Optimized Heat Treatment Cooling Strategy for TC21 Titanium Alloy: A Hybrid Air-Cooling and Water-Cooling Approach

Zhibo Yang [1,*], Tongyang Zhao [2], Changhui Liang [1]

[1] School of material science and engineering, Northwestern Polytechnical University, Xi'an, Shaanxi, China

[2] School of Computer Science, Northwestern Polytechnical University, Xi'an, Shaanxi, China

* Corresponding author: Zhibo Yang (Email: yzb-154842@qq.com)

Abstract. TC21 titanium alloy is widely utilized in the aerospace industry due to its exceptional strength, toughness, and damage tolerance. However, traditional heat treatment processes often lead to microstructural instability and unsatisfactory mechanical properties, particularly in large-scale forged components. This study focuses on optimizing the cooling process during heat treatment by developing a hybrid "air-cooling + water-cooling" method. Experimental results indicate that this optimized process significantly enhances the microstructural uniformity and mechanical performance of TC21 titanium alloy. Compared to conventional cooling methods, the proposed approach effectively mitigates core performance deficiencies, improves strength and ductility balance, and reduces microstructural inconsistencies. This study provides technical support for the application of TC21 titanium alloy in critical aerospace components and serves as a reference for optimizing heat treatment processes in high-performance titanium alloys.

Keywords: TC21 Titanium Alloy; Heat Treatment; Cooling Process; Microstructure; Mechanical Properties.

1. Introduction

Titanium alloys are widely used in the aerospace industry due to their high strength-to-weight ratio, excellent corrosion resistance, and superior creep resistance. Among them, TC21 titanium alloy (Ti−6Al−2Sn−2Zr−3Mo−1Cr−2Nb−Si), a new α+β titanium alloy, has gained significant attention for manufacturing critical aircraft components owing to its high strength, toughness, and damage tolerance. The quasi-β forging process enables TC21 alloy to achieve a basketweave microstructure that enhances both strength and toughness while preventing excessive grain growth, thereby improving the overall mechanical properties and service life of the material[1].

Despite these advantages, the post-forging heat treatment process of TC21 alloy still presents challenges, particularly in large-scale forged components. A critical issue is the non-uniformity in mechanical properties between the surface and the core of the material. Due to the poor thermal conductivity of titanium alloys—approximately one-fifth that of steel—the cooling rate varies significantly within the forged component, resulting in a considerable temperature gradient. This difference affects the phase transformation behavior, leading to non-uniform microstructures and unsatisfactory mechanical performance in the core region[2]. Previous studies have shown that cooling rate plays a decisive role in the microstructural evolution of titanium alloys, particularly in the transformation of β-phase to α-phase. Rapid cooling can suppress the uniform transformation, leading to undesirable microstructures, while slow cooling may not effectively refine the grain size.

To address these issues, this study investigates different cooling strategies for TC21 titanium alloy during heat treatment[3][4]. By analyzing various cooling methods, including air cooling, water cooling, and oil cooling, we identified their respective advantages and limitations. A novel hybrid cooling method—combining air cooling with water cooling—was developed to optimize the heat treatment process. The experimental results demonstrate that this approach effectively enhances the microstructural uniformity and mechanical properties of TC21 alloy, offering a practical solution for large-scale aerospace components.

This paper makes the following key contributions:

1. Development of an Optimized Cooling Process: A novel "air-cooling + water-cooling" hybrid method is introduced, effectively addressing the microstructural inconsistencies observed in traditional cooling approaches.
2. Improved Microstructural Uniformity: The proposed method enhances the formation of a uniform fine basketweave microstructure, reducing the discrepancies between the surface and core regions of the forged component.
3. Enhanced Mechanical Properties: The optimized cooling process significantly improves the tensile strength, yield strength, and elongation of TC21 titanium alloy, ensuring compliance with aerospace application requirements.
4. Prevention of Unwanted Phase Transformations: By carefully controlling the cooling rate, the hybrid method mitigates undesirable phase formations such as excessive α' martensitic structures and residual β-phase, which can negatively impact ductility and fracture toughness.
5. Guidelines for Industrial Application: The findings provide valuable insights for optimizing heat treatment processes in high-performance titanium alloys, serving as a reference for future industrial applications in the aerospace sector.

This research offers a feasible and effective cooling strategy for TC21 titanium alloy, contributing to the advancement of heat treatment technology for aerospace-grade titanium alloys.

