BENDABILITY OF Ti-6Al-4V ALLOY SHEET

M. Ogaya and M. Kisaichi, Nippon Stainless Steel Co., Ltd., Joetsu, Japan
T. Mase and M. Koike, Sumitomo Metal Industries, Ltd., Amagasaki, Japan

Introduction

Thin sheet of 6Al-4V alloy has been often subjected to bending in applications. In evaluating the bendability of sheet, it is assumed that r-value (the ratio of width to thickness strain in a tension test) plays an important role rather than elongation and strength, because sheet is deformed under conditions of nearly plane strain.

On the other hand, the relationship between texture and hot rolling conditions is well established with the view of the texture hardening in 6Al-4V alloy (1 - 3). However, the influence of texture and r-value on the bendability has been less studied.

In this study, cp titanium and 6Al-4V alloy sheets with different r-values, which are prepared under various hot rolling conditions, are bend tested for the purpose of making the effect of r-value on the bendability clear. On the basis of the test results, the relation between r-value and the bendability of 6Al-4V alloy is determined in comparison with cp titanium.

Experimental Procedure

The materials used in this study were plates β-rolled to 20-24 mm thickness. The chemical compositions of these plates were given in Table 1. For this study these plates were hot rolled to 4-6 mm thick sheets under various conditions of starting temperature, finishing temperature, rolling ratio and rolling direction.

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>V</th>
<th>Fe</th>
<th>C</th>
<th>N</th>
<th>O</th>
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</thead>
<tbody>
<tr>
<td>Ti-6Al-4V</td>
<td>6.23</td>
<td>4.00</td>
<td>0.13</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.11</td>
</tr>
<tr>
<td>cp Ti</td>
<td>—</td>
<td>—</td>
<td>0.06</td>
<td>&lt;0.01</td>
<td>0.01</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Table 1: Chemical compositions of materials (wt. %)

After hot rolling, all of them were annealed at 700°C for 30 minutes and then were descaled chemically. In addition, some sheets were cold rolled and annealed to examine the influence of cold rolling on the bendability and r-value. Bend test was performed at room temperature, using machined specimen with a dimension of 3x40x100 mm. The bendability was judged by the minimum bend radius, R/t (R : bend radius, t : thickness of specimen), without any cracks in the outside of the bent portion in bending through the angle of 105° for 6Al-4V alloy and 180° for cp titanium.
Tension specimen was machined to a 1/2-inch wide type piece with 50 mm gauge length and was tested in accordance with ASTM Methods E8. Tension test results determined 0.2% yield strength, tensile strength, total elongation and r-value. The longitudinal direction of both bend and tension test specimen was parallel to the final rolling direction. The texture examinations were performed by a X-ray diffractometer using the reflection method and determined (0002) pole figures.

Results and Discussion

1. Influence of hot rolling conditions on bendability

Fig. 1 shows the bendability and tensile properties of 5 mm thick sheets which are hot rolled in the same rolling direction of plates at starting temperatures in the range of 800-1100°C. While 0.2% yield strength and tensile strength have nearly constant values, elongation increases slightly with lowering temperature. On the other hand, the bendability is intensely dependant on temperature and improves at 950°C. The r-value has a fall at 950°C inversely. From this result, it is obvious that the bendability of 6Al-4V alloy sheet has a good correlation with the r-value as it improves with lowering the r-value.

![Fig. 1: Change of bendability and tensile properties with starting temperature of hot rolling for 6Al-4V alloy](image-url)
Fig. 2 gives (0002) pole figures of sheets rolled at 800, 950 and 1100°C. The (0002) pole figure is intensely affected by rolling temperature. Sheet rolled at 800°C, with high r-value, has a split type texture described as (0002) + 30-40° TD, whose c-axis inclines +30-40° towards the transverse direction. The texture of sheet rolled at 1100°C, shows a random type with transformation component. On the other hand, sheet rolled at 950°C has an edge type texture whose c-axis inclines markedly towards the transverse direction. Sheet with low r-value has a well developed edge type texture characteristically.

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(a) 800°C (r=0.8)   (b) 950°C (r=0.3)   (c) 1100°C (r=0.6)
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2. Comparison with cp titanium

To define the relation between the bendability and r-value for α phase, cp titanium was examined in a similar manner to 6Al-4V alloy as follows. The materials were cut from a β-rolled cp titanium plate with 26 mm thickness. These were hot rolled to 6 mm thickness at starting temperatures of rolling in the range of 500-1000°C in the same direction of plate rolling, and annealed at 700°C for 30 minutes. The change in the bendability and tensile properties with the temperature is shown in Fig. 3. Little change is in 0.2% yield strength and tensile strength while elongation raises up as the temperature falls. The r-value decreases as the temperature increases. Especially, above 950°C it falls rapidly to below 0.5. The improvement in the bendability is also in accordance with low r-value on cp titanium.

As can be seen from Fig. 4, cp titanium sheets rolled at 850°C and 500°C have the texture described as (0002) + 20-30° TD which develops as a stable texture in α-rolling. Furthermore the texture rolled at 500°C has a stronger intensity than at 850°C and the r-value is higher too.

By contrast, the texture of sheet rolled at 950°C with a low r-value is entirely different from these textures and shows edge type. A similar texture to the sheet rolled at 950°C is also obtained at 1000°C.
All of those microstructures have equi-axed $\alpha$ structures while these are not inserted in this paper.

