Infrared brazing of Fe₃Al intermetallic compound using gold-based braze alloy

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Published online: 22 February 2011

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Abstract Infrared-brazing Fe₃Al with Au–44Cu as filler metal has been investigated. The brazed joint consists mainly of a β -phase, Au_{8-x}Cu_{4+x}Al₄, caused by the dissolution of Al from Fe₃Al substrate into the braze alloy. The depletion of Al from Fe₃Al substrate results in the formation of a layer of β -phase particles dispersed in the Fe-rich phase. The highest shear strength for AuCu filler is 327 MPa for specimens infrared brazed at 880°C for 180 s. The brazed joint is mainly fractured along the central β -phase in which the fractograph exhibits quasi-cleavage with dimples. Increasing the brazing time or temperature will deteriorate the bonding strength of the joint, and the fracture mode is prone to cleavage of brittle fracture. Au–44Cu filler demonstrates a great potential for bonding Fe₃Al intermetallic compound.

Keywords Au-based filler · Brazing · Wetting · Fe₃Al

Introduction

Iron aluminides, including FeAl and Fe₃Al, are featured with low density, low cost, and good oxidation resistance [1, 2]. The inherent brittleness of iron aluminides can be

improved by adding 2–5 wt.% Cr [1]. In recent years, iron aluminides have been considered for structural applications. The importance of joining iron aluminides have been increasing in application of such alloys in industry. Compared with welding, vacuum brazing has many advantages, such as relatively lower joining temperature, less oxidation, and lower distortion [3]. Fe₃Al can be joined by brazing without melting the base metal in order to retain its mechanical properties [4, 5].

The selection of filler metal plays an important role in brazing intermetallics, since the presence of brittle intermetallic phase in the joint may significantly impair their bonding strength [6]. Both the wettability of the molten braze on Fe₃Al substrate, and the formation of intermetallic phases in the joint should be taken into consideration. Brochu et al. found that Fe₃Al alloyed with Cr can be wetted by Cu at 1,070°C, which is lower than the melting point of pure Cu [7]. The brazing temperature of Fe₃Al with Cu filler metal is above 1,050°C, which can be decreased by alloying Cu with Au. According to the Au–Cu binary phase diagram, Cu is completely soluble in Au, and Au–44Cu in atomic percent has the lowest melting temperature of 910°C [8]. To the best of our knowledge, the brazing behavior of Au–44Cu braze alloy on the Fe₃Al substrate has not been evaluated in detail. Therefore, it is chosen as the braze alloy in this study.

Compared with traditional furnace brazing, infrared brazing is better suited for studying the microstructural evolution of the joint with the advantage of its rapid heating rate being as high as 50°C/s [9, 10]. A short brazing cycle does less damage to the base metal during infrared brazing. This study focuses on the microstructural evolution and bonding strength of the infrared brazed Fe₃Al joints using Au–44Cu as filler metal. The feasibility of infrared brazing Fe₃Al with Au-based braze alloy is also evaluated.

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Fig. 1 Dynamic wetting angle measurements of Au–44Cu filler on Fe_3Al substrate under various brazing conditions

Fig. 2 EPMA BEIs and WDS chemical analysis results of the Au–44Cu/ Fe_3Al wetting specimen at 880°C for 300 s

at%	A	B	C	D	E
Au	43.1	44.1	0.8	5.9	1.1
Cu	32.0	32.1	1.6	4.2	1.4
Fe	2.7	2.7	85.1	76.0	85.2
Al	20.4	20.5	10.2	10.7	10.1
Cr	1.8	0.6	2.4	3.1	2.2
phase	β -phase	β -phase	Fe-rich	Fe-rich	Fe-rich

Experimental procedure

The base metal used in the experiment was Fe_3Al plate with the composition of Fe–28Al–2Cr (atomic percent). All joined surfaces were ground by SiC papers up to grit 1,200 and then ultrasonically cleaned by acetone prior to infrared brazing. Au–44Cu (atomic percent) foil of 50 μm thick was used as the brazing filler metal. The heating rate of infrared furnace was kept at 10°C/s under the vacuum of 5×10^{-5} mbar. The brazing temperature was 870°C, 880°C, and 900°C, and the brazing time was 180 s and 300 s.

