INFLUENCE OF HOT WORKING ON THE PROPERTIES OF THE

Ti 6Al 4V ALLOY WITH SPECIAL REGARD TO HEAVY SECTIONS

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During the first years of industrial production of semis of titanium alloys, hot working was carried out in a way to achieve a fine grained microstructure with equiaxed alpha and intergranular beta (1). Heating and heat treating in the beta field was believed to be detrimental to the quality of the products because of the grain growth. A reduction by hot working of 80% at 950°C or of 30 to 50% at 900°C was considered necessary to obtain the desired grain refinement of the Ti 6Al 4V-alloy (2).

The relation between microstructure and mechanical properties - as mainly determined by heat treating tests - shows the advantage of the fine grained equiaxed microstructure with respect to elongation and reduction in area (3) (4). Tests on the Ti 6Al 4V alloy have shown that also the fatigue strength of unnotched specimens increases as the alpha grain size is decreasing (5). Data are reported which show no influence of the grain size on the fatigue strength of notched specimens (6) while others indicate a significant effect, if conventional forgings are investigated (7) (8). There is a large scatter of the results of fatigue strength testing if the microstructure shows a non-uniform grain distribution.

In contrast to these properties which are optimized if a fine grained equiaxed microstructure is produced by a high degree of reduction in the alpha - beta field,
an acicular microstructure tends to give good figures of fracture toughness (9) and creep behaviour (10) (11). The acicular microstructure is produced if heat treating temperatures or hot working temperatures above or near the beta transus temperature are used and no or only a small degree of reduction in the alpha – beta field has followed the beta processing.

In the case of titanium alloys the deformation resistance increases very sharply with decreasing hot working temperatures and increasing deformation velocity (12) (13) (14). From this it follows that high hot working temperatures reduce the manufacturing costs and the energy requirements for the reduction by hot working.

In general the hot working conditions influence not only the mechanical properties of titanium alloys but also the ultrasonic inspection and the value of its results. A fine grained microstructure e.g. facilitates the perceptibility of defects on account of a low hash.

The usual specifications for semis of titanium alloys used in the Aircraft industry mostly call for a fine grained microstructure with equiaxed alpha without taking into consideration detrimental influences on the results of fracture toughness and crack propagation testing.

This may explain the fact that the requirements of the European Aircraft industry on the properties of titanium alloy semis which will be used in some prototype developments demand a very fine grained, equiaxed microstructure even for heavy sections. These requirements involve a high amount of reduction in the alpha-beta field and consequently high manufacturing costs.

Results

Ti 6Al 4V hot rolled plate and hand forgings with heavy sections are the subject of this report.

These semis were produced from vacuum arc double-melted 5000 to 10 000 kgs ingots with diameters of 775 to 950 mm (15). The ingots were forged to slabs or hand forgings under hydraulic presses of 1 400 to 2 500 t (16). The hot rolling of the plates was carried out on a two-high/four-high rolling stand with a barrel length of 2980 mm (17).
The chemical composition of the ingots under investigation was uniform with a small scatter of the content of the alloying elements from melt to melt. (typical composition: 6.1% Al, 4.0% V, 0.07% Fe, 0.14% O)

The hydrogen content of the wrought products was in the range of 20 to 60 ppm.

Plate

Two different kinds of slabs were produced to study the effect of hot working on the properties of hot-rolled Ti6Al4V plate with a thickness of 45 to 110 mm (abt. 2 to 4 inch.), as indicated in Table I. The dimensions ranged from 150 to 300 mm in thickness and from 760 to 1260 mm in width, and the weights from 2000 to 3000 kgs.

The slab type 1 was conventionally forged in the beta field by drawing out the ingot, while slab type 2 was hot formed with a higher total deformation by using upset forging between the different draw-out processes, and reduced to a remarkable extent in the beta field. The microstructures of the slabs are shown in Fig. 1. Consequently, slab type 1 shows an acicular alpha and beta and alpha precipitations on the prior beta grain boundaries. Slab type 2, already in the large cross section of $38 \times 10^4$ mm$^2$ (600 sq.inch.), has fined grained equiaxed alpha and a small amount of intergranular beta.

The tensile properties of both slab types, despite their different hot working conditions, are similar with respect to the UTS, but higher than the UTS of the ingot and the limits of the usual specifications. Elongation and R.A. of slab type 2 are higher than those of slab type 1, but there is a more distinct difference between the longitudinal and the short transversal direction.

