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Finite Element Simulation Study on 2A14 Aluminum Alloy Conical Cylinder Parts Based on Simufact

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ABSTRACT

The hot rolling process of a conical cylindrical part made of 2A14 aluminum alloy was investigated using finite element simulation with Simufact-Forming. A numerical rolling model was established, and the forming behavior of the component at different deformation stages was systematically analyzed. The simulation results indicate that the proposed approach effectively reflects the deformation characteristics of conical cylinders and provides practical guidance for the rolling of non-standard ring components. This study demonstrates that finite element simulation not only contributes to improving the forming quality of ring parts and reducing production and development costs but also enhances industrial competitiveness. Furthermore, the findings offer valuable insights for the practical application of radial–axial rolling in complex ring components.

KEYWORDS

2a14 Aluminum Alloy; Finite Element; Conical Cylinder; Ring Rolling.

1. INTRODUCTION

The rapid growth of aerospace, nuclear power, wind power, hydropower and rail transportation has created new demands on ring components. Conventional rectangular-section rings can no longer meet these industrial requirements. The demand for precision-shaped section rings has risen sharply. Machining alone produces such rings with high material waste and long processing time. As a result, advanced ring rolling technology has been applied for the manufacture of shaped-section rings. The rolling of such rings is more complex than that of rectangular rings. Plastic deformation and metal flow vary across different regions. The forming process requires stricter control of roll motion. Ring profile and rolling parameters strongly influence the final quality.Shaped rings are often required to combine high strength with toughness and stability while maintaining reduced wall thickness. In aerospace their structural design requires increasingly complex segmental connections. Conventional rectangular-section rings offer low material utilization and cannot meet these demands. For this reason, the manufacturing of 2A14 aluminum alloy conical cylindrical parts has become urgent.Finite element (FE) simulation is now the most effective method for studying rolling processes. It allows the investigation of microstructure evolution, mechanical property changes and defect prevention. In this study a finite element model of the conical ring rolling process was developed using Simufact-Forming. The hot rolling behavior of 2A14 aluminum alloy conical rings was simulated and analyzed. The results provide theoretical guidance for experimental ring rolling tests.Shaped-section ring rolling is more complex than rectangular-section ring rolling. Ring rolling, also known as ring expansion or radial–axial rolling, uses specialized equipment to reduce wall thickness, lower height, enlarge diameter and form cross-sectional shapes. It is a process of continuous local plastic deformation. Compared with die forging and free forging it offers higher accuracy, less machining allowance, better material utilization, superior internal quality, greater efficiency and lower cost. Ring rolling is now widely used for seamless components such as bearing rings, gear rings, flanges, railway wheels and hubs, and turbine rings. It has broad applications in engineering machinery, aerospace, petroleum equipment and new energy industries[1].

1.1. Research Status

Over the past three decades, finite element analysis (FEA) has been continuously improved on the basis of continuum mechanics and has played a critical role in the analysis of metal elastoplasticity, rigid plasticity, and viscoplasticity. With the rapid development of computer technology, finite element methods have been widely implemented in computational platforms, leading to the emergence of various simulation software. Packages such as Abaqus, QForm, Deform-3D, and Simufact-Forming have been successfully applied to simulate the rolling of both rectangular and shaped-section rings, achieving reliable predictive accuracy.

Extensive studies on ring rolling have been carried out by researchers worldwide. Early investigations adopted simplified approaches, such as plane strain and pseudo-plane strain assumptions. Min[2] et al. simulated two different rolling processes using Abaqus and revealed the metal flow patterns and temperature field evolution during rolling. Their results were validated against experimental data and showed good agreement. Giorleo[3] et al. employed Deform-3D to study the variations of radial size, billet thickness, axial dimension, and rolling force in radial–axial ring rolling, also confirming the validity of the simulation results through production tests. Banerjee[4] et al. used Abaqus to simulate ring rolling, describing stress–strain distributions and discussing the influence of friction and contact stress. Hua[5] et al. developed a recrystallization model combined with Abaqus simulations, which clarified the characteristics of the recrystallization process during ring rolling and the effect of rolling curves on recrystallization behavior.