Dynamic wetting angle on the Fe_3Al substrate was measured by the sessile drop test using a filler ball, approximately 0.15 g, prepared by vacuum arc remelting

[6, 10]. The ULVAC Sinko-Riko RHL-P816C infrared furnace was used as the main body of the vacuum furnace. The dynamic wetting angle was performed in a vacuum of 5×10^{-5} mbar. Infrared rays were generated from infrared lamps, transmitted through a transparent quartz tube and focused on the specimen holder. One end of the quartz tube was attached to the specimen holder, and the other end was designed to transmit the signal into the CCD image recording system. The filler metal was placed on the substrate (Fe_3Al), and a thermocouple was simultaneously contacted with the substrate. A graphite holder was positioned under the substrate to enhance the absorptivity of infrared rays.

Shear tests were performed to evaluate the bonding strength of the brazed joint [10]. The specimen was compressed by a Shimadzu AG-10 universal testing machine with a constant speed of 0.0167 mm/s. The experimental data were averaged from at least two measurements for each brazing condition. Cross sections of joints and their fractographs after shear tests were examined by a JEOL JXA 8600SX electron probe microanalyzer (EPMA) equipped with the wavelength dispersive spectroscope (WDS) using the operation voltage of 15 kV and the minimum spot size of 1 μm .

Results and discussion

Figure 1 shows dynamic wetting angle measurements of Au–44Cu filler on Fe_3Al substrate under various temperatures between 0 and 300 s. As can be seen, the wetting curves of Au–44Cu filler on Fe_3Al substrate at 920 and 930°C are almost identical, and a similar wetting behavior is observed for the specimen tested at 910°C. Since the melting point of Au–44Cu braze alloy is 910°C, the molten braze alloy wets readily the Fe_3Al substrate in 50 s, and the wetting angle is stabilized below 5°. The wetting behavior of Au–44Cu braze at 880°C is different from that above 910°C. For the specimen tested at 880°C, the initial wetting angle is kept at 155° until 20 s, dropped into 12° in 80 s, and finally stabilized at 6° between 100 and 300 s. The wetting curve tested at 860°C shows poor wetting angle of 33° even if the time period is extended to 300 s.

As seen in Fig. 1, the braze alloy still wets effectively the Fe_3Al substrate at 880°C, below the melting point of Au–44Cu. It is deduced that the dissolution of Al from the Fe_3Al substrate into the braze alloy causes decrease in melting point of braze alloy. According to the Al–Au binary alloy phase diagram, the solidus temperature of Au is significantly decreased from 1,064.4°C (pure Au) to 545°C (Au–16Al, atomic percent) [9]. Figure 2 shows

EPMA backscattered electron images (BEIs) and WDS chemical analysis results of the Au–44Cu/ Fe_3Al wetting specimen tested at 880°C for 300 s. There are at least two phases identified from the WDS chemical analysis. The braze alloy consists of 43.1Au–32.0Cu–2.7Fe–20.4Al–1.8Cr in atomic percent as marked by A in Fig. 2. Because the braze alloy consists primarily of Al, Au, and Cu, the Al–Au–Cu ternary alloy phase diagram is cited here in order to explain the phase evolution of the brazed specimen.

Figure 3 displays the isothermal section of the Al–Au–Cu ternary alloy phase diagram in atomic percent [11, 12]. The chemical composition of area A in Fig. 2 is close to the β -phase [11]. The β -phase has a nominal stoichiometry of $\text{Au}_{8-x}\text{Cu}_{4+x}\text{Al}_4$, where for example in Spangold $X \approx 1$. The β -phase stoichiometries for $0 < x < 1$ in $\text{Au}_{8-x}\text{Cu}_{4+x}\text{Al}_4$ will be completely molten on the 750°C isothermal section. The β -phase ($\text{Au}_7\text{Cu}_5\text{Al}_4$) has a solidus temperature of 726°C and liquidus temperature of 767°C, which are much lower than the testing ones. It is obvious that the dissolution of Al from the Fe_3Al substrate into the Au–44Cu braze results in formation of the β -phase melt at 880°C. Accordingly, the wetting of Au–44Cu braze alloyed with Al on the substrate is greatly enhanced even below the melting point of Au–44Cu. The depletion of Al from the Fe_3Al substrate also results in formation of the Fe-rich phase as marked by C in Fig. 2. Additionally, a blocky β -phase in the Fe-rich phase as marked by B- and Fe-rich precipitates in the β -phase as marked by D, as seen in Fig. 2, are also formed due to the limited solubility between the β -phase and Fe-rich phase at room temperature.

