Influences of cold rolling, recrystallization and surface effect on the transformation textures in a TA10 titanium alloy

Yang P1, Wei Z G1, Gu X F1, Cui F E2 and Mao W M1

1School of Mater. Sci.& Eng., Uni. of Sci. and Tech. Beijing, Beijing, 100083, China
2Institute of Advanced Mater. and Tech., Uni. of Sci. and Tech. Beijing, Beijing, 100083, China

Abstract. A transformation treatment based on surface effect induced transformation is applied to cold rolled TA10 titanium alloy sheets to change and control transformation texture. This kind of treatment can promote the α-phase nucleation at sheet surface region during cooling and control the growth of surface α-grains into center layer of sheet. The results indicate that as the heating temperature increased, the transformation textures in the final HCP-structured TA10 sheets changed in helium atmosphere from the recrystallization type texture of <11-20>/RD to the transformation type texture of <11-20>/ND. The textures in sheets treated at low transformation temperature of 1000°C reveal texture memory effect, while those treated at high transformation temperature of 1100°C illustrate the effects of both transformation strain and anisotropy in elastic modules of HCP titanium crystals. The surface effect is promoted by cooling gas of helium, which leads to layered structures along sheet thickness direction. The surface region often shows small equiaxed grains with recrystallization orientations, while the center layer reveals coarse grains with either plate-like or equiaxed grain morphology corresponding to transformation orientation or recrystallization orientation, respectively. The special grain boundaries in plate-like α variants are different from those in equiaxed grains. These differences in morphologies, sizes and orientations are explained in terms of the mechanism change of the factors affecting variant selection.

1. Introduction
Transformation textures in high symmetrical metallic materials obeying orientation relationships (OR) such as the K-S or Burgers OR are generally weak due to the more crystallographically equivalent variants. In special cases, however, transformation texture may be sharper because of strong variant selections. Many models are suggested for the variant selection leading to stronger transformation texture as summarized in [1], such as the special dislocation configurations related with deformation, the special anisotropic elastic strains or transformation strain. The occurrence of strong transformation texture is of both theoretical and practical significances because transformation texture is normally different to deformation or recrystallization textures, thus to demonstrate special physical or mechanical properties. The so-called surface effect induced transformation texture present in electrical steels, namely differently oriented grains nucleate firstly at sheet surface region due to either the anisotropies in strain energy or in surface energy under H2 atmosphere, can be an example of producing favorite {100} texture for a magnetic property improvement [2,3]. Our previous work indicates that the surface effect induced transformation texture of <11-20>/RD with columnar grained structure can be produced...
in pure titanium sheets in Ar atmosphere [4], this work reports the evolution of microstructure and textures in transformation-treated TA10 sheets in helium atmosphere which has a 10 times higher thermal conductivity than that of Ar atmosphere.

2. Materials and processing

The materials used for this study is a commercial HCP-structured TA10 titanium sheets with nominal composition of Ti-0.3Mo-0.8Ni in mass percent. Starting material is a hot rolled and annealed sheet with thickness of roughly 2mm. Then it was cold rolled for 60%-80% reductions and sample was heated quickly to different temperatures above or below the critical transformation temperature ($T_c=910^\circ$C which was measured using DSC method at a heating and cooling rate of 500$^\circ$C/h). Helium gas (He) was used during transformation treatment and compared with those in Ar [4]. The samples for EBSD measurement were electropolished with a polishing solution consisting of 5% perchloric acid and 95% ethyl alcohol with a voltage of 30 V for 30s at room temperature. The EBSD system of Oxford instrument mounted on an SEM Zeiss-FEG under 20KV is applied to reveal microstructure and texture. The allowance of 15$^\circ$ deviation angle is set to determine the area fractions of each texture component.

3. Results and analyses

3.1. Recrystallization texture

For the purpose of comparison the recrystallization texture is firstly determined and shown in figure 1 of TA10 sheet after 80% cold rolling and 800$^\circ$C 15min annealing. As seen in most cold and warm rolled and annealed Ti sheets, a typical TD-rotated basal texture $\{01-13\}<2110>$ is present with an average grain size of 46.6$\mu$m and uniform equiaxed morphology. The misorientation angle distribution shown in figure 1c doesn’t reveal any special peaks related to variants due to Burgers OR.

