Journal of Stress Analysis
Vol. 10, No. 1, 2026, 1-9

Bu-Ali Sina University

ORIGINAL RESEARCH PAPER

# Influence of Preheating Temperature on Residual Stresses and Distortions in Friction Stir Welding of SUS304 Stainless Steel

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## Article info

*Article history:*
Received 2026-04-17
Received in revised form 2026-05-22
Accepted 2026-06-26

*Keywords:*
Friction Stir Welding (FSW)
Preheating, Residual stresses
Numerical simulation
Distortion

**Abstract**

Friction stir welding (FSW) is a solid-state joining process capable of producing high-quality joints with low distortion and excellent mechanical properties. However, due to the high process temperatures required for stainless steels, considerable residual stresses and distortion may still develop during welding. In this study, the effect of preheating temperature on the temperature distribution, residual stresses, and distortion during FSW of SUS304 stainless steel was numerically investigated using a coupled thermo-mechanical finite element model developed in ABAQUS. A user-defined DFLUX subroutine was implemented to simulate the moving heat source, and four preheating temperatures (25, 100, 200, and 300 °C) were evaluated. The numerical model was validated against published experimental data, showing good agreement in terms of temperature history and residual stress distribution. The results indicate that increasing the preheating temperature has only a limited effect on the peak welding temperature but significantly reduces thermal gradients within the workpiece. Furthermore, the elevated temperature decreases the yield strength of SUS304, promoting plastic deformation during welding and consequently reducing the accumulation of residual stresses after cooling. At a preheating temperature of 300 °C, the average longitudinal residual stress decreased by approximately 79.4% compared with the non-preheated condition. In addition, workpiece distortion was noticeably reduced while the peak temperature remained below the melting point of SUS304, confirming that the process retained its solid-state nature. These findings demonstrate that preheating is an effective approach for improving the thermo-mechanical performance of friction stir welded SUS304 stainless steel.

## Nomenclature

| | | | |
|---|---|---|---|
| $Q_{pin}$ | Generated heat by pin | $F_z$ | Downforce |
| $Q_{shoulder}$ | Generated heat by shoulder | $A_{Bpin}$ | Bottom Area of the pin |
| $H_{pin}$ | Pin height | $\omega$ | Rotational speed |
| $R_{Tpin}$ | Pin radius at shoulder | $\sigma_{yield}$ | Yield stress |

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doi 10.22084/jrstan.2026.32590.1282
ISSN: 2588-2597

| | | | |
|---|---|---|---|
| $R_{Bpin}$ | Pin radius at pin bottom | $\alpha$ | Shoulder concavity angle |
| $R_{shoulder}$ | Shoulder radius | $\mu$ | Coefficient of friction |

## 1. Introduction

In recent years, friction stir welding (FSW) has become one of the most widely used solid-state joining techniques because it produces high-quality joints without melting either the workpiece or the tool. Unlike conventional fusion welding, FSW forms a metallurgical bond below the melting temperature of the base material, thereby minimizing common fusion-related defects [1]. Joint formation in FSW is governed by localized plastic deformation and thermal softening generated by the rotating and traversing tool, where the applied stress exceeds the material's yield strength [2]. Since its invention, FSW has attracted considerable industrial interest for joining materials with limited fusion weldability, including aluminum alloys, magnesium alloys, and dissimilar materials [3–5].

During the FSW process, frictional heating and severe plastic deformation promote material flow and microstructural evolution within the weld zone. Consequently, the thermal history of the process strongly influences defect formation, mechanical properties, residual stresses, and workpiece distortion. Insufficient control of the thermal field may result in excessive residual stresses, distortion, and reduced dimensional accuracy of the welded structure [6,7].

