# EXPERIMENTAL AND FINITE ELEMENT INVESTIGATION OF THREE-ROLL SKEW ROLLING OF TITANIUM/STEEL BIMETALLIC COMPOSITE TUBES

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***ABSTRACT*:**Titanium/steel bimetallic composite tubes combine titanium's excellent corrosion resistance with the high strength and low cost of carbon steel, offering considerable potential in petrochemical processing and marine engineering. In this study, a three-dimensional dynamic finite element model was developed for the three-roll skew rolling of 45CS/TA2 bimetallic composite tubes and validated through rolling experiments. The effects of rolling temperature on the stress–strain evolution near the interface, interfacial bonding performance, and elemental diffusion behavior were systematically investigated. Results show that the composite tube undergoes helical forward motion under the three rolls, while its cross-section evolves periodically from circular to a triangular-like profile and back to nearly circular. Rolling temperature significantly affects the interfacial thermomechanical state and bonding performance. At 650 °C, sufficient but controlled elemental diffusion occurs across the interface, with improved deformation compatibility between the two metals, yielding a maximum interfacial shear strength of 260 MPa. At higher temperatures, excessive diffusion thickens the interfacial reaction layer, deteriorating bonding strength. These findings demonstrate that three-roll skew rolling can achieve stable forming and high-strength interfacial bonding, providing a theoretical basis for optimizing rolling parameters.
**KEYWORDS:** THREE-ROLL SKEW ROLLING; TITANIUM/STEEL BIMETALLIC COMPOSITE TUBE; FINITE ELEMENT SIMULATION

## INTRODUCTION

Titanium/steel bimetallic composite tubes consist of titanium and steel layers and combine the excellent corrosion resistance and high-temperature stability of titanium with the high strength, stiffness, and low cost of steel [1,2] .Compared with monolithic tubes, such composite structures can substantially improve corrosion resistance while maintaining sufficient load-bearing capacity and reducing titanium consumption. They therefore have considerable potential for applications in petrochemical processing, energy transportation, marine engineering, and pipelines exposed to highly corrosive environments.

Current manufacturing methods for metallic composite tubes can generally be classified into mechanical and metallurgical bonding processes. Mechanical methods are relatively simple and cost-effective. For example, Salehi et al. [3]fabricated Al/Cu bimetallic tubes by tube sinking, where severe plastic deformation promoted cold-pressure bonding at the interface. However, such interfaces rely primarily on contact pressure and mechanical interlocking, resulting in limited bonding strength and long-term service stability [4,5]. Metallurgical processes can achieve stronger interfaces through elemental diffusion and interfacial reactions. Swarnkar et al. [6] promoted high-temperature diffusion bonding by friction-stir-assisted backward extrusion, while Li et al. [7] fabricated L415QS/N08825 clad pipes by explosive welding and obtained high interfacial bonding strength. Nevertheless, metallurgical bonding techniques generally involve stringent equipment requirements, narrow processing windows, difficult control of interfacial reactions, and limited capability for continuous production. For instance, the centrifugal self-propagating high-temperature synthesis process proposed by Kerdkool et al. [8] may introduce pores into the composite layer. Ji et al. [9] fabricated Cu/Al and Ti/Al composite tubes by solid–liquid casting, but this method is difficult to extend directly to titanium/steel systems because of their high processing temperatures and complex interfacial reactions. Therefore, developing an efficient process that simultaneously provides high interfacial bonding strength and continuous production capability remains a major challenge for titanium/steel composite tubes.

Three-roll skew rolling, a well-established process for seamless tube production, offers continuous rotary feeding, effective radial compression, and good adaptability to tubes with large length-to-diameter ratios [10], providing a promising route to address these limitations. Previous studies have demonstrated its applicability to the forming of bars, axles, titanium-alloy tubes, and metallic composite tubes, with material flow, microstructure, and final properties being effectively controlled through process parameters

[11,12]. However, for titanium/steel composite tubes, the progressive formation of a high-strength interface under the coupled effects of rotation, radial compression, and axial feeding remains insufficiently understood. In particular, the interactions among interfacial compression, plastic deformation, elemental diffusion, and reaction-layer evolution have not yet been systematically clarified.