Figure 4 illustrates EPMA BEIs and WDS chemical analysis results of the Au–44Cu/ Fe_3Al wetting specimen at

Fig. 3 Isothermal section of the Al–Au–Cu ternary alloy phase diagram in atomic percent [11, 12]

Fig. 4 EPMA BEIs and WDS chemical analysis results of the Au–44Cu/Fe₃Al wetting specimen at 860°C for 300 s

at%	A	B	C
Au	48.2	48.2	1.1
Cu	34.3	28.7	2.1
Fe	4.3	3.5	85.7
Al	12.6	18.7	8.5
Cr	0.7	0.9	2.4
phase	α-phase	β-phase	Fe-rich

860°C for 300 s. The Fe-rich phase as marked by C is still seen in the figure. However, the chemical composition of the braze alloy is different from that of the β-phase. In Fig. 4, the Al content in area A is 12.6 at.%, so it is identified as the α-phase according to Fig. 3 [11, 12]. It is also noted that a blocky β-phase is found in the interfacial Fe-rich phase as marked by B in the figure. Dissolution of Al from the substrate into the braze alloy is greatly reduced with decreasing temperature, while the melting point of the braze alloy cannot be significantly decreased by alloying sufficient Al in the Au–440Cu melt. For the specimen

tested at 860°C for 300 s, the wetting angle is above 30°, which is insufficient to wet Fe₃Al during brazing.

Figure 5 displays cross sections of EPMA BEIs and WDS chemical analysis results of Au–44Cu/Fe₃Al specimens infrared brazed under various conditions. Microstructures of infrared brazed joints are quite similar. The brazed joints consist primarily of the β-phase, and β-phase particles are widely dispersed in the interfacial Fe-rich phase.

The corrosion resistance of the brazed joint should be considered for industrial application. For the multi-phase

at%	A	B	C	D	E	F	G	H
Au	40.8	0.8	39.9	37.6	40.3	0.9	40.3	0.9
Cu	28.3	1.8	28.2	29.3	30.0	0.8	30.0	0.8
Fe	2.3	79.8	7.5	3.7	4.7	79.4	4.7	79.4
Al	26.8	15.2	23.1	27.3	23.4	16.3	23.4	16.3
Cr	1.9	2.3	1.3	2.1	1.7	2.6	1.7	2.6
phase	β-phase	Fe-rich	β-phase	β-phase	β-phase	Fe-rich	β-phase	Fe-rich

Fig. 5 Cross sections of EPMA BEIs and WDS chemical analysis results of the Au-44Cu/Fe₃Al specimens infrared brazed at **a** 870°C for 180 s, **b** 880°C for 180 s, **c** 880°C for 300 s, and **d** 900°C for 180 s

structure consisting of highly noble and non-noble phases may be highly susceptible to corrosion. Based on the experimental observation, the brazed joint is mainly composed of β-phase matrix, and β-phase particles are widely dispersed in the interfacial Fe-rich phase. The β-phase is alloyed with high content of Au, so it is considered as a noble phase. In contrast, the interfacial Fe-rich phase primarily alloyed with 8–16 at.% Al is a less

noble phase. Accordingly, the brazed joint is susceptible interfacial corrosion in application, and needs further study.

Table 1 shows shear test results of different brazing conditions. Shear strength of the joint infrared brazed at 870°C for 180 s is 320 MPa. The specimen infrared brazed at 880°C for 180 s has the maximum shear strength of 327 MPa. Maximum shear strengths using other alternative

Table 1 Summary of shear test results for different brazing conditions

Brazing temperature (°C)	Brazing time (s)	Shear strength (MPa)
870	180	320
880	180	327
880	300	210
900	180	233

brazes are lower than that using Au–44Cu braze. For example, maximum shear strengths of the brazed joints are 127 MPa using pure Ag braze, 181 MPa using 72Ag–28Cu (weight percent) braze and 291 MPa using pure Cu braze, respectively [4, 13]. The application of Au–44Cu braze in brazing Fe₃Al demonstrates the highest shear strength among alternative brazes. Besides, the brazing temperature

of Au–44Cu braze is much lower than those of pure Ag and Cu brazes.