One effective approach to improving the thermo-mechanical behavior of welded joints is the application of an appropriate preheating temperature before welding. Preheating reduces the temperature gradient between the weld zone and the surrounding material, leading to more uniform thermal expansion and contraction during the welding cycle. In addition, the elevated initial temperature decreases the yield strength of the material, facilitating plastic deformation and allowing a larger portion of the thermally induced strains to be accommodated during welding. As a result, the magnitude of the residual stresses and distortion after cooling can be significantly reduced [8,9].

Because experimental investigations of FSW are often time-consuming and costly, numerical simulation has become an efficient tool for predicting temperature distribution, material flow, distortion, and residual stress development. Coupled thermo-mechanical finite element models have demonstrated excellent capability in describing the interaction between heat generation, plastic deformation, and residual stress formation [10,11]. Recent numerical studies have also investigated the influence of process parameters, such as rotational speed and traverse speed, on the thermal field and residual stress distribution [12,13]. In addition, in-situ rolling tensioning has been reported as an effective technique for reducing residual stresses and improving the fatigue performance of friction stir welded joints [14]. Since residual stresses significantly influence the fatigue behavior and long-term structural performance of welded components, accurate prediction and effective mitigation of these stresses remain important research objectives [15]. Nevertheless, most previous experimental and numerical investigations have focused primarily on aluminum alloys and their related alloys [12,16].

Several researchers have investigated the influence of preheating on the FSW of aluminum alloys. Muhayat et al. reported that different preheating temperatures (150, 250, and 300 °C) significantly affected the weld microstructure and mechanical properties of AA5052 joints [17]. Zhao et al. demonstrated that preheating improved the mechanical properties of dissimilar copper–aluminum joints produced by FSW [18]. Poongkundran and Senthilkumar showed that preheating enhanced the mechanical performance of AA7075 friction stir welds [19]. Similarly, Yaduwanshi et al. reported improved weldability in aluminum–copper joints when preheating temperatures up to 200 °C were applied [20]. Jabbari developed an analytical model to predict the temperature distribution during preheated FSW and validated the numerical predictions using experimental data [21].

Although preheating has been extensively applied in conventional welding processes and has been investigated for friction stir welding of aluminum alloys, its influence on the thermo-mechanical behavior of friction stir welded SUS304 stainless steel has not yet been systematically investigated. Owing to the substantially higher flow stress and processing temperatures required for stainless steels compared with aluminum alloys, the effectiveness of preheating cannot be directly inferred from previous studies. Therefore, this study develops a coupled thermo-mechanical finite element model in ABAQUS incorporating a user-defined DFLUX subroutine to simulate the moving heat source under different preheating conditions. The effects of four preheating temperatures (25, 100, 200, and 300 °C) on the temperature evolution, longitudinal and transverse residual stresses, and workpiece distortion are systematically evaluated. The results provide new insights into the role of preheating in mitigating residual stresses and distortion during friction stir welding of SUS304 stainless steel while maintaining the solid-state characteristics of the process.

## 2. Numerical Simulation

To investigate the thermo-mechanical behavior of SUS304 stainless steel during friction stir welding

(FSW), a three-dimensional finite element model was developed using ABAQUS. The effects of preheating temperatures of 25, 100, 200, and 300 °C on the temperature distribution, residual stresses, and workpiece distortion were evaluated. The workpiece consisted of two identical plates with dimensions of 5 × 100 × 150 mm. The FSW tool comprised a concave shoulder with a radius of 20 mm and a concavity angle of 2°, together with a conical pin having top and bottom radii of 6 mm and 3 mm, respectively. The welding parameters were kept constant throughout all simulations, with a rotational speed of 1400 rpm and a traverse speed of 150 mm/min, corresponding to typical FSW conditions for SUS304 stainless steel [12].

