Mechanical Properties of High-Temperature Brazed Titanium Materials

Joint clearance proves to be a critical parameter for maintaining joint integrity

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ABSTRACT. The mechanical properties of commercial titanium CPTi and Ti-Al6-V4 joints, brazed with Ti-based filler metals in the system Ti-(Zr)-Cu-Ni-(Pd) are evaluated by tensile test at various temperatures, as well as by fatigue test at room temperature. The influence of the microstructure in the brazing zone on the mechanical properties of the joints was assessed by conducting metallographic analysis. A vacuum furnace and an induction heating furnace were used for the production of the metallographic and tensile samples.

The results from the mechanical and metallographic investigations revealed a strong dependence of the tensile strength of the titanium joints on the microstructure of the brazing zone. The presence of the brittle intermetallic Ti-Cu and Ti-Ni phases in the brazing zone leads to the weakening of the joint. However, the formation of these intermetallic phases can be avoided by using adequate brazing process parameters and by optimizing the joint clearance. In that case, it is possible to fabricate titanium joints with Ti-based filler metals that have excellent mechanical properties comparable to those of the base metal.

Introduction

Titanium and its alloys have been employed in industrial applications for 30 years, especially in the aerospace and chemical industries. Due to the high material cost, an integral fabrication of titanium components is a major economic demand. This, however, requires an adequate joining technique, which on one hand does not restrict the mechanical and chemical properties of the base metal too much and on the other hand is inexpensive and flexible. In addition to several welding techniques, such as gas tungsten arc welding (GTAW), diffusion and electron beam welding, brazing technology is a joining alternative of great interest (Ref. 1).

Suitable filler metals for brazing titanium materials are Ag- and Al-based alloys. The excellent wettability and mechanical properties of these filler metals have been demonstrated in several studies (Refs. 2-7). However, since the fabrication of titanium joints with mechanical and chemical properties comparable to those of the base metal is not possible with Ag- and Al-based filler metals, attention has shifted to titanium-based filler metals that have shown superior mechanical properties, corrosion resistance and high-temperature strength.

A commercially available Ti-based filler metal of common usage is Ti-Cu15-Ni15. The main disadvantage of this filler metal is that it requires very high brazing temperatures (>980°C/1796°F), which in most cases influences the microstructure of the titanium base metal by α-β transformation and grain growth (Ref. 8). Therefore, research activities in the last few years have concentrated on the development of Ti-based filler metals with lower liquidus temperatures than the commercial alloy Ti-Cu15-Ni15.

Development of Ti-Cu20-Ni20, Ti-Cu19-Ni19-Pd2 and Ti-Zr35-Cu15-Ni15 makes it three the number of alloys that allow brazing below the α-β transition temperature of Ti-Al6-V4 (960°C/1760°F) and CPTi (880°C/1616°F), respectively.

The present study examines the suitability of Ti-Cu-Ni(Pd) and Ti-Zr-Cu-Ni filler metals for brazing Ti-Al6-V4 and CPTi. Metallographic and mechanical examinations give hints on adequate processing parameters and application properties of high-temperature brazed titanium materials.

Materials and Experimental Procedure Materials

Commercially pure titanium (CPTi) and the α-β-titanium alloy Ti-Al6-V4 were used as base metals. The chemical composition and physical properties of the base metals are given in Tables 1 and 2. The composition and melting range of the titanium-based filler metals employed in the present study are summarized in Table 3. As can be seen from the last table, all the filler metals are suitable for brazing Ti-Al6-V4 without influencing the microstructure of the base metal, since the maximum brazing temperature of 950°C (1742°F) is below the α-β-transformation temperature, which is about 960°C. Brazing of CPTi, on the other hand, can only be performed with the TiZrCuNi filler metal since the maximum brazing temperature is below the α-β-transformation temperature of the base metal.
metal (880°C).

Since the filler metals in the Ti-(Zr)-Cu-Ni system generally have a brittle character because of formation of intermetallic TiCu- and TiNi-phases, fabrication of homogeneous foils by rolling is impossible. Therefore, the filler metals in the system Ti-Cu-Ni are commonly used in powder form or as laminated brazing foils. The fabrication of homogeneous foils is also possible when using the melt spinning technique. This last fabrication technique makes possible the production of foils with an amorphous microstructure and a thickness of 50 μm by rapid solidification (10⁶ K/min) (Ref. 9). In the present study, filler metal powders were used for the fabrication of metallographic brazing samples, while filler metal foils, produced by melt-spinning, were employed for the production of the brazing samples submitted to tensile and fatigue tests.

