Effect of Twinning on the Deformation Behavior of Textured Sheets of Pure Titanium in Uniaxial Tensile Test

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In this experiment, the uniaxial tensile tests were carried out in four differently textured sheets of pure titanium. The sheets have the texture, some of which show the quite different pole figures and some of which show the quite different relation of the orientation between neighboring grains in spite of showing the similar pole figure. The deformation behavior of these sheets, those were, for example, the anisotropy, that the deformation twinning occur or not, twin systems and ridging, were studied particularly by considering the effect of the orientational relation between neighboring grains and of the manner of the occurrence of the deformation twinning.

The twin systems and the manner of the occurrence of the deformation twinning were classified in three types according to the texture and the stress condition.
1. When the unevenness in the connection with the orientational relation between neighboring grains generate, the tensile or compressive deformation twinning due to the stress condition occurs.
2. When the <0001> orientation of the grain is nearly the direction of the maximum principal stress, which is the tensile direction in this case, the tensile deformation twinning occurs.
3. When the grain deforms to the <0001> direction in order to conform to the deformation of surrounding grains, the deformation twinning occurs.

The stress-strain curves are influenced by the deformation twinning. On one hand, the yield strength as the 0.2% proof stress depends principally on the orientational relation between the tensile direction and the prismatic slip system of the preferred orientation deduced from the pole figures. On the other, the work hardening rate after yielding is influenced not only by such an orientational relation but also largely by the deformation twinning and the orientational relation between the tensile direction and the <0001> orientation of the twin, and furthermore by the orientational relation between the neighboring grains. Especially, when the <0001> orientation of the deformation twin is close to the direction of the maximum principal stress, which is the tensile direction in this experiment, the flow stress and thus the work hardening rate increase.

Keywords: titanium, uniaxial tensile test, deformation twinning, texture, orientational relation between neighboring grains

I. Introduction

Pure titanium has a hcp structure at room temperature. Its main slip systems are \{10\overline{1}0\} <11\overline{2}0>, \{10\overline{1}1\} <11\overline{2}0> and \{0001\} <\overline{1}1\overline{2}0\>\(^\text{(1)}\). Slip directions of all the slip systems are <11\overline{2}0> on the basal plane. Therefore, it is difficult to attribute plastic deformation to slip alone and deformation twinning would play an important role in the deformation. Various workers have reported the effects of deformation twinning on the deformation behavior of pure titanium sheets in terms of the amounts of deformation twins\(^\text{(2)(3)}\). However, little has been known about the role of deformation twinning in connection with the twin systems, the nucleation of deformation twinning, textures and stress conditions\(^\text{(4)(5)}\).

In pure titanium sheets which have the conventional cold-rolled and recrystallization texture as shown in Fig. 1 (process 1), the amount of deformation twinning and thus the work hardening rate are higher in the tensile deformation parallel to the rolling direction than that parallel to the transverse one\(^\text{(2)(3)(5)}\). However, even if the sheets, (process 1) are regarded as a bicrystal with the preferred orientation of such a texture, it is difficult to explain

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the nucleation of a large amount of deformation twinning only in the tensile deformation to the rolling direction. In order to understand the phenomenon, it is very significant to study the effect not only of the texture represented by the pole figure but also of the relations among the deformation twinning, the stress condition and the orientational relation between the neighboring grains.

In the present work four differently textured titanium sheets were used; their textures were those with different pole figures and those with different orientational relations between neighboring grains but with similar pole figures. The deformation behavior of these sheets, e.g., the anisotropy, the presence of deformation twinning, twin systems and ridging, were studied considering the effect of the orientational relation between neighboring grains and of the nucleation of deformation twinning.

II. Experimental

Figure 1 shows the \{1120\} pole figures of titanium sheets used in the present experiments. All sheets were made of a hot-rolled plate 5 mm thick by rolling. The sheet of process 1 was rolled unidirectionally at 873 K. The sheet of process 2 was rolled unidirectionally by about 77% at room temperature using the 2-high rolling mill, the top roll of which had

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**Fig. 1** \{1120\} pole figures.
numerous V-shape grooves in the circumference direction and the bottom roll was a conventional smooth roll\(^6\). The workpiece was turned upside-down every pass. While the top surface was indentated by the top roll, the bottom one was smoothed by the bottom roll. The sheet was then finished by smooth roll of the same rolling mill that was used in process 1 at room temperature. The sheet of process 3 was rolled unidirectionally at 1253 K and that of process 4 was cross-rolled at 873 K. The total thickness reduction of all the sheets was about 84%. The rolled sheets were pickled and annealed in vacuum for 7.2 ks at 1073 K. Thickness of specimen for tensile tests was about 0.8 mm.