Finite element simulation provides access to local temperature, stress, and equivalent plastic strain that are difficult to measure experimentally and is therefore an effective tool for investigating interfacial bonding mechanisms. Previous studies have shown that numerical simulation can not only predict macroscopic forming quality during composite rolling but also quantify interfacial pressure, shear stress, deformation compatibility between layers, and the onset of bonding[13,14]. However, most existing studies have focused on clad plate/sheet rolling or Cu/Al composite tube forming, with limited attention paid to the transition of titanium/steel interfaces from mechanical contact to high-strength metallurgical bonding under coupled rotation, compression, and axial feeding. Moreover, rolling temperature simultaneously affects the flow stress and deformation compatibility of the constituent materials as well as interfacial contact, elemental diffusion, and reaction-layer formation. The mechanism responsible for the pronounced temperature dependence of interfacial bonding strength therefore remains to be clarified.

Accordingly, this study investigates 45CS/TA2 titanium/steel bimetallic composite tubes through combined experiments and finite element simulations. The effects of rolling temperature on macroscopic formability, interfacial bonding strength, and elemental diffusion are systematically evaluated. Temperature, stress–strain fields, interfacial contact stress, interfacial shear stress, and material flow during three-roll skew rolling are analyzed to clarify the coordinated deformation behavior of 45CS and TA2. Combined with interfacial shear tests, SEM observations, and EDS analyses, the mechanism governing interfacial bonding is elucidated, providing a basis for the efficient continuous fabrication and process optimization of titanium/steel bimetallic composite tubes.

## 1 EXPERIMENTAL PROCEDURES AND FINITE ELEMENT MODELING

### 1.1 Materials and Specimens

The billets consisted of an outer seamless 45 medium-carbon steel (45CS) tube (70 mm outer diameter, 6.5 mm wall thickness, 200 mm length) and an inner commercially pure TA2 titanium tube (57 mm outer diameter, 3.0 mm wall thickness, 200 mm length). The chemical compositions are given in Tables 1 and 2.

**Table 1** Chemical composition of 45CS (wt.%)

| Material | C | Mn | S | Si | Cr | Ni | P | Fe |
|---|---|---|---|---|---|---|---|---|
| 45CS | 0.46 | 0.63 | 0.012 | 0.25 | 0.041 | 0.015 | 0.015 | Bal. |

**Table 2** Chemical composition of TA2 (wt.%)

| Material | C | O | N | Si | Fe | Ti |
|---|---|---|---|---|---|---|
| TA2 | 0.08 | 0.015 | 0.03 | 0.01 | 0.03 | Bal. |

### 1.2 Tube Fabrication and Rolling Procedure

The preparation procedure for the 45CS/TA2 bimetallic composite tube is shown in Fig. 1. The TA2 inner tube was inserted into the 45CS outer tube and welded at both ends. The assembled billet was heated in a vacuum furnace at 10 °C/min to the prescribed rolling temperature, held for 20 min, and then rapidly transferred under argon protection to the three-roll skew rolling mill. Rolling was performed using a 46 mm mandrel, a 58 mm roll pass, and a roll speed of 500 r/min, followed by air cooling. Specimens for interfacial shear testing and metallographic characterization were sectioned by wire electrical discharge machining. After grinding, and mechanical polishing, the 45CS/TA2 interface was examined by SEM, while EDS line scans were used to characterize Fe, Ti, and C diffusion. Interfacial shear tests were conducted to evaluate the bonding strength at different rolling temperatures.

