INFLUENCE OF CYCLE PHASE TRANSFORMATION ON TEXTURE AND YIELD STRESS ANISOTROPY IN TITANIUM SHEET①

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ABSTRACT

The influence of cycle phase transformation $\alpha \to \beta \to \alpha$ process on the texture transition and yield stress anisotropy in cold rolled commercially pure titanium (C. P. Ti) sheet was investigated by using the crystallite orientation distribution function (CODF) analysis. The results show that after three cycles of phase transformation, annealing texture component $(\bar{1}013)[1\bar{2}10]$ is almost suppressed and the main transformed texture consists of a $[\bar{2}110] \parallel$ ND fibre texture (ND means the sheet normal direction) and several basal orientation peaks such as $(0002)[3\bar{2}\bar{1}0]$, $(0002)[1\bar{3}20]$ and $(0002)[2\bar{3}10]$ etc. And the original rolling texture $(\bar{2}115)[0\bar{1}10]$ is developed into a partial $[\bar{2}115] \parallel$ ND or $[\bar{2}117] \parallel$ ND fibre texture. All these transformed orientation features provide the lowest anisotropy yield stress.

Key words: cycle phase transformation texture crystallite orientation distribution function titanium

1 INTRODUCTION

It is well known that crystallographic texture can lead to a pronounced anisotropy in mechanical properties, especially for the hexagonal close packed (h. c. p.) metals such as α- titanium due to its restricted slip behaviour[1, 2]. Improvement in anisotropy of mechanical properties could be realized through texture control[3]. Several papers had shown the formation of rolling and annealing textures in titanium sheets[2-4], but very little has been reported of the influence of phase transformation on the texture transition and mechanical property in titanium[5]. Previous work showed that annealing just above the $\alpha \to \beta$ allotropic transformation temperature resulted in an essentially complete return to the α- annealing (550~700 ℃) texture. If the annealing temperature in the β- phase was sufficiently high, >1 100 ℃ for zirconium, then a reorientation due to the $\alpha \to \beta \to \alpha$ sequence did occur[6]. In the previous work, after different temperature, cooling rate and cycle number of phase transformation treatment, the orientation distribution feature and anisotropy in commercially pure titanium (C. P. Ti) sheets have been studied in detail[7]. The results show that, in cold rolled C. P. Ti sheet, annealing just above the $\alpha \to \beta$ allotropic transformation temperature about 50 ℃ will lead to the texture changes. As the cycle number increased, the main orientation distribution changed but irrespective of the heating-cooling rates[7]. In this paper, the transformation texture and yield stress anisotropy in C. P. Ti sheet due to cycle phase transformation $\alpha \to \beta \to \alpha$ process have been investigated in detail so that a good texture control process is realized.

① Received Dec. 12, 1993; accepted in revised form Mar. 2, 1994

2 EXPERIMENTAL

The as-received material was C. P. Ti plate hot-rolled at 850 ℃ and annealed at 760 ℃ for 1 h and cooled in air with a thickness of 8 mm, containing (in wt.-%) 0.13 O, 0.11 Fe, 0.02 C, 0.002 H, 0.02 N, and less than 0.04 Si. Then the specimens were cold rolled 86% reduction in thickness to a final thickness 1.1 mm followed by different treatments. Specimen A was annealed at 700 ℃ for 1 h, then air-cooled. Specimen B was heated to 950 ℃ (above the $\alpha \rightarrow \beta$ polymorphous transformation temperature about 50 ℃) and then air-cooled for 3 cycles so that the cycle phase transformation $\alpha \rightarrow \beta \rightarrow \alpha$ is realized. Specimen C was the specimen conducted by 3 cycle phase transformations and subsequently cold rolled about 20% reduction in thickness and then annealed at 700 ℃ for 1 h to produce equiaxed recrystallized grains.

The samples for texture measurments were prepared from the midsections of the sheet by mechanical and chemical polishing. Four different pole figures (0002), $\{10\bar{1}0\}$, $\{10\bar{1}1\}$ and $\{10\bar{1}2\}$ were determined employing CoK_α radiation. From these results, the CODF were calculated according to the spherical harmonic analysis proposed by Roe[7]. Contoured plots of CODF were produced for those constant φ sections in the volume of Euler space $0 \leqslant \psi \leqslant \pi/2$, $0 \leqslant \theta \leqslant \pi/2$, $0 \leqslant \varphi \leqslant \pi/3$. In the case of h. c. p. metals, most of the important orientations are located on $\varphi = 0°$ and $\varphi = 30°$ sections[2]. Fig. 1 shows the positions of ideal orientations and important fibre textures on these sections (ND, RD and TD represent the normal, rolling and transverse directions of the sheet respectively).