The \(\{11\bar{2}0\}\) pole figures of sheets of process 1 and 2 in Fig. 1 are very similar. The \(\langle11\bar{2}0\rangle\) orientation of the main component is parallel to the rolling direction of the sheet and the \(\langle0001\rangle\) orientation is rocked \(\pm \pi/6\) from the sheet normal toward the transverse direction. Such a texture is typical of the cold-rolled and recrystallization one of pure titanium\(^7\). Although the textures of both sheets resemble each other, there is a significant difference in microstructure. Figure 2 shows the micrograph of the section normal to the rolling direction of the sheet of process 2. The grains whose c-axis tilts to the same direction from the sheet normal toward the transverse direction form a colony. Such a aggregate state of the grains is quite different from that of the sheet of process 1. Two kinds of the colonies penetrate through the sheet thickness and are arranged alternately, so that this sheet is suitable for the model of the sheet of process 1.

The pole figure for the sheet of process 3 shows a great scatter of orientations. However, its texture is characterized by the preferred orientation of \(\langle11\bar{2}0\rangle\) parallel to the rolling direction and \(\langle0001\rangle\) parallel to the transverse one. The sheet of process 4 has a fiber texture with the fiber axis being \(\langle0001\rangle\) normal to the sheet plane. The sheets of processes 3 and 4 have the textures which are quite different from the conventional cold-rolled and recrystallization ones.

Uniaxial tensile tests were carried out in four differently textured titanium sheets. Tensile specimens were cut at 0, \(\pi/4\) and \(\pi/2\) to the rolling direction. The specimens were 3 mm in width and 9 mm in length of the parallel portion, the tensile test speed being \(8.3 \times 10^{-3}\) mm/s. At every 0.5 mm elongation between the chacks, the strains in the longitudinal and lateral directions and the cross-sectional areas were measured. The orientation of individual grains was measured by the etch pit method\(^8\). The effect of the deformation twinning and the orientational relation between the neighboring grains on the deformation behavior of textured titanium sheets was determined from the etch pits formed.

Fig. 2 Micrograph of the section normal to R. D. of the sheet of process 2. The colony of the grains having the same \(\langle0001\rangle\) orientation.

Fig. 3 Reciprocal comparison of the \(r\) value among the process and the tensile directions.
- \(R\): Tensile tested at 0 to the rolling direction.
- \(I\): Tensile tested at \(\pi/4\) to the rolling direction.
- \(T\): Tensile tested at \(\pi/2\) to the rolling direction.
III. Results and Discussion

Figure 3 shows the ratio of thickness to width strain obtained from the uniaxial tension tests at the longitudinal strain of 0.1. The $r$ values are also listed in the figure.

The anisotropy of the sheet of process 2 seems to be slightly larger than that of process 1, and the thickness strain in a tensile test at $\pi/2$ to the rolling direction is practically zero.

In the sheet of process 3, the ratio in uniaxial tension at 0 and $\pi/4$ to the rolling direction shows a high value. Especially, the thickness strain in uniaxial tension parallel to the rolling direction is more than 2.5 times as high as the width strain.

In the sheet of process 4, the thickness strains is very small in every tensile direction. Its deformation is similar to the plane strain one in spite of the uniaxial tension. Such deformation behavior can easily be understood from its texture. Since the slip direction, the $\langle1120\rangle$ orientation, is evenly dispersed in the sheet plane, there are no slip systems to produce the thickness strain, and the sheets can deform only by prismatic slip without accompanying deformation twinning.

Figure 4 shows the stress-strain curves. In the sheet of process 1, the 0.2% proof stress at the rolling direction is smallest and followed by $\pi/4$ and $\pi/2$ to the rolling direction in that order. The work hardening rates at $\pi/4$ and $\pi/2$ to rolling direction are nearly equal, and the one at the rolling direction is highest.

The 0.2% proof stresses of the sheet of process 2 are equivalent to those of the sheet of process 1 at every tensile direction because of the similarity of the texture. However, the work hardening rate of the specimen extended to the rolling direction is smaller at early stage of deformation and then the flow stress is lower as a whole than that of the sheet of process 1.