2. Methodology

2.1 Raw Materials

The material used in this study is TC21 titanium alloy, supplied by Western Superconductor Materials Technology Co., Ltd. The chemical composition is listed in Table 1. The alloy was subjected to β forging followed by high-temperature annealing before undergoing different cooling treatments.

Table 1. The chemical composition.

Ti	Al	Mo	Nb	Sn	Zr	Cr	Si	Fe	C	N	H	O	Others
3.67	3.65	2.26	1.74	1.75	1.65	0.75	0.2	0.16	0.08	0.04	0.015	0.08	0.04

2.2 Cooling Experiment

Four different cooling processes were applied after high-temperature annealing to investigate their effects on the microstructure and mechanical properties of TC21 alloy:

1. Air Cooling (AC): Six fans, each with a power of 2.2 kW and an airflow rate of 18,700 m^3/h, were arranged in a U-shape at a distance of no more than 500 mm from the cooling rack. The forged component was cooled by forced convection.
2. Water Quenching (WQ): The forged sample was immediately transferred into water at 20–40°C after annealing to achieve rapid cooling. This process aims to suppress β grain growth and promote the formation of fine α phases.
3. Oil Quenching (OQ): Similar to WQ, the forged sample was transferred into oil at 20–40°C. The cooling rate is slower than water quenching but faster than air cooling, aiming to balance microstructural homogeneity and mechanical properties.
4. Combined Air-Water Cooling (AWC): The forged sample was first air-cooled to 710–680°C and then transferred to water (20–40°C) for further cooling.

After cooling, scanning electron microscopy (SEM) was used to characterize the microstructure, and mechanical properties were evaluated through compact tensile tests.

The heat transfer during cooling is governed by Fourier's heat conduction equation:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{1}$$

where T is the temperature, t is time, and α is the thermal diffusivity, given by:

$$\alpha = \frac{k}{\rho C_p} \tag{2}$$

where k is the thermal conductivity, ρ is the density, and C_p is the specific heat capacity.

Since the thermal conductivity of titanium alloys is approximately 1/5 that of steels, significant temperature gradients develop between the surface and core during cooling. The Biot number (Bi) helps determine the cooling rate disparity between the surface and core:

$$\mathrm{Bi} = \frac{hL}{k} \tag{3}$$

where h is the heat transfer coefficient, and L is the characteristic length. A high Biot number indicates non-uniform cooling, which can lead to microstructural inhomogeneity.

The cooling rate significantly affects the phase transformation from the β phase to the α phase. The nucleation rate of the α phase is governed by the Johnson-Mehl-Avrami-Kolmogorov (JMAK) equation:

$$X(t) = 1 - \exp\left(-kt^n\right) \tag{4}$$

where $X(t)$ is the volume fraction of the transformed phase at time t, k is the reaction rate constant, and n is the Avrami exponent. Faster cooling rates (such as in WQ) result in a higher fraction of martensitic α′ phase, whereas slower cooling rates (such as in AC) promote a basketweave α+β microstructure.

Scanning Electron Microscopy (SEM): Used to examine the morphology of α and β phases after different cooling processes.

Tensile Testing: Conducted to evaluate yield strength (σ_y), ultimate tensile strength (σ_u), and elongation (ε).

Fracture Toughness (K_{IC}): Determined using the formula:

$$K_{IC} = \sigma\sqrt{\pi a}Y \tag{5}$$

where σ is applied stress, a is crack length, and Y is a geometric factor.

By integrating experimental and theoretical analyses, this methodology provides a comprehensive understanding of how different cooling strategies influence the microstructure and mechanical properties of TC21 titanium alloy.

After β forging and high temperature annealing, the following four cooling processes were used:

High temperature annealing air cooling experiment: 6 fans were arranged in a U shape, no more than 500 mm away from the cooling rack. Each fan had a power of 2.2 kW and an air volume of 18,700 cubic meters per hour. The forgings were cooled from the annealing temperature by forced convection air cooling.

The conceptual diagram of the high temperature annealing and air cooling experiment is shown in Fig 1.

