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Effect of Heat Treatment on Weld Microstructure and Mechanical Properties of TA1 Titanium Tube

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Abstract

This study investigates the effects of heat treatment processes on the microstructure and mechanical properties of high-frequency induction welded TA1 titanium tubes obtained through drawing, aiming to determine the optimal heat treatment parameters. Additionally, molecular dynamics simulations were employed to study the flattening performance of the material under different heat treatment conditions. The results show that at an annealing temperature of 873 K, the sample undergoes a low degree of recrystallization. As the annealing temperature increases, the boundaries of recrystallized grains become progressively clearer, and the grains grow larger. At 973 K, the grains are nearly equiaxed, while at 1073 K, complete recrystallization occurs with the nucleation and growth of new grains. The 873 K annealing condition achieves the best balance of strength, plasticity, and overall performance, making it the optimal choice for improving the compressive properties of titanium materials. High-temperature annealing should be avoided to reduce the risks of grain coarsening and performance degradation caused by microstructural inhomogeneity.

Keywords

TA1 Titanium Tube; Heat Treatment; Molecular Dynamics Simulation; Compression.

1. Introduction

Titanium and titanium alloys are lightweight structural materials with excellent properties, including high specific strength, good biocompatibility, exceptional corrosion resistance, non-toxicity, non-magnetic properties, high fatigue strength, and a narrow deformation temperature range. Their applications in the military field reflect the modernization of national weaponry and can fully demonstrate military strength and technological advancements [1]. Additionally, titanium and titanium alloys modified through surface treatments show promising applications in the biomedical field. For instance, Landor et al. [2] and Kawanabe et al. [3] applied HA (hydroxyapatite) coatings to titanium alloy hip joints and found that the coatings facilitated good bonding between prostheses and surrounding bone tissues, promoting bone recovery. Zhang [4] and Akmal [5] discovered that the bioactivity, hardness, and thermal conductivity of NiTi alloys are affected to varying degrees by HA coatings.

Titanium alloys exhibit distinct allotropic transformation characteristics, and their microstructure and mechanical properties are significantly influenced by plastic deformation processes, chemical composition, and heat treatment techniques [6]. To date, researchers worldwide have conducted extensive studies on forming processes and performance regulation of titanium alloy products. Arab et al. [7] investigated the relationship between microstructure and mechanical properties, demonstrating that water-quenched samples with martensitic structures exhibit high hardness and good plastic deformation capacity. Unlike steel, which achieves austenite grain refinement through

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recrystallization and allotropic transformations, titanium alloys require grain refinement through plastic deformation [8], [9] [10]. However, challenges such as grain refinement and high-temperature deformation difficulties remain. Therefore, studying the effects of macroscopic plastic deformation and heat treatment on the microstructure and properties of titanium alloy products holds significant importance.

In this paper, TA1 titanium tubes obtained through drawing and samples subjected to different heat treatment conditions were analyzed to compare their metallographic microstructures and mechanical properties. The study reveals the effects of various heat treatment processes on the microstructure and mechanical properties of TA1 titanium tubes. The findings aim to provide a theoretical foundation for optimizing heat treatment parameters for industrially pure TA1 titanium tubes and rods after drawing.

2. Experiment

2.1 Experimental Details

This experiment involved four types of materials, as shown in Table 1. The first material was a drawn TA1 titanium tube with a thickness of approximately 0.4 mm, an outer diameter of 7.26 mm, and an inner diameter of 6.46 mm (chemical composition is listed in Table 2). The second material was an annealed TA1 titanium tube (where "×2 min" in the table indicates a holding time of 2 minutes). The high-frequency welding parameters were as follows: the opening angle and current frequency were maintained at 6° and 400 kHz, respectively, with a welding speed of 50 m/min, welding power of 14.0 kW, and an extrusion amount of 0.17 mm.

