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Effects of Solution and Aging Treatment on Tensile Properties and Microstructure of Ti6554 Titanium Alloy

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Abstract

The influence of solution and aging treatment on the microstructure and properties of Ti6554 titanium alloy was systematically investigated. It was demonstrated that solution treatment at 840°C resulted in an initial increase followed by a decrease in mechanical properties with extended holding time. The optimal comprehensive performance was achieved with a 2-hour holding period followed by aging at 525°C for 4 hours, where the ultimate tensile strength, yield strength, and elongation were measured as 1368.58 MPa, 1240.46 MPa, and 10.05%, respectively. When the solution temperature was elevated to 870°C, non-monotonic variations in properties were observed, with both short (0.5h) and long (4h) holding times found to produce favorable strength-ductility combinations. Fractographic analysis revealed that a mixed fracture mode consisting of dimples and cleavage planes was exhibited by all specimens. Microstructural evolution analysis indicated that property variations were primarily governed by the dissolution and coarsening of primary α phase, changes in β grain size, and the precipitation density and distribution of secondary α phase, which collectively determined the final strength-ductility balance of the alloy.

Keywords

Ti6554 titanium alloy; Solution and aging heat treatment; Yield strength; Ultimate tensile strength.

1. Introduction

Ti6554 (Ti-6Cr-5Mo-5V-4Al) titanium alloy is classified as a high-strength-toughness metastable nearβ titanium alloy, which is characterized by its remarkable high specific strength, lightweight properties, and non-magnetic characteristics, and is widely utilized in structural components requiring high mechanical performance[1-3]. Through the application of solution plus aging heat treatment to titanium alloys, strength and ductility can be synergistically optimized. During solution treatment, the metastable β phase structure is retained through rapid cooling from the high-temperature β phase field, thereby preventing α phase precipitation, while the β phase stability and β grain size are determined by this process. During subsequent aging treatment, the decomposition of the metastable β phase governs the morphology and distribution characteristics of α precipitates, during which β→α dispersed precipitation is induced, resulting in the formation of nanoscale α strengthening phases[4-6]. The strength of the alloy is directly influenced by the volume fraction, size, and distribution of the α phase[7-8], whereas the continuity and deformability of the β phase primarily govern the ductility[9]. The coordinated deformation behavior between α and β phases depends on the morphology and volume fraction of the constituents, as well as the distribution and size of the primary and secondary phases[10-12]. Therefore, precise control of heat treatment parameters is essential to achieve an optimal α/β configuration and obtain superior comprehensive mechanical properties.

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According to related studies, the mechanical properties of β-titanium alloys have been demonstrated to be highly sensitive to their microstructural characteristics and phase stability[13]. High-strength β-titanium alloys are typically employed in a solution-treated and subsequently aged condition, where precipitation strengthening is achieved through fine acicular precipitates, which generally enables yield strength levels of approximately 1250–1500 MPa to be obtained[14]; however, a significant reduction in ductility is often observed[15]. In addition to microstructural characteristics, the mechanical properties of β-titanium alloys are also governed by their phase stability, which is in turn determined by the content of stabilizing elements such as Mo, Fe, and V[16]. It was discovered by Zhang et al.[17]that metastable β-titanium alloys exhibit extremely high ductility in the β single-phase region, whereas high strength but significantly reduced ductility are displayed in the α+β two-phase region, which reveals the mechanism for optimizing the strength-ductility balance of such alloys through heat treatment regulation and microstructural control. A metastable β-titanium alloy Ti-5Al-5Mo-5V-3Cr was fabricated by Hendl et al.[18]who demonstrated that high strength up to 1360 MPa and low elongation are achieved by solution treatment plus aging (STA) due to the formation of fine acicular αs precipitates.

The present work systematically investigated the solution treatment (840℃ and 870℃, 0.5-4h) and aging treatment (555℃, 4h) of Ti6554 titanium alloy. To explore the effects of solution temperature, holding time, aging temperature, and aging duration on phase transformations, multi-scale characterization techniques including SEM and metallographic diagrams were employed. The influences of solution-aging parameters on microstructural evolution were quantitatively analyzed, and the potential correlations between microstructural refinement/coarsening and mechanical properties were elucidated, thereby providing theoretical foundation and data support for performance optimization and process design of Ti6554 titanium alloy in fastener applications.

