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The Effect of Cold Rolling Process on Microstructure Evolution and Performance of Thin-Walled Titanium Alloy Tubes

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Abstract

This study conducted two process routes and four passes of cold rolling deformation and annealing treatment on pipes. The microstructure, grain size, and mechanical properties at room temperature were characterized using optical microscopy (OM) and room temperature stretching. The results showed that after cold rolling and heat treatment at 700˚C/3 h, the microstructure of the tube was completely recrystallized and underwent a certain degree of growth. Cold rolling deformation can effectively improve the strength of the pipe. Under process route 1, there is a certain degree of non-uniformity in the deformation of the pipe after each pass. With the increase of deformation passes, the microstructure non-uniformity is improved. After 4 passes of deformation, the grain size difference between the M-state center and edge of the pipe is 2.5 μm. Under the premise of a certain total deformation during rolling, process route 2 can effectively eliminate the unevenness of the pipe structure by increasing the deformation amount for 3 passes. After 4 passes of deformation, the grain size difference between the M-state center and edge of the pipe is 0.4 μm, and the M-state elongation rate for 4 passes is 5.5% higher than that of process route 1.

Keywords

Thin-Walled Tubing, Cold Rolling Deformation, Heat Treatment Regimen, Equiaxed Structure, Grade 4 Titanium Alloy

1. Introduction

Titanium and its alloys are among the most important engineering structural materials, featuring high strength, excellent corrosion resistance, good microstructural stability at high temperatures, and high creep strength [1] [2]. They are widely used in pipeline components for aerospace applications. The development of aerospace technology has put forward higher requirements for the comprehensive performance of these materials. For metallic materials, grain refinement can significantly improve the comprehensive performance. Pilger cold rolling is a commonly used preparation method for high-performance tubes, characterized by local loading, local stress application, local deformation, large deformation amount, high production efficiency, and excellent dimensional accuracy [3] [4].

Wei Dong *et al.* investigated the evolution mechanism of the microstructure of tubes during cold rolling and found that the significant inhomogeneous deformation in the wall thickness direction during the deformation process is an important reason for the unstable mechanical properties of the finished products [5]. In the company's previous research on the microstructure evolution law and properties of TA21 pipe under different billet-making processes, the finished pipe prepared by the rolling + drilling billet-making process exhibited a fine and uniform equiaxed microstructure with significantly improved properties. Its tensile strength, yield strength and elongation reached 750 MPa, 698 MPa and 10%, respectively [6]. Due to the complex loading path of the tubes during cold rolling, coupled with the severe work hardening and poor cold plastic deformation ability of titanium alloys, the deformation inhomogeneity is high and the microstructural uniformity is poor, which further affects the comprehensive performance of the tubes [7]-[9]. At present, there are few domestic studies on improving the microstructural inhomogeneity of large-size thin-walled Gr.4 titanium alloy tubes during rolling deformation. Therefore, studying the microstructural evolution and property changes of the tubes during the forming process is of great significance for improving the deformation uniformity of metals and realizing the high-performance preparation of materials.

In view of the forming characteristics of thin-walled tubes and the performance requirements of the finished tubes, this paper reveals the influence law of distributing the deformation amount of each pass on the microstructure and mechanical properties of Gr.4 titanium alloy by adopting the cold rolling forming method, providing a theoretical basis for the development of high-performance titanium alloy thin-walled tube preparation technology.

2. Experimental Materials and Methods

The experimental material was Grade 1 sponge titanium smelting raw material, which was smelted multiple times in a vacuum consumable arc furnace to produce Gr.4 titanium alloy ingots. Its chemical composition is shown in **Table 1**. The ingot was precision forged through multiple passes of large deformation into a φ180 mm Gr.4 alloy billet rod. The finished tubes of φ50.8 × 0.889 mm were obtained through multi-pass cold rolling and annealing on two-high LG and three-high LD rolling mills. The annealing system for each pass is shown in **Table 2**, and the deformation amount for each pass is shown in **Table 3**.

