Investigation of Deformation Behavior of TC4 Titanium Alloy Bolt in Warm Forming

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Abstract: TC4 titanium alloy is widely used in the manufacture of high-end aerospace fasteners due to its excellent specific strength and thermal stability. However, during warm forming, it is prone to cracking, uneven filling, and complex microstructure evolution, which restrict forming quality and process stability. This study takes TC4 titanium alloy bolts as the research object to investigate the deformation behavior during warm upsetting. Through Gleeble-3500 thermal simulation experiments, the true stress-strain curves of TC4 material are obtained within the temperature range of 800-1010 ℃ and strain rate range of 0.001-10s^{-1}. Meanwhile, a thermo-mechanical-microstructural coupled finite element model is established based on DEFORM-3D to simulate the metal flow, equivalent stress distribution, equivalent strain distribution, forming load, and temperature field evolution during the three-step warm upsetting process. Based on heat loss analysis, the heat dissipation behavior during multi-station forming is revealed, showing that the billet temperature increases significantly during the forming stage of each step. Forming experiments are carried out on a warm upsetting production line, and the finite element model is validated using a high-precision coordinate measuring machine. The results show that the simulated geometric dimensions of the forged parts are in good agreement with the experimental results, with a relative error of less than 1.5%. The three-step forming process effectively avoids defects caused by a single large deformation, and the metal flow lines are uniformly distributed without obvious distortion or underfilling. The forming load increases stepwise, with a peak load of approximately 219 kN. The numerical model and analysis methods established in this study provide a theoretical basis and engineering reference for the optimization and quality control of the warm forming process of TC4 titanium alloy bolts.

Keywords: TC4 Titanium Alloy; Warm Upsetting; Deformation Behavior; Metal Flow Lines; Heat Loss Analysis

1. Introduction

Titanium alloys are increasingly widely used in the aerospace field [1-2] due to their high specific strength, excellent corrosion resistance, and good high-temperature mechanical stability. Among them, TC4 titanium alloy, as a typical α+β two-phase titanium alloy [3-4], has become an important material for manufacturing key load-bearing fasteners such as aircraft engine connectors and fuselage structural bolts. With the continuous improvement of lightweight and reliability requirements for aerospace equipment, higher demands are placed on the forming accuracy, internal microstructure consistency, and mechanical properties of TC4 titanium alloy fasteners.

Bolt head upsetting is a key process in fastener forming, and its forming quality directly determines the service performance of the final product. TC4 titanium alloy exhibits poor plasticity and high deformation resistance at room temperature, making it difficult to achieve precise forming of complex head structures by cold upsetting [5]. Although hot upsetting can improve material fluidity, it is prone to surface oxidation, grain coarsening, and increased energy consumption. Warm forming [6-7], as a process method intermediate between cold forming and hot forming, can balance material formability and microstructure control to some extent, and has gradually become a research hotspot in the field of titanium alloy fastener manufacturing.

During the forming process of TC4 titanium alloy, the material flow behavior [8], temperature field distribution [9], mold-billet interface friction state [10], and multi-step forming path have important effects on the final forming quality. Existing research mostly focuses on hot compression behavior under a single temperature or strain rate condition [11-13], lacking systematic analysis of the entire deformation behavior, heat loss law, and die filling capacity during multi-step warm upsetting. In addition, although finite element simulation has been gradually promoted in the design of titanium alloy forming processes, there is still a lack of high-precision models combined with experimental verification and systematic process evolution law research for the complete three-step warm upsetting process of typical specification bolts (MJ8×36A).

Therefore, this paper takes TC4 titanium alloy aviation bolts as the research object, obtains material constitutive data through thermal simulation experiments, establishes a three-step warm upsetting finite element model based on DEFORM-3D, systematically analyzes the metal flow law, equivalent stress and strain evolution, forming load change, and multi-station heat loss behavior during the warm forming process, and verifies the accuracy of the model with actual warm upsetting experiments. The research aims to reveal the deformation behavior and thermo-mechanical coupling mechanism during the warm forming process of TC4 titanium alloy bolts, providing theoretical support for the optimization design and engineering application of warm forming processes for high-performance titanium alloy fasteners..