2. Experimental Procedures

The chemical composition of Ti6554 titanium alloy is listed in Table 1. A bar with diameter of 40 mm and length of 300 mm was subjected to hot groove rolling, through which the diameter was reduced to 22 mm, followed by heat treatment preparation in a muffle furnace. The β transus temperature of this Ti6554 titanium alloy was determined to be approximately 830℃. The specimens were strengthened under different heat treatment processes shown in Table 2. The tensile test was conducted at a speed of 1 mm/min until yielding and fracture of the specimen occurred. The microstructures and fracture characteristics were characterized by optical microscopy and scanning electron microscopy.

Tab.1 Chemical composition of Ti6554 titanium alloy wt.%

element	C	Cr	V	Mo	Al	Ti
Content/%	0.027	6.12	4.96	4.9	4.28	Bal.

Tab.2 Solution and aging heat treatment scheme for Ti6554 titanium alloy

No.	Solution treatment	Aging treatment
1	840℃-0.5h，AC	520℃-4h，AC
2	840℃-1h，AC	
3	840℃-2h，AC	
4	840℃-4h，AC	
5	870℃-0.5h，AC	520℃-4h，AC
6	870℃-1h，AC	
7	870℃-2h，AC	
8	870℃-4h，AC	

3. Experimental Results

3.1. Analysis of Mechanical Properties

The engineering stress-strain curves and corresponding mechanical properties (including yield strength, ultimate tensile strength, and elongation after fracture) of Ti6554 titanium alloy under various heat treatment conditions involving different solution temperatures and holding times were systematically characterized, and their performance differences were comprehensively compared and analyzed.

The property variations of Ti6554 titanium alloy after solution treatment at 840°C followed by aging at 525°C for 4 hours are presented in Figure 1, which includes key mechanical performance indicators such as yield strength, ultimate tensile strength, and elongation after fracture. As shown in Figure 1a, after the solution and aging heat treatment, both the strength and elongation after fracture of Ti6554 titanium alloy were observed to gradually increase with the extension of holding time. From the stress-strain curves, it can be seen that the difference between the maximum and minimum strengths remained relatively small despite variations in holding time. According to Figure 1b, with the extension of solution treatment holding time from 0.5 hours to 2 hours, both the yield strength and ultimate tensile strength of the alloy exhibited a gradual increasing trend, where the ultimate tensile strength increased from 1317.27 MPa to 1368.58 MPa and the yield strength increased from 1177.35 MPa to 1240.46 MPa. This stage of strength enhancement was primarily attributed to the sufficient dissolution of alloying elements during the solution process, which enabled the precipitation of high-density and fine secondary α phase during the subsequent aging treatment. These precipitated phases effectively hindered dislocation motion, generating a significant precipitation strengthening effect and thereby enhancing the material's strength. However, when the solution holding time was further extended to 4 hours, a significant decrease in alloy strength was observed, with the ultimate tensile strength and yield strength declining to 1259.69 MPa and 1119.17 MPa, respectively. This phenomenon was mainly attributed to the coarsening or partial dissolution of the primary α phase along with significant growth of β grains. The grain coarsening resulted in reduced total grain boundary area, which weakened the grain boundary strengthening effect and became the primary cause for the strength reduction. In terms of ductility, the elongation after fracture exhibited no significant fluctuations with varying holding times, reaching its maximum value of 10.05% at 2 hours of holding, and even when the holding time was extended to 4 hours, the elongation remained at 9.54% with only a minor decrease. Furthermore, no notable changes in elastic modulus were detected, indicating that while achieving strength regulation, this heat treatment process did not negatively impact the material's ductility and rigidity, demonstrating excellent comprehensive performance control capability. In conclusion, under the condition of 840°C×2 h solution treatment followed by 525°C×4 h aging treatment, the room temperature mechanical properties of Ti6554 titanium alloy reached their optimal state, with yield strength and ultimate tensile strength of 1240.46 MPa and 1368.58 MPa respectively, combined with an elongation after fracture of 10.05%, achieving the optimal balance between high strength and good ductility. Thus, these heat treatment parameters can be considered as an optimal processing scheme for Ti6554 titanium alloy.

