Study on Microstructure, Texture Characteristics and Tensile Properties of TA15 Titanium Alloy Sheet

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Abstract: Taking TA15 titanium alloy slab as the research object, a 1.5 mm sheet was obtained after clad rolling and annealing treatment. The microstructure, texture characteristics, mechanical properties and fracture behavior of the sheet were systematically studied by means of microstructure observation, pole figure analysis, room temperature tensile test and fracture morphology characterization. The results show that the sheet is composed of equiaxed α grains, slender strip α grains and reticular residual β phase, and the microstructure is uniform in different directions. The phase proportion and distribution state are highly consistent on the macroscopic scale, without obvious band segregation or local coarsening. The sheet presents an R-shaped texture, and the transverse and rolling direction texture strengths are 6.25 and 6.32, respectively. The in-plane texture is symmetrical and uniform. The tensile test at room temperature shows that the tensile strength (965 MPa, 962 MPa), yield strength (852 MPa, 853 MPa) and elongation (20%, 21%) of the transverse and rolling directions are very close, and there is no obvious anisotropy. This result fully indicates that under the clad lap rolling and annealing process adopted in this paper, the in-plane mechanical properties of the sheet achieve good isotropy, which is of great application value for load-bearing components under complex stress states in practical engineering. The high strength of the sheet is mainly due to the distortion energy and fine grain strengthening accumulated by deformation, and the good plasticity is attributed to the microstructure dominated by equiaxed α grains. The tensile fracture is composed of a large number of equiaxed dimples and a small number of secondary cracks, which is characterized by a ductile + quasi-cleavage mixed fracture, consistent with the excellent matching of strength and plasticity.

Keywords: TA15 Titanium Alloy; Structure Morphology; Texture; Tensile Properties; Fracture Morphology

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1 Introduction

Titanium and its alloys have been widely used in many key fields such as chemical equipment, low-temperature power systems, marine structural parts and aerospace due to their outstanding properties including low density, high specific strength, excellent corrosion resistance and good low-temperature performance [1]. As a typical near-α titanium alloy (nominal composition: Ti-6.5Al-2Zr-1Mo-1V), TA15 titanium alloy not only has excellent thermal stability, but also exhibits good processing and welding properties, and can maintain excellent mechanical properties at room

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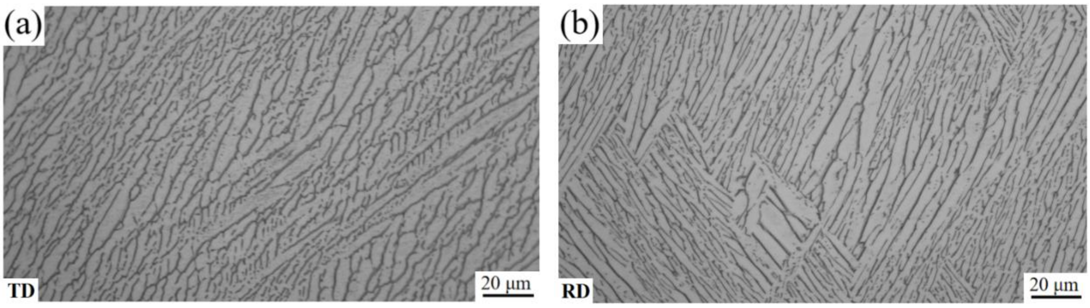
temperature and high temperature [2]. Especially in the medium temperature range (300~500°C), the alloy has high creep resistance and oxidation resistance, which makes it play an important role in aero-engine compressor blades, casings and fuselage structures that require thermal strength [3]. Because of these comprehensive advantages, it has been widely used in aerospace, marine engineering, chemical industry and other fields [4]. With the continuous expansion of the application range of the alloy, the research on TA15 titanium alloy has gradually deepened.