### *2.1. Heat Source Modeling*

The heat input was modeled using a user-defined FORTRAN subroutine (DFLUX), consisting of two heat flux components: a surface heat flux representing the shoulder and a volumetric heat flux representing the pin. The heat flux equations were based on the analytical model proposed by Schmidt et al. [22] and were defined as spatially and temporally varying functions to accurately simulate the movement of the welding tool along the weld path, as follows:

$$Q_{pin} = 2\pi\omega H_{pin}\frac{\sigma_{yield}}{\sqrt{3}}\left(\frac{R_{Tpin}+R_{Bpin}}{2}\right) + \frac{2}{3}\,\pi\omega\mu\frac{F_z}{A_{Bpin}}R^2_{Bpin} \quad (1)$$

$$Q_{shoulder} = \frac{2}{3}\pi\omega\ \frac{\sigma_{yield}}{\sqrt{3}}(R^3_{shoulder} - R^3_{Tpin})(1+\tan\alpha) \quad (2)$$

This dual-source approach has been widely validated in recent finite element simulations of FSW and shown to predict temperature and stress gradients effectively [23,24].

### *2.2. Material Properties*

The material properties of SUS304 were assumed to be temperature-dependent, including density, thermal conductivity, specific heat capacity, Young's modulus, and yield strength, as summarized in Table 1 [25]. Considering the temperature dependence of these properties is essential for accurately predicting the thermomechanical behavior of the material, as thermal softening significantly influences plastic deformation and the development of residual stresses during the FSW process [24].

### *2.3. Boundary and Preheating Conditions*

Heat loss was modeled using convective boundary conditions with heat transfer coefficients of 200 W/m°C at the bottom surface and 15 W/m°C on the remaining exposed surfaces, representing natural convection under an ambient temperature of 25 °C [26]. The selected preheating temperatures were applied as the initial temperature conditions in the thermal analysis to isolate the effect of preheating temperature on the subsequent thermal cycle. The investigated simulation cases and their corresponding preheating temperatures are summarized in Table 2.

The workpiece was assumed to remain fully clamped throughout the welding process and the subsequent cooling stage until it reached ambient temperature. This assumption was adopted to eliminate the influence of clamp release on the residual stress distribution, allowing the effect of preheating temperature to be evaluated independently.

### *2.4. Analysis Procedure*

A sequentially coupled approach was used as follows:

1. Transient thermal step: 60s to simulate the welding phase (matching translation speed) and 340s for cooling.

2. Mechanical step: 400s to calculate residual stresses and distortions.

**Table 1**
Mechanical and thermal properties of SUS304 [25].

| T (°c) | E (Gpa) | Yield stress (MPa) | $C_p$ ($Wm^{-2}K^{-1}$) | $\rho$ ($kgm^{-3}$) | $\alpha$ ($10^{-6\circ}c^{-1}$) |
|---|---|---|---|---|---|
| 25 | 198.5 | 265 | 462 | 7900 | 17 |
| 100 | 193 | 218 | 496 | 7880 | 17.1 |
| 200 | 185 | 186 | 512 | 7830 | 18 |
| 300 | 176 | 170 | 525 | 7790 | 18.6 |
| 400 | 164 | 149 | 540 | 7750 | 19.1 |
| 600 | 159 | 115 | 577 | 7660 | 19.6 |
| 800 | 151 | 91 | 604 | 7560 | 20.2 |
| 1200 | 60 | 25 | 467 | 7370 | 20.7 |
| 1300 | 20 | 21 | 692 | 7320 | 21.1 |
| 1500 | 10 | 10 | 700 | 7320 | 21.6 |

**Table 2**
Cases in the present study.

| State | Name | Preheating temperature (°C) |
|---|---|---|
| 1 | A | 25 |
| 2 | B | 100 |
| 3 | C | 200 |
| 4 | D | 300 |

### *2.5. Mesh and Convergence Study*

The finite element model was discretized using eight-node hexahedral elements, including DC3D8 elements for the thermal analysis and C3D8R elements for the mechanical analysis. Mesh refinement was applied in the friction stir welding (FSW) zone to accurately capture the steep thermal and stress gradients, while a coarser mesh was used away from the weld to improve computational efficiency. The final finite element mesh adopted for the numerical simulations is shown in Fig. 1, consisting of approximately 70,000 elements.