For sample preparation, a polishing powder of 0.05 μm alumina was used, and the etchant was Kroll's reagent (3 ml HF + 6 ml HNO_3 + 91 ml H_2O). During the flattening test, the sample was placed between two parallel plates and compressed uniformly to the specified flattening distance using a press or other methods. The sample's bending deformation area was then inspected. If no cracks, fractures, or weld seam openings were observed, the sample was considered qualified.

Table 1. TA1 Titanium tube material

Numble	Heat-treated	Cooling mode
1	Undisposed	/
2	873K×2 min	Air cooling
3	973K×2 min	Air cooling
4	1073K×2 min	Air cooling

Table 2. TA1 Titanium Tube Chemical Composition Table (wt.%)

Chemical Composition	Ti	H	C	N	O	Fe	Other Elements	
							Single	Sum
GB/T3620.1-2016	≥99.4	≤0.015	≤0.10	≤0.03	≤0.20	≤0.25	≤0.10	≤0.40

2.2 Simulation Details

In this molecular dynamics (MD) simulation, the LAMMPS software was used to construct a Ti model with dimensions of 29.5 Å × 51.0 Å × 46.8 Å, followed by MD simulation calculations. The model was first subjected to energy minimization using the conjugate gradient (CG) method. After relaxing the model for 10 ps, an NPT ensemble was applied for 30 ps to increase the temperature from room temperature to the specific annealing temperature, followed by cooling back to room temperature at the same rate. The model was further relaxed for 10 ps to achieve a stable structure,

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as shown in Figure 1.The atomic interactions were defined using the MEAM potential described by Sa I et al. [11]. Uniform pressure was then applied along the z-axis at a rate of 0.001 Å/ps until the model fractured. The crystal structure was visualized and analyzed using the Ovito software.

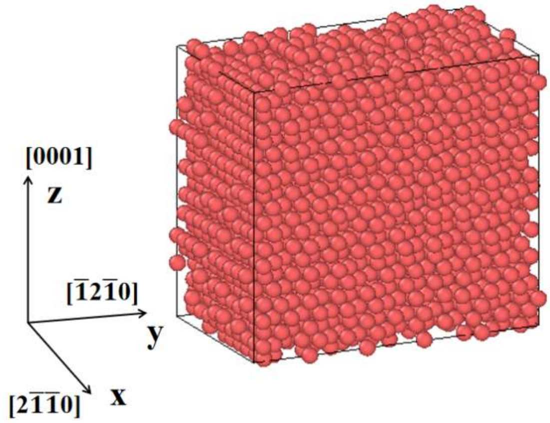

Figure 1. The Molecular Dynamics Model of Ti

3. Results and Discussion

3.1 Macroscopic Morphology Analysis

The untreated sample surface appears silver-white with a metallic luster, and the weld seam is gray, as shown in Figure 2a. After heat treatment at 873K for 2 minutes, the titanium tube surface turns blue, and the weld seam becomes silver-white (Figure 2b). The left end of the titanium tube surface is light purple, the middle section is light blue, and the right end is light green, with the weld seam appearing gray (Figure 2c). The titanium tube surface turns silver-gray, and the weld seam becomes gray-white (Figure 2d).

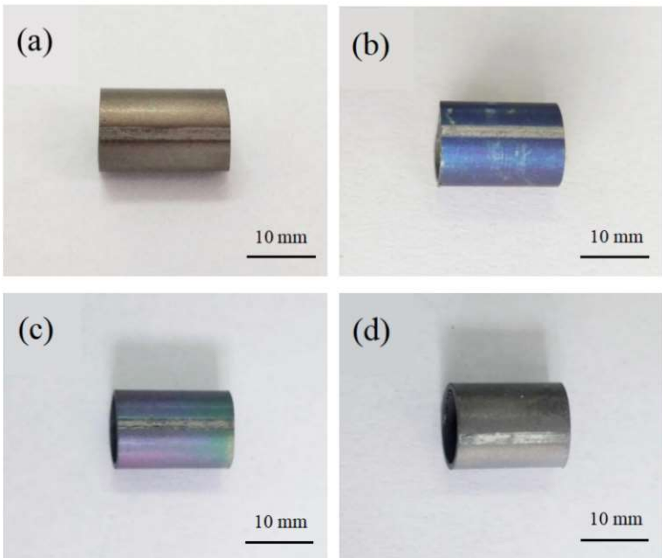

Figure 2. Macroscopic morphology of the titanium tube:
(a)Undisposed; (b)873K×2min; (b)973K×2min; (d)1073K×2min