The property variations of Ti6554 titanium alloy after solution treatment at 870°C (with holding times of 0.5, 1, 2, and 4 hours respectively) followed by aging at 525°C for 4 hours are presented in Figure 1c, where the room temperature mechanical properties exhibited obvious non-monotonic characteristics. From the stress-strain curves, it can be seen that the difference between the maximum and minimum strengths was relatively large due to variations in holding time. As shown in Figure 1d, with the extension of solution holding time from 0.5 hours to 2 hours, a continuous decrease in alloy strength was observed, where the ultimate tensile strength declined from 1347.36 MPa to 1221.29 MPa and the yield strength decreased from 1147.16 MPa to 1026.25 MPa. This stage of strength reduction was mainly attributed to the easier dissolution of primary α phase at the higher solution temperature (870°C), where its volume fraction further decreased with prolonged holding time, while simultaneous coarsening of β grains resulted in reduced total grain boundary area, thereby weakening the grain boundary strengthening effect. Additionally, excessive dissolution of α phase led to increased content of β-stabilizing elements, which reduced the stability of β phase and consequently affected the precipitation driving force, nucleation density, and size distribution of secondary α phase during subsequent aging treatment, ultimately weakening the precipitation strengthening effect. When the holding time was further extended to 4 hours, a recovery in strength was observed, with the ultimate tensile strength and yield strength reaching 1322.25 MPa and 1202.58 MPa, respectively.

3.2. Analysis of Tensile Fractures

Figure 2 presents the SEM images of tensile fractures of Ti6554 titanium alloy obtained through solution treatment at 840°C with holding times of 0.5 h, 1 h, 2 h, and 4 h followed by aging at 525°C for 4 h. Analysis reveals that as the solution holding time is extended from 0.5 h to 4 h (solution temperature 840°C, aging 525°C×4h), the tensile fractures of Ti6554 titanium alloy consistently exhibit mixed fracture characteristics

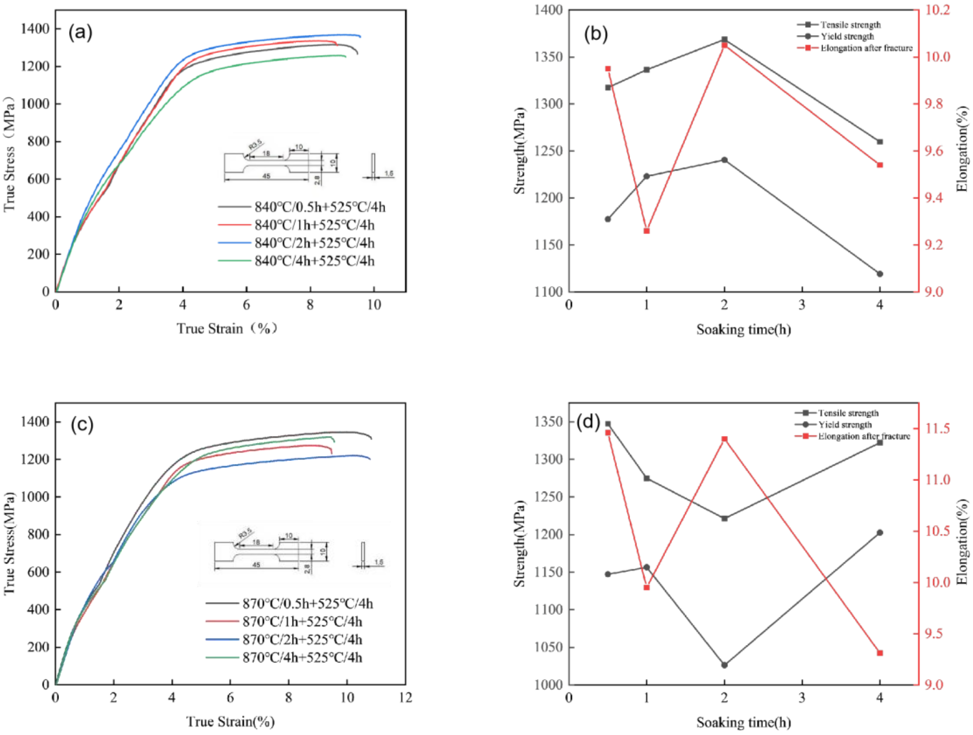


Figure 1. Effect of Solution and Aging Heat Treatment on the Stress-Strain Curves of Ti6554 Titanium Alloy