Brazing Procedure

For the metallographic investigation, high-temperature CPTi and Ti-Al-6-V4 brazed joints were fabricated using a so-called wedge-gap specimen — Fig. 1. The wedge-gap specimen consists of two sheets of base metal, fixed together at the front side by a GTA tack weld. The wedge form of the specimen is achieved by inserting two thin foils of different thicknesses between the two sheets producing a wedge joint clearance between 0–100 μm. These wedge-gap specimens were degreased and rinsed in acetone. Following cleaning, the filler metal powder was placed above the wedge joint clearance and then samples were loaded into the vacuum furnace or induction furnace. During brazing, the molten filler metal penetrates the wedge joint clearance due to gravity and capillary action. After brazing, the wedge-gap sample was metallographically prepared for light microscopic analysis and microhardness measurements. The advantage of using the wedge joint clearance geometry is that it allows the investigation of the relationship between brazing-zone microstructure and joint clearance size, as well as the determination of the maximum joint clearance size.

The maximum joint clearance size characterizes the joint clearance size at which the brittle intermetallic phases first occur. Since the occurrence of these intermetallic phases affect the mechanical as well as the chemical properties of the joint, the maximum brazing joint clearance is considered to be a very important factor in designing a joint.

The mechanical characterization of titanium joints was done by tensile tests and fatigue tests. In the fabrication of the braze joints for tensile and fatigue tests, the ends of cylindrical samples were machined flat and parallel. The samples were then cleaned in acetone and the filler metal foils placed between the facing surfaces of the cylindrical specimens. After brazing in the vacuum or induction furnaces, the samples were machined, as shown in Fig. 2, before being subjected to mechanical tests.

The joining was done by the vacuum furnace brazing process and the induction brazing process using argon as a shielding gas. Figure 3 shows the temperature-time cycles used for the two brazing processes.

Results and Discussion

Metallurgical Examinations

Figure 4 exhibits the microstructures of the Ti-Al-6-V4 and CPTi joints brazed with Ti-Cu-Ni and Ti-Zr-Cu-Ni filler metal, respectively. The microstructure of the brazing zones can be divided into three areas, the formation of which is apparently strongly dependent on joint clearance size. According to literature, the area with the fine Widmanstätten structure, which is called diffusion zone, consists of α- and β-titanium phases (Refs. 10, 11). As Den, et al. (Ref. 10), suggests, the formation of the diffusion zone microstructure at Ti-Al6-V4 Ti-Cu-Ni brazements is attributed to the decrease of the α-β-transformation temperature in this area, due to the diffusion of Cu and Ni into the base metal. The second area, which can be distinguished next to the diffusion zone, is enriched in Cu and Ni, as SEM-analysis of analogous brazements revealed (Refs. 10, 11). Whereas both references report of the existence of β-titanium phases in this area, Den, et al. (Ref. 10), also identified Ti2Cu-phases by using x-ray diffraction analysis. The third area, located in the middle of the brazing zone, has also been analyzed by Den, et al. (Ref. 10), using x-ray diffraction analysis. The results of these examinations, which he carried out on a Ti-Al6-V4 Ti-Cu15-Ni15 brazed joint, revealed, that this area consists mainly of Ti2Ni-phases, and to a minor extent of intermetallic Ti2Cu-phases.