**Fig. 3**: Change of bendability and tensile properties with starting temperature of hot rolling for cp titanium

(a) $500^\circ\text{C}$ ($r=3.5$)  (b) $850^\circ\text{C}$ ($r=2.5$)  (c) $950^\circ\text{C}$ ($r=0.5$)

**Fig. 4**: (0002) pole figures of cp titanium hot rolled
On the basis of these results, it is determined that r-value is correlated to the texture of α crystal and sheet with low r-value has a well developed edge type texture. It is considered that the transformation from β to α has an important influence on developing texture, as follows.

In hot rolling at temperatures in the region of α phase, cp titanium has a stable α-rolling texture described as (0002) + 20-30° TD. It is virtually unchanged with rolling temperature. The texture of the sheet heated above β transus and rolled through β transus shows a edge type.

In 6Al-4V alloy rolled at 800°C, in lower temperature α+β regions, the texture shows a similar split type to α-rolling in cp titanium. The 6Al-4V alloy sheets rolled at 1000°C and 1100°C, above β transus, have β-transformed microstructures and random type textures. Only sheet rolled at 950°C, in higher temperature α+β regions, has a edge type texture. On 6Al-4V alloy, the starting of rolling above β transus causes random type texture unlike cp titanium.

In this study, it can not be confirmed where this difference lies. However, there are differences in the behavior of the transformation from β to α between 6Al-4V alloy and cp titanium. In cp titanium all of β transform to α at β transus in cooling, while in 6Al-4V alloy β transforms gradually to α with decrease of temperature. It is considered that this unlike behavior of transformation causes the difference in rolling temperature for producing the edge type texture between the two. Apart from this question, the transformation from β to α during rolling affects the formation of the edge type texture, as mentioned by Fredrick (4).

3. Correlation between r-value and bendability

For the purpose of making the effect of r-value on the bendability more clear, hot rolled and annealed sheets of 6Al-4V alloy with a wide range of r-value were prepared. These sheets were processed under various rolling conditions such as finishing temperature, reduction ratio and direction in addition to starting temperature. The results are given in Fig. 5 which shows the distribution of the bendability with r-value.

Fig. 5 shows obviously that the bendability improves with lowering r-value. The reason why the bendability is improved by lowering the r-value is considered as follows.

The slip direction of α crystal is <1120> which lies on basal plane. Since this slip can not contribute to the deformation in c-axis direction, the deformation in the thickness direction is severely restrained in the material with the texture whose basal pole directs nearly normal to the rolling plane. Therefore, the sheet with this basal texture possesses high r-value, but shows poor formability when the material is deformed mainly by the thickness reduction such as bending. Conversely, in the material with edge type texture whose r-value becomes low, the deformation in the thickness direction is made easy by the large potential of slipping and the material results in good bendability.
4. Influence of cold rolling

A hot rolled sheet of 6Al-4V alloy with strong edge type texture was cold rolled to total reduction ratio of about 50% in the same direction of hot rolling. This examination was to make the influence of cold rolling on the bendability clear.

Fig. 5: Relation between bendability and r-value for 6Al-4V alloy

Fig. 6: Change of bendability and r-value with reduction ratio of cold rolling for 6Al-4V alloy

Fig. 6 shows the bendability and r-value as a function of the reduction ratio in comparison between annealing at 700°C and
850°C. As reduction ratio rises, r-value increases markedly and then the bendability deteriorates. While little difference in the r-value is between annealing temperature at 700°C and 850°C, the deterioration of the bendability annealed at 850°C is sluggish comparatively. The change of (0002) pole figure with cold rolling is shown in Fig. 7. After 50% cold rolling, the strong edge type texture of hot rolling is weakened and turns into cold rolling peaks described as (0002) ± 30-40° TD and (0002) ± 20-30° RD. The textures of annealing at 700°C and 900°C after cold rolling are shown in Fig. 8. The peaks, (0002) ± 30-40° TD, of as-cold rolled sheet are unchanged substantially. And differences between 700°C and 900°C are not observed too.

(a) hot rolled (b) cold rolled 50%

Fig. 7 : Change of (0002) pole figure after cold rolling for 6Al-4V alloy

(a) 700°C (b) 900°C

Fig. 8 : Change of (0002) pole figure with annealing temperature after cold rolling for 6Al-4V alloy

From these results it is determined that cold rolling causes an increase in r-value and the deterioration of the bendability because of making the edge type texture weaker. The reason why increase in annealing temperature causes the improvement of the bendability is certainly on the α/β phase ratio.
Since the texture has little change with increase of annealing temperature, the improvement of the bendability is caused by decrease of \(\alpha\) phase with poorer formability than \(\beta\) phase.

**Conclusions**

On the basis of the above results, the influence of \(r\)-value on the bendability of 6Al-4V alloy sheet was determined compared with cp titanium.

1. The bendability of 6Al-4V alloy sheet was closely related to the \(r\)-value and improved with lowering the \(r\)-value.
2. The sheet with low \(r\)-value showed a well developed edge type texture in (0002) pole figure.
3. The bendability of 6Al-4V alloy sheet was dependant on the formability of \(\alpha\) phase because of a similar behavior to cp titanium.

Based on this study, the manufacturing thin sheet of 6Al-4V alloy with good bendability has been well established in ours.

**References**