Other scholars have also made significant contributions. Duan[6] applied ANSYS to investigate the rolling process and analyzed the factors affecting the service life of conical rolls. Wang[7] studied the strain distribution, spread variation, and rolling force fluctuations during radial–axial rolling through numerical simulations. Zhou[8] employed Deform-3D to evaluate the influence of mandrel shape on material flow and the occurrence of defects such as folding and fishtailing. Xie[9] conducted simulations with MSC.Marc to identify the causes of ring profile errors and proposed optimization methods. Jiang[10] used FORGE to analyze the influence of forming parameters on residual stress. Xu[11] simulated the cold rolling of high-speed steel rings with Abaqus and found that stresses between the blank, the drive roll, and the mandrel were significantly greater than those within the blank itself, with the mandrel stress showing a more uniform distribution. Kim[12] performed simulations and trial production of outer-grooved shaped rings. Lee[13] employed FORGE to investigate ring forging and found that the growth rate of the ring corresponded to the median of the feasible forming conditions, which could be used to optimize forming processes for reduced ring expansion and uniform plastic deformation.

Hua[14] et al. proposed the biting and forging-through conditions for ring rolling. Liu Yong[15] et al. analyzed defects in the rolling of L-shaped rings using Deform and found that an appropriate mandrel inclination angle can significantly reduce folding defects. Qi[16] et al. applied Deform to study the influence of different initial rolling temperatures on ring forming and observed that rolling temperature affects the uniformity of geometric dimensions. Qian[17] et al. performed numerical simulations and experimental validation on large conical cylindrical parts.At present, most research on ring rolling has focused on large thick-walled rings, while studies on the rolling of small shaped-section rings remain relatively limited.

The conical cylindrical ring rolling simulations were carried out using Simufact Forming, a simulation software developed by Simufact (Germany) based on modules of MSC Software. Compared with other simulation platforms, Simufact Forming provides a simplified user interface, compatibility with widely used operating systems, accessibility for different user groups, and a broad material and process simulation database. Its optimized computational performance, steadily expanding material library, and specialized module for ring rolling further enhance its reliability in simulating ring rolling processes.

The software is highly compatible with commonly used design tools such as AutoCAD and UG, enabling three-dimensional modeling of billets and rolling components. The models are then imported into Simufact Forming for position matching. In the preprocessing stage, key rolling parameters, equipment configurations, and motion settings of the components are defined. To ensure realistic simulation conditions, friction parameters, thermodynamic properties, environmental and surface temperatures, relative constraints between components, and mesh division must be carefully specified. Once the input parameters are confirmed, the simulations are submitted for computation, and the results can be obtained after calculation.

Simufact Forming is known for its intuitive operation, specialized material database, modularized forming machine models, and a high degree of automation in analysis. Its solver integrates the finite element method (FEM) with the finite volume method (FVM), which ensures efficient and robust performance[18]. An Euler-based remeshing technique is employed to avoid severe mesh distortion and improve solution convergence. Adaptive mesh refinement is automatically applied in local regions to enhance calculation accuracy. The solver is capable of analyzing nonlinear material behavior including elastoplasticity, anisotropy, and hyperelasticity. It can also simulate the evolution of temperature fields, velocity fields, and force fields during rolling. Furthermore, parallel computation is supported, with the ring divided into subregions for simultaneous calculation, significantly improving efficiency[19].

For conical cylindrical rings, improvement of material utilization is of particular importance, as it not only reduces unnecessary waste and machining allowances but also helps preserve rolling texture and enhances circumferential properties. The design of shaped rings emphasizes maximizing material efficiency while improving mechanical performance. Based on these considerations, a finite element model of the rolling process for 2A14 aluminum alloy conical cylindrical rings was established in Simufact Forming. Rolling simulations under different initial temperatures were carried out, and the corresponding forming results were analyzed.