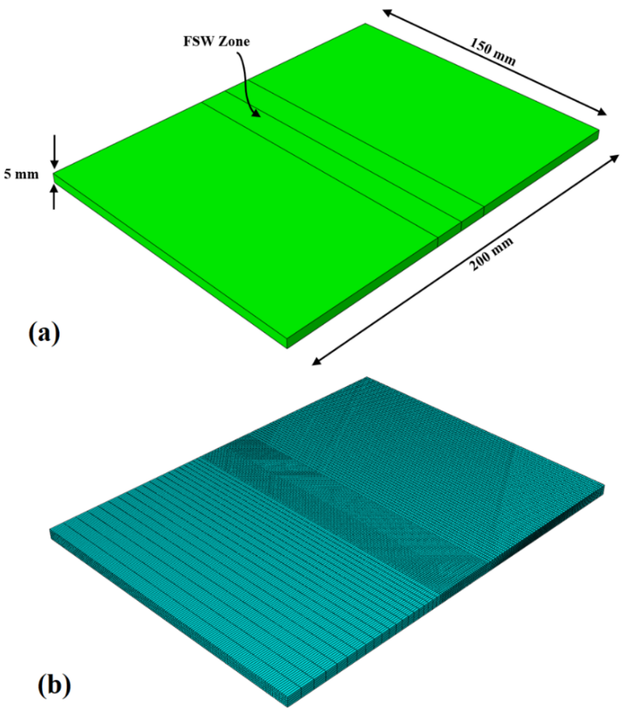


**Fig. 1.** a) Dimensions and geometry of the workpiece b) finite element mesh used in the numerical simulation.

To ensure that the numerical results were independent of the mesh density, a mesh convergence study was first performed using the validated model under identical welding conditions. Seven different global mesh sizes (6, 5, 4, 3, 2, 1, and 0.5 mm) were examined. The predicted peak temperature at the selected monitoring point was used as the convergence criterion because it is highly sensitive to mesh refinement and accurately reflects the quality of the thermal solution.

The results of the mesh convergence study are summarized in Table 3. As the mesh size decreased, the predicted peak temperature gradually converged from 285 °C to 459 °C. The difference between the 1 mm and 0.5 mm meshes was only 1 °C (approximately 0.2%), indicating that further mesh refinement produced a negligible improvement in the numerical solution. Therefore, a global mesh size of 1 mm was selected for all subsequent simulations. It should be noted that the convergence study was performed using the validated model geometry, which contained approximately 46,500 elements for the 1 mm mesh. Owing to the different dimensions of the model investigated in the present study, the same global mesh size of 1 mm resulted in approximately 70,000 elements in the final numerical model.

**Table 3**
Mesh convergence study based on the predicted peak temperature.

| Mesh Size (mm) | Total Number of Elements | Peak Temperature (°C) |
|---|---|---|
| 6 | 2250 | 285 |
| 5 | 3000 | 319 |
| 4 | 4940 | 346 |
| 3 | 8500 | 403 |
| 2 | 19125 | 445 |
| 1 | 46500 | 458 |
| 0.5 | 138000 | 459 |

### *2.6. Post-Processing*

Residual stresses were evaluated in terms of the von Mises, principal, longitudinal, and transverse stress components. Workpiece distortion was quantified as the out-of-plane displacement across the workpiece. All results were analyzed at critical locations, including the weld centerline, shoulder boundaries, and heat-affected zone (HAZ).

### *2.7. Model Assumptions*

1. The plunge and retraction stages were neglected to focus exclusively on the steady-state welding stage.

2. The welding tool was assumed to be rigid, with its thermal behavior considered in the heat transfer analysis.

3. The workpiece was assumed to be isotropic with temperature-dependent material properties.

These assumptions are consistent with previous numerical studies on friction stir welding and are considered appropriate for evaluating the influence of preheating temperature on residual stresses and workpiece distortion. By incorporating temperature-dependent material properties, a dual heat source model, a sequentially coupled thermo-mechanical analysis, and a refined finite element mesh, the proposed finite element model provides a reliable framework for predicting the thermo-mechanical behavior of friction stir welded SUS304 stainless steel under different preheating conditions.

