Microstructure Evolution and Mechanical Properties of Cold-Hearth-Melted TC1 Alloy During Rolling: Post-Print

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Abstract

This study investigates TC1 alloy produced by industrial plasma cold hearth furnace melting, integrating actual production processes and utilizing neutron diffraction technique to examine the effects of different rolling processes on the microstructure and property evolution of TC1 sheets, and to reveal the relationship between microstructure and mechanical properties. The results indicate that the as-cast microstructure of the cold hearth furnace melted ingot exhibits a Widmanstätten structure. After rolling, the α colonies undergo distortion and fragmentation. The alignment of deformed α phase along the rolling direction is more pronounced in unidirectional rolling compared to cross rolling. Following annealing, the deformed α phase in the sheets becomes equiaxed. Both unidirectional and cross rolled sheets display a prismatic texture type, which is the primary reason for the significantly higher transverse yield strength compared to the rolling direction yield strength.

Full Text

Microstructure Evolution and Mechanical Properties of TC1 Alloy Fabricated by Plasma Arc Cold Hearth Melting During Rolling Process

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Abstract

Plasma arc cold hearth melting (PAM) is an effective technology to produce high purity titanium alloy ingots which are widely used in aeronautic and astronautic industries. To date, the development of PAM in our country is still at initial stage. It is necessary to investigate the melting parameters of PAM and the following thermal mechanical processing of the ingots fabricated by PAM. In this study, the TC1 alloy ingots casted by PAM were cogged at β transus temperature and then rolled by unidirectional rolling and cross rolling in the α+β phase field. The typical widmanstatten structure of cast-ingots turned to transformed β morphology after cogging at β transus temperature in which the α phases forms in smaller colonies of laths. After the unidirectinal rolling in the α+β phase field, the α colonies were distorted and the α laths re-arranged along the rolling direction, while they had weaker directivity after cross rolling. The sheets rolled by both unidirectional and cross rolling showed typical prismatic texture. After annealing treatment below the β transus temperature, the α phases turned to equiaxial morphology. The ambient yield strength of the sheet in transverse direction was significantly higher than in rolling direction, which could be attributed to the strong prismatic texture introduced by hot rolling process.

KEY WORDS plasma arc cold hearth melting (PAM), TC1 alloy, hot rolling, microstructure, texture, mechanical properties

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Introduction

Titanium alloys are widely used in aerospace applications due to their high specific strength, excellent high-temperature performance, and superior corrosion resistance. Titanium is a highly reactive metal that readily reacts with many elements, including various oxide refractory materials, at melting temperatures. Consequently, titanium melting must be conducted in vacuum or inert gas environments, and the application of water-cooled copper crucible condensers enables safe solidification of titanium. From an economic perspective, vacuum arc consumable electrode melting has become the primary method for producing titanium ingots. However, due to its short high-temperature holding time and insufficient melting temperature, this method cannot completely eliminate solidification defects such as inclusions and chemical composition segregation in cast ingots.

The United States developed a novel titanium alloy melting technology in the 1980s—cold hearth melting technology. Cold hearth melting is classified into electron beam cold hearth melting and plasma arc cold hearth melting (PAM) according to the heat source, and it emerged to meet the urgent demand for high purity in aerospace titanium alloys. During cold hearth melting, inclusions have sufficient time to be melted at extremely high temperatures or sink to the bottom of the hearth without flowing into the molten pool, thereby significantly eliminating both high-density and low-density inclusions in titanium alloys and effectively improving chemical composition segregation in ingots. At present, international research reports on cold hearth melting of titanium alloys are scarce, and studies on subsequent thermomechanical processing of cold hearth melted titanium alloys are even rarer. The application of industrial PAM for titanium alloys in our country is still in its infancy, with no reports on the development status of related technologies, and exploration of subsequent thermomechanical processing of PAM Ti ingots is even more limited. This study employs industrial PAM titanium alloy for product development.

The microstructure of titanium alloys is significantly influenced by thermomechanical processing parameters. Processing parameters such as deformation temperature, deformation rate, and cooling rate can all lead to changes in titanium alloy microstructure, including α/β two-phase morphology, α colony size, and volume fraction of equiaxed α. Processing also has an important impact on the type and intensity of titanium alloy texture. Generally, the main texture types formed during titanium alloy processing include prismatic texture, basal texture, and pyramidal texture. Texture intensity is primarily determined by the degree of deformation and rolling mode. Microstructure and texture further determine the mechanical properties of titanium alloy products.