The yield stress was measured with specimens taken at angles of 0°, 45° and 90° from the rolling direction according to the ASTM testing standards E8—87a.

3 RESULTS

3.1 *Microstructure*

Fig. 2 shows the microstructures of specimens A, B and C respectively. It can be seen that the typical Widmanstätten lamellar structure of specimen B is developed after 3 cycle phase transformations. And in specimen C an equiaxial structure similar to that observed in specimen A is observed after little cold reduction and annealed at 700 ℃ for 1 h.

3.2 *Annealing and Transformation Textures*

Fig. 3 presents the $\varphi = 0°$ and $\varphi = 30°$ sections of CODF observed in specimen as cold rolled 86%

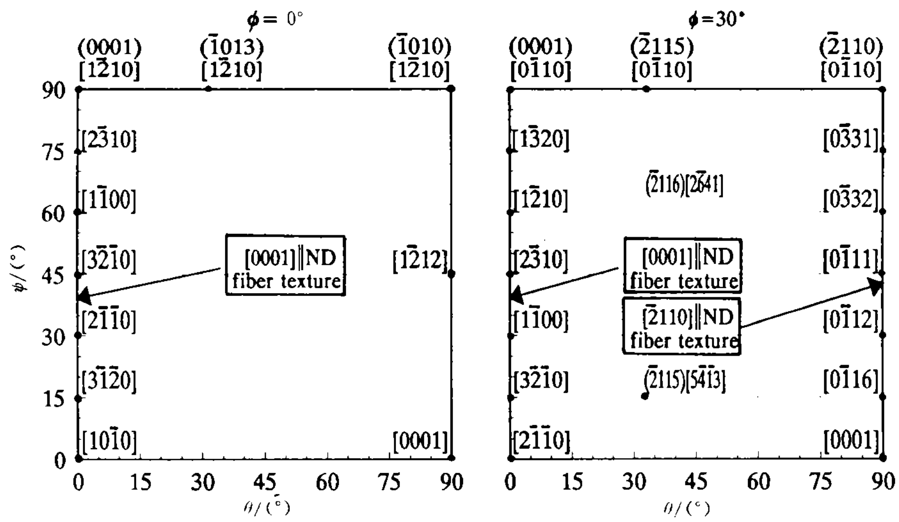

Fig. 1 Positions of ideal orientations and fibre textures on $\varphi = 0°$ and $\varphi = 30°$ sections of CODF

reduction in thickness. It can be seen that the main cold rolling texture component is $(\bar{2}115)[0110]$. And the $\varphi = 0°$ and $\varphi = 30°$ sections of CODF observed in specimen A are illustrated in Fig. 4. By comparing with Fig. 3, it can be found that the annealing texture in C. P. Ti sheet consists of the orientation component $(10\bar{1}3)[\bar{1}2\bar{1}0]$ besides the cold rolling texture component $(\bar{2}116)[2\bar{6}41]$.

Fig. 5 shows the $\varphi = 0°$ and 30° sections of CODF observed in specimen B. After 3 cycles of phase transformation process, the texture mainly consists of two types of orientations i. e. $[\bar{2}110]$‖ ND fibre texture and basal components such as $(0002)[3210]$ etc. which can not be observed in cold rolled and annealed specimens (see Fig. 2 and Fig. 3). It should be also noted that after 3 cycles of phase transformation (Fig. 5) the original rolling texture $(\bar{2}115)[0\bar{1}10]$ is transformed into orientation components such as $(\bar{2}115)[5\bar{4}\bar{1}3]$, $(\bar{2}115)[0\bar{1}10]$ and $(\bar{2}116)[2\bar{3}11]$ etc. concentrated at $\theta = 34°$ line on $\varphi = 30°$ section of CODF existing the trend to develop into a $[\bar{2}115]$‖ ND partial fibre

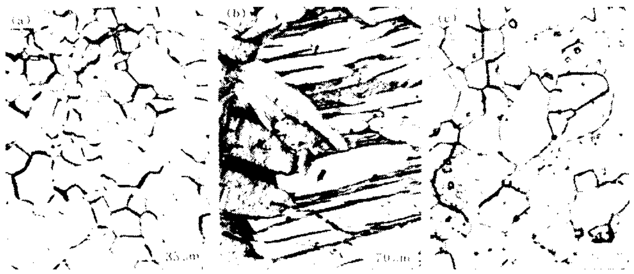

Fig. 2 Micrographs observed in specimens A(a) (cold rolled 86% reduction in thickness and then annealed at 700 ℃ for 1 h), B(b) (cold rolled 86% reduction in thickness and conducted by cycle phase transformation treatment) and c(c) (cold rolled 86% and conducted by cycle phase transformation treatment then cold rolled 20% and annealed at 700 ℃ for 1 h)