comprising both cleavage planes and fine uniform dimples, indicating that the material simultaneously experiences both brittle and plastic deformation mechanisms during fracture. As shown in Figure 2a, the fracture surface of the specimen with 0.5 h holding time is distributed with relatively small and numerous cleavage planes, suggesting that localized brittle fracture regions are densely concentrated in the material at this stage. The dimples were predominantly elliptical in morphology and relatively densely distributed, demonstrating certain plastic deformation capability. In Figure 2b, the specimen with 1 h holding time is observed to contain noticeably enlarged cleavage planes, though their quantity is reduced compared to the 0.5 h specimen. Meanwhile, the dimple morphology gradually transitions from elliptical to equiaxed, indicating improved material plasticity during fracture and the occurrence of uniform plastic deformation in localized regions. Figure 2c shows that the fracture surface of the specimen with 2-hour holding time is characterized by dimples of varying sizes distributed in river patterns, with the number of cleavage planes being significantly reduced, demonstrating a more pronounced tendency toward ductile fracture; the size variation of dimples reflects the inhomogeneity of microscopic plastic deformation. Figure 2d reveals that the specimen with 4-hour holding time exhibits a structure where small cleavage planes coexist with fine equiaxed dimples, wherein the dimple sizes are more uniform, indicating further improved material plasticity under this processing condition, and the overall fracture behavior remains mixed but with more prominent ductile characteristics. It can thus be concluded that under the 840°C solution temperature condition, the solution holding time exerts significant influence on the tensile fracture morphology of Ti6554 titanium alloy, where the overall fracture mechanism is ductility-dominated with certain brittle characteristics, belonging to a typical mixed fracture mode.

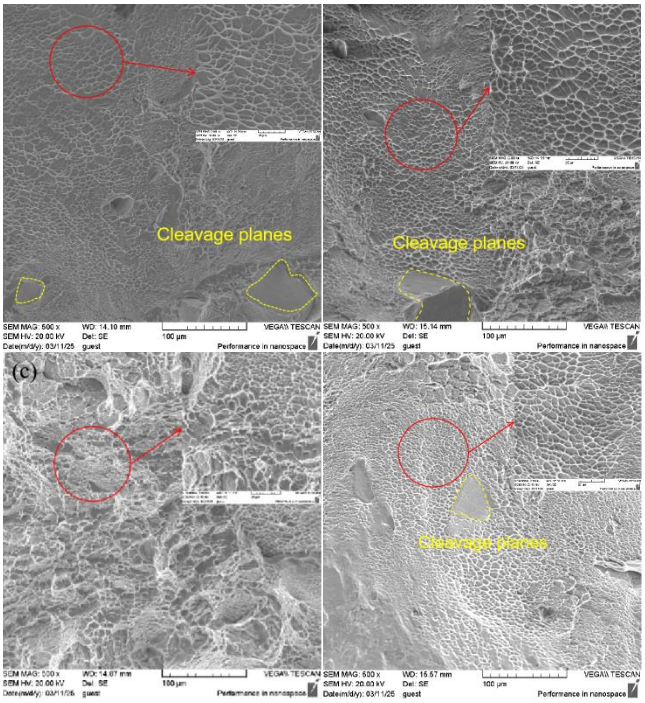


Figure 2. SEM fractographs of the tensile fracture surfaces of Ti6554 titanium alloy at room temperature: (a) 840°C/0.5 h + 525°C/4 h; (b) 840°C/1 h + 525°C/4 h; (c) 840°C/2 h + 525°C/4 h; (d) 840°C/4 h + 525°C/4 h.