2. Formulation of Warm Upsetting Scheme for Tc4 Bolt

Although the plasticity of TC4 titanium alloy in the warm forming temperature range is improved compared to cold forming, it is still a difficult-to-deform material with limited deformation capacity. If a single large deformation upsetting is adopted, the local strain in the head region is too large, which can easily cause cracking, folding, or surface microcracks in the stress concentration area (the transition between head and shank). Decomposing the forming process into three steps keeps each deformation within the material's allowable range, effectively reducing the risk of deformation cracking. The gradual plastic deformation can significantly improve the microstructure and mechanical properties of TC4 titanium alloy. This process decomposes the forging forming process into three continuous and controllable steps, effectively avoiding cracks, folds, and other defects that may be caused by a single large deformation, while promoting the dynamic recrystallization process, thereby refining grains and reducing internal porosity, and improving material densification and uniformity. Step 1 is initial upsetting: the billet is pre-upset, initially forming the head contour, filling the front part of the die cavity, and controlling radial metal flow. Step 2 is intermediate upsetting: further filling the head cavity, promoting axial metal flow, and gradually conforming the material to the die geometry. Step 3 is final upsetting: completing the final head shaping to ensure complete filling of complex structures such as hexagon heads or flanges.

As-forged TC4 titanium alloy (Ti-6Al-4V) bar stock is used, with chemical composition conforming to GB/T 3620.1-2016 standard. According to the bolt model (MJ8×36A) and the principle of constant volume, the initial billet size is determined as φ8.3 mm × 55.2 mm (considering a 0.3 mm allowance added to the nominal diameter). Figure 1 shows the forming process drawing of an MJ4×22A specification bolt based on Q/Y 1073.4-2021.

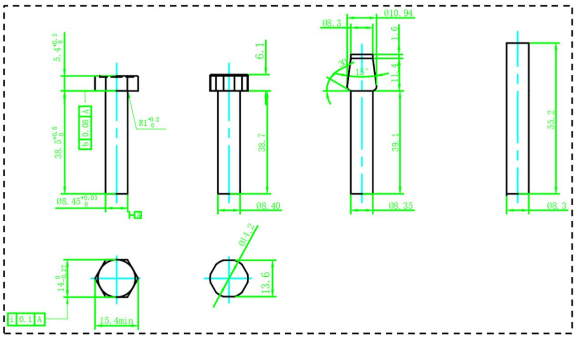
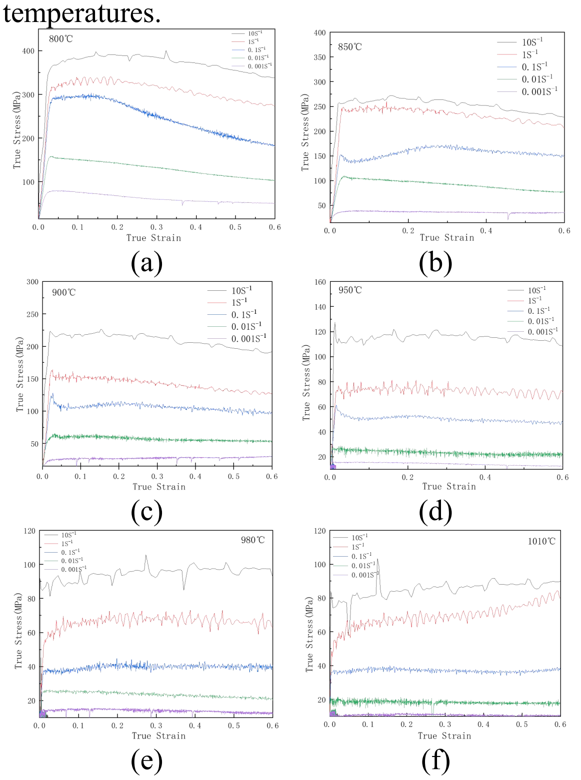


Figure 1. Forming Process Drawing of MJ4×22A Specification Bolt Based on Q/Y 1073.4-2021

3. Finite Element Model Establishment

3.1 Material Model

This study uses TC4 titanium alloy, widely used in high-temperature aerospace fasteners, as the bolt material. Cylindrical compression specimens of φ8 mm × 12 mm were machined from as-forged TC4 bar stock, 30 specimens in total. The thermal compression simulation experiments were conducted on a Gleeble 3500-GTC thermal simulation machine. Tantalum sheets and graphite agent were used to lubricate the cylindrical specimens to reduce friction effects during the experiment, and a vacuum was applied to prevent specimen oxidation. The temperature range covered the typical warm upsetting window of 800-1010 °C, and the strain rates were 0.001 s^{-1}, 0.01 s^{-1}, 1 s^{-1}, and 10 s^{-1}. Figure 2 shows the true stress-strain curves of TC4 titanium alloy at different strain rates and temperatures.