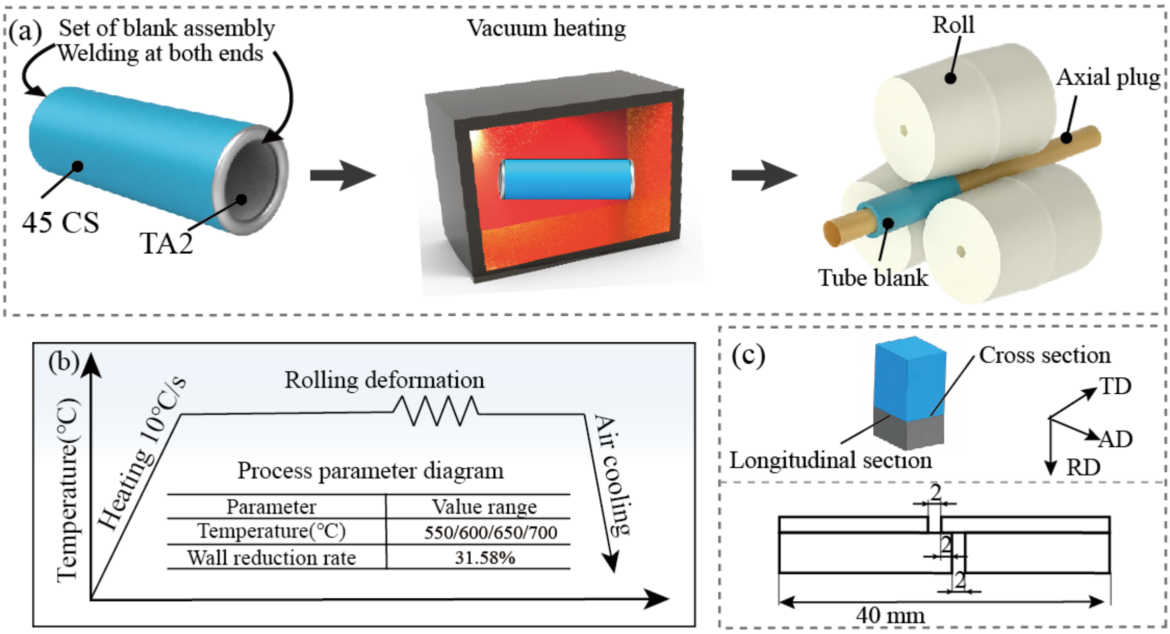

Fig. 1. Schematic of the three-roll skew rolling and specimen sampling of the 45CS/TA2 bimetallic composite tube: (a) billet assembly, vacuum heating, and rolling process; (b) thermomechanical route and key process parameters; and (c) sampling locations, orientations, and dimensions.

### 1.3 Development of the Finite Element Model

Three-roll skew rolling involves large plastic deformation, complex contact, and thermomechanical coupling. In the finite element model, 45CS and TA2 were treated as homogeneous, isotropic, and continuous materials, while the rolls and mandrel were modeled as rigid bodies. To reduce computational cost, the billet length was set to 100 mm, half of the experimental length, with the remaining geometric parameters unchanged. The three-dimensional model is shown in Fig. 2. Surface-to-surface finite-sliding contact was defined between the billet and rolls, billet and mandrel, and at the 45CS/TA2 interface. Considering graphite lubrication, the friction coefficient between the TA2 inner surface and mandrel was set to 0.05. The interfacial mesh was refined to capture local temperature, stress, plastic strain, and contact responses during rolling.

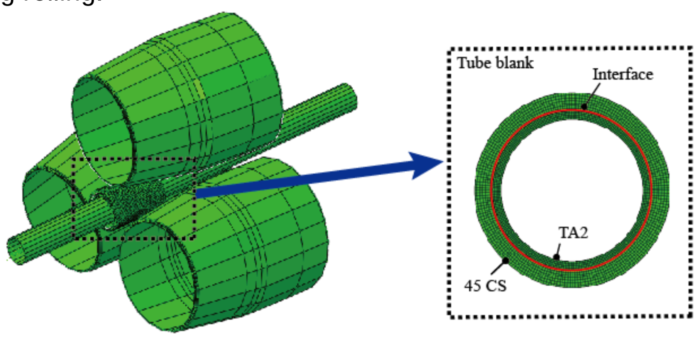

Fig. 2. Three-dimensional finite element model for three-roll skew rolling of the 45CS/TA2 bimetallic composite tube and definition of the 45CS/TA2 interface on the billet cross-section.