## 3. Results and Discussion

### 3.1. Validation of Model

Before performing the parametric simulations, the proposed numerical model was validated against published experimental data [12]. For this purpose, the predicted temperature history and longitudinal residual stress at a surface point located 14 mm from the weld centerline were compared with the corresponding experimental results. The comparisons are presented in Figs. 2 and 3, respectively.

As shown in Figs. 2 and 3, the numerical model accurately predicts both the temperature history and the longitudinal residual stress distribution, demonstrating good agreement with the experimental results [12]. Therefore, the validated model was subsequently employed to investigate the effects of different preheating temperatures on the temperature distribution, residual stresses, and workpiece distortion during friction stir welding of SUS304 stainless steel.

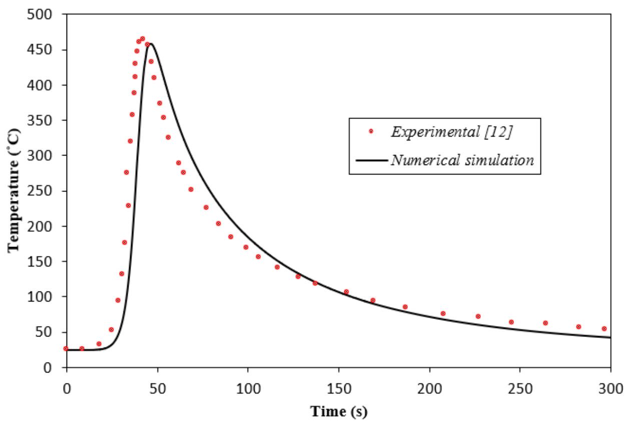


**Fig. 2.** Numerical and experimental temperature history diagrams.

### 3.2. Temperature Distribution During the Process

The effect of preheating temperature on the thermal behavior of friction stir welded SUS304 stainless steel was investigated numerically. Four preheating temperatures (25, 100, 200, and 300 °C) were considered to evaluate their influence on the thermal history of the process. The temperature–time histories at the midpoint of the workpiece during the welding and cooling stages are presented in Fig. 4, while the corresponding peak temperatures are summarized in Table 4.

According to Fig. 4, the temperature histories of all models follow a similar trend. In all cases, after reaching the maximum temperature when the tool passes over the measurement point, the workpiece undergoes a gradual cooling stage with nearly identical cooling rates. Eventually, the temperature of all models returns to the ambient temperature of 25 °C. This indicates that preheating mainly influences the initial thermal condition of the workpiece, whereas the subsequent cooling behavior is primarily governed by heat dissipation through conduction and convection under identical boundary conditions.