(a) (b)

(c) (d)

(e) (f)

Figure 2. True Stress-Strain Curves of TC4 Material at Different Strain Rates and Temperatures: (a) 800 °C, (b) 850 °C, (c) 900 °C, (d) 950 °C, (e) 980 °C, (f) 1010 °C

3.2 Geometric Model

For For the typical forming process of high-strength bolts used in aerospace (with the standard based on Q/Y 1073.4-2021 and the MJ8×36A specification), a symmetrical mold including pre-formed blank, grinding shell, pre-grinding core, grinding middle core, grinding after core, grinding after tooth, grinding through hole, grinding through hole sleeve, punch, and punch through hole sleeve was established.

Key geometric features of the dies, such as punch fillet radius, draft angle of the die cavity, and flash land design, were modeled based on actual engineering drawings and die design manuals to ensure accurate simulation of metal flow, filling behavior, and possible folding defects. The specifically designed three-step dies are shown in Figure 3.

All geometric entities were created in the 3D CAD software SolidWorks and imported into DEFORM V14.0 in STEP format.

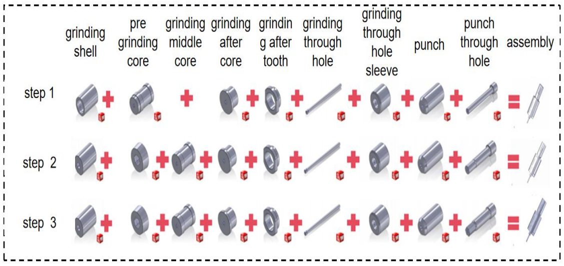


Figure 3. Three-Step Bolt Warm Upsetting Dies

3.3 Simulation Setup

3.3.1 Mesh generation

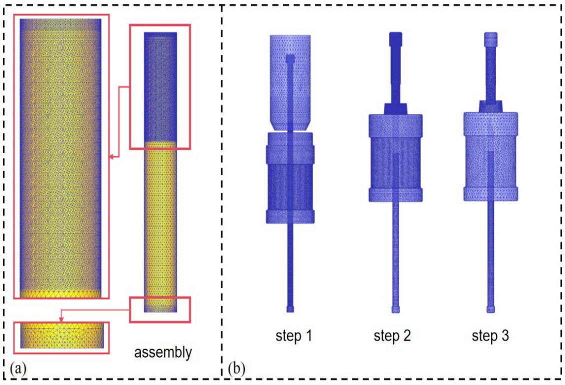


Figure 4. Mesh Generation

Numerical simulation was performed on the DEFORM-3D (v14.0) finite element simulation platform specialized in metal forming processes. The billet was defined as a plastic body and meshed into approximately 400,000 elements, with local refinement in areas expected to undergo severe deformation (bolt head) and in contact with the heading die, as shown in Figure 4(a). The dies-punch, punch sleeve, heading die, front insert, and middle insert-together formed the die cavity. The mesh counts were: punch: 50,000 elements; punch sleeve: 250,000 elements; heading die: 150,000 elements; Step 1 front insert (including front and middle inserts): 500,000 elements; front inserts for subsequent steps: 200,000 elements; middle insert: 300,000 elements. Additionally, the die cavity was refined with a refinement ratio set to 0.1, as shown in Figure 4(b). Automatic remeshing was enabled to handle mesh distortion due to large deformation. All other dies were treated as rigid bodies.

3.3.1 Boundary conditions and process parameters

Boundary conditions and process parameters were set considering literature data, experimental experience, and simulation stability. The specific settings are shown in Table 1.

Table 1. Numerical Simulation Process Parameter Settings

Process parameter	Value
Billet temperature	700-1000℃
Die temperature	70℃
Friction coefficient	0.2-0.5
Friction model	Shear model
Upsetting speed	30 mm/s
Heat transfer coefficient between billet and die	5N/sec/mm/℃
Convection heat dissipation coefficient between billet and environment	0.02
Simulation algorithm	Lagrange multiplier method
Solver	Relaxation method coefficient matrix

Temperature condition: The initial deformation temperature was set to 700-1000℃ to balance material formability and oxidation risk.