## 2 EXPERIMENTAL RESULTS

### 2.1 Macroscopic Morphology and Model Validation

As shown in Fig. 3, stable forming of the 45CS/TA2 bimetallic composite tubes was achieved at 550–700 °C without obvious cracking, collapse, or interfacial separation. The outer and inner diameters and the layer thicknesses varied only slightly with rolling temperature, indicating that the final geometry was mainly controlled by the roll pass and mandrel. The experimental results agreed well with the finite element predictions, with measured 45CS and TA2 layer thicknesses of 5.06–5.20 mm and 2.21–2.34 mm, respectively. The model therefore reliably reproduced the cross-sectional morphology and dimensional evolution, providing a sound basis for subsequent analysis of interfacial thermomechanical behavior.

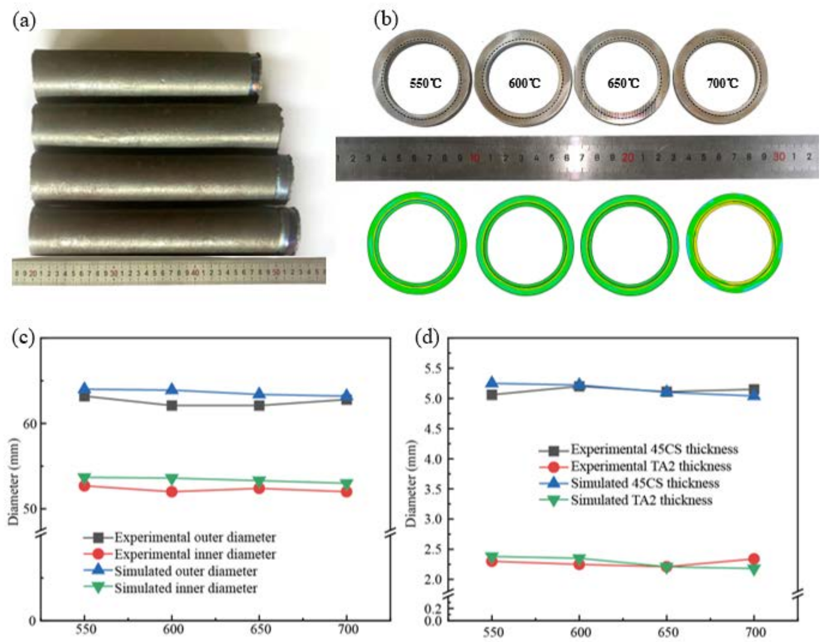


Fig. 3. Forming results of the 45CS/TA2 bimetallic composite tubes at different rolling temperatures and comparison between experimental measurements and finite element predictions: (a) macroscopic morphology of the rolled tubes; (b) experimental and simulated cross-sections at different rolling temperatures; (c) comparison of the experimental and simulated outer and inner diameters; and (d) comparison of the experimental and simulated thicknesses of the 45CS and TA2 layers.

### 2.2 Interfacial Bonding Performance of the Composite Tube

Interfacial shear tests were conducted to evaluate the effect of rolling temperature on bonding performance. As shown in Fig. 4, the average interfacial shear strength increased from 174 MPa at 550 °C to 242 MPa at 600 °C and reached a maximum of 260 MPa at 650 °C, before decreasing to 194 MPa at 700 °C. The value at 550 °C already exceeded the 140 MPa reference requirement specified in GB/T 37606-2019. The peak strength at 650 °C was approximately 49.4% higher than that at 550 °C, whereas the value at 700 °C decreased by about 25.4% relative to 650 °C. These results indicate a non-monotonic dependence of interfacial bonding strength on rolling temperature, motivating further analysis of the interfacial microstructure and elemental diffusion behavior.

