THE PRESS FORMABILITY OF COMMERCIAL PURE TITANIUM AT WARM WORKING TEMPERATURE

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Introduction

In bending of pure titanium sheets under the warm working condition, fracture sometimes occurs extraordinarily easily and is accompanied by pitting on the surface. This phenomenon was pointed out by R.A. Wood et al. (1) who, however, gave little explanation on it.

In addition to bending, the deformation behaviour of this metal was generally examined for various deformation modes under both room temperature and warm working condition, and the forming limit strain diagrams were also investigated. It was found that the poor bendability of pure titanium sheet under the warm working condition coincided with its extremely small forming limit strain in biaxial stretching.

This characteristic of titanium sheet in press forming was discussed mainly metallurgically and the understandable explanation was given to it considering the effect of twin deformation.

Experimental Material and Procedure

Two kinds of materials whose chemical composition and r values are tabulated on Table 1 were used. Material A has far higher r value than B, while grain sizes of these materials are almost same and about 80 μm.

Table 1. r Values and chemical composition

<table>
<thead>
<tr>
<th>mark</th>
<th>r value</th>
<th>chemical composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R.T.</td>
<td>200°C</td>
</tr>
<tr>
<td>A</td>
<td>8.8</td>
<td>11.7</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>0.006</td>
</tr>
<tr>
<td></td>
<td>Fe</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>H</td>
<td>0.0012</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>O</td>
<td>0.072</td>
</tr>
<tr>
<td>B</td>
<td>2.0</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Tensile test was carried out with an Instron type machine at temperature from room temperature to 600°C and at a constant strain rate of 1.25 × 10^{-3} sec.−1. Tensile specimens with 10 mm width, 70 mm parallel length, and 4 mm thickness were machined from the materials parallel to the rolling direction.

Bending test, the method of which is shown in Fig. 1, was performed at approximately same temperature as tensile test was. The dimension of specimen for bending test is 4 mm thickness, 40 mm width, and 65 mm length. Its longitudinal direction is parallel to the rolling direction.
Strains were measured by 6.35 mm dia. scribed circles printed on the surface of the specimen before forming, and the forming limit strain was determined by the strain at the portion very close to fracture point. In order to obtain the forming limit diagram (FLD), various modes of deformation such as uniaxial stretching, biaxial stretching, and bending, as shown in Fig. 2, were applied to the sheet at R.T. and 200°C.

Pole figures were constructed for the (0002) plane to examine the textures of the materials.

Fig. 1. Method of bending test  

\[ r = 0.8 \]  
\[ r \] : bend radius  
\[ t \] : thickness of specimen  

Fig. 2. Procedure for obtaining FLD

Experimental Results

1. Texture of Tested Material

The (0002) pole figures for tested materials are shown in Fig. 3. The texture of the material A is described as (0002) ± 17° T.D. with basal plane tilted ± 17° towards the transverse direction. On the other hand, material B has the texture which is expressed as (0002) ± 30° T.D. Since the slip direction of pure titanium is \text{<1120>} \text{ which lies on basal plane, this slip can not contribute to the deformation in the basal pole direction. The deformation in the thickness direction, therefore, is restrained in the material with the texture whose basal pole directs nearly normal to the rolling plane. The high r value of material A is well understood by this explanation.}

Fig. 3. (0002) Pole figures for tested materials
2. Tensile Test

Dependence of the tensile strength and the elongation on temperature is shown in Fig. 4 and 5. The tensile strengths of both materials decrease similarly with increase of temperature. On the other hand, the elongations of both materials increase linearly from room temperature to 200°C, then vary little up to 400°C, and show sudden increase above 500°C. In the whole range from room temperature to 600°C, the elongation of the material A with high r value is larger than that of the material B with low r value. As to r value shown in Fig. 6, it increase linearly with the increase of temperature up to 200°C, and are approximately constant at temperature from 200°C to 400°C in both materials. In this way, the dependence of r value on temperature coincides with that of the elongation.

Fig. 4. Dependence of tensile strengths on temperature

Fig. 5. Dependence of elongations on temperature

Fig. 6. Dependence of r values on temperature
3. Bending Test

The appearance of the specimens which were bended at the temperature from room temperature to 600°C are shown in Table 2. In the case of the material A with high r value, the crack accompanied with a lot of deep surface pits is observed at 200°C and 400°C. The material B with low r value also shows crack at 200°C, but its appearance is not so serious. In this paper, bend index is applied to express the bendability of the materials, and the larger number of bend index means the poorer bendability. Fig. 7 shows the effect of temperature on bendability using this index. It is evidently observed that the bendability of both materials deteriorates at temperature corresponding to warm working condition and particularly the material A with high r value shows considerable deterioration.

From the results of both tensile and bending tests, characteristics of press formability of pure titanium sheet at warm working temperature can be summarized as follows,

(1) Comparing with the room temperature condition, the warm working condition (100°C to 400°C) is favourable for tensile ductility of pure titanium, but unfavourable for ductility in bending.

(2) The material with high r value has extremely poor bendability under warm working condition, though the high r value contributes to the large tensile elongation.

4. Forming Limit

Forming limits of the materials were examined for the purpose of understanding more comprehensively and precisely the characteristics of the deformation behaviour of pure titanium sheet. The results are shown in Fig. 8 and 9.