Table 1. Main chemical composition (wt.%).

Ingot	Element/%					
	Ti	C	Fe	N	O	H
	Bal.	0.013	0.31	0.006	0.19	<0.0006

Table 2. Heat treatment system for each pass of φ50.8 × 0.889 mm tubes.

Tube	Heat treatment system			
	1 pass	2 pass	3 pass	4 pass
1	600˚C/3 h	700˚C/3 h	700˚C/3 h	600˚C/3 h
2	600˚C/3 h	700˚C/3 h	700˚C/3 h	600˚C/3 h

Table 3. Deformation amount of each pass for different processes of φ50.8 × 0.889 mm tubes.

Tube	Heat treatment system			
	1 pass	2 pass	3 pass	4 pass
1	22%	54%	43%	51%
2	22%	54%	69%	27%

After each cold rolling pass and heat treatment, samples were cut along the axial direction of the pipe for microstructure and mechanical property characterization. For metallographic observation, the samples were first pre-ground and polished, then etched with a solution of $HF:HNO_3:H_2O$ = 3:6:9, and the grain morphology of the samples was observed under an optical metallographic microscope. The microstructure of the extruded pipe billet is shown in Figure 1. The microstructure contains complete and clear primary α grains with distinct equiaxed grain boundary α, and no β phase was detected; the average grain size is 23.52 μm. A universal tensile testing machine was used to analyze the room-temperature mechanical properties of the samples.

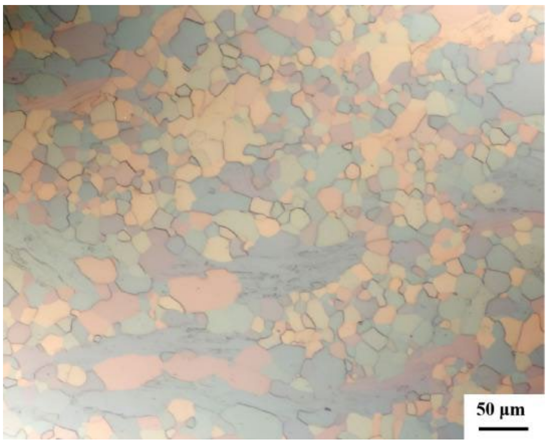

Figure 1. Initial microstructure of the tube billet.

3. Results and Discussion

3.1. Microstructural Analysis

To improve the microstructural uniformity and mechanical properties of thin-walled tubes, it is necessary to conduct in-depth research on the deformation behavior of the tubes after different passes and heat treatments. Figure 2 shows the microstructures of the tubes in the cold-rolled state (Y state) and after heat treatment (M state) at different passes. After one pass of deformation, the structure of the tube is equiaxed, and its morphology does not change significantly compared with the billet structure, with relatively coarse grain size, which is due to the small deformation amount of the first pass. Annealing the tube after the first pass of deformation at 600˚C for 3 hours results in slight grain refinement. After the second pass of deformation, the severe plastic deformation caused by rolling elongates and crushes the grains along the rolling direction, significantly refining the structure and forming a fibrous streamline structure. Annealing the tube after the second pass of deformation at 700˚C for 3 hours provides a strong driving force for recrystallization nucleation due to the increased crystal defects and metal distortion energy caused by deformation. The new distortion-free equiaxed grains replace the cold-deformed structure, forming an equiaxed structure. Compared with the deformed structure, the grains of the annealed structure grow, but their size is significantly smaller than that of the annealed structure after the first pass of deformation. After the third and fourth passes of deformation and annealing, the structure remains equiaxed.

