The Roughness in the Diffusion Welding of Ti-6Al-4V Alloy

Various surface finishes were studied to determine their effect on the quality of diffusion-welded titanium

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ABSTRACT. In this study, we show that the surface finish plays an important part in diffusion welding of titanium alloys. The welded surface area in titanium alloys increases when the finish roughness $R$ decreases and reaches 100% of the surface when roughness is lower than the titanium auto diffusion $X$.

The ratio $X/R$ defined above seems to play a particular part in weld quality ($X = \text{autodiffusion distance of titanium}$, $R = \text{roughness of the surface}$). In the case of joints between the beta $(\beta)$ phase, no defect is observed for values superior to one. For values below one, defects become larger and more numerous. Therefore, this parameter seems to express the effects of time, temperature and surface finish.

Introduction

Diffusion welding associated with superplastic forming operations is a well-proven technique, particularly as used on titanium alloys of the Ti-6Al-4V type (Refs. 1 and 2). Defects in the joint have considerable influence on its mechanical characteristics, such as fatigue. An investigation of these is a very important step in mastering the process. Pilling, et al. (Ref. 3), studied the influence of welding parameters on the percentage of the surface area welded at a surface finish of 30 $\mu$m.

KEY WORDS

Surface Finish
Diffusion Welding
Titanium Alloy
Roughness
Weld Surface Area
Temperature
Weld Defect
Autodiffusion Dist.
Welding Time
Microstructure

R = 1.56 ±0.11 $\mu$m, where $R$ is the mean roughness reading obtained from three longitudinal and transverse profiles made using a mechanical sensor. As defined in the AFNOR standard N.FE-05.015, $R$ is the mean arithmetic deviation of the profile.

The chemically stripped condition was obtained by a two minute immersion in a bath of nitrohydrofluoric acid solution (30% HNO$_3$, 3% HF, 67% H$_2$O) followed by rinsing and drying.

The polished finish was obtained by mechanical polishing with $P$ 1000 ($R = 30 \mu$m) abrasive paper followed by 7 $\mu$m and 1 $\mu$m diamond paste.

Experimental Method

Preparation of Test Pieces

Three surface finishes were investigated: 1) rough (as delivered), $R = 1.72 ±0.13 \mu$m; 2) mechanically polished, $R = 0.54 ±0.14 \mu$m; 3) chemically stripped.

The fixture was placed in an oven whose temperature may be adjusted to ±5°C and in which the pressure was 10$^{-4}$ mbars.

Thermal Cycles

Two maximum temperature levels were reached: 885°C and 850°C. The thermal cycles obtained are as plotted in Fig. 3.
Measurement of the Joint Characteristics

After welding, the sheets formed a cube with a side length of a few mm. The edge of this cube was mechanically polished to remove 0.5 mm. The three welded joints were then inspected under a scanning electronic microscope after being subjected to dilute acid etching (2% HF, 4% HNO₃, 94% H₂O) — Fig. 4.

Within each joint, defects with a 1 μm minimum length were counted. The edges showed a high number of large defects (over 10 μm) caused by the non-uniformity of the pressure applied — Fig. 4A. These were not included when counting defects on a 0.5 mm length. The effective length of the joint was therefore reduced to 4 mm.

The parameters noted were as follows:
N = number of welding defects per mm of joint (16 mm were inspected on the joint); L = the statistical mean length of the defect ± σ (typical deviation); L_D/L_T% : percentage of unwelded length and S% = percentage of welded surface (defects are considered as discs).

\[
S% = 100 \left(1 - \frac{\left(\frac{L_D}{L_T}\right)^2}{\pi}\right) \tag{1}
\]

Results

Defect Distribution

All the samples showed the same equiaxis structure α + β. No defect was noted in β phase. They were all in α phase and extended from a spherical form in the case of small defects (L<2 μm) (Fig. 4D) to an elliptical form for the largest (L > 2 μm) (Fig. 4B, C). Tables 1 and 2 show the results obtained. The M column is the statistical mean value of the parameters noted above.

The results show that the number of defects and their mean length decreased with increases in the welding time and temperature and with a reduction in the roughness of the surface finish. Figure 5 illustrates the variations in L_D/L_T (%) and L (μm) as a function of the roughness for the mean time noted in M. Note that temperature has an important effect on the mean length of the defects and their proportions. This is caused by the vari-
Table 1 — Welding Defect Characteristics at 885°C

<table>
<thead>
<tr>
<th></th>
<th>As-received: Rough</th>
<th>Stripped: R = 1.56 μm</th>
<th>Polished R = 0.54 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>L</td>
<td>S%</td>
</tr>
<tr>
<td>t₀</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>28.71</td>
<td>10.08</td>
<td>17.20</td>
</tr>
<tr>
<td>L</td>
<td>1.58</td>
<td>1.16</td>
<td>1.35</td>
</tr>
<tr>
<td>±σ</td>
<td>1.32</td>
<td>0.47</td>
<td>1.04</td>
</tr>
<tr>
<td>L₀/Lₜ</td>
<td>4.53</td>
<td>1.17</td>
<td>2.32</td>
</tr>
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</table>

Table 2 — Welding Defect Characteristics at 850°C

<table>
<thead>
<tr>
<th></th>
<th>As-received: Rough</th>
<th>Stripped: R = 1.56 μm</th>
<th>Polished R = 0.54 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>L</td>
<td>S%</td>
</tr>
<tr>
<td>t₀</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>N</td>
<td>48.38</td>
<td>36.5</td>
<td>21.76</td>
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<tr>
<td>L</td>
<td>2.32</td>
<td>2.63</td>
<td>1.80</td>
</tr>
<tr>
<td>±σ</td>
<td>2.25</td>
<td>2.72</td>
<td>1.66</td>
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<tr>
<td>L₀/Lₜ</td>
<td>11.22</td>
<td>9.59</td>
<td>3.92</td>
</tr>
<tr>
<td>S%</td>
<td>99.00</td>
<td>99.27</td>
<td>99.87</td>
</tr>
</tbody>
</table>

Fig. 5 — Variations as a function of surface roughness. A — In L₀/Lₜ (%); B — In L (μm).

