Joint Strength Improvement in Dissimilar Friction Welding of Titanium Alloy to Nickel Alloy with Interlayer*

by OGURA Tomo **, IMAI Tomoya*** and SAIDA Kazuyoshi**

Ag-Cu and Ag-Cu-Pd interlayers improved the joint strength between friction-welded Ti-6Al-4V and type-718 Ni-based alloys. Frictional heat melted the Ag-Cu interlayer and partially melted the Ag-Cu-Pd interlayer, and the interlayers were conjointly ejected. This suppressed the formation of intermetallic Ti-Ni compounds at the interface. The tensile strength of the joint increased from 698 MPa (Au-Ni) to 774 MPa (Ag-Cu) and 776 MPa (Ag-Cu-Pd). The underlying mechanism of this strength improvement stemmed from a combination of interlayer brazing and solute diffusion from the base metal to the interlayer. This effect was larger with the Ag-Cu and Ag-Cu-Pd interlayers compared to the Au-Ni interlayer owing to the near absence of Ni-Ti intermetallic compound formation.

Key Words: Friction Welding, Ti-6Al-4V alloy, Type-718 Nickel-based Alloy, Dissimilar Joining, Interlayer, Brazing

1. Introduction

Welding dissimilar materials is attracting attention in commercial use because it can help reduce material costs and improve design flexibility. The Ti-6Al-4V alloy is most commonly used for static and rotating components in aerospace turbine engines. The type-718 nickel-based alloy is a precipitation-hardened nickel-based superalloy, which is used in the aerospace industry because of its superior mechanical properties and oxidation resistance. In aerospace engine applications, where welding and joining must be reliable, it is highly attractive to join dissimilar materials, such as the Ti-6Al-4V and type-718 nickel-based alloys, to promote product design flexibility and new functionality. Conventional welding techniques frequently produce hard and brittle intermetallic compounds (IMCs) in welds owing to the interdiffusion of solutes; this deteriorates joint strength. The laser welding of titanium and nickel alloys readily creates Ti2Ni and TiNi3 IMCs within a weld, resulting in low-strength welds that can generate interfacial fractures over time.

The diffusion of solutes can be controlled by applying less heat to suppress the formation of IMCs, making friction welding interesting. Friction welding is a well-established solid-state joining process, and it is one of the most economical and productive methods for joining similar and dissimilar metals. A maximum tensile strength of 450–460 MPa was obtained in the dissimilar friction welding of titanium and nickel, resulting in low-strength welds that can generate interfacial fractures over time.

Their strengths are over 1000 MPa and 1400 MPa, respectively. The overall mechanical properties are limited by the quality of the joint, which is the weakest link, during use.

Interlayers help suppress the formation of brittle IMCs during the welding and joining of dissimilar materials. We have recently reported that the Au-18 mass% Ni interlayer can improve the friction weldability of the Ti-6Al-4V alloy to the type-718 nickel-based alloy by suppressing IMCs. The tensile strength of the joint significantly increased from 460 MPa for direct friction-welded joints to 698 MPa with the added interlayer. The strength improvement of the friction-welded joint stemmed from a combination of interlayer brazing and solute diffusion from the base metal to the interlayer. Extremely small amounts of IMCs containing nickel and titanium were still observed in the residual interlayer because the nickel solute in the Au-Ni interlayer reacted with the dissolved titanium. The authors surmise that if the nickel solute can be entirely removed, the joint strength can be further improved owing to the absence of IMCs in the metal interlayer.

Ag-28 mass% Cu (BAg-8) and Ag-25 mass% Pd-20 mass% Cu (BPd-6) were selected as interlayer materials for this work because they are already widely applied for the brazing of aerospace materials. We aimed to clarify the effects of these interlayers on the friction weldability of the Ti-6Al-4V alloy to the type-718 nickel-based alloy.

2. Experimental procedure

We used the type-718 nickel-based alloy and Ti-6Al-4V alloy and a 100-μm thick Ag-28 mass% Cu and Ag-25 mass% Pd-20 mass% Cu foil as the interlayer. The chemical compositions of these alloys are shown in Table 1. Ag-28 mass% Cu is the eutectic composition with a melting point of 780 °C. Ag-25 mass% Pd-20...
mass% Cu exhibits a two-phase (Cu and Ag:Pd) microstructure; the solidus and liquidus temperatures are 870 °C and 950 °C, respectively. The dimensions of the base metals are shown in Figure 1(a). W-Re thermocouples were set at three different points on the surface of the type-718 nickel-based alloy to measure the temperature during friction welding as shown in Figure 1(b). The shape of the specimens used for the tensile tests is shown schematically in Figure 1(c).