Figure 3 presents the tensile fracture morphologies of Ti6554 titanium alloy after solution treatment at 870°C with holding times of 0.5 h, 1 h, 2 h, and 4 h respectively, followed by aging treatment at 525°C for 4 h. Comprehensive analysis indicates that as the solution holding time is extended from 0.5 h to 4 h, all specimens exhibit mixed fracture characteristics comprising uniform dimples coexisting with microcracks, reflecting a composite fracture mechanism dominated by overall ductile fracture accompanied by localized brittle cracking. As shown in Figure 3a, the fracture surface of the specimen with 0.5 h holding time reveals numerous fine and uniformly shaped equiaxed dimples, where the distribution of dimples exhibited inhomogeneity with localized aggregation of fine dimples in certain regions, and no significant microcracks were observed in the fracture at this stage, indicating relatively good plastic deformation capability of the material. Figure 3b displays the fracture surface of the specimen with 1 h holding time, where noticeably enlarged equiaxed dimples with non-uniform size distribution are present, showing localized aggregations of both large dimples and small dimples in different regions; simultaneously, tear ridges are observed in the fracture, demonstrating the occurrence of localized tearing during plastic deformation. In the specimen with 2-hour holding time shown in Figure 3c, the dimple size was observed to become more uniform without significant aggregation characteristics, indicating more homogeneous plastic deformation; additionally, microcracks were initiated on the fracture surface, suggesting that the brittle tendency in localized regions increased with prolonged holding time. Figure 3d demonstrates that the fracture surface of the 4-hour holding time specimen exhibited a coexistence morphology of uniformly distributed fine dimples and microcracks, where the dimples appeared fine with consistent distribution while microcracks were clearly visible, further confirming the simultaneous operation of both ductile and brittle mechanisms during material fracture under this processing condition. It can thus be concluded that at the 870°C solution temperature, variations in holding time significantly influenced the microscopic fracture morphology of Ti6554 titanium alloy, with the overall behavior characterized by a mixed fracture mode predominantly governed by ductile mechanisms accompanied by certain brittle features.

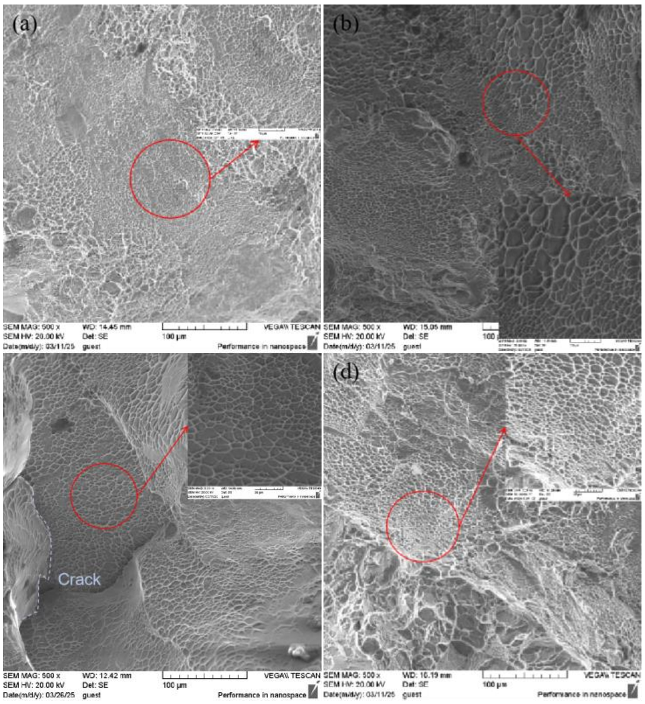
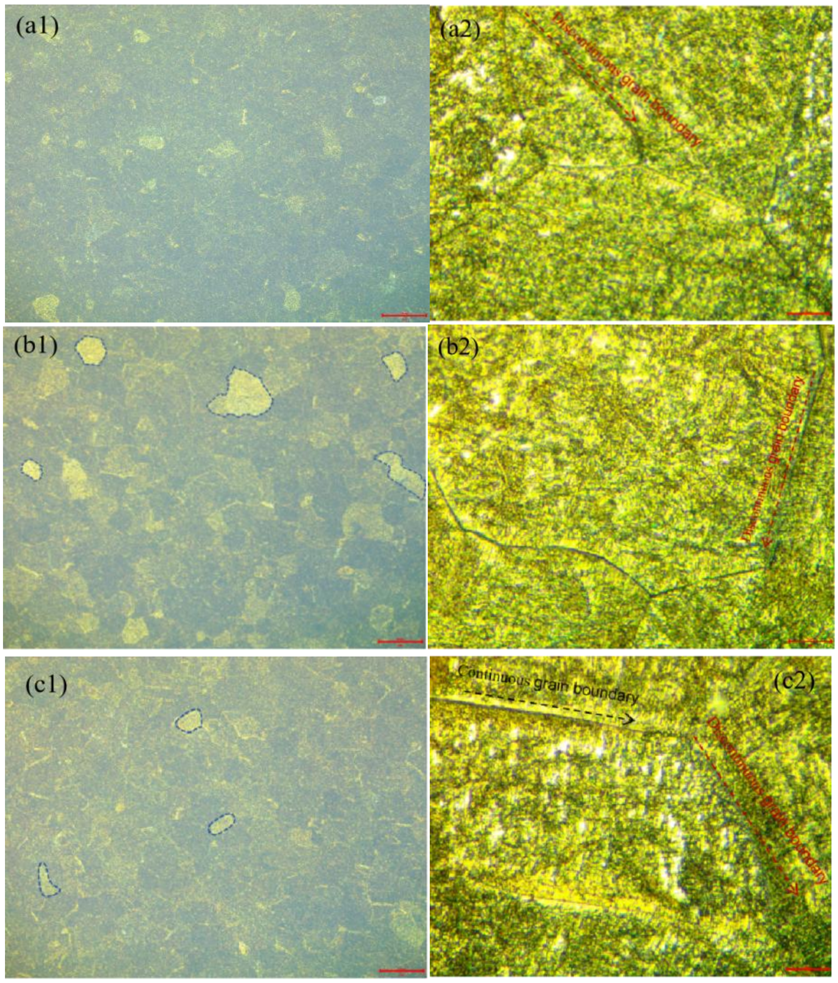