Comparing with forming limit strains under room temperature, those under warm working condition are extremely small in the region of $\varepsilon_y > 0$ where the strains in bending and biaxial stretching are dotted. Decrease of forming limit strain in this region is more remarkable in the material A with high r value. On the other hand, forming limit strains in uniaxial stretching (tensile elongation) are rather large at the temperature of warm working condition and are also improved with the increase of r value. Forming limit diagrams obtained at warm working temperature well explain the inconsistency between large tensile elongation and poor bendability of titanium sheets, particularly, that with large r value.
These FLD also give us another very important information. That is, the forming limit curves are described approximately parallel to the straight line, \( \varepsilon_y = -\varepsilon_x + \text{const.} \), which expresses the constant thickness strain. The formability at warm working temperature as shown in Fig. 8 and 9, therefore, is dominated only by thinning limit of sheet metal. On the other hand, under room temperature, forming limit is determined by necking, because the strain at thinning limit is larger than necking strain and is presumed to form the lines shown by dotted ones in Fig. 8 and 9 (2).

**Discussion**

Poor bendability under the warm working condition can be explained by the lack of ductility in thickness direction. This decrease of ductility in thinning results in fracture accompanied with pits in both bending and biaxial stretching under warm working condition.

Slip direction of pure titanium sheet is \(<11\bar{2}0>\) which lies on the basal plane. The titanium sheet with high \(r\) value has the texture whose basal pole directs rather similar to the normal direction of the rolling plane, so the deformation in the thickness direction by the slip along \(<11\bar{2}0>\) is severely restrained in this material. It is well known that twinning is important mechanism in plastic deformation of h.c.p. metals such as titanium. The \((11\bar{2}2)\) twinning is considered to operate actively for thinning instead of slipping in the case of the texture of small angle between the basal pole and the normal direction of the rolling plane(3). In addition to the contribution of twinning itself to thinning, this twinning operation causes 64.4-deg. reorientation of basal plane, and it brings about the new texture which is far favourable for thinning compared with the initial texture. Thus, once twinning generates this new texture, even the material with high \(r\) value shows rather large ductility in thinning. Twinning is particularly effective in both bending and biaxial stretching which require the large reduction of thickness.

The generation of twin, however, decreases markedly as the temperature increases (4), which was also confirmed in biaxial-stretch forming under warm
working condition in this investigation. Photo 1 shows the microstructures of the material A which was subjected to thickness strain, $\varepsilon_t$, of $-0.16$ in biaxial stretching at room temperature and $200^\circ$C. High density of the twin was observed at room temperature, but the twin density was very small at $200^\circ$C. The decrease of twin generation results in the deterioration of the ductility in the thickness direction. Extraordinarily poor formability which was observed in both bending and biaxial stretching at warm working temperature as shown in Fig. 8 and 9 was reasonably understood by considering the reduction of twin generation.

![Photo 1. Microstructures of material A which was subjected to biaxial stretching](image)

Since the material with high $r$ value has smaller potential of slipping relating to thinning than that of the material with low $r$ value, forming limit of the former material decreases remarkably in bending and biaxial stretching at warm working temperature. In the case of uniaxial stretching at warm working temperature, the decrease of forming limit does not occur because of the contribution of large width reduction to the elongation. The elongation is rather large as a result of increase in $r$ value at warm working temperature and the increase of $r$ value may also be caused by restraint of twinning.

From the above discussion, it is predicted that no remarkable deterioration of both bendability and stretchability at warm working temperature occurs in the material which has been subjected to twinning in pre-straining under cold working condition. The effect of pre-strain at a lower temperature on the bendability at a higher temperature was examined for the material A, as shown in Fig. 10. The bending was carried out at $200^\circ$C after pre-strain had been given by slight bending at both room temperature and $-196^\circ$C. The bendability under warm working condition was obviously improved by the pre-strain at both room temperature and $-196^\circ$C. The pre-strain at $-196^\circ$C is more effective on the improvement of the bendability at warm working temperature than that at room temperature as shown in Photo 2 because of the larger activity of twinning in lower temperature. These results prove that the deterioration of the press formability of pure titanium sheet under warm working

![Fig. 10. Effect of pre-strain at R.T. and $-196^\circ$C on bendability of material A at $200^\circ$C](image)
condition is caused by the decrease of ductility in the thickness direction as a result of the small potential of twinning at higher temperature.

It was reported\(^{(5)}\) that the decrease of elongation and the increase of flow stress were observed in pure titanium under warm working condition and this phenomenon was explained as the effect of the dynamic strain ageing. The dynamic strain ageing, therefore, was also considered to influence the decrease of the forming limit at warm working temperature, but nothing which proved this assumption was observed in this study. It cannot also be explained satisfactorily by the effect of the dynamic strain ageing that the extremely poor formability under warm working condition was observed in bending and biaxial stretching which required large thinning and was remarkably improved by the pre-strain at cold working temperature. Accordingly, the dynamic strain ageing seems to have no relation to the deterioration of the formability at higher temperature observed here.

**Conclusion**

This study showed that characteristics of the press formability of commercial pure titanium at warm working temperature was reasonably explained by both texture and twinning.

Poor formability of pure titanium sheets, particularly, those with high \(r\) value, was observed in both bending and biaxial stretching under warm working condition, though there was no deterioration in tensile elongation.

It was made cleared that the deterioration of bendability at warm working temperature was caused by the decrease of ductility in the thickness direction as a result of decrease of twinning at higher temperature.

The formability in bending under warm working condition was improved markedly by generating a lot of twins in pre-strain which the material had been subjected to at room temperature or \(-196^\circ\text{C}\).

**Reference**