The thermal cycles obtained (Fig. 3) are not rectangular. The holding time for the test pieces at high temperature is not sufficient to characterize the welding operation, and the temperature rise and decrease time have to be taken into account. If the heating and cooling phases are made linear, our heating cycle is similar to that shown in Fig. 6.

The Time Effect

The Introduction of an Equivalent Time

The parameter resulted in the definition of a rectangular thermal cycle that was the equivalent of any trapezoidal cycle. Thus, the holding time tₑ of the rectangular cycle A'B'C'D' equivalent to the ABCD cycle of the same temperature Tₑ was equal to the time during which the temperature remained higher, in the true cycle, than a temperature Tₑ provided by the equation

\[ P = \left( \frac{1}{T} - \frac{1}{C \log \left( \frac{t}{t₀} \right)} \right)^{-1} \]

where

- C = a constant derived from activation heat
- t = time
- t₀ = reference time
- T = absolute temperature

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\[ Tₑ = T_p - \frac{T_p - T_p}{Q} \]

There is an increase in defects of 49% between 850° and 885°C. This results in an increase of the mean free movement of the atoms of 22% calculated using the equation

\[ X = 2\sqrt{\pi D t} \]
where \( Q/R = 14760 \) (a nondimensional number). Thus for titanium \( \alpha \) with \( T_p \) at 885°C, \( T_E = 795°C \); with \( T_p \) at 850°C, \( T_E = 765°C \). We can calculate \( t_E \) for thermal cycles without a time at which the maximum temperature is held. Thus, we obtain

\[ t_E = 3 \, h \, 40 \, min \] for an 885°C cycle (without a temperature holding time), and

\[ t_E = 3 \, h \, 15 \, min \] for an 850°C cycle.

Therefore, the notion of equivalent time becomes very important. It allows us to compare the results of different thermal cycles providing the phenomena under investigation are based on diffusion.

**Variations in the Defect Characteristics As a Function of the Equivalent Time**

After clearly defining the equivalent time, we considered the variation in the mean length of the defects and their proportion as a function of this parameter. Figure 7 shows the results obtained for the three surface finishes: \( R = \) rough, \( S = \) stripped and \( P = \) polished. The mean length of the defect and the percentage of unwelded length decreased significantly with the diffusion time.

The diffusion time appears in the calculation of the autodiffusion distance by

\[ X = 2\sqrt{\pi D t} \]

where \( t = t_E \) and \( D = D_0 \exp \left( \frac{Q}{T} \right) \) (7)

Tables 3 and 4 show the development in the autodiffusion distance of titanium in \( \alpha \) phase and \( \beta \) phases as a function of the time and temperature.

The autodiffusion distances of titanium in \( \beta \) phase are all significantly greater than the grain size and surface finish roughness (\( R = 1.76 \, \mu m \) maximum of our test pieces in that they varied between 66 and 124 \( \mu m \)). This explains the freedom of defects in this phase.

However, in \( \alpha \) phase, Tables 3 and 4 and Fig. 7 show that as long as the roughness of the surface finish remained lower than the autodiffusion distance, the dimensions of the defects remained small (< 2 \( \mu m \)) and the percentage of unwelded length was also small (< 5%). Consequently, the ratio of this distance to the surface finish roughness \( X/R \) seemed fundamental for the quality of the welds obtained. As a comparison, the results obtained by Pilling, et al. (Ref. 3), showed much lower welded area percentages; i.e., a much higher percentage of defects. In these experiments, the welding pressure, the grain size and the

![Fig. 6 — Trapezoidal and rectangular thermal cycles.](image)

![Fig. 7 — Variations as a function of equivalent time. A — In \( L/D \)/\( L_T \) (%); B — In \( L \) \( \mu m \).](image)

![Fig. 8 — Variations in the welded length percentage as a function of \( X/R \).](image)
temperature were roughly identical to ours; it was only the roughness and the pitch of the surface finish irregularities that were different (R = 30 μm and AR = 60 μm).

Under these conditions, the percentage of surface area welded was only 70% in 3 h. This confirmed our initial conclusions regarding the importance of surface finish. Thus, for a roughness below 1 μm, the welding time was 3 h at 850°C and for a finish roughness of 30 μm, it required 15 h at 877°C to obtain a welded joint of the same quality. These conclusions are illustrated in Fig. 8 in which we have shown our results and those of Pilling (Ref. 6) as a function of X/R.

Discussion and Conclusions

The absence of any defects in β phase is explained by the coefficient of diffusion which was ten times larger than it was in α phase, thus welding in α phase is preferable. The percentage of the surface area welded was greater than 99.5% in every case; however, it only reached this value after 5 h of heating in the study cited in Ref. 3.

This study has shown that the ratio between the autodiffusion distance (X) and the roughness (R) plays an important part in the diffusion welding of titanium alloys. For temperatures between 850° and 885°C, the autodiffusion distance varied between 66 and 124 μm for β phase and between 1.36 and 2.54 μm for α phase, whereas the finish surface roughness varied from 0.54 to 1.72 μm. This provides an X/R ratio of several tens of units in β phase and a few units in α phase. This may explain the absence of defects in β phase. Furthermore, we have shown by comparing our results with those of other authors that the welding time can be significantly reduced for a given weld quality by reducing the surface finish roughness.

References