![EBSD maps of 80% cold-rolled TA10 sheet with 0.4 mm thickness following recrystallization annealing at 800°C for 15min, (a) orientation map shown in IPF-ND; levels:1,2,3…(b) pole figures; (c) misorientation angle distribution](image)

**Figure 1.** EBSD maps of 80% cold-rolled TA10 sheet with 0.4 mm thickness following recrystallization annealing at 800°C for 15min, (a) orientation map shown in IPF-ND; levels:1,2,3…(b) pole figures; (c) misorientation angle distribution

3.2. Influence of heating temperature

Figures 2-4 show the EBSD maps of TA10 sheets subjected to 80% cold rolling and subsequent heating in He gas for 1-3min to 920$^\circ$C, 1000$^\circ$C and 1100$^\circ$C ($T_c=910^\circ$C) respectively. The cooling rate during transformation is 300$^\circ$C/h and final thickness is 0.4mm. It is seen that at all temperatures grain sizes are un-uniform, small grains formed at surface region and coarse grains developed in center layer. The grain morphologies are different. At 1100$^\circ$C (figure 4) plate-like grains/variants (green color) with $<11-20>$//ND orientation are easily formed and their grain boundaries tend to be parallel to ND. Concerning grain boundary types it is seen that at low heating temperature (figure 2) the 5 special misorientation angles and axes among 12 variants (they are listed in the up-right of figure 2) which are related to
variants for Burgers OR are less, whereas at 1100°C, the <11-20>60° grain boundaries increased from 2.1% to 15.3%. This indicates that the formation of corresponding variants can reduce transformation strain very effectively. 15.8% grains are in <11-20>//ND oriented (green color) in area fractions and 9.53% are <10-10>//ND oriented at 920°C, while 40.8% and 20.6% are present for two kinds of orientations at 1100°C totally amounting to 61.4%. Rotated basal recrystallization texture is still the main texture component as seen in figure 2c and figure 2d and they can be both small grains at surface region and coarse grains in center layer. The arrows in figure 2a, 3a, 4a reveal that a surface small grain with either of two kinds of orientations can grow into center layer to become a coarse grain. It is noted that the rotated basal texture here is regarded as transformation texture rather than recrystallization texture because grains are subjected to transformation, it is a texture memory effect.

![Figure 2. EBSD maps of 80% cold-rolled TA10 sheet with 0.4 mm thickness and heated to 920°C (Tc=910°C) for 3 min, and then cooled with a rate of 300°C /h, (a) orientation map shown in IPF-ND; (b) Kikuchi band quality map with 5 special grain boundaries in figure 2a; (c) pole figures; (d) misorientation angle distribution](image)

![Figure 3. EBSD maps of 80% cold-rolled TA10 sheet with 0.4 mm thickness annealed at 1000°C for 1min, (a) orientation map shown in IPF-ND; (b) Kikuchi band quality map with 5 special grain boundaries in figure 3a; (c) pole figures; (d) misorientation angle distribution](image)
3.3. Influence of rolling reduction

Figure 5 and figure 6 show the EBSD maps of TA10 sheet subjected to 60% cold rolling and subsequent 1000°C and 1100°C ($T_c=910^\circ C$) annealing in He for 1min. The final thickness is 0.4mm (initial thickness is 1mm). By comparison to figure 3 and figure 4 of 80% rolled and transformation treated sheets, it is seen that there is no large difference between them and the main difference in grain morphologies and orientation distribution are due to heating temperature. At medium heating temperature of 1000°C, the $<11\overline{2}0>$/ND texture is slightly stronger than the rotated basal texture and 28.5% grains in area fractions are $<11\overline{2}0>$/ND oriented (green color) and 9.37% are $<10\overline{1}0>$/ND oriented.

In figure 6 of transformed sheet at 1100°C, 44.1% grains are in $<11\overline{2}0>/ND$ orientation (green color) in area fractions and 15.9% are $<10\overline{1}0>/ND$ oriented totally amounting to 57.05%. The $<11\overline{2}0>-60^\circ$ grain boundaries (red lines in figure 6b) increased to 18.6%. Figure 6e exhibits the 3 variants orientations
in pole figures within a round large grain boundary as shown in an arrow in figure 6a and it shows that these 3 variants have a common [11-20] direction parallel to ND.