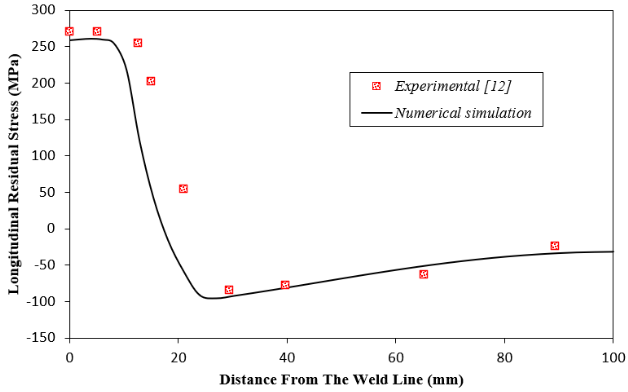


**Fig. 3.** Numerical and experimental longitudinal residual stress diagrams in mid-plane of workpiece.

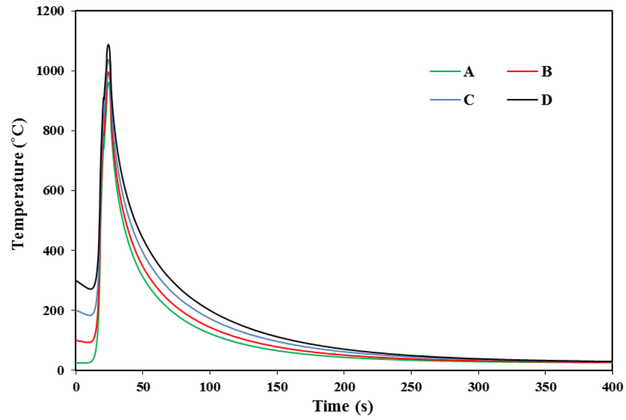


**Fig. 4.** Temperature history curve of the studied models.

**Table 4**
Maximum temperatures of the studied models.

| Model | Preheating temperature (°C) | Maximum tmperature (°C) |
|---|---|---|
| A | 25 | 957.5 |
| B | 100 | 993.7 |
| C | 200 | 1041 |
| D | 300 | 1090 |

Based on Fig. 4 and Table 4, increasing the preheating temperature results in only a slight increase in the peak process temperature. This behavior can be explained by the fact that the dominant heat source during FSW is frictional and plastic deformation heat generated beneath the rotating tool. Since the welding parameters, including rotational speed, traverse speed, and tool geometry, remain unchanged in all simulations, the heat generation rate is nearly constant. Therefore, preheating increases the initial temperature of the workpiece but has only a limited influence on the maximum temperature achieved in the weld nugget. Furthermore, preheating decreases the temperature gradient between the weld zone and the surrounding material. Consequently, thermal expansion and subsequent contraction occur more uniformly throughout the workpiece, reducing the driving force for residual stress formation and distortion.

According to Table 4, the maximum temperature in Model D is approximately 13.8% higher than that of Model A. Nevertheless, the peak temperature remains well below the melting point of SUS304 (1450 °C), confirming that the joining process remains entirely in the solid state. This observation also indicates that preheating enhances the thermal condition of the workpiece without altering the fundamental joining mechanism of friction stir welding.

### *3.3. Residual Stresses*

Residual stresses are among the most important factors affecting the performance and service life of welded structures. They are generally classified into tensile and compressive residual stresses [26,27]. Compressive residual stresses are generally beneficial because they improve both the static and fatigue strength of welded joints. In contrast, tensile residual stresses adversely affect fatigue life and increase the susceptibility to crack initiation and propagation. Therefore, controlling residual stresses, particularly in the weld region, is of considerable importance [28].

The temperature distribution developed during welding is one of the primary factors governing residual stress formation. Applying an appropriate preheating temperature reduces the thermal gradient between the weld zone and the surrounding material, resulting in more uniform thermal expansion and contraction during the welding cycle. Consequently, the magnitude of the residual stresses can be effectively reduced [29].

In this study, the effects of different preheating temperatures on both the longitudinal and transverse residual stress distributions were numerically investigated. Figs. 5 and 6 present the longitudinal residual stresses (parallel to the welding direction) and the transverse residual stresses (perpendicular to the weld line), respectively, after the completion of the cooling stage for the four investigated preheating temperatures.

According to Fig. 5, applying an appropriate preheating temperature significantly reduces the longitudinal residual stresses in the workpiece. As the preheating temperature increases, the tensile residual stresses in the weld region decrease considerably. At the preheating temperature of 300 °C, the average longitudinal residual stress is reduced by approximately 79.4% compared with the case without preheating. This substantial reduction can be attributed to the lower thermal gradients established during welding. Since the workpiece is initially at a higher temperature, the temperature difference between the weld zone and the surrounding material decreases, resulting in lower thermal contraction during cooling and consequently lower residual stress generation. Moreover, the lower temperature gradients developed during welding promote a more uniform thermo-mechanical response throughout the workpiece, thereby minimizing incompatible plastic deformation and further reducing the magnitude of the final residual stresses.