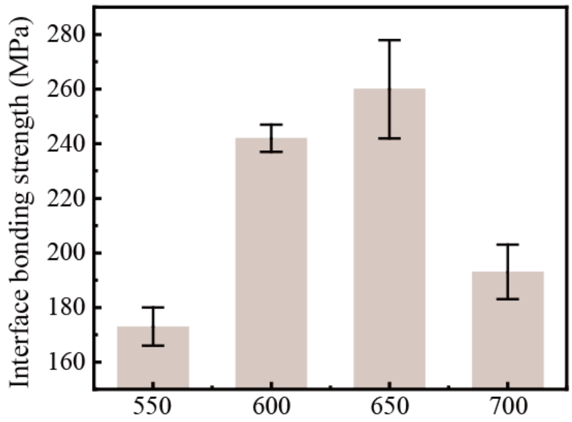


Fig. 4. Interfacial shear strength of the 45CS/TA2 bimetallic composite tubes rolled at different temperatures.

### 2.3 Microstructural Analysis

Figure 5 shows the interfacial microstructures and EDS line-scan profiles at different rolling temperatures. As the temperature increased from 550 to 700 °C, the Fe and Ti concentration gradients became progressively less steep, while the elemental transition-zone width increased from 3.1 to 3.5, 3.7, and 4.2 μm, respectively. No obvious continuous reaction layer was observed at 550 °C. Local TiC formed at 600 °C with a characteristic thickness of about 0.3 μm, increasing to approximately 0.5 μm at 650 °C and 0.9 μm at 700 °C. Thus, both elemental interdiffusion and TiC growth were progressively enhanced with increasing rolling temperature.

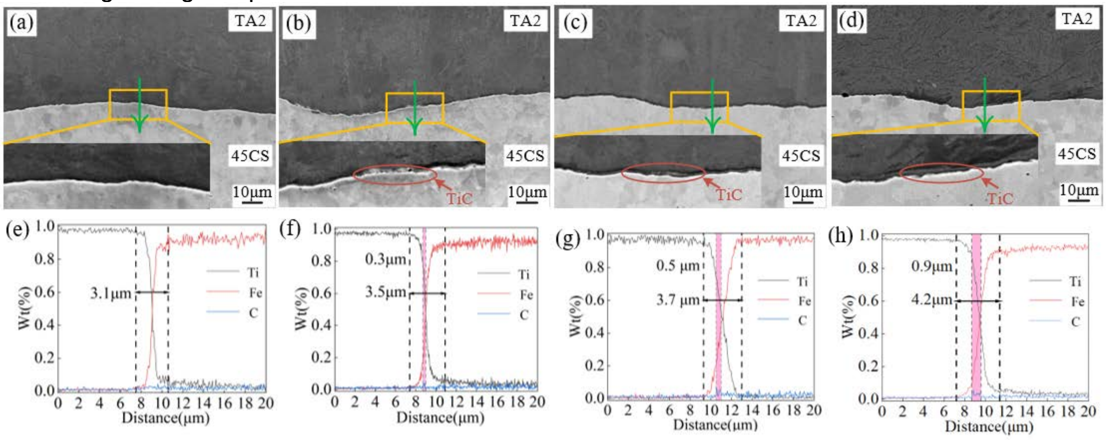


Fig. 5. Interfacial microstructures and EDS line-scan profiles of the 45CS/TA2 bimetallic composite tubes rolled at different temperatures: (a, e) 550 °C; (b, f) 600 °C; (c, g) 650 °C; and (d, h) 700 °C.

## 3 DISCUSSION

The experimental results show that the interfacial shear strength first increases and then decreases with rolling temperature, reaching a maximum at 650 °C, whereas both the elemental transition-zone width and TiC reaction-layer thickness increase continuously. These trends indicate that interfacial bonding is governed by the coupled thermal and plastic-deformation histories during rolling. To clarify the origin of the strength variation, the thermomechanically coupled finite element model was used to analyze material flow trajectories, representative cross-sectional deformation, temporal evolution of interfacial thermomechanical responses, and the spatial distribution of interfacial shear stress. These analyses provide insight into the formation of high-strength interfacial bonding.