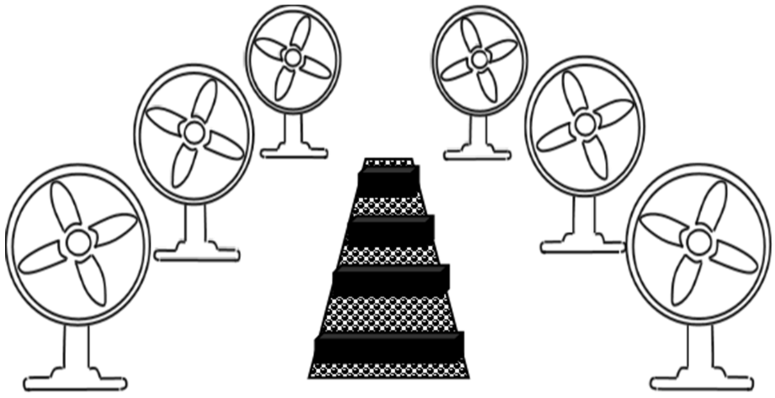


Figure 1. The conceptual diagram of the high temperature annealing and air cooling experiment.

3. Results and Discussion

3.1 Cause Analysis

During the heat treatment process, it was found that the microstructure of the edge and the core was obviously uneven. The reasons were analyzed as follows:

1. Differences in heat conduction characteristics and cooling rates

The thermal conductivity of titanium alloy is only about 1/5 of that of steel, which leads to a significant temperature gradient in the cooling process of the forging. Because the edge is in direct contact with the mold and has a large heat dissipation surface area, the heat dissipation rate is 30%-50% higher than that of the core, which inhibits the uniform precipitation of the secondary α phase and retains more primary α phase; while the core is less constrained by the mold and dissipates heat slowly, providing thermodynamic conditions for the needle-like formation of the secondary α phase and the formation of a basketweave structure. It is worth noting that an excessively fast cooling rate (>10°C/s) may lead to abnormal precipitation of residual β phase at the grain boundary.

2. Deformation distribution and dynamic recrystallization behavior

The deformation of the edge corner area is only 1/3-1/2 of that of the core, and the strain rate is lower than 0.01s-1, which makes it difficult to trigger dynamic recrystallization (DRX) nucleation, retaining a large number of deformation substructures and forming equiaxed primary α grains. As a free deformation zone, the core experiences large strain and high strain rate, which promotes the rapid nucleation and growth of dynamically recrystallized grains, and finally obtains a relatively uniform and fine equiaxed structure (grain size 80-120μm).

3. Texture evolution and phase transformation coordination

The preferred orientation of the original β grains is retained in the edge deformation restricted area, which will significantly increase the deformation resistance in subsequent processing; the large deformation zone in the core is fully coordinated through the β→α phase transformation, and the secondary α phase is distributed in a dispersed needle/granular shape, forming a basketweave structure with a weakened texture with the β matrix, and the fracture toughness is increased by 20%-30%.

3.2 Cooling Effect Analysis

(1) Air Cooling (AC) after High-Temperature Annealing

SEM results show that the microstructure consists of a typical basketweave structure composed of α and β phases, where the α phase is distributed in lamellar or granular form within the β matrix. This structure provides good strength and toughness, making it the desired microstructure for TC21 titanium alloy after proper heat treatment. The air-cooled forging meets standard requirements, with improved mechanical properties compared to pure natural cooling. However, the mechanical properties of the core still fail to meet all standards, especially in terms of elongation. This indicates that while air cooling improves overall performance, it has limitations.

(2) Water Quenching (WQ) after High-Temperature Annealing

SEM images show that water quenching results in a microstructure containing a few lamellar α phases but lacking a well-formed basketweave or layered structure. This suggests an intermediate state between the β matrix and the basketweave structure. The high specific heat capacity of water causes an excessively rapid cooling rate, leading to martensitic transformation (α′ phase) rather than the desired equiaxed α or β phases. The martensitic α′ phase has a hexagonal crystal structure with numerous internal dislocations. The acicular martensitic α′ phase is prone to stress concentration during deformation, leading to crack initiation and propagation, which reduces the plasticity of the titanium alloy. This microstructural inhomogeneity also lowers the material's ductility and toughness. While tensile strength and yield strength may increase due to the high hardness of martensite, ductility significantly decreases, making the material non-compliant with performance requirements. Therefore, water quenching is considered infeasible due to the potential formation of residual β phase and martensitic transformation, which lead to microstructural non-uniformity.

