Some characteristic data on anisotropy and forming behaviour
of commercially pure titanium

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Introduction

Commercially pure titanium is used extensively for parts being subject to corrosion and high stress at low weight. Often high formability at room temperature is required. The materials primarily used are the softer grades, Ti 3.7025 and Ti 3.7035 (to German specification DIN 17 850) corresponding to grades 1 and 2 of ASTM B-265. By far the greatest quantities of these materials are needed as sheet. During the past, most of the flat products have been rolled on hand mills. By changing the rolling direction during final rolling of sheet bars to sheet, so-called cross rolling, anisotropy was practically avoided.

Although strip rolling offers important quality and cost advantages, such as improved thickness tolerances and flatness, better surface and greater production lots with uniform properties, the uni-directional rolling results in differences of longitudinal and transverse properties. In this paper some test results on the anisotropy and the forming behaviour of commercially pure titanium are presented.
Materials and Procedures

Ingots of 3000 kg weight of the two c.p. titanium grades Ti 3.7o25 and Ti 3.7o35 were converted to hot band of 3 mm thickness under standard mill conditions. These hot bands were strip-rolled on a reverting 4-high mill to 0.7 mm applying different degrees of deformation with or without an intermediate annealing. The final annealing of the coils was carried out in continuous or batch furnaces.

The chemical composition of the investigated materials is shown in Table 1.

Table 1 Chemical Composition of Ti 3.7o25 and 3.7o35

<table>
<thead>
<tr>
<th>DIN-No.</th>
<th>ASTM-Grade</th>
<th>Fe</th>
<th>C</th>
<th>N</th>
<th>O</th>
<th>H</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti 3.7o25</td>
<td>1</td>
<td>0.07</td>
<td>0.012</td>
<td>0.008</td>
<td>0.047</td>
<td>0.003a</td>
<td>Balance</td>
</tr>
<tr>
<td>Ti 3.7o35</td>
<td>2</td>
<td>0.03</td>
<td>0.018</td>
<td>0.018</td>
<td>0.10</td>
<td>0.0028</td>
<td></td>
</tr>
</tbody>
</table>

Strength and Elongation

The directionality of tensile properties in strip rolled titanium is the result of uni-directional rolling. In transverse direction (LT) ultimate tensile strength and yield strength are higher than in longitudinal direction (L). In LT direction total elongation is higher, the uniform elongation lower than in L direction (1, 2). Furtheron, increasing grain size reduces tensile and yield strength and improves elongation (3). Results of Erichsen cup tests show higher values with growing sheet thickness and, within certain thickness ranges, growing surface roughness (3).

The results of specified tensile and bend tests are normally the criteria for the materials behaviour for simple forming operations. But for more critical forming processes additional information for a better characterization of the material is needed.
Work-Hardening Behaviour

Figure 1 shows the work-hardening effect for both grades of commercially pure titanium. As expected, tensile strength and yield strength for Ti 3.7035 are higher than for Ti 3.7025, but the work-hardening is about the same for both grades and relatively low. Even after 60% deformation, both grades increase their ultimate tensile strength by not more than 300 N/mm².

The decrease of elongation at higher deformation is also about the same for both materials. Surprisingly, it is for Ti 3.7035 higher than for Ti 3.7025.
Recrystallization

Depending on the previous degree of deformation the microstructure of the material is modified by the final recrystallization annealing treatment. Long-time batch annealing after a high deformation of 67 % produces a coarse grain, but a deformation of only 30 % results in a fine grained microstructure, as is shown in Figure 2. This means, that the recrystallization is accelerated by the high deformation, leaving more time for grain growth, if the total time is kept constant.

Fig. 2  Effect of Cold-Deformation Prior to Heat Treatment on the Microstructure of Commercially Pure Titanium

This behaviour is different from that observed on cold-drawn wire which had after up to 2 hours annealing time a finer microstructure after 70 % than after 30 % cold deformation (4). The higher content of fine beta phase in
the alpha matrix of Ti 3.7o35 than in Ti 3.7o25 reduces grain growth during elongated annealing due to the higher number of nuclei available for the recrystallization. Coarse grain size produces orange peel effect and limits formability.