For further characterization of the different phases in the brazing zone, microhardness measurements were performed across the brazing zone on a Ti-Al6-V4 Ti-Cu-Ni(Pd) joint and a CPTi-Ti-Zr-Cu-Ni
joint, as shown in Fig. 5. The microhardness rises toward the center of the brazing zone, reaching a maximum value of 550 HV0.05, most probably due to the presence of the intermetallic phases. The microhardness of the diffusion zone, on the other hand, is slightly above that of the base metal. The embrittlement of the brazing zone as a result of the formation of intermetallic phases lowers the mechanical properties of the titanium joint as will be demonstrated later. An effective method to prevent embrittlement of the titanium joint is by adjustment of the joint clearance size. Figure 6 shows the influence of joint clearance size on the microstructure of the brazing zone of a Ti-Al6-V4 joint brazed with Ti-Cu-Ni. For small joint clearances (<20 μm), the microstructure of the joint consists of fine Widmanstätten structure only (Fig. 6A), and it has a ductile character. By increasing the joint clearance (Fig. 6B), β-titanium phase forms in the middle of the brazing zone. Yet, further increases in joint clearance leads to the formation of intermetallic phases at the center of the brazing zone — Fig. 6C. These results imply that reduction of the joint clearance sizes will be advantageous to avoid formation of brittle intermetallic phases in the brazing zone.

Besides joint design, the microstructure of the brazing zone can be influenced by variation of the brazing process parameters. Figure 7A-C shows the relation between brazing time and microstructure of a Ti-Al6-V4 joint, brazed with a 50-μm-thick Ti-Cu-Ni filler metal foil. For a short brazing time (5 min), the microstructure of the Ti-Al6-V4 joint consists of the same areas characterized above, including the brittle intermetallic phases in the center of the brazing zone — Fig. 7A. By increasing the brazing time from 5 to 10 min, the brittle intermetallic phases disappear and the brazing zone now consists of the diffusion zone and the β-titanium phase, as shown in Fig. 7B. Brazing times of 30 min produced an increase in the width of the diffusion zone and reduction of the β-titanium phase. This was probably caused by the diffusion of Cu and Ni into the base metal.

For an adequate selection of brazing process parameters and joint design, it is important then to have some information of the maximum brazing joint clearance, at which intermetallic phases form for the first time. Figure 8 shows the maximum joint clearance sizes of vacuum and induction brazed Ti-Al6-V4 and CPTi joints, determined by metallographic analysis of the wedge-gap specimen. The maximum brazing joint clearance of the CPTi Ti-Zr-Cu-Ni joints is seen to be clearly smaller than that of the Ti-Al6-V4 Ti-Cu-Ni(Pd) joints. In the Ti-Al6-V4 joints, joint clearances of 90 μm are sufficient to avoid formation of the intermetallic phases at a brazing time of 10 min. Embrittlement of the CPTi Ti-Zr-Cu-Ni joints, caused by formation of intermetallic phases, occurs at brazing joint clearances of about 20 μm, when the brazing time is also 10 min.

A comparison of the vacuum brazing process to the induction brazing process with regard to the maximum brazing joint clearance shows that the vacuum brazed Ti-Al6-V4 and CPTi joints allow larger joint clearances without inducing formation of intermetallic phases.

**Tensile Strength of Joints**

The relationship between brazing zone microstructure and mechanical properties of Ti-Al6-V4 and CPTi joints brazed with 50-μm thick filler metal foil, has been established in this investigation. Fig. 9 presents the tensile strengths of the joints, processed as a function of brazing time and type of brazing process. The vacuum brazed Ti-Al6-V4 joints for example, show excellent tensile strength independent of the brazing time. All samples failed at tensile stresses of 930 MPa.
(135 ksi) in the base metal. This correlates with the absence of intermetallic phases in the brazed joints of samples vacuum processed. On the other hand, the Ti-6Al-4V joints, which were induction brazed, show tensile properties lower than those of the vacuum brazed joints, as seen in Fig. 9A. These poorer mechanical properties can be correlated with the presence of intermetallic phases since the actual brazing joint clearance of these brazed joints (50 μm) is greater than the maximum required to avoid the formation of intermetallics as described before in Fig. 8. The tensile strength values of the induction brazed joints also show a strong scattering, which increases as the difference between the actual brazing joint clearance and the maximum joint clearance of the system becomes larger. This larger clearance difference would be expected to increase the amount of brittle phases in the brazing zone. Those joints, which have been induction brazed at 5 min, have the best mechanical properties of all induction brazed joints, and the smallest brazing joint clearance difference.