However, although the existing literature has carried out a lot of discussions on TA15 titanium alloy, and the research content covers many aspects such as thermal deformation behavior, heat treatment process, microstructure evolution law and mechanical property optimization, it is found that the existing work has focused on medium and thick plates (usually ≥10 mm) [5], bars [6], forgings [7] and other product forms. For thin plates with a thickness of less than 2 mm, the relevant reports are extremely limited due to the difficulty of rolling process, the complexity of edge crack control, and the difficulty in ensuring the uniformity of microstructure. In addition, the recrystallization kinetics, grain growth behavior and texture genetic effect of thin plates during annealing are significantly different from those of thick plates. If the process parameters of thick plates are directly used, it is often difficult to obtain ideal performance matching. In fact, thin plates have irreplaceable advantages in application scenarios where lightweight requirements are urgent, such as aerospace and chemical equipment. However, the size effect, texture evolution and performance anisotropy caused by thickness reduction make the regulation mechanism of microstructure and properties more complicated than that of thick plates, which needs to be further studied. In particular, although pack rolling technology can effectively avoid the problems of edge cracks and excessive temperature drop in the rolling process of thin plates, the bonding quality of the rolling interface, the coordination of inter-layer deformation and the influence of subsequent annealing process on the interface structure are still lacking systematic experimental data support. Based on this, in view of the research status, this paper takes the pack rolling process as the starting point, and uses this process to prepare TA15 titanium alloy sheet with a thickness of 1.5 mm, and systematically analyzes the internal relationship between the microstructure, texture evolution and mechanical properties of the sheet, in order to provide reference for practical engineering applications.

2 Test Materials and Methods

The TA15 titanium alloy slab was selected as the test material (the ingot was opened in the single-phase region and prepared by 1~2 heating fires). Figure 1 shows the microstructure morphology of the slab. It was found that the microstructure similarity of the slab in different directions was high, which was composed of coarse flaky α grains, showing typical Widmanstätten structure characteristics. This initial structure has high hardness and low plasticity. In the subsequent rolling process, it is necessary to strictly control the deformation and rolling temperature of each pass to avoid cracking. TA15 titanium alloy was processed by a 2450 hot rolling mill. The cladding layer is made of low carbon steel with a thermal expansion coefficient similar to that of TA15. The slab is welded and sealed with the cladding layer before rolling to reduce high temperature oxidation and edge cracks. Through multi-pass rolling, the initial slab is gradually rolled to 1.5 mm. The rolling process adopts reciprocating reversible rolling, the pass reduction rate is controlled between 10% and 20%, and the finishing rolling temperature is not less than 850 °C, so as to ensure that the alloy is always deformed in the α+β two-phase region. The chemical composition of the finished sheet was analyzed, and the mass fraction (%) of each element in the sheet was measured as follows: Al 6.53, Mo 1.73, V 2.21, Zr 2.21, O 0.15, Ti balance. The phase transition temperature of TA15 titanium alloy sheet was 997 °C measured by continuous heating metallographic method. According to the measured phase transition point, the recrystallization temperature was selected, and the rolled sheet was annealed at 880 °C for 2 hours and air-cooled.

When cutting samples from the sheet, samples were taken along the transverse (TD) and rolling direction (RD) for subsequent microstructure observation, texture characterization and room temperature tensile test. The morphology of the microstructure was observed by Axio metallographic microscope and the images were collected. The EBSD test was performed using the ZEISS scanning electron microscope's own lens to obtain the texture characteristics of the sheet; the EBSD scanning step is set to 0.2 μm, and the scanning area is not less than 200 μm × 200 μm to ensure the representativeness of the statistical results. The pole figure data were processed and analyzed by Channel 5 software. The tensile test was carried out on the CCS-44100 universal electronic testing machine. Three parallel samples were set in each direction, and the final test results were taken as the arithmetic average. In addition, the tensile fracture morphology was observed and photographed by scanning electron microscopy.



