validated using the FE model. This validation study is shown in Figure 8. A good correlation is obtained between the results predicted by the ANN model and with the FE model. After ensuring the accuracy of the ANN model this ANN model is used in the optimization study.

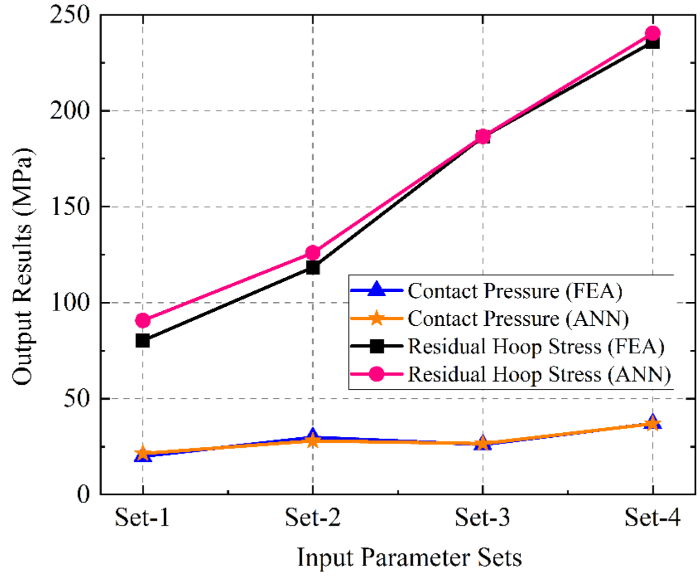

Figure 8. A comparison of the obtained outputs from the ANN and FEA results.

For a good rolled joint, there are two desired outputs: high contact pressure and less tensile residual hoop stress. Therefore, to find the optimized parameters for the rolled joint, a multiobjective optimization study is used in the current work. A non-dominated sorting genetic algorithm (NSGA-II) is used for the optimization of the current rolled joint problem. This algorithm is based on a genetic algorithm, which works on the concept of "survival of the fittest". In this algorithm, an initial population of input parameters is created, and the best-fit individuals are selected from the group. The selection of the best-fit individual is based on the objective function, non-dominated sorting process, and genetic operators. Unlike single-objective optimization, more than one optimized set of parameters is possible in multiobjective optimization. All these optimal solutions lie on a curve, and this curve is known as the Pareto front. For the given problem of the PT-EF rolled joint, the Pareto front diagram is shown in Figure 9.

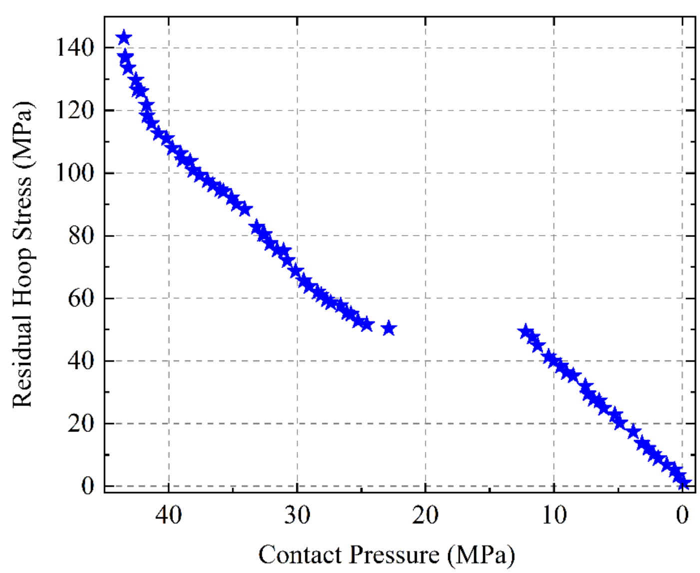

Figure 9. Pareto front for maximum contact pressure and minimum residual hoop stress in a rolled joint problem.