The plates were produced from these slabs by hot rolling in one heat at a constant rolling speed and a constant reduction per pass. The hot rolling temperatures were changed in such a way that the deformation data given in Table I shows a variation in deformation below the beta transus temperature ($\ln F/F_1 = 0 - 1.1$ with $F$ as cross section area). Temperature control was carried out at the beginning of the rolling operation, at an intermediate stage and at the end of the process.

Fig. 2 shows the microstructures of the plates listed in Table I in the longitudinal direction and in the
<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>STARTING MATERIAL</th>
<th>SECTION SIZE F</th>
<th>DEFORMATION ( \frac{\log F_0}{\log F_1} ) TOTAL (&lt; 980^\circ C )</th>
<th>SAMPLING</th>
<th>TENSILE PROPERTIES 1)</th>
<th>NOTCHED TENSILE STRENGTH</th>
<th>NOTCHED TIME FRACTION, 2)</th>
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</thead>
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<tr>
<td>INGOT</td>
<td>SLAB 1 INGOT</td>
<td>68·10⁻⁴</td>
<td>-</td>
<td>T</td>
<td>82.0 0.900 % 4.5 9</td>
<td>134</td>
<td>126 1.4</td>
</tr>
<tr>
<td>113·10⁻⁴</td>
<td>-</td>
<td>1.25</td>
<td>0</td>
<td>L</td>
<td>93.0 0.899 % 11.1 18</td>
<td>134</td>
<td>126 0.2</td>
</tr>
<tr>
<td>23·10⁻⁴</td>
<td></td>
<td></td>
<td></td>
<td>ST</td>
<td>91.5 0.908 % 9.1 19</td>
<td>134</td>
<td>126 0.8</td>
</tr>
<tr>
<td>SLAB 2</td>
<td>INGOT</td>
<td>38·10⁻⁴</td>
<td>-</td>
<td>L</td>
<td>92.7 0.925 % 13.1 26</td>
<td>136</td>
<td>126 3.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LT</td>
<td>93.5 0.930 % 14.4 30</td>
<td>134</td>
<td>126 2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ST</td>
<td>94.3 0.920 % 80 26</td>
<td>135</td>
<td>126 4.3</td>
</tr>
<tr>
<td>PLATE 1</td>
<td>SLAB 1</td>
<td>3.4·10⁻⁴</td>
<td>-</td>
<td>L</td>
<td>952·19 0.925 % 13.5·14 26·2</td>
<td>137</td>
<td>126 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LT</td>
<td>982·15 0.930 % 12.9·1.7 23·2</td>
<td>138</td>
<td>126 0.1</td>
</tr>
<tr>
<td>PLATE 2</td>
<td>SLAB 1</td>
<td>49·10⁻⁴</td>
<td>-</td>
<td>L</td>
<td>962·17 0.930 % 133·0.7 29·3</td>
<td>139</td>
<td>140 0.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LT</td>
<td>982·17 0.940 % 128·0.8 27·5</td>
<td>142</td>
<td>133 2.80</td>
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<td></td>
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<td></td>
<td>ST</td>
<td>969·16 0.890 % 102·1.3 25·4</td>
<td>137</td>
<td>133 0.38</td>
</tr>
<tr>
<td>PLATE 3</td>
<td>SLAB 1</td>
<td>8.4·10⁻⁴</td>
<td>-</td>
<td>L</td>
<td>934·16 0.951 % 128·1.9 27·3</td>
<td>138</td>
<td>119 2.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LT</td>
<td>968·19 0.965 % 118·2.2 25·4</td>
<td>140</td>
<td>126 0.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ST</td>
<td>984·19 0.915 % 100·1.5 19·4</td>
<td>131</td>
<td>119 1.34</td>
</tr>
<tr>
<td>PLATE 4</td>
<td>SLAB 2</td>
<td>12.5·10⁻⁴</td>
<td>-</td>
<td>L</td>
<td>93·122 0.932 % 167·1.1 36·1</td>
<td>139</td>
<td>126 1.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LT</td>
<td>950·33 0.925 % 134·2.5 32·7</td>
<td>130</td>
<td>133 1.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ST</td>
<td>94·120 0.896 % 153·2.2 28·4</td>
<td>138</td>
<td>126 1.77</td>
</tr>
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</table>

1) AVERAGE VALUES AND STANDARD DEVIATION.
2) TEST SPECIMEN ACCORDING TO AMS 4928 INITIAL STRESS 119 \( kp/mm^2 \) INCREASING BY 7 \( kp/mm^2 \) EVERY 5 hrs.
Fig. 1. Typical microstructures of slabs forged under different hot working conditions.
Fig. 2. Typical microstructures of Ti-6Al-4V plate rolled under different hot rolling conditions.
annealed condition. Plates 1, 2, and 3 were hot rolled from slab type 1.