Heat exchange: Since the billet is in a warm upsetting state, there is a large temperature gradient between the billet and the surrounding air. Therefore, convection and radiation were included in the heat transfer model. The die temperature was defined as 70 ℃, with a heat transfer coefficient of 5 N/sec/mm/℃ between billet and die, and a convection heat dissipation coefficient of 0.02 between billet and environment.

Friction condition: A shear friction model was used at the billet-die contact interface to handle boundary friction. The friction force F is expressed as: $F = m \times k$, where m is the friction factor and k is the shear yield strength of the deforming material. The friction factor m was set in the range of 0.2-0.5.

Motion condition: The punch moves downward at a constant speed (range: 30-60 mm/s) to complete the warm upsetting process, while the other dies are fixed.

To ensure simulation accuracy, the true stress-strain data obtained from Gleeble experiments were imported into the Deform-3D material library. Figure 1 shows the true stress-strain curves of TC4 titanium alloy at different temperatures. The main deformation in bolt head upsetting is plastic deformation. Due to the high forging temperature and large deformation, elastic deformation can be neglected. Therefore, the billet type was selected as plastic in warm upsetting forming. Since die deformation is small, the dies were selected as rigid bodies.

The simulation algorithm selected the Lagrange multiplier method, with the relaxation method coefficient matrix solver, and the direct iteration method was used for numerical simulation calculation. Each simulation was calculated to a predetermined stroke, outputting key results such as maximum equivalent stress, maximum equivalent strain, forming load, and die wear for subsequent process analysis and optimization.

4. Simulation Result Analysis

4.1 Metal Flow Law during Warm Upsetting

Bolt warm upsetting is the process of forming the bolt head, where the head region fills the die cavity under die extrusion to meet shape and size requirements.

Taking the forming conditions of TC4 titanium alloy billet temperature of 700 ℃, warm upsetting speed of 30 mm/s, and friction coefficient of 0.35 as an example, Figures 5(a), 5(b), 5(c), and 5(d) show the changes at the simulation model, Step 1, Step 2, and Step 3, respectively.

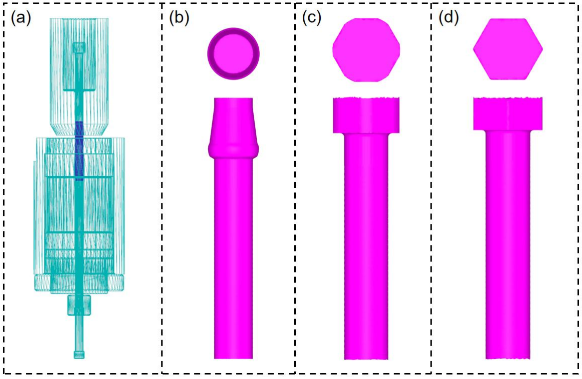


Figure 5. Warm Upsetting Process of TC4 Titanium Alloy Bolt Head: (a) Simulation Model, (b) Step 1, (c) Step 2, (d) Step 3

During the warm upsetting process of the bolt head, the upper die moves downward, causing the billet to flow radially. As the upper die stroke increases, the contact area between the billet and the upper die cavity gradually increases, leading to increased friction, i.e., increased resistance to radial metal flow. At this point, the metal begins to flow axially. As the upper die continues to descend, the metal billet gradually deforms according to the die shape. The metal flow line patterns inside the TC4 titanium alloy bolt head at different die strokes are shown in Figure 6, and the external metal flow patterns are shown in Figure 7. From Figures 6 and 7, it can be seen that when the die strokes correspond to Step 1, Step 2, and Step 3, the metal flow distribution in the inner and outer regions of the bolt head is uniform, with no obvious distortion and good filling.

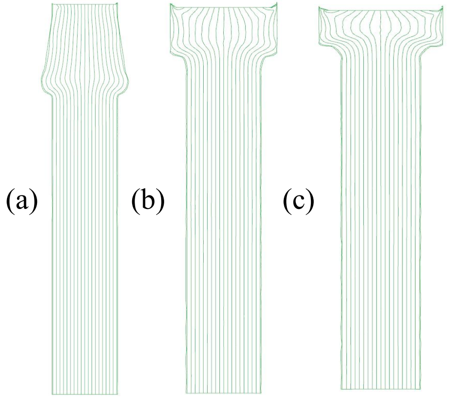


Figure 6. Internal Metal Flow Lines in TC4 Titanium Alloy Bolt Head Billet during Warm Upsetting: (a) Step 1, (b) Step 2, (c) Step 3