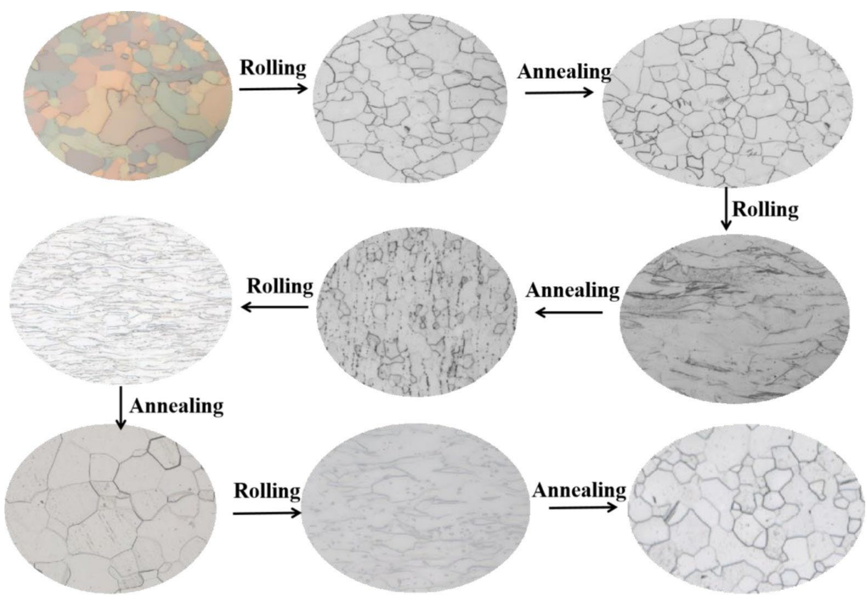

Figure 2. Microstructures of process route 1 after different passes and heat treatments.

Figure 3 and Figure 4 show the microstructures of the pipe in the Y state and M state after one rolling pass. As observed in both Figure 5 and Figure 6, small-sized clustered lath structures are found within the α grains, which are distributed in a staggered manner with a certain orientation; these are twins formed by twinning deformation of the pipe. Since the α phase has a hexagonal close-packed (HCP) structure with low symmetry and a limited number of slip systems, twinning deformation occurs in the crystal when the crystal orientation is not conducive to slip and the resolved shear stress exceeds the critical resolved shear stress for twinning. After twinning, the crystallographic orientation of the deformed regions changes, which can transform the slip planes originally in hard orientations into soft orientations and thus improve the plastic deformation capacity of the metal [10]-[12]. The size of the equiaxed α grains determines the grain boundary area inside the tube. The finer the equiaxed grain size, the larger and more dispersed the grain boundary area per unit volume, which significantly increases the resistance to dislocation movement during plastic deformation, thereby improving the mechanical properties of the alloy [13] [14]. In this paper, Image Pro Plus software used to statistically analyze the grain size of the two types of tubes in the M state. The grain sizes under different process routes are shown in **Figure 7**. After annealing, the structure of the two types of tubes after the first pass of deformation is refined compared with the billet structure, but the microstructural uniformity is poor, with the grain sizes of the core and edge being 22.12 μm and 20.06 μm respectively. **Figure 5** shows the microstructural morphology of the tube in the M state after the second pass. The grains are further refined by deformation, but there are still significant differences between the core and edge structures. The grain sizes of the core and edge are 20.44 μm and 18.26 μm respectively, and there are still a few coarse grains of 33.6 μm in the core. This is because the normal stress along the loading direction gradually decreases in absolute value as the force-bearing area expands during local loading, and the deformation amount of this pass does not fully "roll through" the core of the tube.