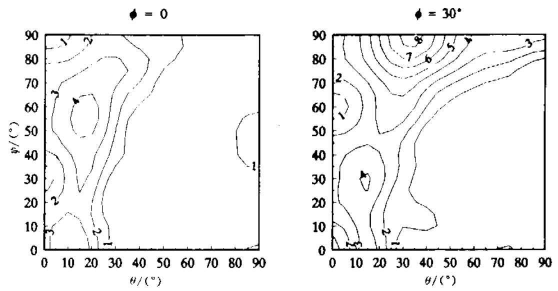

Fig. 3 $\varphi = 0°$ and 30° sections of CODF observed in specimen as cold rolled 86% reduction in thickness
(The maximum orientation density is 8.84 times random.)

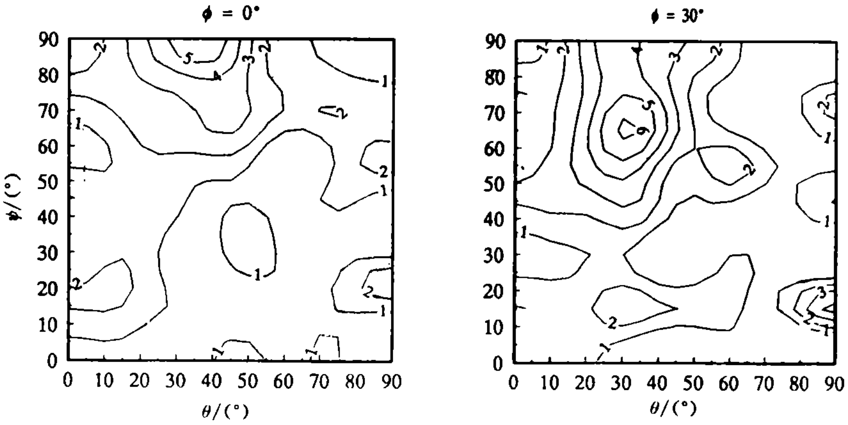

Fig. 4 $\varphi = 0°$ **and** $30°$ **sections of CODF observed in specimen A**
(The maximum orientation density is 6. 62 times random.)

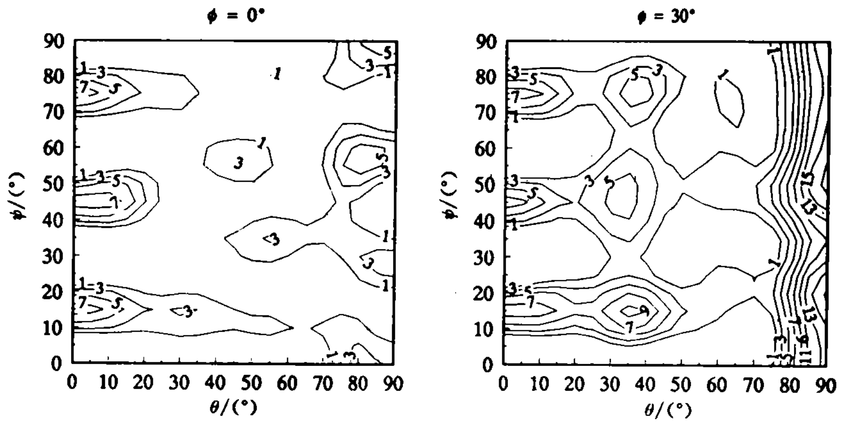

Fig. 5 $\varphi = 0°$ **and** $30°$ **sections of CODF observed in specimen B**
(The maximum orientation density is 17. 82 times random.)

texture. In order to improve the Widmanstätten lamellar structure, little cold rolling reduction is conducted after the cycle phase transformation treatment.

Fig. 6 shows the $\varphi = 0°$ and $\varphi = 30°$ sections of CODF observed in specimen C. The orientation distribution feature is very similar to that developed in specimen B but without basal texture. And the $(\bar{2}117)$ orientation peaks lying on $\theta = 25°$ line at $\psi = 0°$, $30°$, $60°$ and $90°$ on $\varphi = 30°$ section tend to form a $[\bar{2}117] \parallel$ ND partial fibre texture.