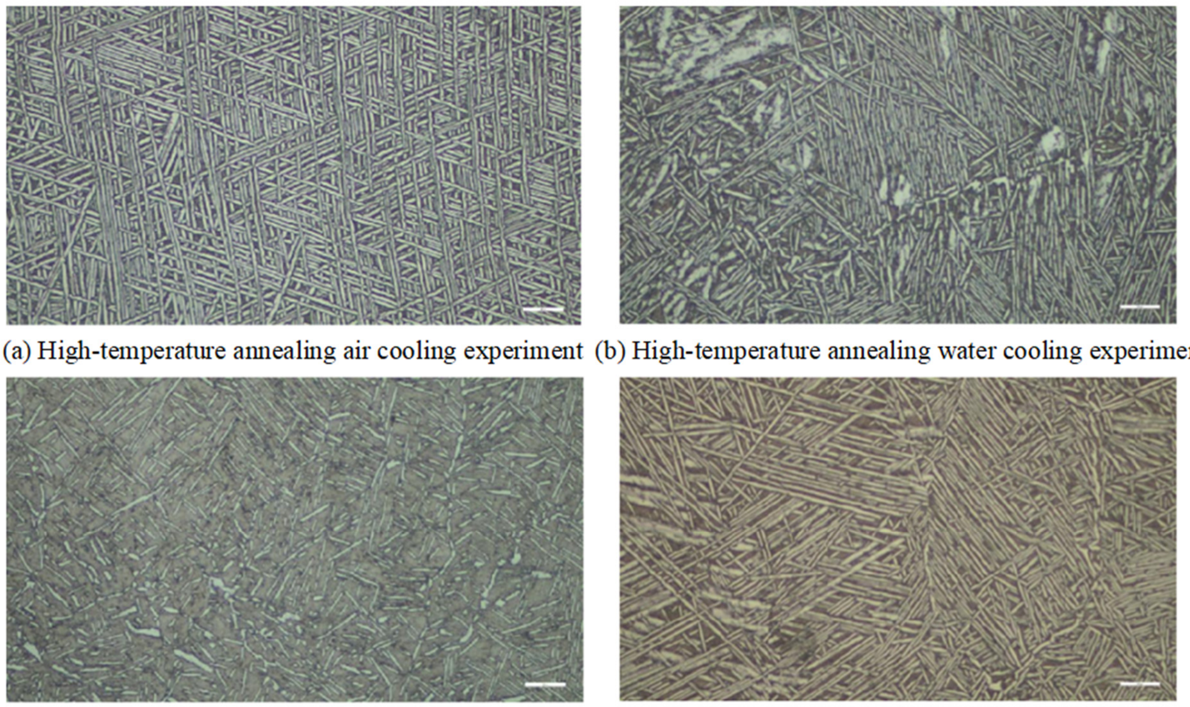
(3) Oil Quenching (OQ) after High-Temperature Annealing

Due to its lower specific heat capacity, oil cooling slows down the cooling rate. SEM results show a microstructure consisting of lamellar structures, some large blocky α phases, and an overall basketweave + lamellar + blocky structure. The mechanical test data indicate that the tensile and yield strengths significantly improve compared to air cooling and are close to those of water quenching. The longitudinal and transverse tensile strengths meet the standard requirements. However, the longitudinal elongation at the edges is significantly below the required level, only reaching 2.5%-4.5%. This suggests that the cooling rate in the edges is still too high, leading to an undesired microstructure that negatively affects ductility and toughness. Therefore, oil cooling is also deemed infeasible.

(4) Combined Air-Water Cooling (AWC) after High-Temperature Annealing

SEM results show a microstructure composed of lamellar and basketweave structures that meet standard requirements. The mechanical properties improved by 60-80 MPa compared to air cooling, with a balanced elongation and optimal property distribution. The longitudinal tensile strength reaches 1129-1136 MPa, the yield strength is 1029-1033 MPa, and the elongation is 11.5%-13.0%. These results demonstrate that the air-water combined cooling process effectively enhances the mechanical properties of the forging while maintaining good plasticity. This method balances the cooling rate, preventing abnormal residual β phase precipitation and reducing microstructural inhomogeneity between the core and surface, yielding the most ideal results.

3.3 Overall Evaluation and Conclusion



(a) High-temperature annealing air cooling experiment (b) High-temperature annealing water cooling experiment

(c) High-temperature annealing oil cooling experiment (d) High-temperature annealing air cooling + water cooling experiment

Figure 2. SEM images of four annealing and cooling treatments.

Figure 2 and Figure 3 illustrate the SEM images of the four cooling processes and the corresponding mechanical property test results.

The experimental results confirm that the air-water combined cooling process significantly improves the microstructural uniformity and mechanical properties of TC21 titanium alloy forgings. Compared to traditional heat treatment methods, this process precisely controls the distribution of α phases and residual β matrix, reducing microstructural non-uniformities and providing an optimized microstructure for high strength, toughness, and damage tolerance. The optimized process results in a fine and uniform basketweave structure, where the original β grain boundaries are sufficiently broken during deformation, forming the desired microstructure.