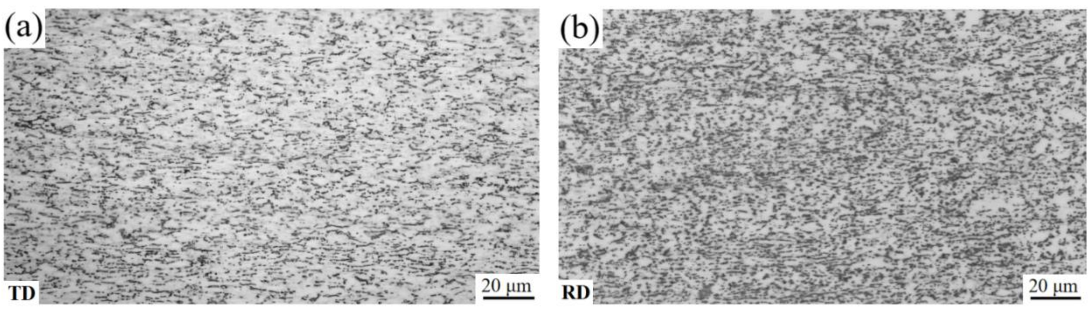
(a) TD (b) RD

Figure 1 Slab structure morphology

3 Results and Discussion

3.1 Metallographic Structure

Figure 2 shows the microstructure of TA15 titanium alloy sheet. It can be observed from the diagram that the α grains are the main body of the matrix in the sheet, and the black residual β phase with continuous or discontinuous network shape is distributed between the grains. The microstructure observed along the rolling direction (RD) and the transverse direction (TD) is basically the same, and no obvious anisotropy is shown, indicating that the microstructure of the sheet under this process condition has good uniformity in the plane. This is mainly due to the good temperature drop control during the pack rolling process and the sufficient recrystallization during the annealing stage, so that the grain morphology and size distribution in the two directions tend to be consistent. The α grains are mainly characterized by two types of morphology, one is approximately equiaxed granular grains, and the other is slender strip grains, which are interwoven and distributed, and the traces of deformation streamline and grain elongation left in the rolling process can still be identified in the structure.



(a) TD (b) RD

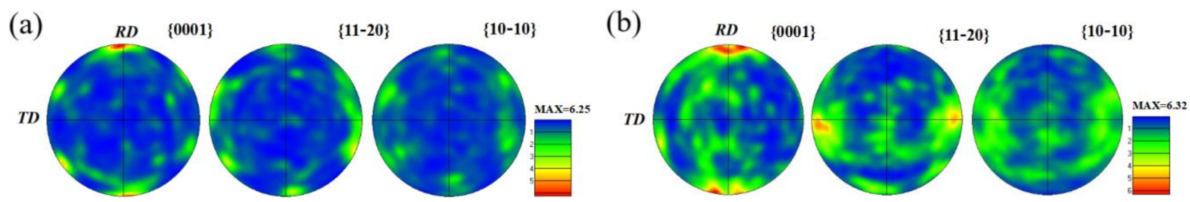
Figure 2 Microstructure of sheet

In the rolling deformation stage, the external stress causes significant plastic deformation of the α grains in the original slab [8]. The final morphology of the grains depends on a number of process parameters, including the amount of deformation, alloy composition, deformation temperature and strain rate. With the increase of deformation degree, the original α grains are gradually flattened, elongated and broken, and obvious distortion and elongation occur along the rolling direction [9]. When the cumulative deformation reaches a certain critical value, the thin strip α grains begin to appear in the thin plate structure, and its formation is related to the activation of different slip systems. Specifically, in the process of plastic deformation, the initiation of basal slip and prismatic slip does not change the crystal orientation of α grains, and the grains only rotate around the c-axis, while the behavior of pyramidal slip is different. It not only makes α grains tilt to a certain extent, but also induces the overall rotation of grains, thus promoting the formation of slender strip structure. Due to the high critical shear stress, the pyramidal slip system is usually activated in the late stage of deformation or in the local stress concentration area. Its initiation not only contributes to the additional deformation, but also introduces a large number of non-basal dislocations, which is helpful to refine the sub-grain structure [10]. This deformation mechanism dominated by pyramidal slip is the key to the preferred orientation growth of strip α grains during rolling. In the subsequent annealing treatment, the distortion energy stored in the deformed structure drives the recrystallization process, and some regions finally generate equiaxed α grains through the nucleation and growth mechanism, thus restoring the uniformity and plasticity of the structure to a certain extent [11].

3.2 Texture

Figure 3 is the pole figure characterization results of TA15 titanium alloy sheet samples. It is found that the pole figures of the transverse (TD) and rolling direction (RD) of the sheet show R-type texture characteristics. Further observation shows that the texture intensity of the two is close to 6.25 and 6.32, respectively.

TA15 titanium alloy (hexagonal close-packed structure) sheet is subjected to plane strain compression during rolling, and the prismatic slip system {10-10} is preferentially activated. In order to coordinate the deformation, the grain gradually turns the c-axis with the lowest energy to the rolling (RD) direction through slip and rotation, and finally forms a typical R-shaped texture (the normal of the basal plane is parallel to the RD). Different from the common basal texture (basal normal parallel to ND) or prismatic texture, R-type texture is relatively rare in titanium alloy sheets. Its formation requires a specific matching of rolling temperature, deformation rate and cumulative strain, which usually occurs under medium-low temperature and large deformation rolling conditions. Due to the orthogonal symmetry of the texture in the plate surface, the pole figures observed from the rolling direction (RD) or the transverse direction (TD) will show similar R-type distribution characteristics. At the same time, the texture intensities in the two directions are 6.25 and 6.32, respectively, and the values are very close, indicating that the degree of grain orientation concentration is equivalent and the in-plane texture of the plate is uniform, which reflects that the rolling process is well controlled and does not lead to excessive enhancement of preferred orientation in a certain direction. Texture uniformity is of positive significance for reducing the springback difference and cracking risk of thin plates in subsequent stamping, bending and other secondary forming processes, because the anisotropy caused by texture often leads to inconsistent yield stress and hardening behavior in different directions.