**Work-Hardening Exponent and Stretch Forming**

The work-hardening exponent $n$, as the logarithm of uniform elongation, shows in rolling direction the highest and transverse the lowest values. The differences is more distinct in the softest grade Ti 3.7o25 reaching 0.07. Hence, for bending, brake-forming, trimming or folding material, the direction of main strain should conform to that of maximum formability namely transverse (LT).

On the other hand, the low work-hardening exponent indicates that c.p. titanium has unfavourable stretch forming properties with advantages of the softest grade Ti 3.7o25 over Ti 3.7o35.

It is known, that materials with a low tendency for work-hardening are well suitable for deep-drawing operations.

**Limiting Drawing Ratio and Deep-Drawing**

Besides stretch forming, deep-drawing is another fundamental forming process. It is known that materials with a low tendency for work-hardening offer good capacity for deep-drawing in one or more steps.

The formability of materials by deep-drawing is often tested by the Erichsen cup test in which the depth of the impression into the sheet before cracking is determined. Cracking takes place in rolling direction at the bottom of the cup in the zone of highest strain. An orange peel effect on the surface before cracking signalizes that the limits of the material formability are nearly reached.
A better rating of the deep-drawing behaviour of a material is possible by the limiting drawing ratio (5), as shown in Figure 3 for two different grain sizes of Ti 3.7025 and Ti 3.7035. The results mark, contrary to stretch forming, an extremely good deep-drawing behaviour of commercially pure titanium.

A fine to medium size, equiaxed microstructure results in better deep-drawing properties than a coarse or very fine structure. Furthermore, the grade of high strength, Ti 3.7035, exhibits excellent formability which even exceeds that of the softer grade Ti 3.7025. The outstanding result is that both grades of c.p. titanium range above other materials normally used for deep-drawing purposes. This is demonstrated by a cylindrical part of 0.7 mm sheet drawn in one step to a \( \beta \)-ratio of 2.3. By plastic coating this can be increased even to 2.5 without annealing and embrittlement.
Since deep drawing is strongly affected by operating conditions, such as equipment, tooling, lubrication, pressing speed etc., it seems possible to reach by optimization $\beta$ values of 3.4 without intermediate annealing and only one single drawing operation for square rectangular and cylindrical sections even with vertical walls.

Both grades, Ti 3.7025 and Ti 3.7035, are not sensitive to cracking.

### Anisotropy

Distortion wedges are formed because of the anisotropy of the material which should be taken into consideration for critical forming operations of unsymmetrical parts. Figure 4 also shows several deep drawn parts of commercially pure titanium and their tendency to form distortion wedges. This tendency is lower for sheet with fine than with coarse microstructure.

Fig. 4 Deep Drawn Parts of Commercially Pure Titanium
Rating of the anisotropy can be based on the r-value. This is a function of the direction, especially in strip-rolled material. Figure 5 shows,

Fig. 5: Effect of Angle Relative to Rolling Direction on Anisotropy of Commercially Pure Titanium

that in rolling direction the r-value reaches under 90° a maximum. While normally distortion wedges are disadvantageous, it is possible to make use of them, if unsymmetrical parts are to be formed.

In these cases, the blanks should be positioned in a way that material utilization is reaching optimum economic results.
Some material characteristics of strip-rolled sheet of c.p. titanium regarding formability in stretch forming and deep drawing and anisotropy were studied. Due to low work hardening, the stretch-forming behaviour of the two softer grades Ti 3.7025 and Ti 3.7035 are not too good. Whenever possible, maximum strain should be positioned in longitudinal direction relative to rolling. A fine to medium size microstructure shows better formability than a very fine or a coarse grain size.

The results of deep-drawing tests proved outstanding formability of Ti 3.7025 and of Ti 3.7035. A deep-drawing ratio of 2.3 and of 2.5 with plastic coating were reached which rates c.p. titanium above other materials being used for deep-drawing purposes. By optimization of process, equipment, tolering and other conditions, values of 3.4 seem possible without intermediate annealing.

The results of anisotropy testing revealed that strip-rolled c.p. titanium has four distortion wedges under 0° and 90°, 180° and 270° to the rolling direction. This anisotropy can be used in asymmetrical shapes for increasing the material yield by appropriate positioning of the blank relative to the rolling direction.
References

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