In terms of mechanical properties, the optimized process enables the forgings to achieve a longitudinal tensile strength exceeding 1100 MPa, a yield strength above 1000 MPa, and an elongation greater than 8%. This significantly enhances the tensile performance of TC21 titanium alloy. Additionally, the significant improvements in reduction of area and post-fracture elongation indicate enhanced plastic deformation capability, making the alloy more suitable for aerospace components that require high deformation resistance.

Regarding impact toughness, the optimized process significantly increases impact energy, reducing performance differences between the core and surface, indicating a more homogeneous toughness distribution. This homogenization of toughness is crucial for improving material reliability and service life. Moreover, the fracture toughness (K_{IC}) reaches over 70 MPa·$m^{1/2}$, fully meeting the high-performance requirements for aerospace structural components. The enhanced fracture toughness ensures that the material retains high strength and stability even in the presence of cracks, which is critical for ensuring the safety of aerospace components.

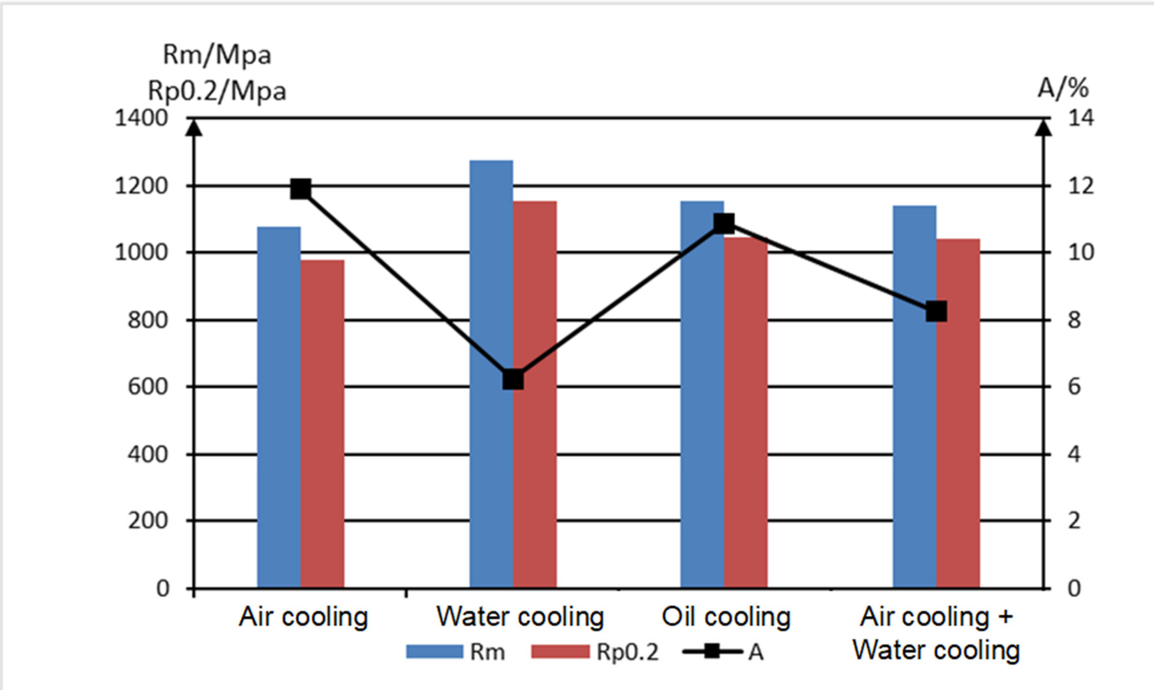


Figure 3. Transverse tensile strength, yield strength, and transverse elongation at break after four cooling treatments

4. Conclusion and Future Work

This study developed an optimized heat treatment cooling strategy for TC21 titanium alloy by introducing a hybrid "air-cooling + water-cooling" approach. The findings demonstrate that this method effectively mitigates the microstructural inhomogeneity and mechanical property deficiencies commonly observed in large-scale forged components. Compared to conventional cooling techniques, the hybrid strategy balances the cooling rate, reducing the temperature gradient between the surface and core regions. As a result, it promotes the formation of a fine and uniform basketweave microstructure, ensuring a more homogeneous α-phase distribution within the β matrix.