There are around 70 optimal solutions obtained on the Pareto front shown in Figure 9. These optimal solutions can be further modified according to the joint's requirement. For the condition of contact pressure greater than 32 MPa and tensile residual hoop stress less than 80 MPa, the optimized set of parameters is given in Table 1. This optimized result is further verified using the FEA simulation and there is good agreement is found between the results.

Table 1: Optimized set of parameters for the given condition.

Rolling Process Parameters			Residual Stress (MPa)		Contact Pressure (MPa)	
Clerance (mm)	Percentage wall reduction	Coefficient of friction	NSGA-II	FEA	NSGA-II	FEA
0.0558	10.12 %	0.27	77.522	85.185	32.12	37.62

CONCLUSION

In this work, a multiobjective optimization study of rolling process parameters of PT-EF rolled joints is done. The contact pressure and residual stress at the end of the rolling process are obtained using the FE simulations. Based on these FE simulations, an ANN model is trained and this ANN model is used as an objective function in the multiobjective optimization algorithm NSGA-II. The main findings of the current work are given below,

- The results obtained from the 2D axisymmetric model of the rolled joint are well aligned with the 3D results available in the literature. In the axisymmetric modeling, the computational efforts are less as compared to the 3D model.
- The initial clearance, percentage wall reduction of the PT, and coefficient of friction between the PT and EF are the main rolling parameters which affect the performance of the rolled joint.
- An increase in clearance reduces the contact pressure while increasing the residual hoop stress. In contrast, a higher percentage of wall reduction enhances both contact pressure and residual hoop stress. Additionally, an increase in the coefficient of friction raises the contact pressure but decreases the residual hoop stress.
- The proposed ANN and NSGA-II-based framework effectively optimizes the rolling process parameters to achieve minimal tensile residual stress and maximum contact pressure in the PT-EF rolled joint.

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REFERENCES

Al-Aboodi, A., Merah, N., Shuaib, A.R., Al-Nassar, Y. and Al-Anizi, S.S., (2008). "Modeling the effects of initial tube-tubesheet clearance, wall reduction and material strain hardening on rolled joint strength," *Journal of pressure vessel technology*, 130(4).

COMSOL 6.2. COMSOL online documentation; 2024.

Jha, A., Sarkar, S., Singh, I.V., Mishra, B.K., Singh, R. and Singh, R.N. (2022). "A study on the effect of residual stresses on hydride assisted crack in Zr-2.5 Nb pressure tube material using XFEM," *Theoretical and Applied Fracture Mechanics*, 121, p.103536

Roy, V., Chatterjee, S., Halder, P. and Maheshwari, N.K., (2023). "Investigating the impact of roller position on pressure tube-end fitting rolled joint performance using 3D explicit finite element analysis," *International Journal of Pressure Vessels and Piping*, 206, p.105057.

Sharma, R. K., Bind, A. K., Avinash, G., Singh, R. N., Tewari, A., & Kashyap, B. P. (2018). "Effect of radial hydride fraction on fracture toughness of CWSR Zr-2.5% Nb pressure tube material between ambient and 300 C temperatures," *Journal of Nuclear Materials*, 508, 546-555.

Sharma, S.K., Mishra, B.K, Singh, I.V. (2024). "A multiobjective optimization framework based on FEA, ANN, and NSGA-II to optimize the process parameters of tube-to-tubesheet joint," *Finite Elements in Analysis and Design*, 241, 104225.

Sharma, S.K., Sarkar, S., Singh, I.V., Mishra, B.K. and Sharma, R.K., (2023). "A numerical estimation of leak-tightness in rolled joint under thermal creep," *International Journal of Pressure Vessels and Piping*, 205, p.105005.

Singh, R. J., Jonnalagadda, K. N., Guruprasad, P. J., & Kushwaha, H. S. (2019). "A three-dimensional explicit finite element analysis of rolled joint process by varying the roller path," *International Journal of Pressure Vessels and Piping*, 177, 103975.