In air, titanium tends to react with oxygen, nitrogen, and hydrogen, three non-metallic elements, and the reaction process is closely related to temperature. At room temperature, titanium is relatively stable in air. When heated, titanium reacts with oxygen in the air to form a dense oxide film. This oxide film not only protects the titanium surface but also causes a color change on the surface. Molten

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titanium reacts intensely with nitrogen at temperatures above approximately 1073K. The reaction between titanium and nitrogen forms titanium nitrides and Ti–N solid solutions. At 1323K, the maximum solubility of nitrogen in titanium is about 7%, and at 2293K, the maximum solubility decreases to 2%. Compared to the reaction speed of titanium with oxygen, the reaction with nitrogen is much slower. Hence, titanium in air primarily absorbs oxygen.It can be observed that the surface color of TA1 titanium tubes changes under different heat treatment conditions. The temperature and holding time significantly affect the surface coloration.

3.2 Metallographic Microtissue Analysis

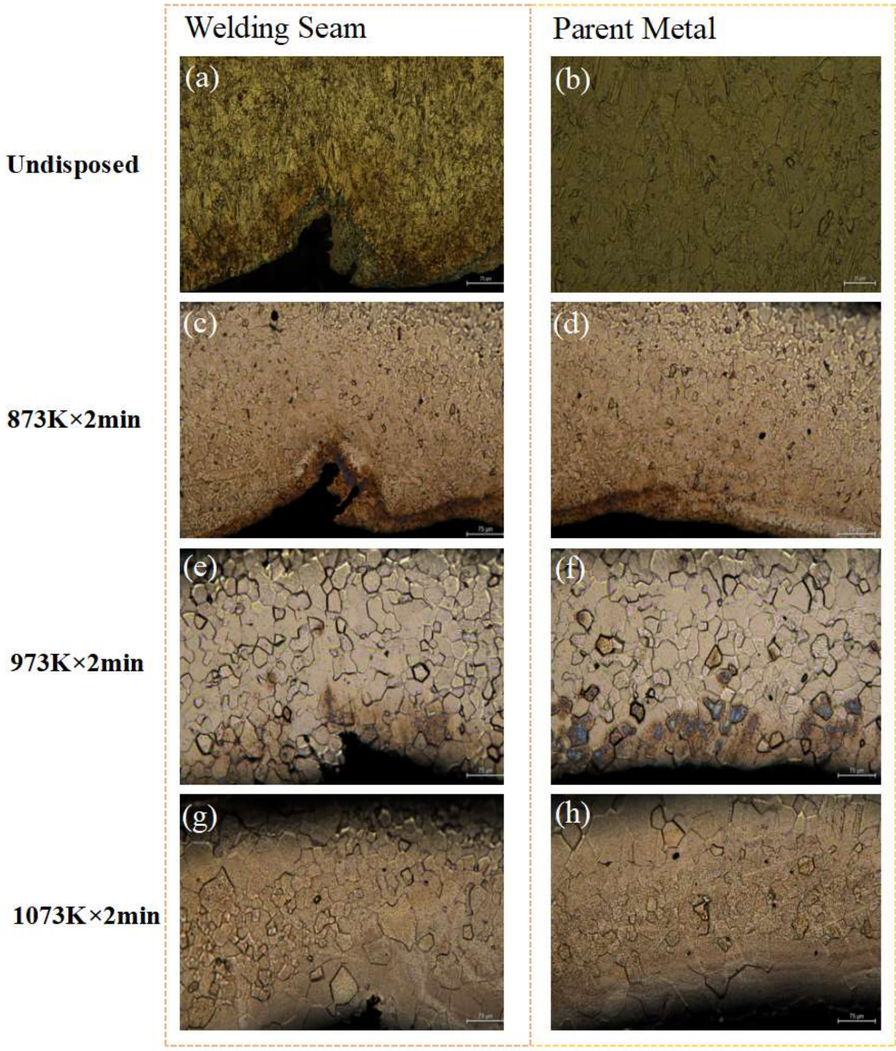

Figure 3. Metallographic Microtissue of titanium tubes

From Figure 3a, it can be observed that during welding, the molten pool was not fully filled, resulting in an inward concave defect. The concave area underwent oxidation, turning part of the structure blue. After drawing, the microstructure experienced deformation without directional preference, transforming from equiaxed and regularly shaped polygonal grains to fibrous structures. Some grains were elongated into irregular block shapes, with grain boundaries almost invisible. Under high magnification, only a few grain boundaries and polygonal grains were observed in the base metal, as shown in Figures 3a and 3b. Compared to the base metal, the weld seam exhibited more intense deformation. Figures 3c and 3d show the metallographic microstructure of titanium tubes heat-treated at 873 K for 2 minutes. The recrystallized grain boundaries are relatively clear, with fine grains and mostly curved grain boundaries. Only a few grains appear polygonal, and the microstructure is uneven. Figures 3e and 3f depict the metallographic microstructure of titanium tubes heat-treated at 973 K for

2 minutes. The recrystallized grain boundaries are clearer, and the grains are slightly larger. In the weld seam, particularly near the concave areas, the grain boundaries are curved, while other grains are polygonal. In the base metal, most grain boundaries are polygonal. The grains in the weld seam are slightly larger than those in the base metal, and the microstructure remains uneven for both the weld seam and the base metal. Figures 3g and 3h illustrate the metallographic microstructure of titanium tubes heat-treated at 1073 K for 2 minutes. The microstructure becomes even more uneven, with coarse grains observed at both ends of the sample, while smaller grains cluster in the middle. The recrystallized grain boundaries are mostly curved, forming irregularly shaped structures.

3.3 Flattening Test

The flattening test was used to evaluate the deformation performance of TA1 titanium tubes compressed to a specified size and to reveal any defects. The bending deformation areas of the samples were inspected, and as shown in Figure 4, cracks appeared in the weld seam of the sample heat-treated at 1073K for 2 minutes, rendering it unqualified, while all other samples passed the test. The flattening test results are presented in Table 3. The untreated sample exhibited the highest compressive strength due to its fibrous grain structure, which enhanced the material's axial load-bearing capacity. However, the fibrous structure in the weld seam region showed uneven microstructure, posing potential failure risks. After annealing at 873K, the microstructure was optimized, particularly in the base metal region, which became more uniform. However, the weld seam region retained some microstructural unevenness, leading to a slight reduction in compressive strength compared to the untreated sample [12].