2. FINITE ELEMENT MODELING OF CONICAL CYLINDER PARTS

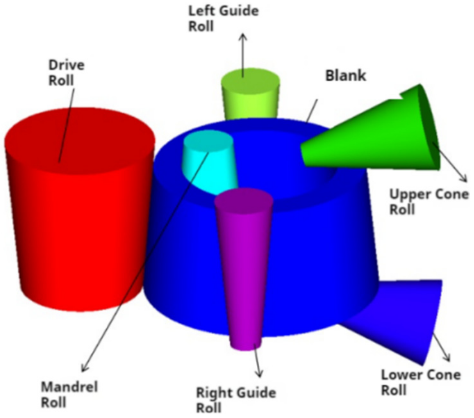


Figure 1. Schematic diagram of radial-axial ring rolling principle

During the ring rolling process, the main roll rotates at a constant speed while the mandrel feeds toward it. Unlike conventional radial rolling, two conical rolls are positioned at the upper and lower end faces of the ring. The upper conical roll feeds downward along the axial direction and simultaneously moves backward as the ring diameter increases. The lower conical roll remains in contact with the lower end of the ring, moving backward with the expanding diameter while maintaining a constant linear velocity. Its function is to ensure the flatness of both end faces.

Support rolls are arranged on both sides of the ring. Their role is to apply a holding force that clamps the ring and allows it to rotate synchronously, thus maintaining stability during rolling. When the process enters the circular sizing stage, the support rolls stop feeding and instead remain in position, rotating with the ring to correct the outer surface, as illustrated in Fig. 1.

Compared with pure radial rolling, radial–axial rolling introduces two additional conical rolls. This configuration improves the flatness of the end faces, ensures higher forming quality, reduces rolling time, and enhances overall production efficiency.

2.1. Blank Design for Conical Cylinder Components

As shown in Fig. 2, the schematic diagram of blank dimension design illustrates the principle. A reasonable design of the blank geometry and dimensions enables the rolled ring to achieve the required sectional profile and geometric accuracy, which has a significant influence on the stability of the rolling process and the efficiency of production. In this study, the blank shape and dimensions were determined based on the conditions of volume conservation and shape similarity in ring rolling, together with the forging drawing of the ring. The degree of deformation during the rolling process was also evaluated accordingly.

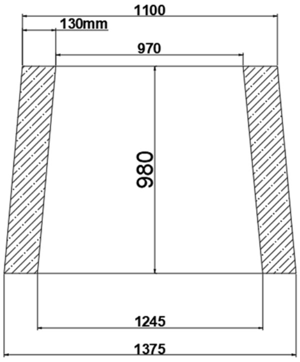


Figure 2. Schematic diagram of blank dimensions

2.2. Establishment of the Roll Model

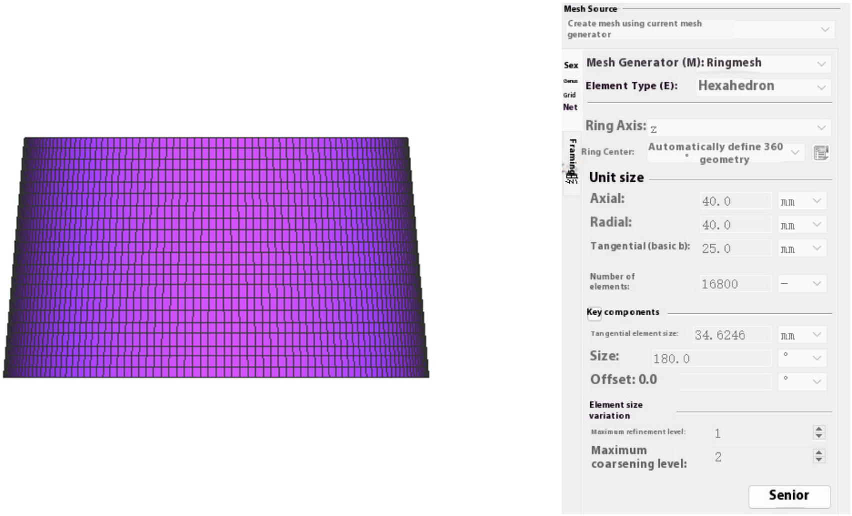
Radial–axial ring rolling is an advanced near-net-shape forming technology in which the radial profile is generated by the drive roll and mandrel, while the axial profile is simultaneously formed by the axial conical rolls. In this process, the wall thickness in the radial direction and the height in the axial direction of the ring are reduced, resulting in diameter expansion and height reduction of the ring blank. In the present study, the height of the conical cylindrical blank is consistent with that of the final forging, and thus axial reduction is not required. Radial–axial rolling is widely applied in the production of large-scale rings.