Figure 3. SEM fractographs of the tensile fracture surfaces of Ti6554 titanium alloy at room temperature: (a) 870°C/0.5 h + 525°C/4 h; (b) 870°C/1 h + 525°C/4 h; (c) 870°C/2 h + 525°C/4 h; (d) 870°C/4 h + 525°C/4 h.

3.3. Analysis of Microstructural

Figure 4 presents the microstructural images of Ti6554 titanium alloy after solution treatment at 840°C with holding times of 0.5 h, 1 h, 2 h, and 4 h followed by aging treatment at 525°C for 4 h. From Figure 4(a1), it can be seen that after being held for 0.5 hours, the titanium alloy was observed to contain a relatively low content of α phase with small dimensions and relatively uniform distribution at the macroscopic level, where the microstructure was dominated by β phase and primary α phase was present at grain boundaries. According to the microstructural image in Figure 4(a2), the α phase was mainly composed of secondary α phase, with primary α phase distributed along grain boundaries, and the grain boundaries between α and β phases exhibited discontinuous characteristics. From Figure 4(b1), it is evident that after being held for 1 hour, the content of α phase in the titanium alloy was significantly increased with relatively coarse grain size at the macroscopic level, while the β phase was gradually decreasing and transforming into α phase. The microstructural image in Figure 4(b2) shows that the grain boundaries between α and β phases exhibited two morphological types: discontinuous grain boundaries and continuous grain boundaries. According to Figure 4(c1), after being held for 2 hours, the β phase in the titanium alloy was further transformed into α phase with a trend toward uniform distribution at the macroscopic level, where partial aggregation of β phase was observed, and the α phase exhibited coarse grains including large primary α phase grains. The microstructural image in Figure 4(c2) reveals that the grain boundaries between α and β phases coexisted in both discontinuous and continuous states, with primary α phase being uniformly distributed within the grain interior. From Figure 4(d1), it can be seen that after being held for 4 hours, coarser α grains containing notably large primary α grains were present in the titanium alloy microstructure at the macroscopic level, where the α phase became the dominant structural morphology while the β phase existed as relatively large isolated grains. The corresponding microstructural image in Figure 4(d2) demonstrates that the grain boundaries had completely transformed into a continuous boundary structure.