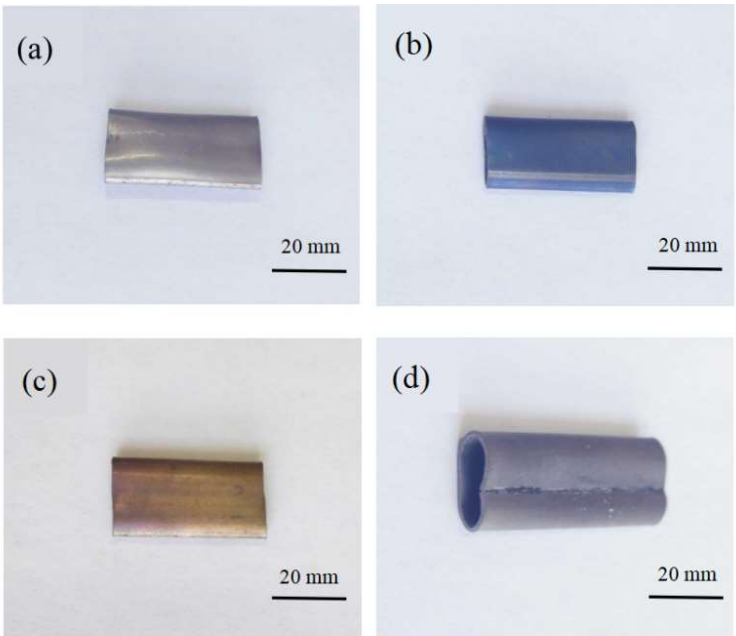

Figure 4. The results of the flattening test

Table 3. Sample flattening test results

Sample	Maximum Load /N	Compressive Strength /MPa	Maximum Compression /mm
Undisposed	1061.581	123.146	6.541
873K×2 min	974.013	112.988	6.592
973K×2 min	913.094	105.921	6.687
1073K×2 min	739.611	85.797	6.626

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At the same time, the maximum compression displacement increased slightly, indicating improved material ductility. Under the 973K annealing condition, microstructural uniformity further improved, and grain size increased slightly. Although the load and compressive strength showed a slight decline, the maximum compression displacement increased further. This condition exhibited a good balance of mechanical properties overall, with the weld seam region still acceptable, though not as uniform as the base metal. Annealing at 973K caused significant grain growth, particularly in the weld seam region, where microstructural unevenness was most severe. This structure directly led to a significant decrease in compressive strength, making the weld seam a potential stress concentration point and rendering the sample unqualified for compression performance [13]. Although ductility increased slightly, the substantial reduction in strength and the presence of weld seam cracks further diminished the load-bearing capacity of the material.