### 3.1 Analysis of Material Motion Trajectories

Because the same reduction, roll speed, and geometric constraints were used at all temperatures, the overall trajectories of interfacial material points were similar; thus, 650 °C was selected as a representative condition. As shown in Fig. 6, the material points follow a helical forward path resulting from circumferential rotation driven by roll friction and axial feeding induced by the axial velocity component of the inclined rolls. After entering the main deformation zone, the trajectory radius gradually decreases with increasing radial reduction and then stabilizes in the rounding stage. This motion reflects the combined effects of rotation, axial feeding, and radial compression, and promotes interfacial compression, tangential relative motion, and subsequent bonding.

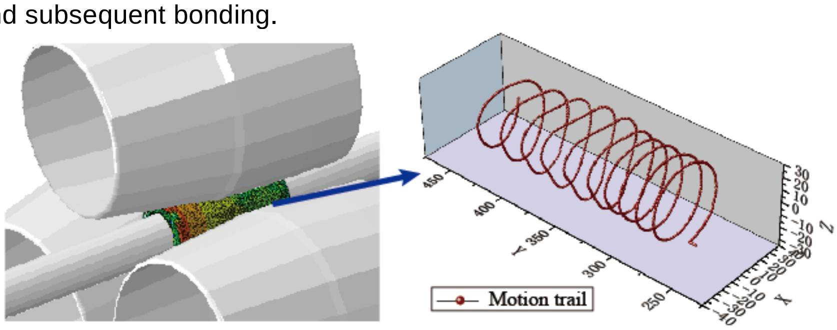


Fig. 6. Helical trajectory and radial evolution of a material point at the steel/Ti interface within the deformation zone during three-roll skew rolling.

### 3.2 Thermo-Mechanical Coupling Behavior

The thermomechanical deformation behavior at representative cross-sections was analyzed at 650 °C, as shown in Fig. 7. The deformation zone was divided into the bite-in, reduction, and rounding zones, corresponding to cross-sections I–III, while cross-section IV represents the final formed section. During rolling, the tube cross-section evolves from circular to triangular-like and then returns to nearly circular under periodic radial compression and circumferential plastic flow. The temperature increases markedly in the reduction zone because of plastic deformation and frictional heating, then becomes more uniform in the rounding zone. The von Mises stress is relatively high during bite-in, redistributes during reduction, and decreases toward the rounding stage. In contrast, PEEQ accumulates continuously from cross-sections I to III. These coupled thermal and mechanical effects promote interfacial closure, surface-film disruption, fresh-metal contact, elemental diffusion, and ultimately metallurgical bonding.

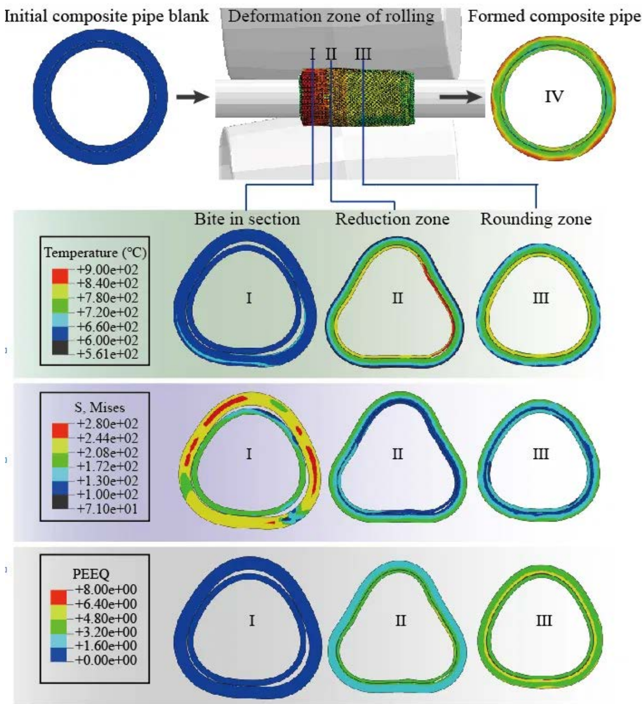


Fig. 7. Evolution of temperature, von Mises equivalent stress, and equivalent plastic strain (PEEQ) at representative cross-sections of the 45CS/TA2 bimetallic composite tube during three-roll skew rolling at 650 °C.