The interlayer foil was placed on the cratered surface of the type-718 nickel-based alloy to prevent the interlayer from moving during friction welding with a vertical friction welding machine (NITTO SEIKI Co., Ltd). The type-718 nickel-based alloy specimen was fixed on a bottom plate, while the Ti-6Al-4V alloy specimen was fixed to the top plate, enabling it to rotate at the top. The friction welding conditions are shown in Table 2. Rotation speed, friction pressure, upset pressure, and upset time were maintained as constants to investigate the effect of friction time on the formation of interfacial microstructures.

The room temperature tensile strength of the friction-welded joint was evaluated at a test speed of 1.0 mm/min. The average strength was calculated from the measurements of three samples for each welding condition. The resulting microstructure was examined using scanning electron microscopy (SEM), and elemental analysis was performed using electron probe microanalysis (EPMA).

Table 1 Compositions of base metals and insert metal (mass%).

| Material                  | Cr  | Fe  | Nb  | Mo  | Ti  | Al  |
|---------------------------|-----|-----|-----|-----|-----|-----|
| Type-718 nickel-based alloy| 18.8| 17.6| 5.3 | 3.0 | 1.0 | 0.5 |
| Interlayer                | 0.2 | 0.1 | 0.1 | 0.1 | Bal.|
| Ti-6Al-4V                 | 6.0 | 4.0 | 0.1 | 0.2 | Bal.|

Table 2 Conditions of friction welding used in this study.

| Parameter                  | Value |
|----------------------------|-------|
| Rotational speed [rpm]     | 1500  |
| Friction pressure [MPa]    | 150   |
| Friction time [s]          | 15-40 |
| Upset pressure [MPa]       | 160   |
| Upset time [s]             | 5     |

3. Result and discussion

3.1 Microstructures of the interface

Figure 2 shows the typical SEM images of the interface of the friction-welded joint. An intermediate layer (white area in the image) was observed at the interface of the joint obtained during friction welding. This intermediate layer fully covered the grooved region and the edge of the specimen where the Ti-6Al-4V alloy and type-718 nickel-based alloy had been attached. The magnified images of the interface of the joint, including the thickness of the intermediate layer, are shown in Figure 3. Regardless of the type of interlayer, the thickness of the intermediate layer decreased with increasing friction welding time. However, the intermediate layer thickness of the joint with the Ag-Cu-Pd interlayer was larger than that of the joint with the Ag-Cu interlayer.

The thermal behavior of the specimens during the friction welding process was investigated. The temperature at the joint interface was estimated by extrapolating the data shown in Figure 4, which depicts the temperature during welding for durations of 25 s each. The exponential extrapolation was referred to two-dimensional transient heat conduction equation to calculate the interface temperature of friction welding. The temperature of the joint interface was 941 °C for the Ag-Cu interlayer and 893 °C for the Ag-Cu-Pd interlayer. This implies that the Ag-Cu interlayer melted and Ag-Cu-Pd interlayer partially melted during both friction welding tests. The eutectic point or solid–liquid coexistence is indicated by the dotted line in Figure 4 for reference.

![Fig. 1 Schematic illustrations of (a) specimen for friction welding, (b) position of thermocouple and (c) friction-welded specimen for tensile test.](image1)

![Fig. 2 Cross-sectional images of the interface of Ti-6Al-4V and type-718 Ni-based alloy joints friction welded for 15 s with (a) Ag-Cu and (b) Ag-Cu-Pd interlayers.](image2)
The elemental distribution in the central region of the joint interface was investigated using EPMA mapping, as shown in Figure 5 and Figure 6. The original SEM image is shown in Figure 3. Figure 5 shows that the thickness of the intermediate layer gradually decreased to approximately 4 μm after 25 s of friction welding. This indicates that the Ag-Cu interlayer material was melted and mechanically ejected from the sample as welding time increased. The base metal elements, particularly titanium, were detected in the intermediate layer as friction time increased to 25 s owing to its diffusion toward the residual Ag-Cu interlayer. Figure 6(a) shows that the intermediate layer was composed of Ag, Cu, and Pd. However, titanium was also detected in the thin intermediate layer as welding time increased. This indicated that titanium diffused to the residual Ag-Cu-Pd interlayer, similar to...
Ag-Cu. In the joint with the Au-Ni interlayer, the nickel solute in the Au-Ni interlayer formed Ni-Ti IMCs with the diffused titanium solute\(^{15}\)). However, the joints with the Ag-Cu or Ag-Cu-Pd interlayers formed no IMCs.