3.4 MD

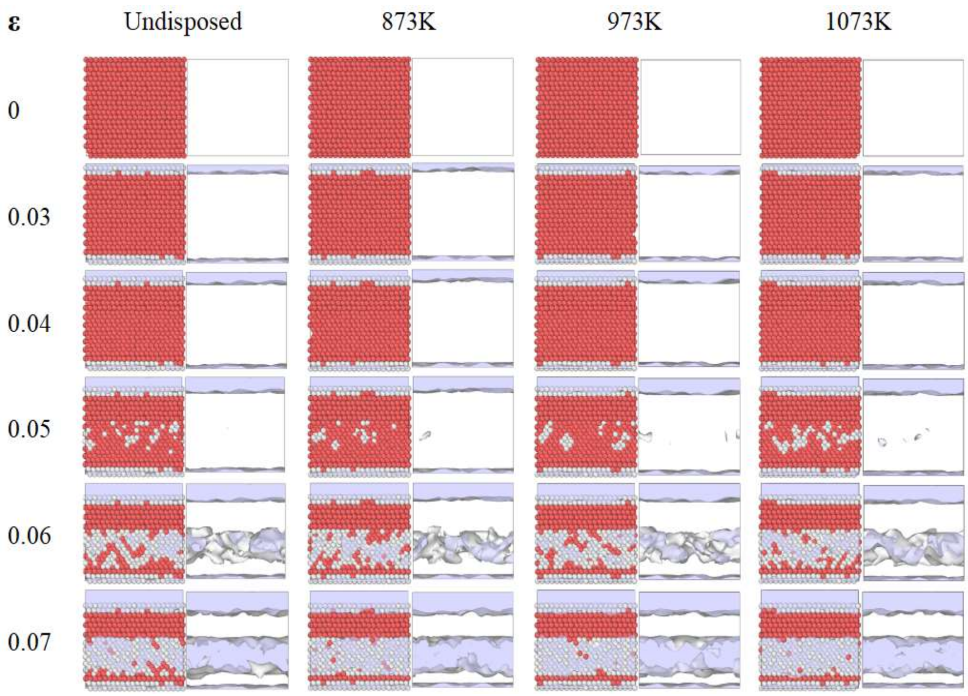

Figure 5. Squlate the simulation process

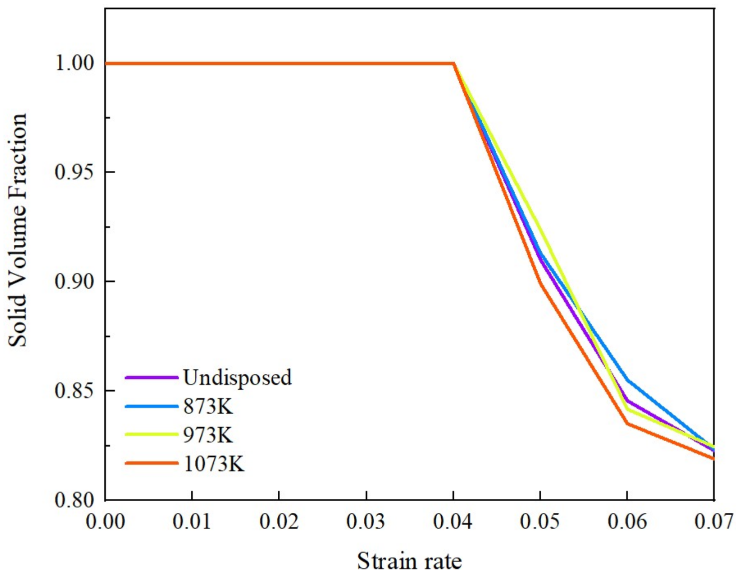

Figure 6. Model solid volume fraction during flattening

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Figure 5 illustrates the flattening process of the four models. The untreated sample exhibits strong crystalline integrity, with slower void expansion during higher strain rates (0.06–0.07) and a relatively high solid volume fraction overall. The untreated sample's dense structure, with elongated grains but no significant recrystallization, provides strong resistance to void formation under compressive strain.After annealing at 873 K, fewer voids appear in the model during the low strain stage (<0.05). At higher strain rates (>0.05), voids gradually connect to form cracks, but the voids remain relatively small in number and size. This is due to partial recrystallization of the titanium material, which optimizes the grain structure and strengthens the grain boundaries, suppressing void formation to a certain extent.In the 973 K annealed model, void formation occurs more rapidly than in the 873 K model during the low strain stage. At higher strain rates, voids expand quickly and aggregate along grain boundaries, leading to localized rupture. The increased grain size and emerging structural inhomogeneity weaken the local grain boundary strength, making void formation and expansion easier.For the 1073 K annealed model, voids appear earlier and are more densely distributed. During the high strain stage, voids expand rapidly, eventually penetrating the structure, resulting in a significant increase in defect volume fraction and material failure. As shown in Figure 6, the 1073 K annealed model demonstrates a higher tendency to generate voids and defects under the same strain rate, further highlighting the detrimental effects of high-temperature annealing.