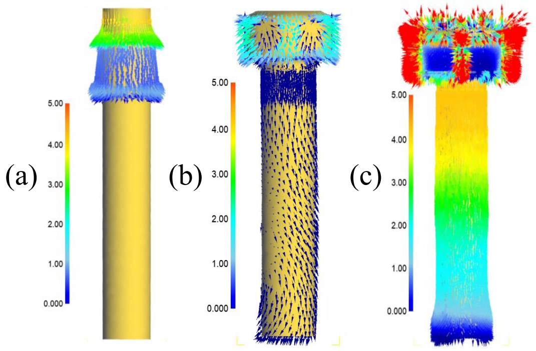


Figure 7. External Metal Flow Velocity in TC4 Titanium Alloy Bolt Head Billet during Warm Upsetting: (a) Step 1, (b) Step 2, (c) Step 3

4.1 Stroke Load and Stress Evolution Analysis

Taking the above forming conditions as an example, the bolt head warm forming process is divided into three stages, as shown in Figure 8. The first stage is the initial deformation stage of the bolt head. The billet is first in a free upsetting state, then constrained by the die cavity, gradually filling the cavity. In this stage, less metal fills the die cavity, the billet deformation is small, and the load increases relatively slowly. In the second stage, the billet continuously fills the die cavity, its free surface decreases, and as the contact area with the die gradually increases, the metal flow resistance increases, and the forming load gradually becomes larger. In the third stage, as the die continues to descend, the free surface of the billet is very small. To completely fill the die cavity, the metal deformation resistance increases, and the forming load shows a sharp increase. From Figure 8, the load required for warm upsetting of the TC4 bolt head is 219 kN.

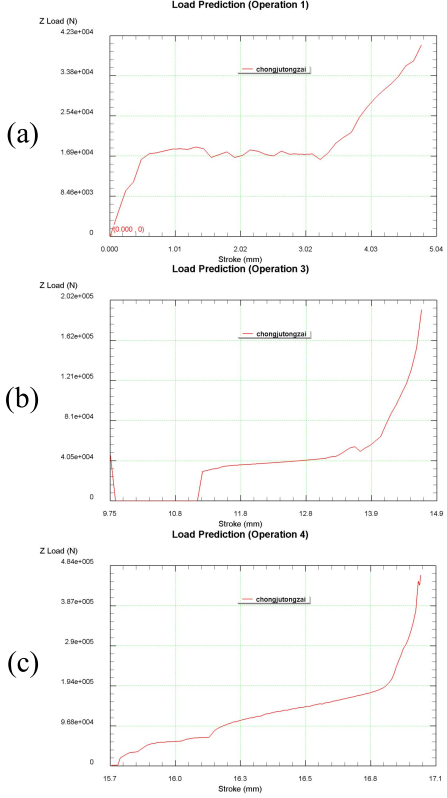


Figure 8. Load-Stroke Curves for Warm Upsetting of TC4 Titanium Alloy Bolt Head: (a) Step 1, (b) Step 2, (c) Step 3

The equivalent stress distribution at different stages of bolt head forming is shown in Figure 9. In the early stage of plastic deformation, the stress value in the outer region of the billet increases significantly. As deformation increases, the billet fills the die cavity, and the stress distribution gradually becomes uniform. The equivalent strain distribution at different stages of bolt head forming for TC4 material under these conditions is shown in Figure 10. From Figure 10, the equivalent strain distribution during the plastic deformation of the billet is relatively uniform.

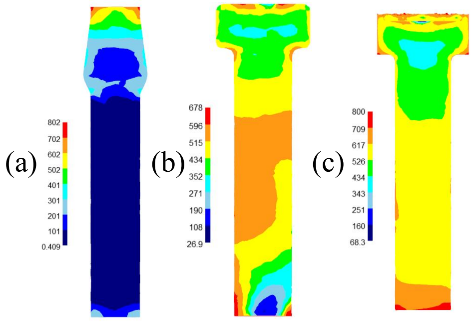


Figure9. Evolution of equivalent Stress Distribution in TC4 Titanium Alloy Bolt: (a) Step 1, (b) Step 2, (c) Step 3