(a) TD (b) RD

Figure 3 Characterization of sheet pole figure

3.3 Tensile Properties

Figure 4 shows the tensile properties of TA15 titanium alloy sheet samples measured at room temperature. The results show that the tensile strength (R_m) of transverse direction (TD) and rolling direction (RD) are 965 MPa and 962 MPa, respectively. The yield strength ($R_{p0.2}$) in TD and RD directions are 852 MPa and 853 MPa, respectively. The elongations (A) are 20% and 21%, respectively. The mechanical indexes in the two directions are close to each other, and the difference is small, indicating that the internal structure of the thin plate is evenly distributed, the texture type and strength are similar, and no obvious anisotropic characteristics are shown.

Further observation shows that the TA15 titanium alloy sheet still maintains good plasticity while obtaining higher strength. This performance combination is mainly due to its specific microstructure. The high strength mainly comes from the large-scale plastic deformation experienced by the microstructure during the rolling stage. During the severe deformation process, high-density dislocations, vacancies and other crystal defects are accumulated inside the lattice, thus storing higher distortion energy and significantly improving the energy storage level of the microstructure. At the same time, during the crushing and stretching process of the original α grains, recrystallization occurs preferentially near the grain boundary and the local area of deformation. Combined with the subsequent annealing treatment, a fine and uniform equiaxed α grain structure is finally formed. According to the mechanism of fine grain strengthening (Hall-Petch), the finer the grain size, the higher the volume fraction of grain boundary is, and the stronger the hindrance to dislocation movement [12]. When tensile at room temperature, dislocation slip is strongly hindered by fine grains, and fine grain boundaries are more likely to cause the formation of dislocation pile-up groups. In order to make the dislocation continue to move and achieve macroscopic plastic deformation, higher external stress must be applied to overcome the grain boundary resistance, which is the internal reason for the high strength of the thin plate.

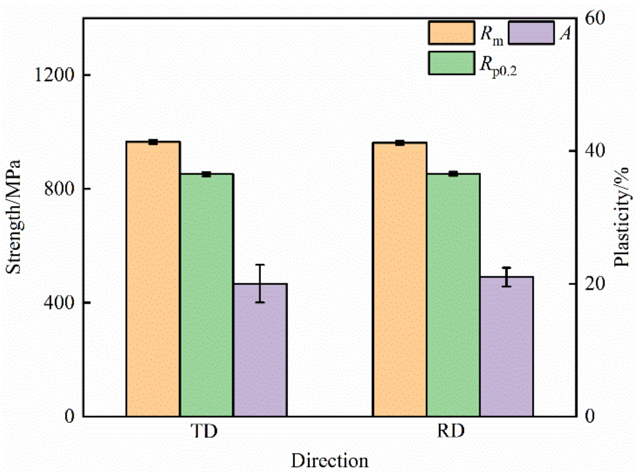
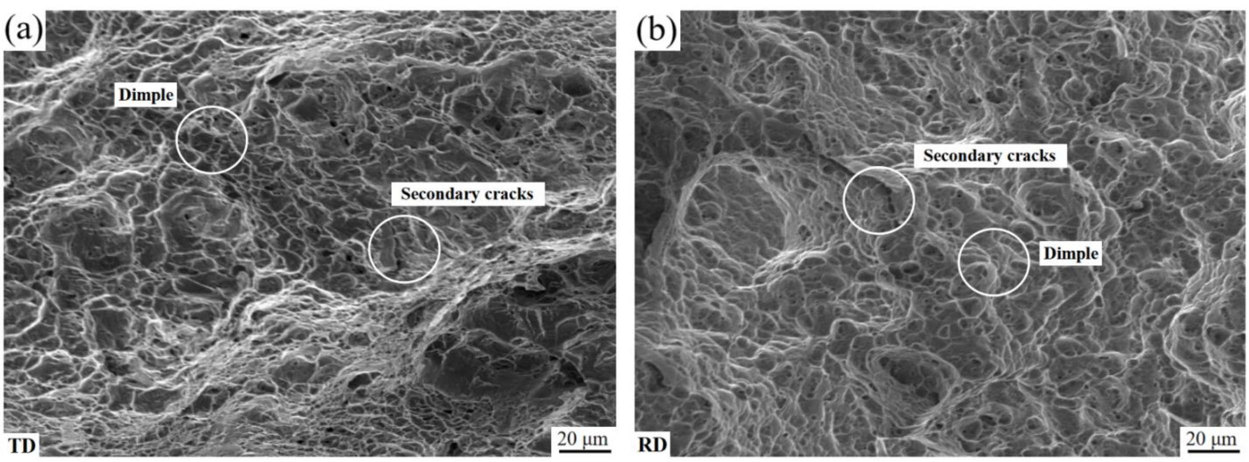