During radial–axial rolling, the cross-section and diameter of the ring change, while both mass and volume remain constant. Accordingly, a specific relationship exists among the rolling reduction, the radial–axial feed rate, and the ring growth rate. Moreover, the motion of each roll plays a critical role in determining the rolling conditions and the overall forming process. The roll parameters for the conical cylindrical part are listed in Table 1.

Table 1. Geometric parameters of the roll model

Parameter	Value (mm)
Outer radius of blank at large end	1375
Inner radius of blank at small end	1100
Outer radius of blank at small end	970
Inner radius of blank at large end	1245
Outer radius of drive roll at small end	346
Outer radius of drive roll at large end	425
Height of drive roll	1000
Radius of conical roll at small end	67.5
Radius of guide roll at small end	87.5
Radius of guide roll at large end	166.5
Height of guide roll	1000
Height of mandrel	1000
Radius of mandrel at small end	140
Radius of mandrel at large end	218.5
Radius of conical roll at large end	250

3. MESH GENERATION



Mesh Source
Create mesh using current mesh generator
Mesh Generator (M): Ringmesh
Element Type (E): Hexahedron
Ring Axis: z
Ring Center: Automatically define 360 ° geometry
Unit size
Axial: 40.0 mm
Radial: 40.0 mm
Tangential (basic b): 25.0 mm
Number of elements: 16800 –
Key components
Tangential element size: 34.6246 mm
Size: 180.0 °
Offset: 0.0 °
Element size variation
Maximum refinement level: 1
Maximum coarsening level: 2

Figure 3. Mesh generation

The rolling model was established using hexahedral elements. Initially, a two-dimensional quadrilateral mesh was generated on the cross-section of the three-dimensional models of the drive roll, mandrel, guide roll, conical rolls, and blank in the Forging & Metalforming Features module. By revolving the 2D mesh around the origin, a hexahedral mesh was obtained. A finer mesh provides higher accuracy but reduces computational efficiency; therefore, the mesh size was controlled to achieve a balance between accuracy and efficiency. Local mesh refinement was applied in regions where the blank directly contacted the mandrel, drive roll, and conical rolls, since these areas experience severe deformation.

The RingMesher function was employed to generate structured hexahedral meshes. Compared with tetrahedral elements, hexahedral meshes show better adaptability in nonlinear plastic deformation analysis and provide more consistent distributions of thermal, stress, and velocity fields, as illustrated in Fig. 3. The external mesh size was defined in length, width, and height, and then converged radially toward the ring center, with independent resolution in axial, radial, and circumferential directions. In addition, key regions were locally refined, especially in the mandrel–drive roll pass, where plastic deformation is much greater than in the conical roll region. This dynamic meshing strategy reduced the total element number and improved computational efficiency. When excessive element distortion occurred, the RAW module automatically remeshed the distorted regions to maintain accuracy.

3.1. Development of Material Constitutive Model

The blank material was 2A14 aluminum alloy with a density of 2800 kg/m³, Poisson's ratio of 0.33, Young's modulus of 71 GPa, specific heat capacity of 838 J/(kg·K), and a linear thermal expansion coefficient of 2.25×10^{-5} °C^{-1}[21]. These material properties were defined in Simufact Forming by modifying a similar reference material, and the true stress–strain curve was subsequently imported into the simulation, as shown in Fig. 4.