Given the current state of PAM development in our country, this study investigates the microstructure and texture evolution of TC1 alloy plates during rolling, and discusses the effects of thermomechanical processing on plate microstructure and properties, using TC1 alloy ingots produced by PAM from Baosteel Special Metals Co., Ltd. and employing neutron diffraction technology. The objective is to provide theoretical guidance and experimental basis for subsequent thermomechanical processing of PAM TC1 titanium alloy.

Experimental

The TC1 alloy ingots used in this study were melted by plasma arc cold hearth melting (PAM) at Baosteel Special Metals Co., Ltd., with ingot dimensions of 1550 mm × 750 mm × 330 mm. The nominal composition of TC1 alloy is Ti-2Al-1.5Mn, with detailed chemical composition (mass fraction, %) of: Al 1.0-2.5, Mn 0.7-2.0, Fe ≤ 0.12, C ≤ 0.05, H ≤ 0.015, N ≤ 0.03, O ≤ 0.15, Ti balance. A 36 mm thick slab was cut from the core of the PAM TC1 alloy ingot as the initial material for rolling deformation. After holding in the β phase region, the ingot was subjected to breakdown rolling at the phase transformation temperature. The rolled blank was then reheated to the two-phase region and rolled to a final plate thickness of 3 mm. The two-phase region rolling deformation processes included unidirectional rolling (UR) and cross rolling (CR). Unidirectional rolling refers to maintaining the initial rolling direction throughout each pass until rolling deformation is completed. Cross rolling involves rotating the plate 90° relative to the initial pass rolling direction for rolling, then performing another 90° rotation and maintaining this rolling direction for subsequent passes. No annealing process was performed between passes during plate rolling. To investigate the effects of subsequent annealing on the microstructure and properties of TC1 plates, 3 mm plates processed by both rolling deformation methods were annealed at 750 °C for 30 min.

Texture test samples were cut from plates processed by both rolling deformation methods, with dimensions of 24 mm × 14 mm × 2 mm. After mechanical grinding and polishing, macro-texture measurements were conducted using the STRESS-SPEC thermal neutron diffractometer. During texture testing, the incident thermal neutron beam had a wavelength of 0.174 nm and a diameter of 25 mm, which could completely cover the entire sample. Complete pole figure measurements were performed on the {0002}, {1010}, and {1120} planes of the samples. Compared with conventional X-ray diffraction technology, the neutron beam has strong penetration capability, enabling detection of grain orientations throughout the bulk sample, and neutron diffraction can achieve α angles up to 90° when using reflection and transmission methods to test pole figure data, allowing detection of complete pole figure data.

Room temperature tensile property testing of plates processed by both rolling deformation methods and corresponding annealing treatments was conducted using an MTS 810 testing machine at a strain rate of 0.0017 s^{-1}. The tensile specimen dimensions are shown in Fig. 1a [Figure 1: see original paper]. During testing, tensile samples were cut along both the rolling direction (RD) and transverse direction (TD) of the plates for room temperature tensile property testing. The direction schematic is shown in Fig. 1b.

Metallographic specimens were obtained through mechanical grinding and electrolytic polishing, and were etched using Kroll’ s reagent (87 mL H_2O + 10 mL HNO_3 + 3 mL HF). The microstructure of rolled plates was observed using an AXIO IMAGER M2m optical microscope (OM). The OM observation planes of rolled plates were the rolling plane (RD-TD plane) and longitudinal section (RD-ND plane).

2.1 Metallographic Microstructure

Fig. 2 [Figure 2: see original paper] shows typical as-cast OM images of the TC1 alloy ingot core fabricated by PAM. The low-magnification OM image indicates that the ingot exhibits a Widmanstätten structure (Fig. 2a), with initial β grain size of approximately 8 mm. Coarse α colonies formed within the original β grains, with non-uniform α colony size distribution—large colonies reaching 4 mm and some small colonies approximately 50 m. The α colonies showed relatively obvious orientation, with different orientations in adjacent β grains. Fig. 2b shows a high-magnification OM image of the as-cast microstructure, revealing that each α colony consists of nearly parallel α lamellae with β phase located between the α lamellae. The lamellae thickness is approximately 2 m. Additionally, primary α phase borders are present on original β grain boundaries.