To improve the microstructural inhomogeneity of the tubes during rolling, two rolling processes were set for the third and fourth passes. Under the premise of the same total rolling deformation, the deformation amount of each of the third and fourth passes was distributed as shown in **Table 3**. **Figure 6** shows the microstructural morphology of the tube in the M state after the third pass of Process Route 1. Due to the smaller deformation amount of the third pass compared with the second pass, the grain refinement strengthening effect of the tube is reduced, and the grain size increases, with the grain sizes of the core and edge being 32.4 μm and 26.1 μm respectively. After the finished product rolling and heat treatment along Process Route 1, due to the reduced heat treatment temperature and increased deformation amount, the grain sizes of the core and edge are refined to 19.8 μm and 17.3 μm respectively, and their microstructural morphology is shown in **Figure 8**. The degree of microstructural inhomogeneity of the tube is improved compared with the previous passes. Under Process Route 2, the grains of the tube after the third pass are significantly refined, and the microstructural inhomogeneity is basically completely eliminated, as shown in **Figure 9**. The grain size of the core is reduced to 16.8 μm, and the grain size of the edge is reduced to 16.3

μm. This is because the stress value along the loading direction is increased, and in accordance with the local loading law, the compressive stress value borne by the grains in the pipe core is elevated. After the finished product rolling and heat treatment along Process Route 2, the grain sizes of the core and edge increase to 18.5 μm and 18.1 μm respectively, and their microstructural morphology is shown in **Figure 10**. Comparing the two process routes, it can be found that increasing the deformation amount of the third pass to 69% while keeping the total rolling deformation amount unchanged during the cold rolling of Gr.4 alloy can effectively eliminate the microstructural inhomogeneity of the tubes.

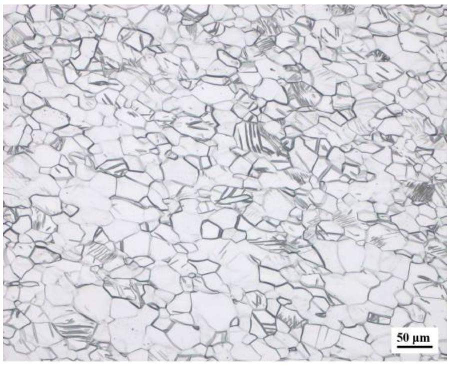

Figure 3. Microstructure of the tube in the Y state after the 1st pass.

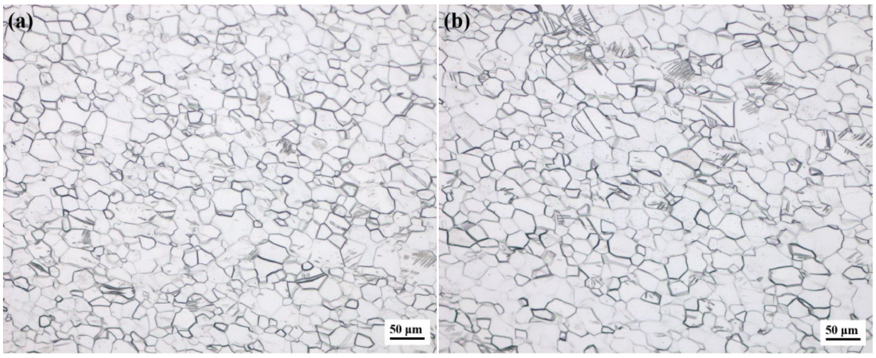

Figure 4. Microstructures of the Tube at different positions after the 1st pass heat treatment: (a) Edge; (b) Core.

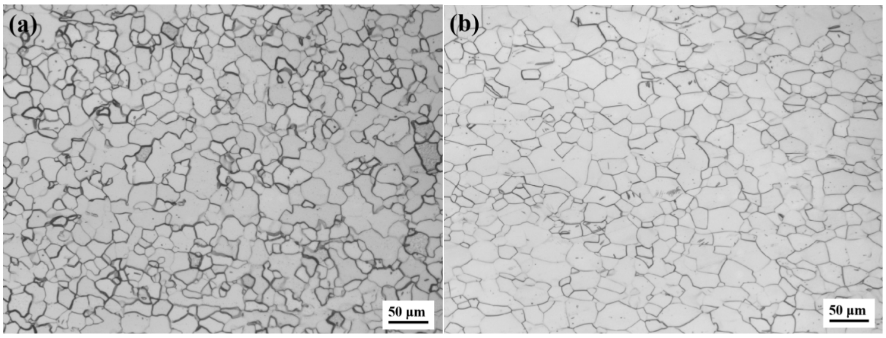

Figure 5. Microstructures of the tube at different positions after the 2nd pass heat treatment: (a) Edge; (b) Core.