First, the deformation behavior of the sheet of process 2, which is a model of the sheet of process 1, was studied in order to study the deformation behavior of the sheet of conventional cold-rolled and recrystallization texture as that of process 1. Figure 5 shows tensile specimens after failure in a macroscopic scale. In tensile tests to the rolling and transverse directions, the ridging occurs along the boundaries of colonies. Along the same boundaries of colonies which penetrates through the specimen thickness, the convex and the concave ridging occur on the reverse sides of the specimen, respectively. In tensile tests to the rolling direction, the convex ridging occurs along the one side of the boundaries of colonies where the $\langle0001\rangle$ orientations of the colonies are facing each other on the surface of the specimen. On the other hand, the concave ridging occurs along the reverse side of the boundaries of colonies where the $\langle0001\rangle$ orientations of the colonies are apart from each other on the surface of the specimen. In tensile tests to the transverse direction, the convex ridging eventually occurs along the one side of
Fig. 4 Stress-strain curves.
the boundaries of colonies where the \( \langle 0001 \rangle \) orientations of the colonies are apart from each other on the surface of the specimen, while the concave ridging occurs along the reverse side of the boundaries of colonies where the \( \langle 0001 \rangle \) orientations of the colonies are facing each other on the surface of the specimen. In tensile tests at \( \pi/4 \) to the rolling direction, the strong shear occurs along the one side of the boundaries of colonies where the \( \langle 0001 \rangle \) orientations of the colonies are facing each other on the surface of the specimen, and then the deformation is mild along the reverse side of the boundaries of colonies where the \( \langle 0001 \rangle \) orientations of the colonies are apart from each other on the surface of specimen. Therefore, the intensity of shear is strong at one side of the specimen along the boundary of colonies but is mild at the reverse side of the specimen along the same boundary of colonies because the shear penetrates inside the colony.

Figure 6 represents the micrographs on the section parallel to the sheet plane of the sheet of process 2 after the tensile deformation. Figure 6 (a) shows the micrograph of the specimen extended to the rolling direction. Numerous deformation twins are observed along the boundaries of colonies. In the specimen extended at \( \pi/4 \) to the rolling direction (Fig. 6(b)) the nucleation of the deformation twins is very few and the deformation twins observed seem to be independent of the boundaries of colonies. In the specimen extended to the transverse direction (Fig. 6(c)) the deformation twins take place along the boundaries of colonies as the specimen in the elongation to the rolling direction (Fig. 6(a)). However, the amount of the deformation twins is smaller than that in the elongation to the rolling direction.

Figure 7 shows the micrographs on the section parallel to the sheet plane of process 2. Etch pits were revealed on them after tensile deformation. In the uniaxial tension to the rolling direction, \( \{1122\} \) deformation twins were typical, Fig. 7(a). In the uniaxial tension to the transverse direction, Fig. 7(b), \( \{1012\} \) deforma-
tion twins were typical. Thus, the compressive deformation twins were observed on the specimen extended to the rolling direction and inversely the tensile deformation twins were observed on the one extended to the transverse direction. The <0001> orientation of the deformation twins in the specimen extended to the rolling direction was near the tensile direction. Inversely, the <0001> orientation of the deformation twins in the specimen extended to the transverse direction was almost normal to the tensile direction.

Since the ridging and the deformation twinning occurred along the boundaries of colonies in the sheets of process 2, it is apparent that the deformation behavior of the sheets having such a texture is related to the orientation between the neighboring grains. Therefore, the orientational relation between the neighboring grains was studied. Figure 8 shows the frequency of the angle between the <0001> orientations of a grain and its neighboring grains. In the case of processes 1 and 2, the two peaks were observed in the immediate vicinity of 0 and π/3. In process 2, the frequency in the range from 0 to π/18 is higher than 60% because of the colonies.

Figure 9 shows the frequency of the angle between the <1010> orientations of a grain and its neighboring grains. In the case of processes 1 and 2, the two peaks were observed in the immediate vicinity of 0 to π/6 in both processes. Therefore, the orientational relation between the neighboring grains in respect to the a-axis of the hcp structure can be left out of consideration for the deformation behavior of the sheets.