3. 3 *Yield Stress Anisotropy*

Fig. 7 shows the anisotropies of the 0. 2% proof yield stress($\sigma_{0.2}$) of specimens A, B and C. It is indicated that the anisotropy of the yield stress of specimen A is quite large, the difference between TD and RD is as much as 50 MPa. However, in specimen B, the anisotropy of yield stress is highly minimized due to the process of cycle phase transformation. And after 20% cold rolling reduction and annealed at 700 ℃ for 1 h, the specimen C shows a good isotropy trend of yield stress.

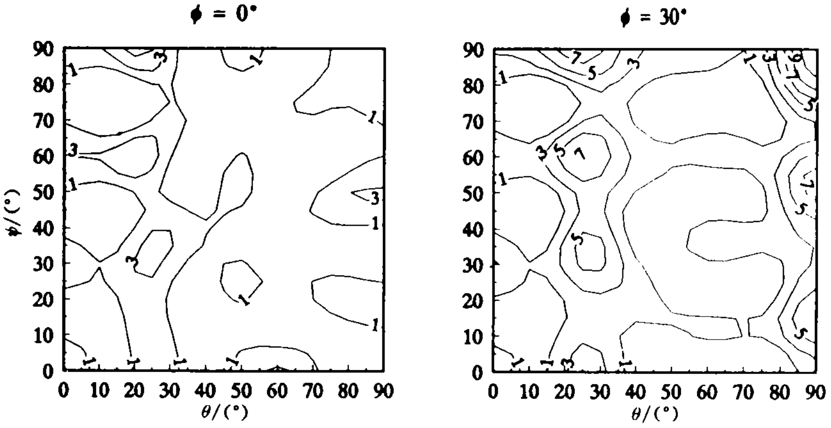

Fig. 6 $\varphi = 0°$ **and** $30°$ **sections of CODF observed in specimen C**
(The maximum orientation density is 13.03 times random.)

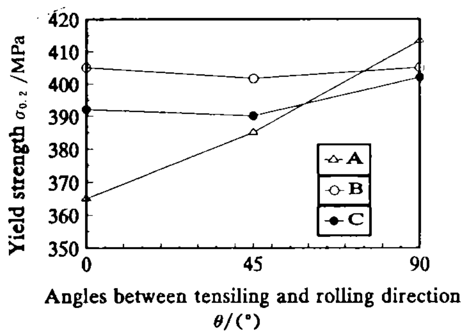

Fig. 7 Anisotropies of $\sigma_{0.2}$ observed in specimens A, B and C

4 DISCUSSION

The main texture in C. P. Ti sheet cold rolled 86% and annealed at 700 ℃ for 1 h consists of component $(\bar{1}013)[1\bar{2}10]$ and $(\bar{2}116)[2\bar{6}41]$ (Fig. 4). And texture $(\bar{1}013)[1\bar{2}10]$ is the recrystallization texture which is preferentially developed at the expense of the cold rolling texture such as $(\bar{2}115)[0\bar{1}10]$ etc. The similar phenomena were also observed by Naka *et al*[9].

When a phase transformation takes place in a metal, there is frequently an orientation relationship between the parent and product phases[5]. For titanium and its alloys, during double transformation $\alpha \rightarrow \beta \rightarrow \alpha$, Burgers' relationship[10], namely $\{110\}_\beta \| \{0001\}_\alpha$ and $\langle 111\rangle_\beta \| \langle 11\bar{2}0\rangle_\alpha$ is realized. By examining the phase transformation in α- Zr metal, Glen and Pugh[11] pointed out that starting with a single component of texture in α- phase, a total of 72 reorientations are possible after the double transformation $\alpha \rightarrow \beta \rightarrow \alpha$, although only 57 of these are measurable. And from these they also deduced that repeated cycling through the transformation sequence should result in a random texture. In fact, present results show that in C. P. Ti only the orientations with the product α phase (0001) at 60° to original (0001) have been preferentially developed, and no new orientations should appear on continued heating and cooling through the transformation temperature. On the other hand, due to the reversibility of orientations, original rolling texture $(\bar{2}115)[0\bar{1}10]$ etc. reappears and develops into a partial $[\bar{2}115] \|$ ND or $[\bar{2}117] \|$ ND fibre texture.