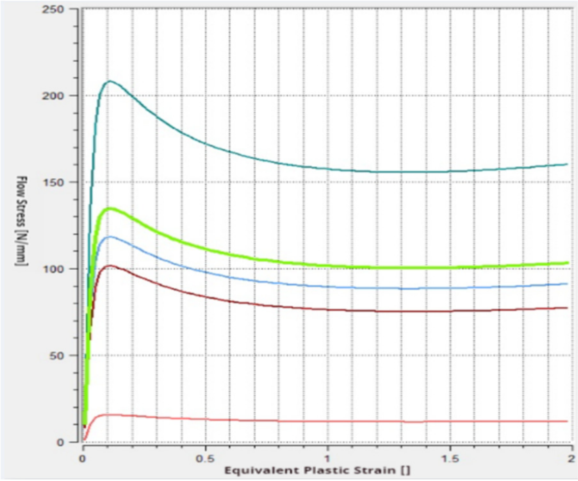
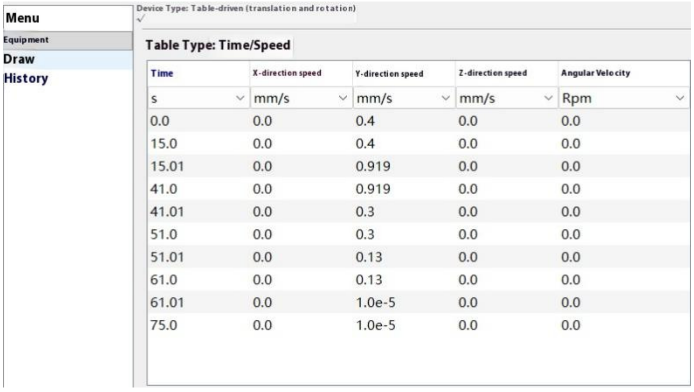


Figure 4. True stress–strain curve

In the simulation, the mandrel, guide rolls, and conical rolls were defined with specific motion strategies to reflect the real rolling process.

For the mandrel, the feed along the y-axis was divided into three stages: the biting stage, where the feed rate must remain small to ensure smooth engagement; the steady rolling stage, during which the inner and outer diameters of the conical blank expand; and the rounding stage, where the geometry approaches the final circular shape.

The RAW definition in Simufact Forming provides a convenient framework for complex roll motions. The guide rolls in practice rotate around a reference circular arc centered at a pivot point, following the radial growth of the ring. The end-face conical rolls simultaneously move downward along the axial direction while retreating radially with the ring expansion. The rolling process is thus divided into multiple stages to capture these coupled motions. Figure 5. illustrates the cross-sectional definition of the guide roll, demonstrating a more intelligent kinematic modeling approach for both guide rolls and conical rolls.

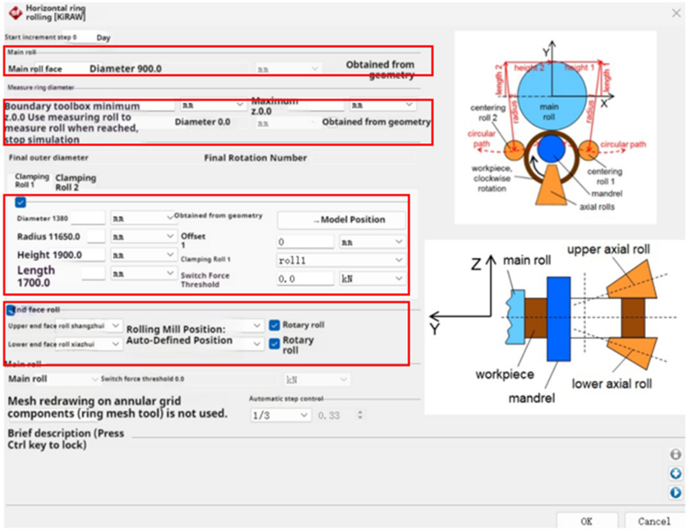


Device Type: Table-driven (translation and rotation)

Table Type: Time/Speed

Time	X-direction speed	Y-direction speed	Z-direction speed	Angular Velocity
s	mm/s	mm/s	mm/s	Rpm
0.0	0.0	0.4	0.0	0.0
15.0	0.0	0.4	0.0	0.0
15.01	0.0	0.919	0.0	0.0
41.0	0.0	0.919	0.0	0.0
41.01	0.0	0.3	0.0	0.0
51.0	0.0	0.3	0.0	0.0
51.01	0.0	0.13	0.0	0.0
61.0	0.0	0.13	0.0	0.0
61.01	0.0	1.0e-5	0.0	0.0
75.0	0.0	1.0e-5	0.0	0.0