Figure 4 Tensile properties of samples

As for the good plasticity, it is related to the equiaxed morphology of α grains in the structure. The equiaxed α phase has more uniform crystal orientation distribution and higher geometric symmetry, so it has better deformation coordination ability. During tensile loading at room temperature, slip will preferentially initiate in equiaxed α grains with larger orientation factors, which are easy to meet the conditions of critical shear stress [13]. With the increase of the proportion of equiaxed α phase, the deformation can be quickly and uniformly dispersed into a large number of equiaxed α grains, so as to avoid the premature concentration of stress at a few grains or phase boundaries due to local strain concentration, thus effectively delaying the initiation and propagation of cracks. In addition, as a soft phase, the residual β phase distributed in the network can alleviate the stress concentration by coordinating grain boundary sliding and dislocation climbing during the deformation process. At the same time, the diffusion of β-stabilizing elements such as V and Mo in the β phase is slow, which helps to inhibit grain boundary embrittlement and further improve plasticity.

3.4 Fracture Morphology

Figure 5 shows the fracture morphology of the tensile specimen at room temperature after fracture. It can be seen that the fracture characteristics taken from the TD direction and the RD direction are almost identical, both of which are composed of a large number of equiaxed dimples. This kind of fracture morphology obviously belongs to the typical characteristics of ductile fracture. Generally speaking, the more the number of dimples in the fracture and the larger the size, the better the plasticity of the material [14]. On the contrary, if the dimples are less and smaller, it means that the plasticity is poor. The morphology of Figure 5 is consistent with the tensile properties of Figure 4, that is, the samples in the TD and RD directions of the sheet have very good plasticity.



(a) TD (b) RD

Figure 5 Fracture morphology of sample

In the SEM images of the tensile fracture shown in Figure 5, in addition to the widely distributed and relatively uniform dimples, a small number of secondary cracks can also be observed. The existence of a large number of dimples is a typical feature of micropore aggregation fracture, indicating that the material undergoes significant plastic deformation before fracture, while the secondary crack reflects the micro-cracking induced by local stress concentration or insufficient coordinated deformation ability at the phase boundary and grain boundary during the tensile process. The secondary cracks indicates that the sheet has good plasticity and high strength at the same time, that is, the fracture mode presents a typical ductile+quasi-cleavage mixed feature, which is a common fracture form of high-strength and good-plasticity materials.

4 Conclusion

(1) The TA15 titanium alloy slab presents a typical Widmanstätten structure. After rolling and annealing, a uniform microstructure composed of equiaxed α grains, slender strip α grains and reticular residual β phases is formed. The formation of slender strip α grains is mainly attributed to the plastic deformation mechanism dominated by pyramidal slip.

(2) The R-shaped texture with orthogonal symmetry is formed after rolling, and the texture strength of the transverse and rolling directions is similar (6.25 and 6.32, respectively), indicating that the in-plane texture of the plate is uniform and the rolling process is well controlled. This uniform texture helps to reduce the performance fluctuation of the sheet during subsequent loading in all directions and improve the dimensional stability of the formed part.

(3) The sheet has similar tensile properties in the transverse and rolling directions (the tensile strength is about 963 MPa, the yield strength is about 852 MPa, and the elongation is about 20.5%), and does not show obvious anisotropy. Its high strength is mainly due to the distortion energy and fine grain strengthening effect accumulated by deformation, while the good plasticity is attributed to the excellent deformation coordination ability of the microstructure dominated by equiaxed α grains. Compared with the medium-thick plate, the sheet achieves the simultaneous improvement of strength and plasticity under the combined action of fine grain strengthening and dislocation strengthening, showing good comprehensive mechanical properties.

(4) The room temperature tensile fracture of the sheet in the transverse and rolling directions is composed of a large number of equiaxed dimples, accompanied by a small amount of secondary cracks, showing a typical ductile+quasi-cleavage mixed fracture characteristics, corresponding to the good plasticity and high strength of the material. The fracture analysis further confirms the positive effect of equiaxed α grains on delaying crack propagation and the contribution of residual β to relieving stress concentration.

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