Furthermore, the proposed cooling process significantly enhances the mechanical properties of TC21 alloy[2][5]. It improves tensile and yield strength while maintaining sufficient ductility and toughness, making it suitable for high-performance applications such as aerospace structural components. The approach effectively suppresses undesirable phase transformations, such as excessive martensitic α' phase formation and residual β-phase segregation, which are common in traditional water- or air-cooling methods. By achieving a well-balanced microstructure and property distribution, this optimized heat treatment process provides a reliable and scalable solution for improving the performance of TC21 titanium alloy[6].

Beyond its scientific contributions, this research offers valuable industrial insights, providing a feasible and practical cooling strategy for manufacturing large-scale titanium alloy components. The hybrid cooling approach not only enhances material performance but also ensures consistency and repeatability in heat treatment processes. These findings contribute to the advancement of titanium alloy processing technology, paving the way for further applications in aerospace and other demanding engineering fields.

While this study has demonstrated the effectiveness of the hybrid cooling method, several areas require further investigation to refine the process and extend its applicability:

1. In-depth Phase Transformation Analysis: Future studies should employ advanced characterization techniques, such as in-situ high-temperature X-ray diffraction (XRD) and electron backscatter diffraction (EBSD), to further understand the phase transformation mechanisms during cooling[4][7].
2. Optimization of Cooling Parameters: Additional studies should explore the influence of cooling rate variations, airflow intensity, and water immersion time to further fine-tune the hybrid cooling process for different component sizes and geometries[8].
3. Long-term Performance Evaluation: Further research should assess the long-term stability of the optimized microstructure under cyclic loading, thermal exposure, and environmental conditions to ensure the method's reliability in real-world applications[9].
4. Scaling Up for Industrial Applications: Pilot-scale production trials should be conducted to verify the feasibility of implementing the hybrid cooling method in industrial heat treatment processes, considering factors such as cost, energy efficiency, and processing time.
5. Exploration of Alternative Cooling Mediums: Investigating the use of other cooling mediums, such as polymer-based quenching solutions or controlled gas cooling, could further improve the flexibility and efficiency of the heat treatment process[10].

By addressing these aspects, future research can further refine the proposed cooling strategy, enabling broader industrial adoption and enhancing the overall performance of TC21 titanium alloy in aerospace and other high-performance applications.

References

[1] Long W, Zhang S, Liang Y, et al. Influence of multi-stage heat treatment on the microstructure and mechanical properties of TC21 titanium alloy[J]. International Journal of Minerals, Metallurgy and Materials, 2021, 28: 296-304.

[2] Chu S, Huang W, Liang G, et al. Research Trends in Isothermal Near-Net-Shape Forming Process of High-Performance Titanium Alloys[J]. Materials, 2025, 18(3): 578.

[3] Nemani A V, Ghaffari M, Bokati K S, et al. Advancements in additive manufacturing for copper-based alloys and composites: a comprehensive review[J]. Journal of Manufacturing and Materials Processing, 2024, 8(2): 54.

[4] Deng R, Xue S, Xu M, et al. Dynamic recrystallization behavior of TC21 titanium alloy[J]. Journal of Materials Research, 2025: 1-14.

[5] Li X, Huang C, Yang J, et al. Optimization of quasi-β forging parameters to control trimodal microstructure parameters and performance of TC21 forgings[J]. Materials Science and Engineering: A, 2024, 909: 146824.

[6] Zhang Y, Mao X, Wang L, et al. Effect of heat treatment on microstructure and mechanical properties of TiBw/TC18 composites[J]. Ceramics International, 2024, 50(11): 20224-20234.

[7] Shi Z, Guo H, Zhang J, et al. Microstructure− fracture toughness relationships and toughening mechanism of TC21 titanium alloy with lamellar microstructure[J]. Transactions of Nonferrous Metals Society of China, 2018, 28(12): 2440-2448.

[8] Ke W, Wu M, Zhao R E N, et al. Static globularization and grain morphology evolution of α and β phases during annealing of hot-rolled TC21 titanium alloy[J]. Transactions of Nonferrous Metals Society of China, 2021, 31(9): 2664-2676.

[9] Tao C, Ouyang D, Cui X, et al. Experimental study and numerical simulation of α lamellar globularization for TC21 titanium alloy during multidirectional forging[J]. Materials Research Express, 2022, 9(8): 086509.

[10] Dong H B, Wang G C. Superplasticity and microstructure of TC21 titanium alloy during thermomechanical treatment[J]. Materials Science and Technology, 2013, 29(8): 943-946.