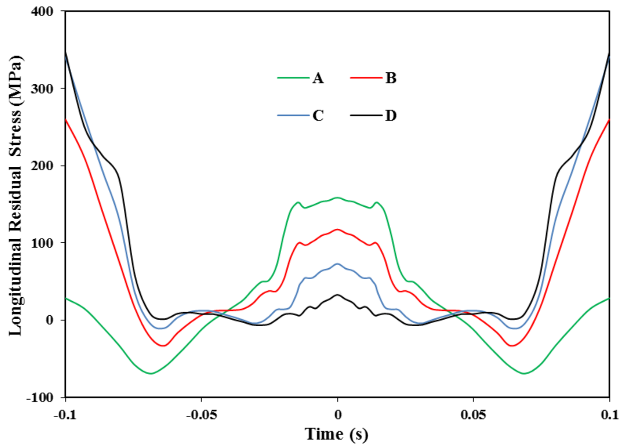


**Fig. 5.** Longitudinal residual stress curve of different models.

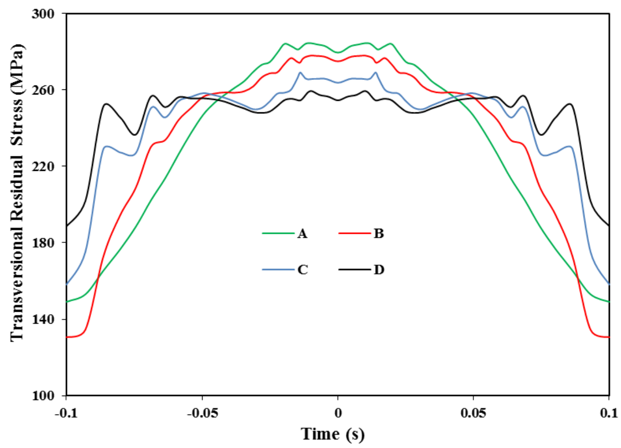


**Fig. 6.** Transverse residual stress curve of different models.

In addition, the elevated preheating temperature decreases the yield strength of SUS304, allowing the material to accommodate a greater portion of the thermally induced strains through plastic deformation during welding. Consequently, less elastic strain energy remains stored in the material after cooling, leading to lower residual stresses. Therefore, the reduction in residual stress is attributed not only to the lower temperature gradients but also to the temperature-dependent mechanical behavior of the material.

The results also indicate that increasing the preheating temperature shifts the location of the maximum longitudinal residual stress from the weld center toward the lateral regions of the workpiece. This redistribution of the stress field reduces the concentration of tensile stresses within the weld nugget, where crack initiation is most likely to occur, thereby improving the structural integrity of the welded joint. The relatively high stresses observed near the plate edges are mainly associated with the applied boundary constraints. In practical welding conditions, these edge stresses are expected to decrease after the release of the clamping system.

A similar trend is observed for the transverse residual stresses, as illustrated in Fig. 6. Increasing the preheating temperature generally reduces the transverse residual stress in the weld region while causing only a slight increase near the constrained edges. This behavior is also associated with the reduction in thermal gradients and the more uniform temperature distribution achieved through preheating. Consequently, thermal expansion and subsequent contraction become more homogeneous throughout the workpiece, leading to lower residual stress levels after cooling.

Overall, the results demonstrate that preheating effectively moderates the thermo-mechanical response of SUS304 during friction stir welding. By reducing thermal gradients and promoting more uniform plastic deformation, preheating minimizes both longitudinal and transverse residual stresses, which is expected to improve the dimensional stability and service performance of the welded joint.