Figure 5. Mandrel feed



Start increment step 0 Day

Main roll

Main roll face Diameter 900.0 mm Obtained from geometry

Measure ring diameter

Boundary toolbox minimum z.0.0 Use measuring roll to measure roll when reached, stop simulation mm Maximum z.0.0 mm

Diameter 0.0 mm Obtained from geometry

Final outer diameter

Final Rotation Number

Clamping Roll 1 Clamping Roll 2

☑

Diameter 1380 mm Obtained from geometry → Model Position

Radius 11650.0 mm Offset 1 0 mm

Height 1900.0 mm Clamping Roll 1 roll1

Length 1700.0 mm Switch Force Threshold 0.0 kN

☑ End face roll

Upper end face roll shangzhui Rolling Mill Position: Auto-Defined Position ☑ Rotary roll

Lower end face roll xiazhui ☑ Rotary roll

Main roll

Main roll Switch force threshold 0.0 kN

Mesh redrawing on annular grid components (ring mesh tool) is not used.

Automatic step control 1/3 0.33

Brief description (Press Ctrl key to lock)

Figure 6. Automated motion definition strategy

Figure 6. illustrates the definition of the guide roll cross-section, showing the automated motion definition strategy.

Main roll – The main roll was selected as the driving tool for the simulation. Its diameter was automatically detected by the software.

Ring diameter measurement – During the rolling process, the ring diameter was dynamically detected. Two methods were available: (i) global diameter detection using the maximum and minimum values along the global y-axis, or (ii) the use of a designated signal roll for direct measurement. A stop condition was also defined to automatically terminate the simulation once the target diameter was reached.

Guide rolls (Guide roll 1 and Guide roll 2) – Positioned along the positive and negative x-directions, respectively, the guide rolls controlled the lateral displacement of the ring, independent of their passive rotation. The software determined their trajectory based on the center of the circular arc motion, defined by roll height, length, and radius. An offset function was introduced to fine-tune the detected ring diameter: a negative offset pressed the roll closer to the ring (increasing clamping force), while a positive offset reduced the contact force or caused separation. An automatic positioning function was activated for Guide roll 1. A switching force threshold was defined to limit the maximum clamping force; once exceeded, the guide rolls automatically released the ring.

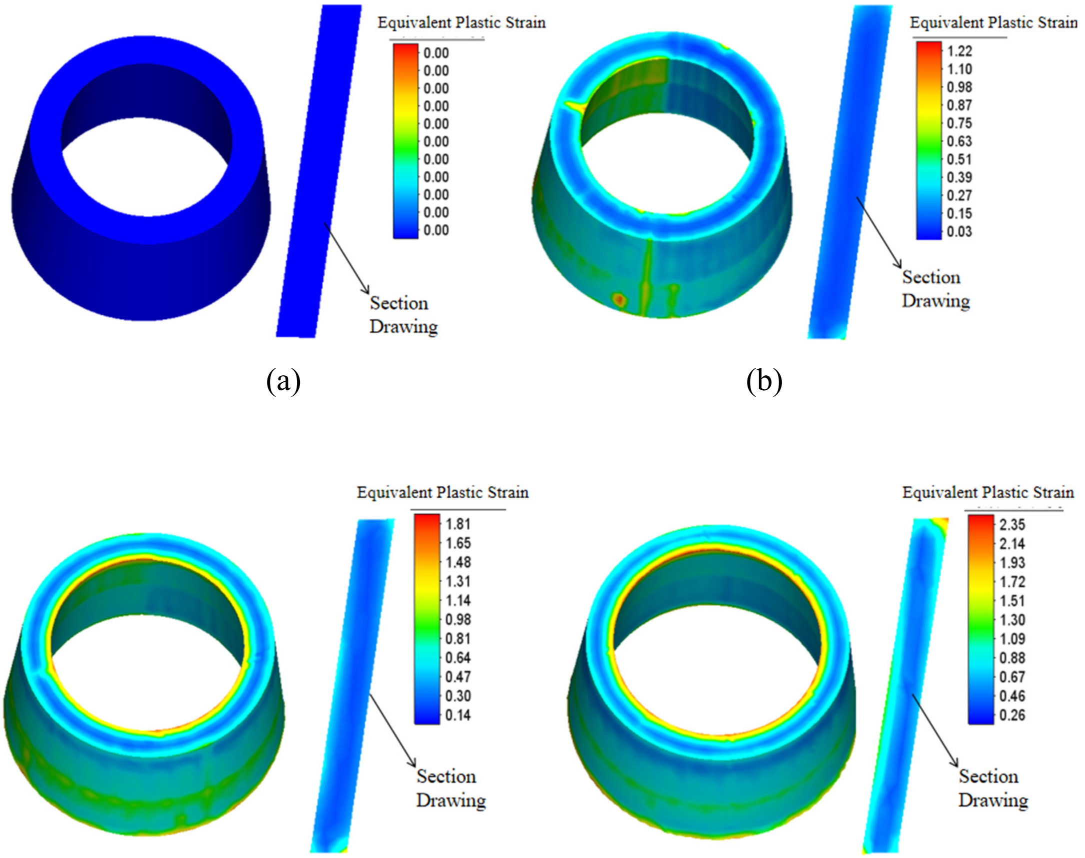
End-face conical rolls – The upper and lower conical rolls were controlled simultaneously. The roll position function ensured that the tips of the rolls remained aligned with the ring's central axis; as the ring diameter increased, the axis shifted, and the rolls followed this displacement. The rotation function was also activated, enabling the rolls to rotate at a speed automatically calculated from the main roll rotation and the current ring diameter.