Figure 6. EBSD maps of 60% cold-rolled TA10 sheet with 0.4 mm thickness annealed at 1100°C for 1 min, (a) orientation map shown in IPF-ND; (b) Kikuchi band quality map with special grain boundaries in figure 6a; (c) pole figures; (d) misorientation angle distribution; (e) pole figure of 3 variants within a large round grain boundary as shown by the left arrow in figure 6a

4. Discussion
Based on the above presented EBSD data it is clearly seen that surface effect plays important role by changing transformation texture from recrystallization type to transformation type. Heating temperature is also a key factor for controlling transformation texture because it changes the grain sizes of β-phase. If the grain size in β-phase is small at low heating temperature, namely slightly above critical transformation temperature, strong variant selection and less variant, possibly only one variant, may nucleate leading to texture memory effects and retaining of recrystallization texture as transformation texture. At high heating temperature, however, β-phase grows to large sizes and residual stress or crystal defects are released, therefore more variants are possible to nucleate at grain boundaries obeying Burgers OR, at the same time the high flow rate of helium gas of 8 Litre/min with high thermal conductivity maintains the nucleation in surface region, thus promoting <11-20>//ND grain formation and moreover the 3 variants with same <11-20> parallel to ND can more effectively reduce transformation strain which can be easily confirmed by calculation and comparison of transformation strain tensors between one variant and three variants. The preferred nucleation of <11-20>//ND is ascribed to the lowest elastic module in HCP titanium, the hardest direction is <0001> in Ti crystals. It is noted that the <11-20>//ND grains are rather less before the transformation from α to β phase during heating.

Protecting atmosphere is also an important factor. In our previous work [4] we used the less thermally conductive Ar and only obtained surface induced microstructure of two layers of columnar grains, but the resulted texture is a retained recrystallization texture of <11-20>//RD, namely only texture memory
effect is activated. The higher thermal conductivity of He gas can induce 3 plate-like variants building a round normal grain boundary in which a lot of <11-20>-60° special grain boundaries are present. This means that He gas promotes <11-20>/ND texture more effectively than Ar gas does.

Finally it should be noted that in our previous work [5], the similar <11-20>/CA (compression axis) as the <11-20>/ND texture in this work is observed during compression of β-phase at high temperature with subsequent water quenching. The same transformation texture of <11-20>/CA or ND is observed in two cases, but the processing routes are different, one is the compression of β-phase and let it transform into α-phase and the other is the cold rolling of α-phase and heat it quickly and let it transform according to α→β→α sequence. In the first case there is no surface effect and the <11-20> texture is explained in terms of the release of transformation strain/stress during compression because the basal plane spacing of {0001} in α-phase is larger than that of {110} in BCC β-phase. In the second case of this work surface effect is activated by blowing He gas on the sheet surface to promote the preferred nucleation at surface region and further the preferred growth into center layer, thus the underlying mechanisms for two cases are different.

5. Conclusions
1) The TA10 titanium sheet shows a typical TD-rotated basal recrystallization texture {01-13}<2110> below transformation temperature. At low heating temperature above Tc the transformation texture is similar to the recrystallization texture, showing the so-called texture memory effect, although microstructure is totally changed from uniform equiaxed grains to bi-grain sized microstructure with small grains locating at surface region.
2) At high heating temperature of 1100°C dominant <11-20>/ND texture is present with plate-like variants and their boundaries tending to be parallel to ND. The typical 3 <11-20>/ND variants show a common [11-20] axis towards ND. This feature is ascribed to the surface effect-induced transformation and the soft <11-20> direction with lowest elastic module. Over 50% grains in area fraction can be <11-20> or <1-100>/ND oriented.
3) At medium heating temperature of 1000°C, there exists a competition between rotated basal texture and prismatic texture of <11-20>/ND. The resulted texture is in general weak and microstructure is rather inhomogeneous consisting in the small grains at surface region with recrystallization texture orientation, the coarse round grains grown from surface region with recrystallization texture orientation and the plate-like grains also grown from surface region with prismatic texture orientations.
4) Rolling reduction didn’t play larger role than heating temperature. High thermal conductive helium flow promotes plate-like variant formation more effectively in comparison to Ar atmosphere.

Acknowledgments
This work is finally supported by the National Natural Science Foundation of China (No. 51771024 and 51571024).

References
[1] Tomida T 2018 Variant selection mechanism by elastic anisotropy and double K-S relation for transformation texture in steel; difference between martensite and ferrite Acta Materialia. 146 25–41
[2] Sung J K, Lee D N, Wang D H and Koo Y M 2011 Efficient generation of cube on-face crystallographic texture in iron and its alloys ISIJ Int. 51 284–90
[3] Zhang L W, Yang P, Wang J H and Mao W M 2016 Transformation of {100} texture induced by surface effect in ultra-low carbon electrical steel J Mater Sci. 51 8087–97
[4] Li K and Yang P 2018 Texture control of pure titanium sheet by the surface effect during phase transformation Metals. 8(5) 358
[5] Li K and Yang P 2016 Interaction among deformation, recrystallization and phase transformation of TA2 pure titanium during hot compression Trans. Nonferrous Met. Soc. China. 26 1863–70