For the tensile specimen on which etch pits were revealed before the tensile test, the frequency of the angle, θ, between the <0001> orientations of the neighboring grains which have a joint grain boundary where the deformation twins adjoin, is shown in Fig. 10 after tensile testing at the rolling direction up to the tensile strain of about 0.10. The frequency in the range near π/3 is high. Figure 10(b) shows the relationship between the <0001> poles of these grains and the tensile direction. It is apparent that the compressive deformation twinning occurs easily in the grain which has the...
angle, $\theta$, of $\pi/3$ with its neighboring grain and is extended to normal to the $\langle0001\rangle$ orientation, that is, the rolling direction.

Figure 11 shows the frequency of the angle $\theta$ Fig. 11(a) and the $\langle0001\rangle$ poles and the tensile direction, Fig. 11(b), for a tensile specimen tested to the transverse direction. In this case, it can also be said that the tensile deformation twinning occurs easily in the grain which has the angle, $\theta$, of $\pi/3$ with its neighboring grain and is extended to the transverse direction. Therefore, the mechanism, for the nucleation of deformation twinning was studied by modeling such a orientational relation.

If a rectangle of which the $\langle0001\rangle$ orientation tilts $\pi/6$ from the sheet normal toward the transverse direction is uniaxially elongated to the rolling direction, the plane normal to the tensile axis is deformed by prismatic slip, the primary slip system, as shown in Fig. 12(a). In this case, since the rectangle is not forced to the transverse direction, the compatibility at the boundary is satisfied by the rotation as shown in Fig. 12(b). Therefore, the convex ridg-
Ing occurs along the one side of the boundaries where the \langle0001\rangle orientations of the colonies are faced each other, and then the concave ridging occurs along the reverse side of the boundaries where the \langle0001\rangle orientation of the colonies are apart from each other, Fig. 12(c). If the deformation keeps in this way, the occurrence of the deformation twinning is not required. However, as the ridging becomes more conspicuous, the force to suppress the ridging is imposed. In order to cope with the force, the deformed rectangle with be returned to the rectangle by basal slip and rotation, or adapted by the deformation twinning as shown in Fig. 12(d). In the case of basal slip and the rotation, the thickness of the rectangle becomes larger and such deformation is in conflict with the direction of the constraint. Therefore, it is more reasonable to define that a large amount of deformation twinning (compression) is nucleated in order to satisfy the compatibility at the boundaries of the colonies in the uniaxial elongation to the rolling direction.

In the uniaxial elongation to the transverse direction, the rectangle will be deformed as shown in Fig. 13(a) by prismatic slip. In this case, since the rectangle is forced to the transverse direction, the coherency at the boundary is not satisfied by the rotation because of the opposite direction of the rotation to the constraint, but by the basal slip as shown in
Fig. 13(b). The convex ridging occurs along the one side of the boundaries where the <0001> orientation are apart from other, and the concave ridging occurs along the reverse side of the boundaries where the <0001> orientation of colonies are faced each other, as shown in Fig. 13(c). As the deformation proceeds and the flow stress becomes higher, the compatibility at the boundaries of the colonies seem to be satisfied by the rotation and basal slip, Fig. 13(d). Since the deformed rectangle can be returned to the rectangle by adapting itself to the constraint to the thickness direction by the rotation and basal slip, the amount of the deformation twins are smaller than that in the elongation to the rolling direction, differ from the case of elongation to the transverse direction. However, the deformation twin (tension) can also be observed along the boundaries of the colonies, Fig. 13(d).

Figure 14 shows the schematic representation of the deformation mechanism in the uniaxial elongation to $\pi/4$ to the rolling direction. The compressive stress acts at one side of the boundaries where the <0001> orientation are apart from each other, and the tensile stress acts at the reverse side of the boundaries where the <0001> orientation of the colonies are facing each other as is the case with the elongation to the transverse direction. Since the direction of the maximum shear stress lies on the boundaries, the strong shearing along the boundaries where the tensile stress acts occurs by prismatic slip. The deformation proceeds in such way as shown in Fig. 14. Thus, the amount of the deformation twins is very small and the deformation can be well explained by this mechanism.