Plate 1 has a worked beta structure with partially deformed alpha + beta. The precipitation of alpha at the prior beta grain boundaries was avoided by rolling the last deformation at the beta transus temperature.

Plate 2 which was rolled with a certain but small degree of deformation below the beta transus temperature shows a worked beta structure, partially deformed acicular alpha + beta and fine elongated alpha + beta.

Plate 3 was hot rolled completely below the beta transus temperature. The microstructure consists of elongated alpha + beta and partially equiaxed alpha with small amounts of beta. A significant banded structure with different bands and grain sizes is visible.

Plate 4 was hot rolled from a slab of type 2 under the same conditions as used for plate 3. The microstructure is fine grained with equiaxed alpha in a very uniform distribution. This is due to the special forging method of the slab with a high total deformation partially below the beta transus temperature.

The properties of the plates listed in Table I are the standard properties called for in the usual specifications. The tensile properties are listed as average values, with the standard deviation of approximately 2σ single tests per plate. A comparison of the UTS figures reveals no significant difference between the different plates processed in four different ways. Consequently, the variation of the UTS is less influenced by the hot working conditions than it may be determined by the variation of the interstitial additions within the tolerance range of the specifications.

The ratio of yield point to tensile strength is not significantly changed by the different hot rolling conditions. The influence of the content of primary alpha after an additional heat treatment may be more important.

A high total deformation together with an extensive deformation at a hot working temperature below the beta transus temperature results in a pronounced increase of elongation and reduction in area, as shown in Table I, plate 4.
The notched tensile strength is not influenced by the hot working conditions of the hot rolled plates under consideration. The notched time fracture test seems to give better results for an uniform microstructure (plate 2 and plate 4) in comparison to plates with a non-uniform grain size or grain distribution (plate 3) and such plates where the microstructures show the tendency for unbroken alpha precipitations on prior beta grain boundaries.

Preliminary tests to determin fracture toughness figures are in accordance with published data (6) (9) which show higher fracture toughness values in the case of acicular microstructures as shown in Fig. 2, plate 1 and plate 2. The influence of hot rolling conditions on the fatigue strength has still to be investigated.

The macrostructures of the plates 3 and 4 are shown in Fig. 3. There is a significant difference in these structures which were achieved by using the same rolling conditions but different forging methods to process the slabs. The macrostructure of plate 4 is better qualified for the ultrasonic inspection on account of the low hash.

Forgings

A large variety of microstructures from acicular to elongated alpha + beta grains and fine grained equiaxed alpha was previously found in forgings (18). Today uniform structures with fine grained equiaxied microstructures and a defined percentage of primary alpha are required by recently published specifications. Even the die forging industry demands billets with a fine grained macrostructure as starting material (19). Contradictory opinions were published in literature, one saying that a fine grained starting billet shows a fatigue life superior to that obtained with similiarly processed forgings from coarse grained billets (20), the other saying that a prior beta grain size has little influence on fatigue strength (7).

These facts and the general opinion that a fine grained material is superior to a coarse grained one are the background of the requirements of the European Aircraft industry on Ti 6Al 4V forgings. Hand forgings of heavy sections and billet stock as well are required with a fine grained equiaxed structure despite the
Fig. 3. Macrostructures of hot rolled Ti-6Al-4V plate.

Plate 3 x1
Plate 4 x1
better fracture toughness values of acicular structures.

In Table II the properties, section sizes and deformation data of some hand forgings are listed. The microstructures of the various forgings are described.

Forged rings weighing 130 kgs were processed under different hot working conditions. A high total deformation with an extensive deformation below the beta transus temperature results only in better values for elongation and reduction in area, while the UTS and the YS show no significant difference. A slight increase of the UTS without loss of elongation and reduction in area is achieved if these forgings are solution treated and overaged. The notched time fracture test reveals satisfactory results in the annealed condition but is increased by solution treating and overaging. There is no decrease in the ratio of yield point to tensile strength from the annealed to the s.t.o.a.-condition on account of a primary alpha content of 30%. The difference between the properties in the different directions is not very distinct, but the results of the specimens taken in the radial direction are in this case lower.