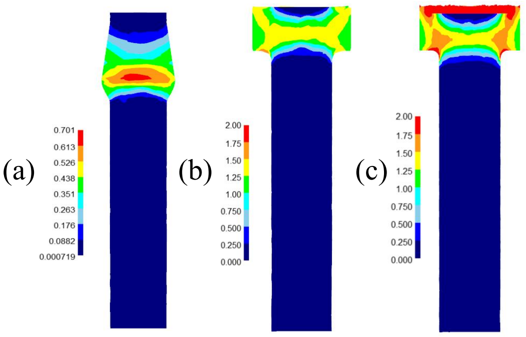


Figure10. Evolution of Equivalent Strain Distribution in TC4 Titanium Alloy Bolt: (a) Step 1, (b) Step 2, (c) Step 3

4.3 Heat Loss Analysis during Multi-Station Warm Upsetting

During multi-station warm upsetting, the workpiece undergoes continuous forming through multiple stations, and its temperature changes significantly during transfer between stations. Temperature change mainly comes from two sources: convective heat exchange with the air during inter-station movement, and contact heat transfer during workpiece-die contact. Accurately determining the actual working temperature at each station is of great significance for optimizing process parameters and ensuring product quality.

4.3.1 Heat loss calculation model

For the heat loss problem during multi-station warm upsetting, a transient thermal analysis model was established using ANSYS Workbench software. Due to the small size of the workpiece (diameter 8.3 mm, length 55.2 mm), verified by the Biot number (Bi < 0.1), the internal temperature distribution of the workpiece can be approximately considered uniform, so the lumped parameter method was used for temperature field calculation.

The convective heat transfer coefficient during workpiece movement in air was calculated using the Churchill-Bernstein correlation:

$$Nu = 0.3 + \frac{0.62Re^{0.5}Pr^{1/3}}{\left[1 + (0.4/Pr)^{2/3}\right]^{0.25}} \qquad (1)$$

Where Re is the Reynolds number and Pr is the Prandtl number. According to the actual operating conditions (air velocity 333.3 mm/s, air temperature 25 ℃), the air convective heat transfer coefficient was calculated to be approximately 27.3 W/(m²·K).

The contact heat transfer coefficient between the workpiece and the die is related to factors such as contact pressure and surface roughness. In this study, 500 W/(m²·K) was used as the calculation parameter. The die preheating temperature was set to 70 ℃, consistent with actual production conditions.

4.3.2 Process parameters for typical part

The initial billet diameter was determined by adding 0.3 mm to the nominal bolt diameter, and the billet length was 55.2 mm. The typical work step configuration and initial billet parameters are shown in Table 2。

Table 2. Typical Part Station Configuration and Initial Billet Parameters

Typical part	Model	Material	Number of stations	Initial diameter (mm)
Typical part 1	MJ8×36A (hexagon head)	TC4	3	8.3

The die material configuration was: die holder: H13 steel; liner insert: ST7 steel; backing block: SKD-11 steel; punch sleeve: SKH-9 steel. The transfer speed between stations was adjustable, with a production rate of 50-80 pieces/min, corresponding to a single inter-station transfer time of approximately 0.3 seconds and a single upsetting time of approximately 0.4 seconds.

The initial billet size for the typical part was φ8.3 mm × 55.2 mm, with a surface area of approximately 1547.56 mm², a volume of approximately 2986.66 mm³, and a mass of approximately 13.23 g. The initial heating temperature was set to 700 ℃. The temperature changes at each stage obtained from the simulation are shown in Tables 3.

Table 3. Temperature Changes at Each Stage for Typical Part (MJ8×36A)

Stage	Start temperature (℃)	End temperature (℃)	temperature difference (℃)
Step 1	700	790	90
Step 2	790	946	156
Step 3	946	967	21

Figure 11 shows the temperature changes at each stage during warm upsetting of the TC4 titanium alloy bolt head. During the upsetting process of each step, the heat generated by plastic deformation was significantly greater than the heat lost through contact conduction with the die, resulting in an overall upward trend in billet temperature. The temperature rise in Step 2 was 156 ℃, indicating that the deformation heat effect is significant during warm upsetting. Inter-station heat loss was limited; the inter-station transfer time was only 0.3 s, and the temperature drop caused by convective heat exchange was small. The temperature remained basically stable during the inter-step transition. As the process progressed, the billet temperature increased stepwise. By the final upsetting stage (Step 3), the billet temperature had reached 967 ℃, which is within the ideal hot working range for TC4 titanium alloy (800-1010 ℃), favorable for metal flow and microstructure control.