The deformation mechanism described above can be applied to the deformation of the sheet of process 1 because of having the similar orientational relation between the neighboring grains. Since the sheet of process 1 has no colonies, the phenomenon observed in the sheet of process 2 occurs locally. Figure 15(a) shows the micrographs of the section parallel to the sheet plane of process 1 in the tensile test to the rolling direction. The large amount of deformation twins occurs dispersively. In the case of the tensile test at $\pi/4$ to the rolling direction, the amount of the deformation twins is very
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small as shown in Fig. 15(b). On the surface of the deformed specimen which had been etched before elongation, the strong shear was observed locally. In the case of the tensile test to the transverse direction, the deformation twins were hardly detectable on the surface of the sheet but were observed inside the specimen as shown in Fig. 15(c). However, the amount is smaller than that in the tensile test to the rolling direction.

Figure 16 shows an example of the deformation twins of the sheets of process 1. The compressive deformation twin in the tensile test to the rolling direction and the tensile deformation twin to the transverse direction were observed as in the case of those in process 2. The compressive deformation twinning is chiefly the \{1122\} twin or rarely \{1124\}, while the tensile one is chiefly the \{10\bar{1}2\} twin or rarely the \{11\bar{2}3\} twin in processes 1 and 2. The \langle0001\rangle orientation of the deformation twins is closer to the tensile direction in the tensile test to the rolling direction, while it is closer to normal to the tensile direction in the tensile test to the transverse direction. The above result is the same in the sheets of processes 1 and 2.

On one hand, as shown in Fig. 4, the yield strength as the 0.2% proof stress depends principally on the orientational relation between the tensile direction and the prismatic slip system of the preferred orientation deduced from the pole figure. On the other, the work hardening rate after yielding seems to be influenced largely by deformation twinning. In the tensile test to the rolling direction, not only the abundance of the deformation twins and thus the boundaries but also the close distance of the \langle0001\rangle orientation of the deformation twin to the tensile direction increase the work hardening rate. Such "reorientation hardening" in hcp metals was already suggested by Reed-Hill(9). In the tensile test to the transverse direction, since the \langle0001\rangle orientation of the deformation twins are nearly normal to the tensile direction and the amount of those are small, the work hardening rate is of the same level as in the tensile test at \pi/4 to the rolling direction in spite of the occurrence of the deformation twinning.

The difference of the stress-strain curves between processes 1 and 2 depends on the presence of the colonies. In process 2, the amount of the deformation twins are relatively small and concentrated along the boundaries of the colonies.

In the sheet of process 3, which have high flow stress in the tensile test to all directions, the large amount of the deformation twins were observed on all tensile specimens. Figure 17 shows the micrographs of the section parallel to the sheet plane of process 3 after the tensile test up to the strain of about 0.1 to the transverse direction. The large amount of the deformation twins are observed. In the case of the tensile test at 0 and \pi/4 to the rolling direction, the amount of the deformation twins are the same each other but smaller than that in the case tested to the transverse direction.

Figure 18 shows the frequency of the angle

Fig. 16 Micrographs of the section parallel to the sheet plane. Tensile strain is about 10%. (a): Tensile tested at 0 to R. D. (b): Tensile tested at \pi/2 to R. D.

Fig. 17 Micrographs of the section parallel to the sheet plane. Process 3. Tensile tested at \pi/2 to R. D. Tensile strain is about 10%.
between the \langle0001\rangle orientation of a grain and that of its neighboring grains. The frequency of the angle distribute in the whole range from 0 to \(\pi/2\), although there is a slight increase near \(\pi/3\). In respect to the \langle10\bar{1}0\rangle orientation, the frequency distributes in the range from 0 to \(\pi/6\) as in the case of other processes.

Figure 19 shows the \{0001\} pole figure obtained from the \{0001\} poles of the grains whose orientations were determined from etch pits. Although there are many grains whose \langle0001\rangle orientation are nearly the transverse direction, the \{0001\} poles are dispersed on the circumference normal to the rolling direction. Arrows represent the tensile direction. The occurrence of the tensile deformation twinning by elongation to the \langle0001\rangle orientation can be easily expected because the \{0001\} poles of many grains are nearly the tensile direction in the case tested to \(\pi/4\) and \(\pi/2\) to the rolling directions. However, the occurrence of the deformation twinning under such orientational relation cannot be expected in the case tested to the rolling direction.

Figure 20 shows the \{0001\} pole figures of the sheet of process 3 tested to \(\pi/4\) and \(\pi/2\) to the rolling direction, which are constructed by the \{0001\} poles of the grains having the deformation twins. In both tensile directions, most of the angle between the tensile direction and the \langle0001\rangle orientation of the grains having the deformation twins are within \(2\pi/9\).