The influence of microstructure of the brazing zone on the mechanical properties of the titanium joints is also demonstrated by the results of the tensile tests of CPTi joints. As can be seen in Fig. 9B, the tensile strengths of the vacuum-brazed and induction-brazed CPTi joints are clearly below that of CPTi, which is about 375 MPa (54 ksi). All samples tested failed at the joint interface. The reason for the low average tensile strength and the relatively high scattering of the strength values of the CPTi joints can be seen in the lower maximum brazing joint clearance of the system CPTi-Ti-Zr-Cu-Ni. According to Fig. 8, formation of brittle intermetallic phases in the brazing zone of the tensile CPTi specimens, brazed with 50-μm filler metal foil, is expected in both the vacuum-brazed and induction-brazed samples. The best mechanical properties are achieved by those joints, where the maximum brazing joint clearances are only slightly lower than the brazing clearance of 50 μm, and therefore, a minimum of intermetallic phases within the brazing zone is expected. Consequently, the CPTi joints brazed in a vacuum furnace at 30 min brazing time have the highest tensile strength among all CPTi joints. The samples failed above the yield strength of the base metal in the interface of the joint.

Tensile Strength at Elevated Temperatures

In Fig. 10, the results of the tensile tests at elevated temperatures are given. For the fabrication of the tensile specimen, filler metal foils with a thickness of 50 μm...
were used with process parameters of 950°C/5min (1733°F) for the Ti-Al6-V4 Ti-Cu-Ni-Pd brazing system and 870°C/10 min (1553°F) for the CPTi Ti-Zr-Cu-Ni brazing system. The joining of all these samples was done in the vacuum furnace. These process parameters have been chosen in order to provide ductile joints, at least in the case of Ti-Al6-V4, which are free of brittle intermetallic phases.

As can be seen from Fig. 10, the tensile strength of the Ti-Al6-V4 joints and the CPTi joints, as well as that of the base metal samples, is reduced with increasing test temperature. In the case of Ti-Al6-V4 joints, the reduction of tensile strength of the brazed joint is comparable to that of Ti-Al6-V4. However, with increasing test temperature, the reliability of the brazed joints becomes poorer, which is characterized by an increase in scattering of the tensile strength values.

On the other hand, the tensile strength of the CPTi-joints is much more dependent on test temperature. The average tensile strength of brazed CPTi-joints is reduced by 50% when test temperature increases from 25°C (77°F) to 150°C (302°F). A further increase of test temperature to 300°C (572°F) leads to a further decrease of the average tensile strength of about 25%. It can also be seen from Fig. 10B that the CPTi base metal samples also show a large strength reduction at the test temperature of 300°C. The relation of tensile strength of the brazed joint and tensile strength of CPTi base metal is therefore nearly constant across the test temperature range.

Tensile Strength of Preoxidized Titanium Joints

For the determination of the influence of oxidation on the mechanical properties of titanium joints, vacuum-brazed samples, as well as Ti-Al6-V4 and CPTi base metal, were exposed to air at 300°C for 120 and 240 h, respectively, before tensile tests. The results of the tensile tests of preoxidized brazed titanium joints are given in Fig. 11. The tensile strength of vacuum-brazed Ti-Al6-V4 joints as well as of CPTi joints is strongly reduced after heat treatment in oxidizing atmosphere. Beside reduction of average tensile strength, the vacuum-brazed Ti-Al6-V4 Ti-Cu-Ni-Pd joints especially show a large scattering of strength values, which become larger with larger exposure times. On the contrary, the Ti-Al6-V4 base metal samples were nearly unaffected by the heat treatment. These results demonstrate that the reduction of tensile strength of brazed joints due to heat treatment in air is attributed to an oxidation attack of the brazing zone. This local oxidation of the brazed sample leads to a stress peak at the brazing zone and induces failure of the brazed joint. The higher susceptibility of the brazing zone compared to the bulk material is also manifested by a discoloring of the brazing zone after oxidation treatment in air.
**Fig. 8** — Maximum brazing joint clearance of (A) Ti-Al6-V4 Ti-Cu-Ni(Pd) and (B) CPTi Ti-Zr-Cu-Ni joints; Brazing temperature: 950°C (A), 870°C (B).

**Fig. 9** — Room-temperature tensile strength of (A) Ti-Al6-V4 TiCuNi(Pd) and (B) CPTi Ti-Zr-Cu-Ni joints. Brazing temperature: 950°C (A), 870°C; (B) joint clearance size: 50 μm.