### 3.2 Mechanical properties of the joints with Ag-Cu and Ag-Cu-Pd interlayers

The relationship between tensile strength and welding time is shown in Figure 7. The maximum strength of the joint formed without an interlayer was 460 MPa\(^{12}\)). The tensile strength of the joint formed with the Ag-Cu and Ag-Cu-Pd interlayers increased with friction time. The maximum mean strengths of the joints with the Ag-Cu and Ag-Cu-Pd interlayers were 774 MPa for 30 s and 776 MPa for 30s, respectively. These strengths were higher than those of the joints without an interlayer or with the Au-Ni interlayer\(^{15}\)). The joint strength gradually decreased over 30 s during friction welding using the Ag-Cu and Ag-Cu-Pd interlayers.

The joint interface was analyzed after fracture to correlate the tensile properties and microstructures. Figures 8 and 9 show the typical EPMA joint interface maps formed using the Ag-Cu interlayer after tensile tests for 15 s (258 MPa) and 25 s (880 MPa) and using the Ag-Cu-Pd interlayer for 25 s (389 MPa) and 30 s (889 MPa). In the case of the low-strength joints, a high content of interlayer elements was detected at the fractured surface. This showed that the fracture occurred within the residual interlayer. The high-strength specimen contained titanium at the fracture surface. This showed that fracture occurred within the small residual interlayer.

### 3.3 Friction welding mechanism with interlayer

Heat was generated from friction welding mainly at the edges of the base metals, where the Ti-6Al-4V and type-718 nickel-based alloys were joined when the Ag-Cu interlayer was applied. This heat melted the Ag-Cu interlayer, which was ejected by rotational forces and applied pressure. The residual liquid interlayer acted as brazing and reduced the strength of the alloy joint after 15 s of friction welding. The thickness of the residual interlayer gradually decreased as welding time increased. The solute from the base metals, particularly titanium, diffused to the interlayer at this stage. The further mechanical ejection of the liquid and the solute diffusion from the base metals to the interlayer occurred as welding proceeded. This effect was similar to diffusion bonding. The residual interlayer acted as a barrier coat and prevented base metal reaction and the formation of Ni-Ti IMCs and significantly increased the joint strength after 25 s of friction welding. A series of Ti-Ni IMCs would have been easily formed if the interlayer had been fully ejected from the specimen. This would have decreased the joint strength after 35 s of friction welding. High-strength friction-welded joints were obtained owing to the formation of a thin intermediate layer from liquid interlayer brazing and base metal diffusion to that interlayer.

In contrast, the Ag-Cu-Pd interlayer only partially melted because frictional heat reached the solid–liquid coexistence temperature. The decrease in the thickness of the Ag-Cu-Pd interlayer was smaller than that of the Ag-Cu interlayer because the mechanical ejection of the semisolid layer was smaller than that of the fully liquid layer, depending on the difference in the viscosity of the layers. Therefore, the time required to reach similar joint strength was longer in the case of the Ag-Cu-Pd interlayer compared to the Ag-Cu interlayer because of the same phenomenon.

The maximum strength of the joint with the either the Ag-Cu or Ag-Cu-Pd interlayers was higher than that of the joint with the Au-Ni interlayer (698 MPa\(^{15}\)). This was probably because in the joint with the Au-Ni interlayer, the nickel solute in the Au-Ni interlayer formed minor Ni-Ti IMCs with the diffused titanium solute. However, no Ni-Ti IMCs were formed in the joint with the Ag-Cu or Ag-Cu-Pd interlayers, resulting in the increased joint strength.

### 4. Conclusions

The Ag-Cu and Ag-Cu-Pd interlayers were used in the dissimilar metal friction welding of the Ti-6Al-4V and type-718 nickel-based
alloys to improve joint strength. Thermal analysis revealed that the Ag-Cu interlayer fully melted and the Ag-Cu-Pd interlayer partially melted during friction welding. The melted material was ejected during friction welding. This prevented direct reaction between the base metals and suppressed the formation of IMCs. The highest mean tensile strengths of the Ag-Cu and Ag-Cu-Pd interlayer joints were 774 MPa and 776 MPa, respectively. These strengths were higher than that of the joint with the Au-Ni interlayer (698 MPa). This increase in strength was explained by the considerably reduced Ni-Ti IMC formation.

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