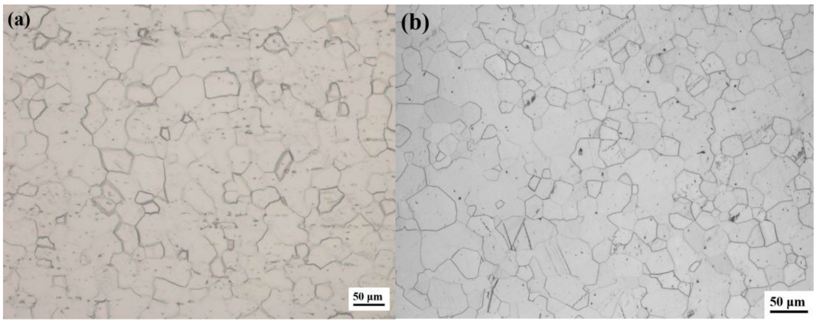

Figure 6. Microstructures of process route 1 tube at different positions after the 3rd pass heat treatment: (a) Edge; (b) Core.

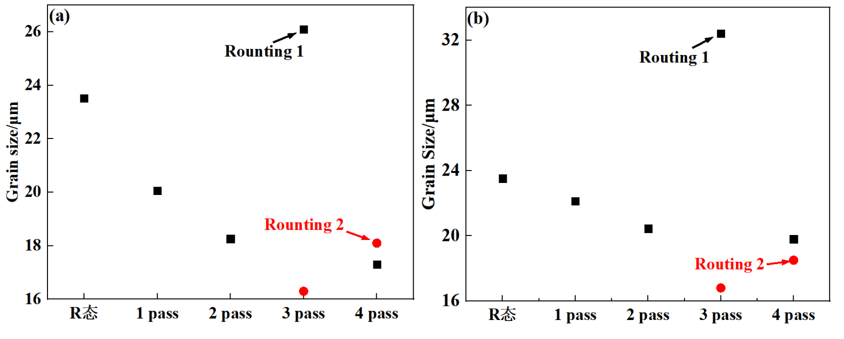

Figure 7. Grain sizes of the tubes in the M state at different passes for the two process routes: (a) Edge; (b) Core.

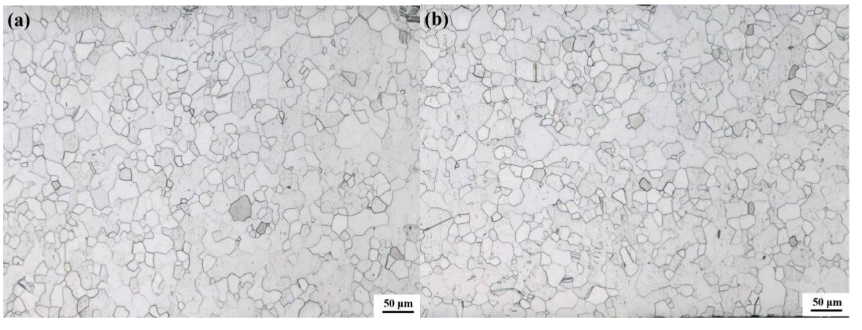

Figure 8. Microstructures of process route 1 tube at different positions after the 4th pass heat treatment: (a) Edge; (b) Core.