### 3.3 Interfacial Stress–Strain Evolution under Different Temperatures

As shown in Fig. 8, the same material point at the 45CS/TA2 interface was tracked to examine the evolution of temperature, equivalent plastic strain (PEEQ), and normal contact stress at different initial rolling temperatures. The time axis represents the complete deformation history from entry into the rolling zone to the end of rolling. As the initial temperature increases from 550 to 700 °C, the interfacial temperature rises overall and increases further during the main deformation stage because of plastic deformation and frictional heating. PEEQ accumulates continuously and shows a slight increase in its final value with increasing temperature, indicating enhanced plastic flow and deformation compatibility at elevated temperatures. In contrast, the normal contact stress exhibits pronounced periodic fluctuations caused by the cyclic compression of the three rolls, with major peaks concentrated at approximately 0.35–0.65 s. Its peak value does not increase monotonically with temperature because thermal softening reduces the deformation resistance of both materials.The coupled thermomechanical response varies significantly with temperature. At 550 °C, although relatively high contact-stress peaks are generated, the interfacial temperature and accumulated plastic strain remain low, limiting thermal activation, fresh-metal contact, and subsequent diffusion. At 600–650 °C, plastic strain increases while sufficient periodic compression is maintained. In particular, 650 °C provides a favorable combination of high interfacial temperature, accumulated plastic deformation, and adequate normal contact pressure, promoting interfacial closure, surface-film disruption, real contact area, and elemental interdiffusion. At 700 °C, although temperature and PEEQ continue to increase, excessive thermal softening weakens the normal compressive contact. These results indicate that the optimum bonding condition is governed by the coordinated balance among interfacial temperature, plastic deformation, and normal contact pressure rather than by any single thermomechanical factor.

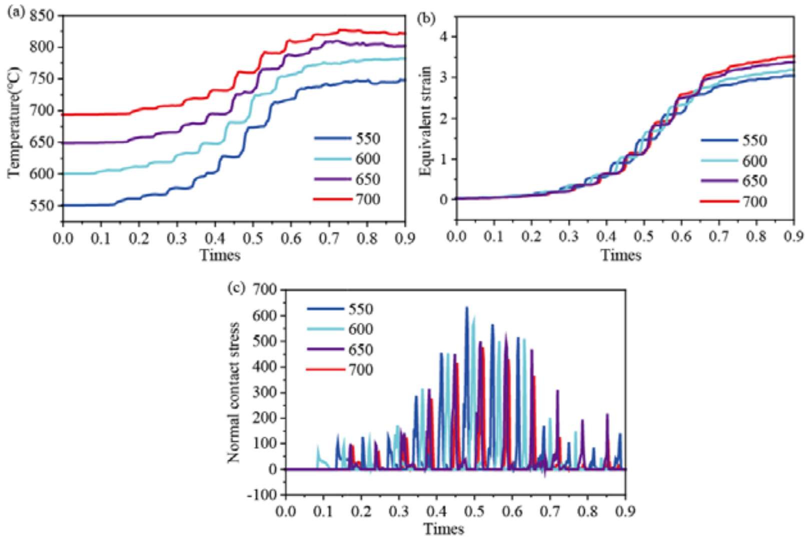


Fig. 8. Temporal evolution of thermomechanical responses at the 45CS/TA2 interface under different initial rolling temperatures: (a) interfacial temperature; (b) equivalent plastic strain (PEEQ); and (c) normal contact stress.