### *3.4. Workpiece Distortion*

Distortion is one of the most common defects encountered in welding processes and is primarily caused by non-uniform thermal expansion and contraction during heating and cooling. During friction stir welding, the applied heat is unevenly distributed throughout the workpiece, causing localized heating in the weld region followed by thermal contraction during cooling. Consequently, permanent deformation develops due to the combined effects of thermal gradients and temperature-dependent plastic deformation.

One of the most effective approaches for minimizing welding-induced distortion is the application of an appropriate preheating temperature. Preheating promotes a more uniform temperature distribution, reduces thermal gradients, and decreases the yield strength of the material at elevated temperatures, allowing thermally induced strains to be accommodated more uniformly during welding. As a result, the magnitude of the final workpiece distortion is reduced. Fig. 7 presents the out-of-plane distortion profiles measured across the workpiece in the direction perpendicular to the weld line for the four investigated preheating temperatures.

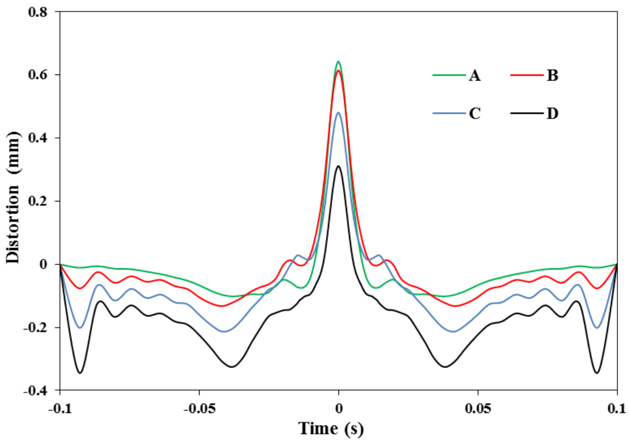


**Fig. 7.** Weld cross-sectional distortion for different models

As shown in Fig. 7, increasing the preheating temperature effectively reduces the distortion in the central region of the weld. The reduction becomes more pronounced as the preheating temperature increases. This behavior can be attributed to the more uniform temperature distribution and lower thermal gradients developed during welding, which reduce differential thermal expansion and contraction. Furthermore, the lower yield strength of SUS304 at elevated temperatures allows a greater portion of the thermally induced strains to be accommodated through plastic deformation during welding, resulting in lower residual stresses and consequently reduced workpiece distortion.

## 4. Conclusion

The effects of **preheating temperature** on the temperature distribution, residual stresses, and workpiece distortion during friction stir welding (FSW) of SUS304 stainless steel were numerically investigated using a coupled thermo-mechanical finite element model developed in ABAQUS. The moving heat source was implemented through a user-defined DFLUX subroutine. Four preheating temperatures (25, 100, 200, and 300 °C) were evaluated. The main conclusions are summarized as follows:

1. The proposed finite element model showed good agreement with the published experimental results, confirming its capability to accurately predict the temperature history and residual stress distribution.

2. Increasing the preheating temperature had only a limited influence on the peak welding temperature, indicating that preheating does not significantly alter the thermal conditions within the weld nugget.

3. Even at the highest preheating temperature, the peak temperature remained below the melting point of SUS304, confirming that the welding process retained its solid-state nature.

4. Increasing the preheating temperature significantly reduced the longitudinal residual stresses in the weld region. At a preheating temperature of 300 °C, the average longitudinal residual stress decreased by approximately 79.4% compared with the non-preheated condition (25 °C).

5. As the preheating temperature increased, the location of the maximum longitudinal residual stress shifted from the weld centerline toward the outer regions of the workpiece.

6. Increasing the preheating temperature also reduced the transverse residual stresses throughout the welded joint.

7. The reduction in residual stresses is attributed to the lower thermal gradients and the temperature-dependent reduction in the yield strength of SUS304, which promotes plastic deformation during welding and reduces the accumulation of thermally induced residual stresses after cooling.

8. Preheating effectively reduced the out-of-plane distortion of the workpiece, with greater distortion reduction observed at higher preheating temperatures.

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