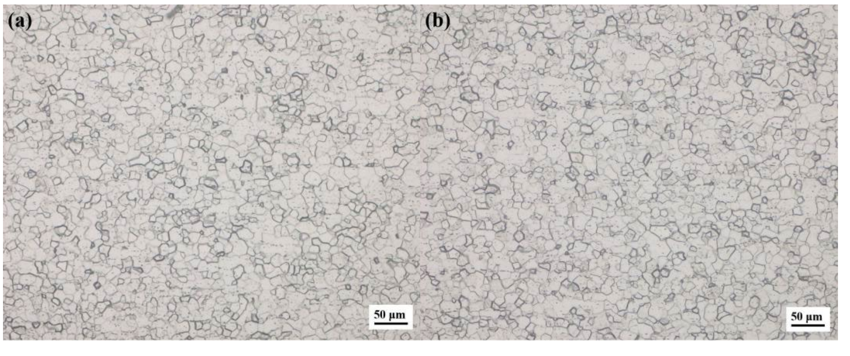

Figure 9. Microstructures of process route 2 tube at different positions after the 3rd pass heat treatment: (a) Edge; (b) Core.

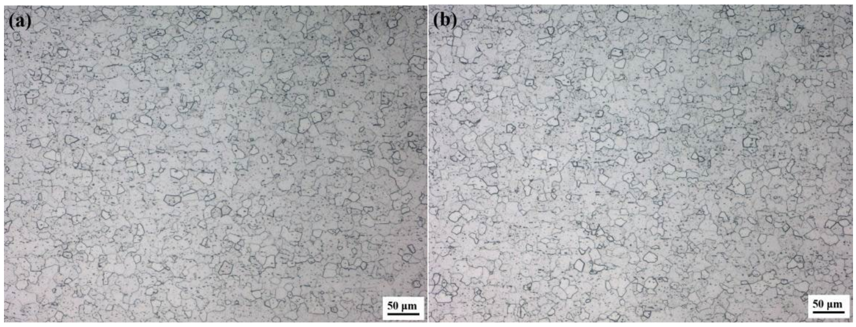

Figure 10. Microstructures of process route 2 tube at different positions after the 4th pass heat treatment: (a) Edge; (b) Core.

3.2. Mechanical Properties

Figure 11 shows the room-temperature tensile properties of Tube 1 in the Y-state and M-state under different passes of Process Route 1. After 1 and 2 passes of rolling deformation, the tensile strength and yield strength of the tube in the Y-state are significantly improved: the tensile strength increases from 555 MPa to 727 MPa, and the yield strength increases from 383 MPa to 703 MPa. This is because the grains of the tube are crushed and refined during the rolling process, and the plastic deformation leads to an increase in dislocation density, enhanced interaction between dislocations, formation of a high-density "dislocation forest", which increases the resistance to dislocation movement and thus improves the resistance to plastic deformation [15] [16]. Therefore, the strength improvement in the Y-state is mainly caused by dislocation strengthening and grain refinement strengthening, among which grain refinement strengthening plays a dominant role.

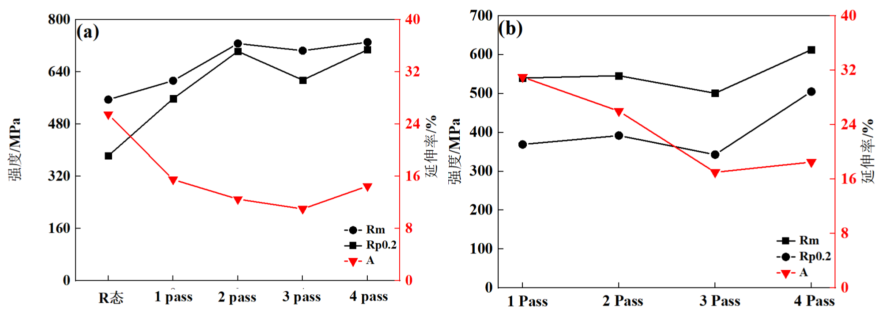

Figure 11. Room-Temperature tensile properties of the tube in the Y state and M state at different passes of process route 1: (a) Y state; (b) M state.