After breakdown rolling, both the plate rolling plane and longitudinal section exhibited transformed β microstructure, with the rolling plane OM image shown in Fig. 3 [Figure 3: see original paper]. The image shows that α colonies with different orientations are interwoven, with colony size significantly reduced from the millimeter level to approximately 400 m, while small colonies are only a few microns in size. Original β grain boundaries remain in the microstructure, and primary α phase borders have dissolved and disappeared. Fig. 3b shows a high-magnification OM image of the interwoven α colonies. Compared with the as-cast microstructure (Fig. 2), after breakdown rolling, the α lamellae arrangement becomes denser and the lamellae thickness is significantly reduced to approximately 0.7 m.

Fig. 4 [Figure 4: see original paper] shows typical OM images of the rolling plane and longitudinal section of TC1 plates after unidirectional rolling and cross rolling. After two-phase region rolling deformation, α colonies became distorted and fragmented, and original β grain boundaries could no longer be distinguished. The rolling plane and longitudinal section microstructures showed certain differences. After unidirectional rolling, α phases on the rolling plane aligned along the rolling direction (Fig. 4a). After cross rolling, α colonies on the rolling plane were more thoroughly fragmented, and the microstructure directionality was less obvious than in unidirectional rolling (Fig. 4c). The longitudinal section microstructures of both unidirectional and cross rolling were similar, with α phases distributed in bands along the rolling direction and showing obvious processing flow lines, which appear as elongated deformed α phases at high magnification (Figs. 4b and d).

Fig. 5 [Figure 5: see original paper] shows typical OM images of the rolling plane and longitudinal section of plates after unidirectional and cross rolling, followed by holding at 750 °C for 30 min and air cooling. Figs. 5a and c indicate that after annealing, both unidirectional and cross rolled plates exhibit equiaxed α phases on the rolling plane, with β phases distributed around the α phases. The unidirectional rolled sample shows certain directionality of lamellar α phases in most regions (Fig. 5a). The longitudinal section microstructures of both processes are similar, showing mixed microstructures of equiaxed and strip-shaped α phases (Figs. 5b and d).

2.2 Macro-Texture Evolution

Fig. 6 [Figure 6: see original paper] shows complete pole figures of the {0002}, {1010}, and {1120} planes of the α phase measured by neutron diffraction after breakdown rolling of the ingot. Fig. 6a indicates that after ingot breakdown rolling, the normal direction of the α phase {0002} plane is mainly parallel to the TD direction, with a small portion distributed in the ND direction and at positions approximately 45° from the RD and TD directions. Fig. 6b shows that the normal direction of the α phase {1010} plane is mainly parallel to the ND direction and deviates from ND toward RD. Fig. 6c shows the {1120} pole figure, which is similar to the {1010} plane, with the normal direction of the {1120} plane mainly located within a range of approximately 5° deviation from ND toward RD.

Complete pole figures of the {0002}, {1010}, and {1120} planes of the α phase after unidirectional and cross rolling are shown in Fig. 7 [Figure 7: see original paper]. Fig. 7a indicates that for unidirectional rolling, the normal direction of the α phase {0002} plane is mainly parallel to the TD direction, with a pole intensity of 6.8. Fig. 7b shows that the {1010} plane normal direction is mainly distributed along the RD direction and at positions approximately 60° deviation from ND toward RD, with a small number of grains having {1010} plane normals parallel to the ND direction. Fig. 7c shows the {1120} pole figure, where the {1120} plane normal direction is mainly distributed at approximately 30° deviation from ND toward RD and in the RD direction. Figs. 7a-c indicate that unidirectional rolling exhibits primarily prismatic texture characteristics. The {0002} pole figure for cross rolling shows that poles are similarly located in the TD direction, with a pole intensity of 5.6 (Fig. 7d). Fig. 7e shows that the {1010} plane normal direction is mainly distributed at approximately 30° deviation from ND toward RD and in the RD direction. Fig. 7f shows the {1120} pole figure, where the {1120} plane normal direction is located at approximately 60° deviation from ND toward RD, with a small number of grains having {1120} plane normals parallel to the ND direction. Similar to unidirectional rolling, the plate after cross rolling still exhibits prismatic texture characteristics, but with weaker texture intensity than unidirectional rolling (Figs. 7d-f).