Figure 5 shows the microstructural images of Ti6554 titanium alloy after solution treatment at 870℃ with holding times of 0.5 h, 1 h, 2 h, and 4 h followed by aging treatment at 525℃ for 4 h. As shown in Figure 5(a1), after being held for 0.5 hours, the alloy was characterized by a relatively low content of β phase, which was distributed in localized aggregations, while the α phase was composed of a mixture of primary and



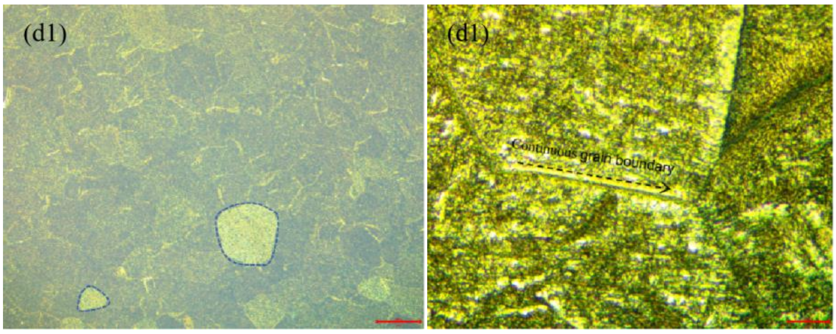
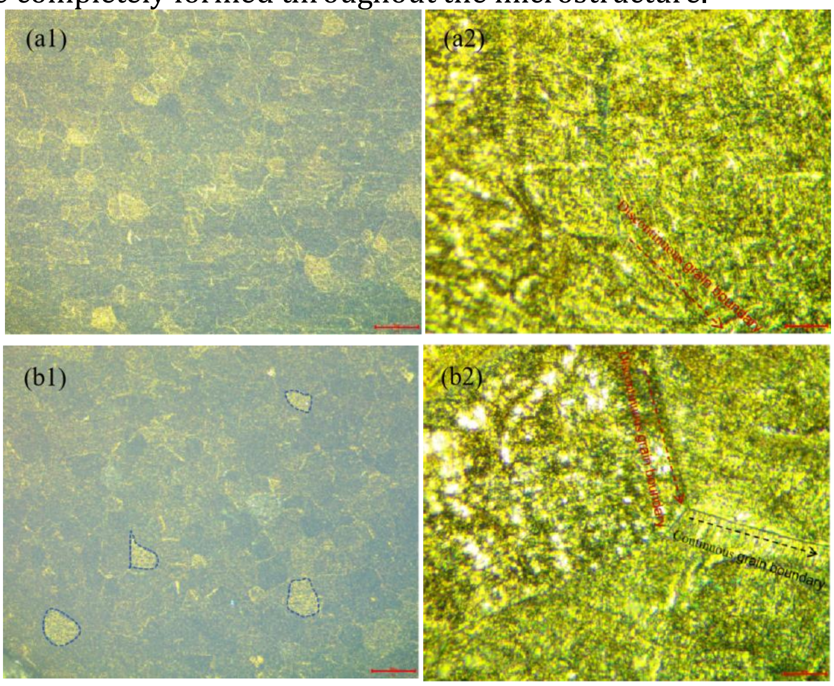


Figure 4. Metallographs of the microstructure of Ti6554 titanium alloy under different solution holding times followed by aging treatment: (a) 840°C/0.5 h + 525°C/4 h; (b) 840°C/1 h + 525°C/4 h; (c) 840°C/2 h + 525°C/4 h; (d) 840°C/4 h + 525°C/4 h.