Figure 21 shows the micrographs of the section parallel to the sheet plane of the sheet of process 3 in the tensile test at \(\pi/4\) and \(\pi/2\) to the rolling directions. In both tensile directions, \{10\bar{1}2\} tensile deformation twins occurred. However, the \langle0001\rangle orientation of the deformation twin in the specimen tested at \(\pi/4\) to the rolling direction are nearly normal to the sheet plane but those in the specimen tested to the transverse direction are close to the rolling direction; i.e. the direction of shearing of twin versus the sheet are different each other in spite of the same twin system between two different tensile directions. This difference of the manner of the occurrence of the deformation twinning is owing to the ratio of the thickness to
width strains as shown in Fig. 3, and so to the orientational relationship between the tensile direction and the preferred orientation.

In the case of the tensile test to the rolling direction, there were few deformation twin on the surface but large one inside the specimen. Figure 22 shows the examples of the deformation twins. The example of Fig. 22(a) is the compressive deformation twins (\{11\overline{2}2\}) observed on the grain, whose \langle0001\rangle orientation is nearly normal to the sheet plane and which is surrounded by the grains having the \langle0001\rangle orientation close to the transverse direction. Since the grains having the \langle0001\rangle orientation close to the transverse direction elongate to the tensile direction, which is the rolling direction in this case, and shrinks to the thickness direction by the slip as understood from the strain ratio in Fig. 3, the neighboring grain having the \langle0001\rangle orientation nearly normal to the sheet plane must conform oneself to such deformation by the deformation twinning which permits thinning to the \langle0001\rangle orientation.

The example of Fig. 22(b) is the deformation twinning occurred by the same mechanism as that of the sheet of processes 1 and 2 in the tensile test to the rolling direction. In the sheets of process 3, the amount of the deformation twins are smaller than that of the sheets of processes 1 and 2 because the angle between the \langle0001\rangle orientation of a grain and that of its neighboring grain are large. The \langle0001\rangle orientation of the deformation twin of such type are close to the tensile direction, so that the work hardening rate is higher than that tested at \pi/4 to the rolling direction in spite of nearly the
same amount of the deformation twinning. Figure 23 shows the frequency of the angle between the \(<0001>\) orientation of a grain and that of its neighboring grain, in the case of the sheet of process 4. The frequency of the angle is over 90\% in the range from 0 to \(\pi/18\). The angle for \(<10\bar{1}0>\) orientation is also small. Therefore, the constraint originated by the orientational relation between the neighboring grains is very small. The work hardening rate of the sheet of process 4 at the early stage of the deformation is much smaller than that in the tensile test at \(\pi/4\) to the rolling direction of process 1 or 2, in which the deformation twinning are rare too, because of the degree of the constraint originated by the orientational relation between the neighboring grains.

IV. Conclusion

In this experiment, the uniaxial tensile tests were carried out for four differently textured sheets of pure titanium.

The twin systems and the manner of the occurrence of the deformation twinning are classified in three types according to the texture and the stress condition.

1. When the unevenness in the connection with the orientational relation between neighboring grains generate, the tensile or compressive deformation twinning due to the stress condition occurs.

2. When the \(<0001>\) orientation of the grain is nearly the direction of the maximum principal stress, which is tensile direction in this case, the tensile deformation twinning occurs.

3. When the grain deforms to the \(<0001>\) direction in order to conform to the deformation of surrounding grains, the deformation twinning occurs.

The stress-strain curves are influenced by the deformation twinning. On one hand, the yield strength as the 0.2\% proof stress depends principally on the orientational relation between the tensile direction and the prismatic slip system of the preferred orientation deduced from the pole figures. On the other, the work hardening rate after yielding is influenced not only by such orientational relation but also largely by the deformation twinning and the orientational relation between the tensile direction and the \(<0001>\) orientation of twin, and furthermore by the orientational relation between neighboring grains. Especially, when the \(<0001>\) orientation of the deformation twin are close to the direction of the maximum principal stress, which is the tensile direction in this experiment, such an orientation decreases the Schmid factor for prism slip. Therefore, if there are enough deformation twins, whose \(<0001>\) orientation are close to the tensile direction, just as sheets of processes 1 and 2 tested to the rolling direction, the work hardening rate increases.

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