2.3 Plate Room Temperature Properties

The room temperature tensile properties along the rolling direction (RD) and transverse direction (TD) of TC1 plates after unidirectional and cross rolling are listed in Table 1 . The table shows that the transverse yield strength of both unidirectional and cross rolled plates is higher than the corresponding rolling direction strength, while the transverse ultimate tensile strength and elongation are not significantly different from the corresponding properties in the rolling direction.

The room temperature tensile properties along RD and TD of TC1 plates after unidirectional and cross rolling, followed by holding at 750 °C for 30 min and air cooling, are listed in Table 2 . Table 2 shows that after annealing, the plates still retain anisotropy. The transverse yield strength of both unidirectional and cross rolled plates remains higher than the rolling direction yield strength, while the difference between longitudinal and transverse ultimate tensile strength and elongation is not significant. Comparing the room temperature tensile data under the two rolling methods, within experimental error, the elongation of unidirectional rolled plates after annealing is slightly higher, while other data are not significantly different from cross rolled plates.

3.1 Effect of Rolling Deformation Process on Metallographic Microstructure

When TC1 alloy undergoes α phase transformation during cooling from the β phase region after PAM, a Widmanstätten structure forms (Fig. 2). During ingot breakdown rolling, deformation first begins at the phase transformation point. When the temperature drops to the two-phase region, the α phase undergoes large deformation, resulting in finer microstructure dimensions (Fig. 3). After breakdown rolling, both α colony size and lamellae thickness are significantly refined, thereby improving alloy plasticity and enhancing subsequent processing performance.

The effects of unidirectional rolling and cross rolling processes on titanium alloy microstructure have been reported in the titanium alloy system. Song et al. found that for TC4 alloy, the directionality of strip-shaped α phases is more severe under unidirectional rolling than under cross rolling. Zheng and Lei investigated the effects of one-time cross rolling and non-cross rolling processes on TC4 alloy microstructure. The results showed that the non-cross rolling process resulted in mostly strip-shaped microstructure with only a small amount of equiaxed α phases, while one-time cross hot rolling led to microstructure homogenization and improved strip-shaped microstructure. Gurao et al. studied the microstructure of a β titanium alloy under unidirectional rolling and multi-pass cross rolling processes, concluding that both processes produced rolling flow lines in titanium alloy microstructure. In unidirectional rolling, the rolling flow lines are basically parallel to the rolling direction, while in multi-pass cross rolling,

rolling flow lines in two directions are arranged in a cross pattern. In this study, after ingot breakdown rolling and rolling deformation (including unidirectional and cross rolling), α lamellae undergo distortion, fragmentation, and refinement under local shear stress (Fig. 4). The rolling plane of unidirectional rolled plates shows obviously aligned deformed α phases along the rolling direction (Fig. 4a). Due to different stress histories of α phases in different rolling modes, the alignment of α phases along the rolling direction is less obvious on the rolling plane of cross rolled plates (Fig. 4c). However, the microstructures on longitudinal sections of both processes are arranged along the deformation direction (Figs. 4b and d), which is consistent with results reported in references [13,15].

On the other hand, although the rolling temperature in this study was above the recrystallization temperature, the fast deformation rate prevented complete recrystallization of TC1 alloy microstructure, thus retaining a large amount of deformed microstructure. During subsequent static recrystallization annealing, the deformed lamellar α phases become equiaxed and grow (Fig. 5).