From Fig. 7 it can be seen that in cold rolled and annealed C. P. Ti sheet pronounced yield stress anisotropy is developed. However, the anisotropy of yield stress in specimens B and C can be highly minimized due to the transformed orientation distribution as shown in Fig. 5 and Fig. 6. These phenomena can be explained by the resolved shear stress for slip and twinning in h. c. p. metals as shown in Fig. 8. Since the textures $(\bar{2}115)[0\bar{1}10]$ and $(\bar{1}013)[1\bar{2}10]$ are related by a rotation of 30° about the [0002] direction, and these two textures make the c-axis inclined aboout 32° from ND to TD. So when the tensile stress axis is along RD, the active deformation mechanism would be $\{1\bar{1}00\}\langle\bar{1}\bar{1}20\rangle$ prismatic slip deformation mode for the η angle close to 90° (Fig. 8). On the other hand, when the tensile stress axis is along direction TD (in this case η angle is about $30\sim40°$), deformation would be accommodated by the operation of the more difficult basal $(0002)\langle1\bar{2}10\rangle$ or $(1\bar{2}11)[11\bar{2}3]$ $\langle c+a\rangle$ slip modes (Fig. 8), since the critical resolved shear stress (c. r. s. s.) for basal slip $(0002)\langle1\bar{2}10\rangle$ is about four times the c. r. s. s. for prismatic slip $\{1\bar{1}00\}\langle\bar{1}\bar{1}20\rangle$ at room temperature[12]. These are the nature that the yield stresses along TD are always greater than those along RD for cold rolled and annealed C. P. Ti sheets.

For specimens B and C, due to the fact that fibre texture $[\bar{2}110]\parallel$ ND, the c-axis $[0002]$ of h. c. p. Ti is normal to ND, and the η angle (Fig. 8) varies randomly between 0° and 90° when the tensile stress is loaded along any angle between 0° and 90° from RD, so that fibre texture can present the equal probability to activise the deformation mechanisms.

Similarly the fibre texture $[\bar{2}115]\parallel$ ND or $[\bar{2}117]\parallel$ ND can also give the equal probability to activise the deformation mechanisms. In the case of basal (0002) texture, η angle equals to 90° while loading at any direction on the sheet plane, the deformation resistance is always the same. So that specimens B and C show the lowest anisotropy in yielding stress.

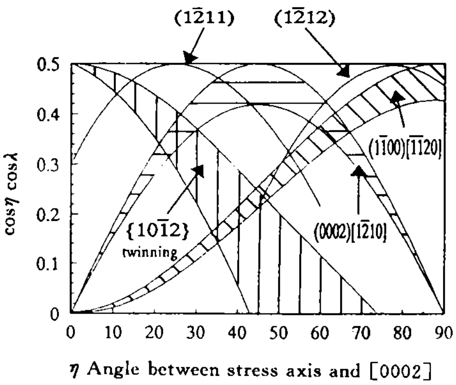

Fig. 8 Orientation dependence of resolved shear stress for slip and twinning in h. c. p. titanium

5 CONCLUSIONS

(1) After 3 cycles of $\alpha\rightarrow\beta\rightarrow\alpha$ phase transformation of cold rolled C. P. Ti sheet, the transformation texture mainly consists of the $[\bar{2}110]\parallel$ ND fibre texture and several basal peaks such as $(0002)[3\bar{2}\bar{1}0]$, $(0002)[1\bar{3}20]$ and $(0002)[2\bar{3}10]$ etc. The cold rolling texture component $(\bar{2}115)[0\bar{1}10]$ is transformed into several $(\bar{2}115)$ orientation peaks which form a partial $[\bar{2}115]\parallel$ ND fibre texture.

(2) After 3 cycles of $\alpha\rightarrow\beta\rightarrow\alpha$ phase transformation and then cold rolled 20% and annealed at 700 ℃ for 1 h, the orientation distribution is characterized by $[\bar{2}110]\parallel$ ND fibre texture and $[\bar{2}117]\parallel$ ND partial fibre texture.

(3) The yield stress exhibits a pronounced anisotropic trend associated with development of cold rolling texture $(\bar{2}115)[0\bar{1}10]$ and annealing texture $(\bar{1}013)[1\bar{2}10]$ after cold rolled 86% and annealed at 700 ℃ for 1 h in C. P. Ti sheet.

(4) After $\alpha\rightarrow\beta\rightarrow\alpha$ cycle phase transformation process, the anisotropy of the yield stress is significantly minimized due to the development of the transformation texture such as the fibre texture $[\bar{2}110]\parallel$ ND and basal (0002) orientations.

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