4. Conclusion

In this work, the untreated sample exhibited the highest compressive strength (123.146 MPa) and resistance to void formation. Its fibrous grain structure, formed by elongated grains, resulted in a dense microstructure that effectively suppressed the formation of voids and defects. However, its ductility was slightly inferior, with a maximum compression displacement of 6.541 mm. Annealing at 873 K achieved a balance between grain refinement and microstructural uniformity, with good compressive strength (112.988 MPa) and ductility (6.592 mm). Void formation was effectively suppressed under this condition, making 873 K the recommended annealing temperature for optimizing the performance of titanium materials. At 973 K, grain growth became evident, and structural inhomogeneity began to appear. The compressive strength decreased further (105.921 MPa), while ductility increased (6.687 mm). Voids began to form at lower strain levels, but the overall performance remained acceptable. However, annealing at 1073 K caused significant grain coarsening and severe microstructural inhomogeneity. The weld seam region became a stress concentration point, with a large number of voids and defects forming rapidly. The solid volume fraction dropped sharply, and the compressive strength reached its lowest value (85.797 MPa). Although ductility slightly improved (6.626 mm), the overall performance deteriorated significantly.

In conclusion, annealing at 873 K provides the optimal balance of strength, ductility, and overall performance, making it the best choice for improving the compressive properties of titanium materials. High-temperature annealing (e.g., 1073 K) should be avoided to reduce the risks of performance degradation caused by grain coarsening and microstructural inhomogeneity.

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