The properties of a 200 kgs hand forging of square section (140 sq. inch.) are similar. The lowest but still excellent value are obtained in the ST direction.

A comparison of the heavy-section forgings with a small-section hand-forged ring shows that properties may be obtained which are generally significant for small-section forgings only if the heavy sections are processed with a high total deformation accompanied by an extensive deformation at temperatures below the beta transus temperature and applying upset forging between the draw out and expanding processes. Consequently, the microstructure of the specially forged heavy-section parts is fine grained with equiaxed alpha, as described in Table II. The macrostructure, as a result of the high total deformation with an important portion in the alpha-beta field, is very fine grained and therefore qualified for high perceptibility of defects by ultra-sonic inspection.
Table II. Mechanical properties of Ti-6Al-4V forgings with different cross sections

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>MAIN DIMENSIONS</th>
<th>SECTION SIZE</th>
<th>DEFORMATION</th>
<th>SAMP.LING</th>
<th>NO. OF PIECES TESTED</th>
<th>TENSILE PROPERTIES</th>
<th>NOTCHED TIME FRACTURE</th>
<th>STRUCTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>F</td>
<td>( (\ln \frac{F_2}{F_0}) &lt; 980^\circ C )</td>
<td></td>
<td></td>
<td>UTS</td>
<td>YS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>mm</td>
<td>mm²</td>
<td></td>
<td></td>
<td>kPa</td>
<td>%</td>
</tr>
<tr>
<td>RING (ANNEALED)</td>
<td>500/260 x 200</td>
<td>24.10³</td>
<td>220 (+0.9)</td>
<td>0.50</td>
<td>TANG</td>
<td>1</td>
<td>96.9</td>
<td>0.940</td>
</tr>
<tr>
<td>RING (ANNEALED)</td>
<td>500/260 x 200</td>
<td>24.10³</td>
<td>3.20 (+1.80)</td>
<td>126 (+1.20)</td>
<td>AX</td>
<td>TANG</td>
<td>1</td>
<td>95.1</td>
</tr>
<tr>
<td>RING (S.T.O.A.)</td>
<td>500/260 x 200</td>
<td>24.10³</td>
<td>3.20 (+1.80)</td>
<td>126 (+1.20)</td>
<td>AX</td>
<td>TANG</td>
<td>1</td>
<td>95.1</td>
</tr>
<tr>
<td>SQUARE-SECTION (S.T.O.A.)</td>
<td>385x240</td>
<td>92.10³</td>
<td>2.90 (+1.38)</td>
<td>0.99</td>
<td>L</td>
<td>LT 1</td>
<td>1</td>
<td>97.4</td>
</tr>
<tr>
<td>RING (ANNEALED)</td>
<td>540/466 x 60</td>
<td>2.3.10³</td>
<td>3.50 (+1.70)</td>
<td>19.0 (+1.70)</td>
<td>TANG</td>
<td>36</td>
<td>947±17</td>
<td>0.952</td>
</tr>
<tr>
<td>RING (S.T.O.A.)</td>
<td>540/466 x 60</td>
<td>2.3.10³</td>
<td>3.50 (+1.70)</td>
<td>19.0 (+1.70)</td>
<td>TANG</td>
<td>1</td>
<td>103.0</td>
<td>0.920</td>
</tr>
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</table>

1) AVERAGE VALUES AND STANDARD DEVIATION.
2) TEST SPECIMEN ACCORDING TO AMS 4928. INITIAL STRESS 119 kPa/mm², INCREASING BY 7 kPa/mm² EVERY 5 hrs.
Summary

The influence of the hot working conditions on the properties of forged slabs, hot rolled plates and heavy-section hand forgings of Ti6Al4V-alloy were investigated.

1. The relation between the hot working conditions and the properties investigated is similar for the forged slabs, the rolled plates and the forgings.

2. The UTS is not significantly influenced by the hot working conditions in the deformation range investigated.

3. Elongation and reduction in area increase considerably with increasing deformation below the beta transus temperature.

4. The difference between the value of elongation and reduction in area in the different directions becomes more distinct with increasing deformation below the beta transus temperature.

5. The notched time fracture test gives good results if uniform microstructures are produced in the material being tested.

6. The perceptibility of defects by ultra-sonic inspection is improved if fine grained macro- and micro-structures are produced by a high total deformation with an extensive deformation below the beta transus temperature.

The improvement of some properties by an extremely high deformation particularly below the beta transus temperature may be justified if other properties not investigated will be improved as well.

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