3.2 Effect of Rolling Deformation Process on Texture

During plate rolling, the main internal processes are plastic deformation dominated by dislocation movement and dynamic recrystallization dominated by recovery, nucleation, and grain growth. These processes occur simultaneously or alternately during rolling, thereby affecting the intensity and type of deformation texture. According to Philippe et al., the deviation of {0002} plane normals toward the TD direction is the result of coordination among $\{11\bar{2}3\}$ $<11\bar{2}2>$ compression, $\{11\bar{2}0\}$ $<11\bar{2}0>$ tensile twinning, and $\{10\bar{1}1\}$ $<10\bar{1}2>$ twinning systems. Therefore, in this study, after ingot breakdown rolling, the normal direction of α phase {0002} planes showed obvious deviation toward the TD direction (Fig. 6a). Considering that the breakdown temperature in this work was in the β transformation temperature range and there was no intermediate heating between passes, the relatively strong β deformation texture and dislocation substructure had an enhancing effect on the α orientation selection process. Consequently, the TD texture component of the plate after breakdown rolling is very strong (Fig. 6a). The texture component deviating 45° from the RD and TD directions results from orientation selection during the $\beta \to \alpha$ phase transformation due to titanium alloy breakdown rolling at the phase transformation temperature.

Generally, after rolling in the low-temperature region of the $\alpha+\beta$ two-phase zone, TC series titanium alloys exhibit mixed texture types of prismatic and basal textures, i.e., {0002} plane normals parallel to both TD and ND directions. Further research by Singh and Schwarzer showed that multi-pass cross rolling causes deviation of alloy {0002} plane normals from ND toward RD. However, in this study, regardless of unidirectional or cross rolling, the texture type was dominated by prismatic texture with mixed texture characteristics containing basal texture, and {0002} plane texture did not show obvious deviation toward RD (Fig. 7). This is because the number of cross rolling passes in this study was small, so the plates mainly exhibited unidirectional rolling texture characteristics. Nevertheless, the different rolling modes still resulted in weaker texture intensity for cross rolling compared with unidirectional rolling.

3.3 Effect of Rolling Deformation Process on Plate Room Temperature Properties

The room temperature properties of rolled plates are mainly affected by plate microstructure and texture. In this study, the microstructure morphologies of plates prepared by the two rolling processes were similar, so the room temperature property data were not significantly different (Table 1). However, for both unidirectional and cross rolling, the yield strength along the TD direction was greater than that along the RD direction. For titanium alloys, at room temperature, the critical resolved shear stress of prismatic slip is much smaller than that of other slip mechanisms. Both rolling deformation processes produced prismatic texture. When the stress axis is along the RD direction, prismatic slip is easily activated; when the stress axis is along the TD direction, the angle between the c-axis and stress axis is very small, making prismatic slip difficult to operate, and the deformation mechanism is dominated by more difficult-to-activate basal slip or <a+c> slip. This results in obvious yield strength anisotropy in plates. Texture has a significant effect on yield strength but little effect on ultimate tensile strength, which is consistent with research results by Zhu et al. on the tensile properties of pure Ti corresponding to different texture types.

After annealing at 750 °C, the α phases in plates prepared by both processes become equiaxed (Fig. 5), and the microstructures are similar. In terms of properties, plate plasticity is improved while yield strength and ultimate tensile strength are reduced. For titanium alloys, annealing cannot significantly change texture type, so the transverse yield strength of annealed plates remains significantly higher than the rolling direction yield strength.

Conclusions

1. The metallographic microstructure of plasma arc cold hearth melted ingots is Widmanstätten structure. After breakdown rolling at the β transformation temperature, the microstructure transforms to transformed β morphology, with reduced α colony size and α lamellae thickness. After two different rolling deformation processes in the $\alpha+\beta$ two-phase region following breakdown rolling, α colonies undergo distortion, fragmentation, and rearrangement. The deformed α phases in unidirectional rolled plates align more obviously along the rolling direction than those in cross rolled plates.

2. After breakdown rolling at the β transformation temperature, plates exhibit primarily prismatic texture. After subsequent rolling in the $\alpha+\beta$ two-phase region, plates prepared by both processes show mixed texture characteristics dominated by prismatic texture with basal texture components, while cross rolled plates have weaker texture intensity than unidirectional rolled plates.
3. Under both rolling deformation processes, the transverse yield strength of prepared plates is higher than the rolling direction yield strength, while ultimate tensile strength and elongation are basically similar. After annealing, plate strength decreases and elongation increases, while the transverse yield strength remains higher than the rolling direction yield strength.

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