After 3 and 4 passes of deformation, the tensile strength of the tube is 705 MPa and 731 MPa respectively, the yield strength is 615 MPa and 708 MPa respectively, and the elongation is 11% and 14.5% respectively, maintaining high plasticity. Its strength first decreases and then increases. The reason is that the semi-intermediate annealing temperature is relatively high, the deformation amount of the 3rd pass is reduced, and the microstructure of the tube continues to grow after complete recrystallization, resulting in a certain degree of grain growth. The deformation amount of the 4th pass increases and the final heat treatment temperature decreases, so the strength increases again. After 4 passes of rolling deformation, the tensile strength of the M-state semi-finished product remains between 501 - 613 MPa, the yield strength remains between 343 - 505 MPa, and the elongation remains between 17% - 31%.

Figure 12 shows the room-temperature tensile properties of the tube in the cold-rolled state (Y state) and annealed state (M state) at different passes of Process Route 2. Compared with Process Route 1, the tensile strength of the tube in the Y state at the third and fourth passes is increased by 66 MPa and 19 MPa respectively, the yield strength is increased by 134 MPa and 16 MPa respectively, and the elongation is increased by 3% and 2.5% respectively. The tensile strength of the tube in the M state at the third and fourth passes is increased by 119 MPa and 17 MPa respectively, the yield strength is increased by 194 MPa and 22 MPa respectively, and the elongation is increased by 1.5% and 5.5% respectively. The elongation of the tube under Process Route 2 is significantly improved, which is because the degree of microstructural inhomogeneity of the tube under Process Route 2 is basically eliminated.

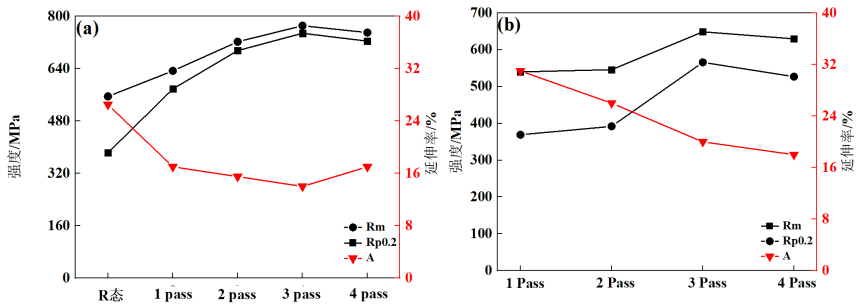

Figure 12. Room-Temperature tensile properties of the tube in the Y state and M State at different passes of process route 2: (a) Y state; (b) M state.

4. Conclusions

1) After the first pass of deformation of the Gr.4 alloy tube, the microstructure morphology does not change, retaining part of the coarse original structure of the billet. A large number of twins are found in both the Y state and M state. This is because the deformation amount is small, and to coordinate the deformation, the grains stimulate more slip systems through twinning, and twinning dominates the deformation at this time. After the second, third, and fourth passes of deformation, the Y state structure is fibrous, the grain size is elongated along the rolling direction, and the structure is transformed into an equiaxed structure through recrystallization after annealing. No twins are found in the Y state and M state of the subsequent rolling passes. This is because when the deformation amount is large, dislocation slip dominates the deformation, and twinning deformation is inhibited.

2) The microstructure of the Gr.4 alloy tube after each pass of deformation via Process Route 1 has a certain degree of inhomogeneity. With the increase in the number of deformation passes, the degree of microstructural inhomogeneity is improved. The microstructural inhomogeneity of the tube after the third and fourth passes of deformation via Process Route 2 is eliminated. Increasing the single-pass rolling deformation amount while keeping the total rolling deformation amount unchanged can significantly improve the microstructural inhomogeneity.

3) Compared with Process Route 1, the elongation of the finished Gr.4 alloy tube via Process Route 2 is significantly improved. This is because the microstructural inhomogeneity of the tube is eliminated, and the overall deformation coordination ability and fracture resistance of the tube are improved.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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