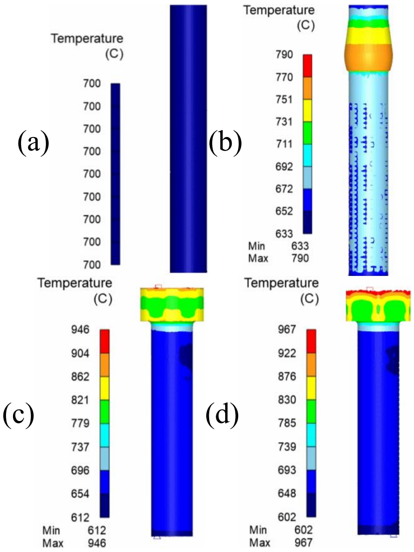


Figure11. Temperature Changes at Each Stage during Warm Upsetting of TC4 Titanium Alloy Bolt Head: (a) Billet, (b) Step 1, (c) Step 2, (d) Step 3

5. Bolt Head Warm Upsetting Experiment

To verify the reliability of the finite element model for bolt head warm upsetting, relevant experiments were carried out on a bolt warm upsetting machine in a forging workshop. Cylindrical billets were cut, placed in a box furnace, heated to 700 ℃ and held, and the billet temperature was monitored by an infrared thermal imager. The heated billets were transferred by conveyor belt to the warm upsetting machine for upsetting.

5.1 Verification of the Finite Element Model

According to the parameters in Table 1, the final forged part obtained from the warm upsetting experiment is shown in Figure 12. A high-precision coordinate measuring machine was used to measure the geometric dimensions of the final forged part, and the main dimensions from the experimental results were compared with the finite element results to verify the reliability of the finite element model.

Figure12. Final Forged Part.

The main dimensional comparison data between the final part and the finite element simulation results are shown in Table 4. As shown in Table 4, the relative error is less than 1.5%. The geometric dimensions of the bolt are in good agreement with the finite element simulation, indicating that the finite element model has high accuracy in predicting geometric dimensions.

Table 4. Comparison Data Table

Comparison data	Simulated part	Actual part	Error
Nominal diameter	6.38mm	6.32mm	0.94%
Nominal diameter	32.50mm	32.88mm	1.17%
Shank length	4.32mm	4.36mm	0.93%
Hexagon head thickness	10.17mm	10.03mm	1.38%
Across flats distance	10.91mm	11.07mm	1.47%
Across corners distance	6.38mm	6.32mm	0.94%

Figure 13 shows the cross-sections of the forged part at different steps. As the upper die stroke increases, the contact area between the billet and the upper die cavity gradually increases, the resistance to radial metal flow increases, and the metal flows axially. The internal metal flow line directions in the cross-section coincide with the finite element simulation laws, indicating that the finite element model has high accuracy in predicting warm upsetting forming.

Figure13. Forged Part Cross-Section

6. Conclusions

(1) The true stress-strain curves of TC4 titanium alloy in the range of 800-1010 ℃ and strain rates of 0.001-10 s^{-1} were obtained through Gleeble-3500 thermal simulation experiments, revealing the flow stress behavior of the material under warm forming conditions and providing a reliable material data basis for finite element simulation.

(2) A thermo-mechanical-microstructural coupled finite element model for the three-step warm upsetting process of TC4 titanium alloy bolts was established based on DEFORM-3D,

and experimental verification was carried out on an actual warm upsetting production line. The simulated geometric dimensions of the forged part were in good agreement with the experimental results, with a relative error of less than 1.5%, indicating that the model has high prediction accuracy.

(3) The three-step warm upsetting process can effectively avoid defects such as cracking and folding caused by a single large deformation. The metal flow lines are uniformly distributed without obvious distortion or underfilling, indicating that the multi-step process is beneficial for improving the plastic flow and forming quality of the material.

(4) The forming load increases in stages, with slow growth in the initial stage, gradual increase in the middle stage, and a sharp increase in the final upsetting stage. The peak load is approximately 219 kN, providing a reference for process equipment selection and die design.

(5) During the multi-station warm upsetting process, the heat generated by plastic deformation is significantly greater than the heat lost through contact conduction with the dies, and the billet temperature shows an overall upward trend. The temperature rise in Step 2 is 156 ℃, and the billet temperature reaches 967 ℃ in the final upsetting stage, which is within the ideal hot working range for TC4 titanium alloy, favorable for metal flow and microstructure control. Inter-station heat loss is limited, and the temperature drop caused by convective heat exchange is small.

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