Figure 6 illustrates EPMA cross sections and fractographs of Fe₃Al specimens after shear test of the joint infrared brazed at 870°C and 880°C for 180 s, respectively. Both cracks are initiated and propagated along the β -phase as displayed in Figs. 6a, c. As seen in Figs. 6b, d, fractured surfaces are featured with quasi-cleavage with dimples.

Further increasing the infrared brazing temperature or time results in deterioration of shear strength of the joint below 240 MPa. Because the chemical composition of β -phases as marked by A, D, E, and G in Fig. 5 are approximately the same, the fracture mechanism of higher brazing temperature/longer brazing time is different from that of lower temperature/shorter time. Figure 7 illustrates

Fig. 6 EPMA cross sections and fractographs of specimens after shear test of the joint infrared brazed at **a, b** 870°C for 180 s and **c, d** 880°C for 180 s

the grain-boundary penetration of the braze alloy after infrared brazing under various brazing conditions. It is obvious that the Au-based melt penetrates along the grain boundaries of Fe_3Al substrate. It is consistent with previous reports of wetting the Fe_3Al substrate by pure Cu [7, 14]. The dissolution of Al from the Fe_3Al substrate into the Cu melt results in formation of the interfacial Fe-rich layer. Lattice constants of Fe_3Al with DO_3 structure and $\alpha\text{-Fe}$ are 0.578 and 0.298 nm, respectively. The formation of the Fe-rich phase next to the Fe_3Al substrate leads to decrease in substrate volume during brazing, and the molten braze penetrates the substrate along its grain boundary. The effect of grain-boundary penetration is enhanced by increasing the brazing temperature and/or time as displayed in Fig. 7.

Figure 8 shows the EPMA cross section and fractographs of Fe_3Al after shear test of the joint infrared brazed at 880°C

for 300 s. As can be seen, the presence of β -phase at the grain boundary weakens greatly the strength of the Fe_3Al substrate. Cracks propagate along the grain-boundary β -phase as indicated by an arrow in Fig. 8a. Fractograph of the fractured surface shows the concave Fe_3Al substrate (Fig. 8b), and cleavage-dominated fracture is widely observed from the fractured β -phase in the brazed zone (Fig. 8c).

Conclusions

Wetting, microstructural evolution and shear strength of infrared brazed Fe_3Al intermetallic compound using Au–44Cu (atomic percent) braze alloy have been investigated. The braze alloy demonstrates excellent wettability of the Fe_3Al substrate above 910°C . Wettability of the Au–44Cu

Fig. 7 Grain-boundary penetration of the braze alloy after infrared brazing at **a** 870°C for 180 s, **b** 880°C for 180 s, **c** 880°C for 300 s, and **d** 900°C for 300 s

Fig. 8 a Cross section and b, c EPMA fractographs of the specimen after shear test of the joint infrared brazed at 880°C for 300 s

brazed joint consists mainly of β -phase, $\text{Au}_{8-x}\text{Cu}_{4+x}\text{Al}_4$, caused by the dissolution of Al from the Fe_3Al substrate into the braze alloy. Meanwhile, depletion of Al from the Fe_3Al substrate results in the formation of a layer of β -phase particles dispersed in the Fe-rich matrix. The specimen infrared brazed at 880°C for 180 s has the maximum shear strength of 327 MPa. Further increasing the infrared brazing temperature or time leads to deteriorate the shear strength of the joint below 240 MPa. The presence of grain-boundary β -phase along the Fe_3Al substrate is attributed to decreasing strength of the Fe_3Al substrate. Cracks propagate along the grain-boundary β -phase, and cleavage-dominated fracture is widely observed from fractographs of the brazed zone. Infrared brazing using Au–44Cu filler metal shows potential application in joining Fe_3Al intermetallic compound.

Acknowledgments The authors gratefully acknowledge the financial support of this study from the National Science Council (NSC), Republic of China, under grant no. 97-2221-E002-037-MY3.

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