3.2. Establishment of Boundary Conditions

Through a series of parametric simulation trials, the friction factor was set to 0.7 between the main roll and the ring, while a value of 0.2 was applied between the mandrel and the ring, the upper and lower conical rolls and the ring, as well as the guide rolls and the ring.Heat transfer in the model included conduction between the ring and rolls, and radiation between the ring and rolls, between the ring and the environment, and between the rolls and the environment. Excessive temperature loss during rolling can negatively affect forging quality and dimensional accuracy. Based on practical production experience, the heat transfer coefficient between the ring and rolls was set to 150 W/(m·K), and the emissivity of the ring was defined as 0.25[21].

4. SIMULATION RESULTS AND ANALYSIS

Based on the combination of theoretical analysis and the Simufact Forming platform, extensive simulation adjustments were performed and verified against previous studies. A reasonable forming strategy was finally achieved for the 2A14 conical cylindrical blank, ensuring both feasibility and quality. Figure 7. presents the plastic strain distribution at four representative stages of the ring rolling process: the initial stage before rolling, the intermediate stage during mandrel feeding, the stage corresponding to the maximum mandrel feed, and the final stage after rolling.



(a) (b)

(c) (d)

Figure 7. Illustrates the time-dependent evolution of equivalent plastic strain (PEEQ) during the rolling process:(a) 0s (b) 15s (c) 25s (d) 4**0s**

At the early stage, as the mandrel gradually feeds forward, the blank material is compressed and expands outward, leading to the progressive enlargement of the conical ring. In the middle and late stages, continued mandrel feed along the positive y-axis causes further plastic deformation. The upper and lower regions of the blank gradually align with the inclination determined by the mandrel and the driver roll. With further feed, the conical ring expands steadily until the rolling process is completed, at which point the geometry of the formed part approaches the target profile.

5. CONCLUSION

Based on the structural characteristics of the 2A14 conical ring, finite element simulations were conducted using Simufact Forming. The approach effectively shortens the design–verification cycle, reduces development costs, and enhances the market competitiveness of ring rolling products. A billet design strategy was established according to design principles and available equipment conditions, leading to a feasible rolling scheme for the 2A14 conical ring. The rolling process was simulated using Simufact Forming, and the study further elaborated on several detailed software settings that are seldom discussed in existing domestic manuals. Finally, a rolling strategy was proposed and verified, demonstrating that Simufact Forming can be effectively applied to evaluate and ensure the forming quality of 2A14 conical ring rolling.

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