### 3.4 Spatial Distribution of Interfacial Shear Deformation

Figure 9 shows the interfacial shear-stress distributions in the reduction zone at different rolling temperatures. In the local coordinate system, the circumferential shear stress alternates between positive and negative values because of the periodic compression of the three rolls and the circumferential rotation of the tube billet. The sign reflects the shear direction, whereas the magnitude and spatial gradient characterize the intensity and heterogeneity of the local shear state.At 550 °C, localized high-shear-stress regions and discontinuous stress distributions are evident, indicating relatively high flow resistance and localized deformation. At 600 °C, the shear-affected region extends along the interface, although pronounced stress gradients remain. At 650 °C, the shear-stress distribution becomes more continuous and uniform, with more dispersed high-stress regions and smoother transitions between positive and negative shear zones. This indicates improved deformation compatibility between the outer 45CS layer and the inner TA2 layer during radial compression and circumferential flow. Such a moderate and continuous shear state, together with normal compression, promotes relative interfacial sliding, surface-film disruption, and effective fresh-metal contact. At 700 °C, although thermal softening reduces the overall deformation resistance, local variations in shear direction and stress gradients become more pronounced, indicating reduced flow uniformity.Therefore, 650 °C does not produce the maximum shear stress, but provides the most uniform and coordinated interfacial shear state. Combined with the normal contact stress and PEEQ results, this condition offers the most favorable balance among compression, plastic deformation, and shear coordination, thereby promoting high-strength interfacial bonding.

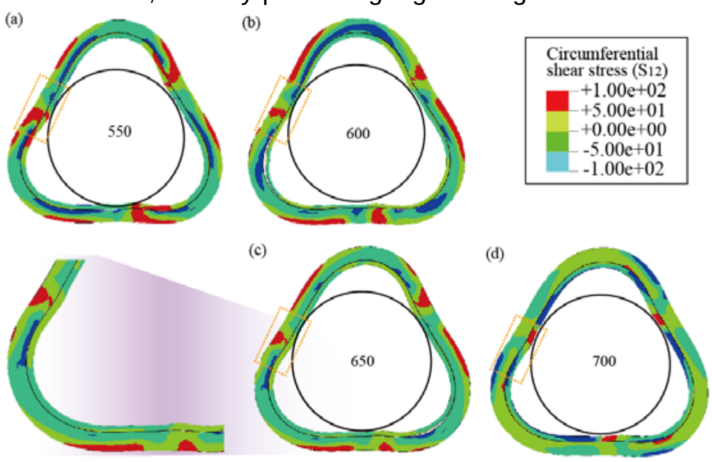


Fig. 9. Distribution of radial–circumferential shear stress at the 45CS/TA2 interface under different initial rolling temperatures: (a) 550 °C; (b) 600 °C; (c) 650 °C; and (d) 700 °C.

## 4 CONCLUSIONS

(1) 45CS/TA2 bimetallic composite tubes were successfully fabricated by three-roll skew rolling. Stable forming was achieved at 550–700 °C without obvious cracking, folding, or interfacial delamination, and the two layers exhibited good deformation compatibility.

(2) Rolling temperature significantly affected the interfacial bonding strength. The average shear strengths at 550, 600, 650, and 700 °C were 174, 242, 260, and 194 MPa, respectively. The maximum strength was obtained at 650 °C, where interfacial compression, plastic deformation, elemental diffusion, and moderate TiC formation were favorably balanced. Excessive TiC growth at 700 °C led to interfacial embrittlement and strength degradation.

(3) The composite tube successively underwent bite-in, reduction, and rounding during rolling. Interfacial material points followed helical trajectories and experienced combined radial compression, circumferential shear, and axial flow, which promoted interfacial closure, surface-film disruption, fresh-metal contact, and subsequent metallurgical bonding.

(4) Finite element analysis revealed that the non-monotonic variation in bonding strength originated from differences in thermomechanical coordination. At 650 °C, the interfacial temperature, plastic deformation, normal compression, and shear distribution exhibited the most favorable combination, indicating that thermomechanical synergy is critical to achieving high-quality interfacial bonding.

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