secondary α phases coexisting within the microstructure. The microstructural image in Figure 5(a2) indicates that the grain boundaries were discontinuous with relatively blurred contours and low interfacial clarity. From Figure 5(b1), it can be observed that after being held for 1 hour, the contents of α phase and β phase in the titanium alloy became approximately equivalent, with both phases exhibiting relatively uniform grain sizes and no significant coarsening phenomenon. Figure 5(b2) micrograph reveals that the phase boundaries between α and β phases simultaneously exhibited both continuous and discontinuous morphologies, while the grain boundary structure began to show increased distinctness. According to Figure 5(c1), the titanium alloy microstructure after 2-hour holding was predominantly composed of relatively coarse α and β phases, both demonstrating clustered distribution characteristics. The microstructural image in Figure 5(c2) indicates that continuous grain boundaries were primarily established as the main grain boundary type. At this stage, significant grain growth was observed along with remarkable changes in phase distribution morphology. From Figure 5(d1), it is demonstrated that the titanium alloy after 4-hour holding primarily existed in a two-α-phase condition. The microstructural image in Figure 5(d2) confirms that continuous grain boundaries were completely formed throughout the microstructure.



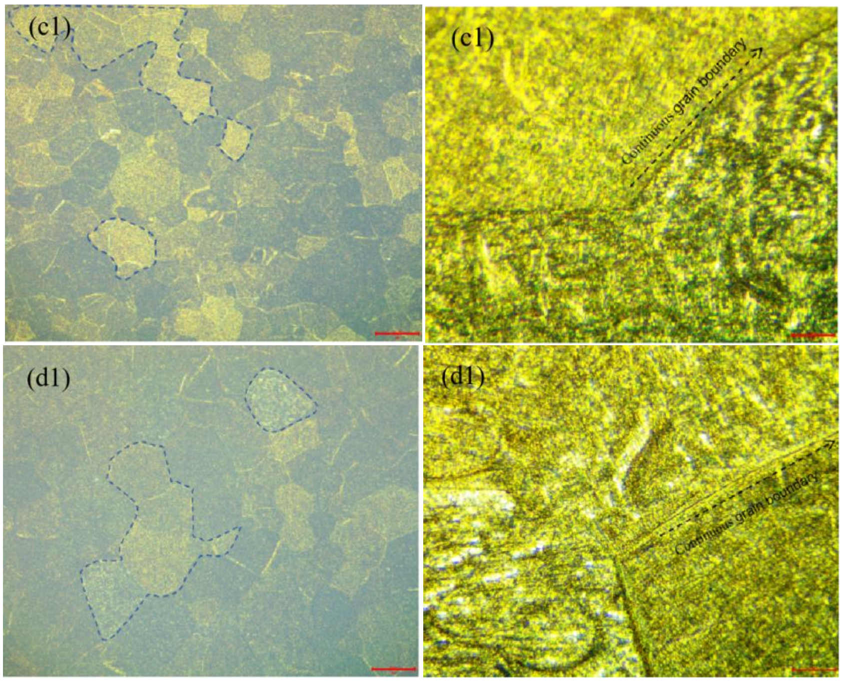


Figure 5. Metallographs of the microstructure of Ti6554 titanium alloy under different solution holding times followed by aging treatment: (a) 870℃/0.5 h + 525℃/4 h; (b) 870℃/1 h + 525℃/4 h; (c) 870℃/2 h + 525℃/4 h; (d) 870℃/4 h + 525℃/4 h.

4. Conclusion

1. The mechanical properties of Ti6554 titanium alloy were found to be strongly dependent on the solution and aging treatment parameters. When solution treatment was conducted at 840℃, a peak-type variation in properties with holding time was observed, with the optimal condition achieved at 2 hours; whereas at 870℃, non-monotonic variations were demonstrated, where favorable strength-ductility combinations were obtained through both short and long holding times.

2. All tensile fractures under different processing conditions were characterized by mixed fracture features with cleavage planes coexisting with dimples. Significant alterations in dimple size, morphology, and distribution were induced by varying process parameters, indicating that while the fracture behavior was predominantly ductile, the local brittle-ductile tendencies were effectively regulated by heat treatment procedures.

3. The evolution of alloy properties was fundamentally governed by microstructural transformations. The dissolution and coarsening of primary α phase, the growth of β grains, along with the precipitation density and distribution of secondary α phase during aging, were identified as key factors collectively influencing both grain boundary strengthening and precipitation strengthening effects, which ultimately determined the final strength-ductility combination of the material.

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