**Fig. 10** — Tensile tests at elevated temperatures of vacuum brazed (A) Ti-Al6-V4 Ti-Cu-Ni-Pd and (B) CPTi Ti-Zr-Cu-Ni joints. Brazing temperature: 950°C (A); 870°C (B); brazing time: 5 min (A), 10 min (B); joint clearance: 50 μm.

**Table 3** — Chemical Compositions and Critical Temperatures of the Filler Metals

<table>
<thead>
<tr>
<th>Filler Metal</th>
<th>Ti</th>
<th>Zr</th>
<th>Cu</th>
<th>Ni</th>
<th>Pd</th>
<th>$T_{\text{solv}}$</th>
<th>$T_{\text{liq}}$</th>
<th>$T_{\text{braze}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiCuNi</td>
<td>60</td>
<td>—</td>
<td>20</td>
<td>20</td>
<td>—</td>
<td>923</td>
<td>934</td>
<td>950</td>
</tr>
<tr>
<td>TiCuNiPd</td>
<td>60</td>
<td>—</td>
<td>19</td>
<td>19</td>
<td>2</td>
<td>923</td>
<td>934</td>
<td>950</td>
</tr>
<tr>
<td>TiZrCuNi</td>
<td>35</td>
<td>35</td>
<td>15</td>
<td>15</td>
<td>—</td>
<td>832</td>
<td>850</td>
<td>870</td>
</tr>
</tbody>
</table>
Such a discoloring of the brazing zone can also be observed after heat treatment of brazed CPTi-TiZrCu-joints. Although tensile strength of CPTi joints is also reduced after oxidation treatment, scattering of the tensile strength values is much smaller.

Fatigue Properties of Titanium Joints

Fatigue tests were conducted under a tension-tension mode with a stress cycle of 0.2 Hz and a stress ratio of 0.1. The results of the fatigue tests with Ti-Al6-V4 Ti-Cu-Ni-Pd joints brazed with 50-μm-thick filler metal foil in a vacuum furnace at 945°C for 5 min are given in Fig. 12.

Although the brazed joints exhibit shorter lives than those of the base metals, the fatigue properties of the Ti-Al6-V4 joints are considered to be quite good. It can be seen from Fig. 12 that the joints do not fail after 10^5 cycles at a maximum stress of 700 MPa (101.5 ksi), which corresponds to 75% of the static tensile strength of the Ti-Al6-V4 base metal. However, when maximum stress exceeds 700 MPa, the fatigue life of the Ti-Al6-V4 joints decreases dramatically. At a maximum stress of 730 MPa (105.8 ksi) fracture of the joints occurs after 18,000 cycles.

Summary and Conclusions

The mechanical properties of Ti-Al6-V4 and CPTi-joints brazed with Ti-(Zr)-Cu-Ni-(Pd) filler metals are strongly dependent on the microstructure of the brazing zone, especially with the formation of brittle intermetallic phases in the center of the brazing zone, which reduce the mechanical strength of the brazed joints. These phases form due to an exceeding of the maximum joint clearance size of the joint to be brazed and by enhancement of brazing time.

In contrast to the Ti-Al6-V4 joints, the fabrication of CPTi-joints with mechanical properties comparable to those of the base metal was not possible. The reason can be seen in the much lower maximum joint clearance of the system CPTi Ti-Zr-Cu-Ni, with regard to the formation of intermetallic phases. Therefore under the given circumstances (50-μm filler metal foils), formation of intermetallic phases could not be avoided.

This study also revealed that the induction brazing process is an interesting alternative to the vacuum furnace brazing process. Especially from the economic point of view, the induction brazing process under inert atmosphere has a lot of advantages due to the short processing time. On the other hand, the short processing time is responsible for much higher requirements on brazing joint clearance compared to the vacuum process.
brazing process. However, fabrication of titanium joints with mechanical properties comparable to those of the base metal by induction heating is possible, when the maximum brazing joint clearance of the system is not exceeded. This requires extremely small joint clearances of <30 µm in the case of Ti-Al6-V4 Ti-Cu-Ni-Pd joints and <20 µm in the case of CPTi-joints.

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References


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