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INTERFACE SCIENCE

Microstructure and mechanical properties of brazed titanium/steel joints

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Abstract Microstructure and fracture behavior of brazed joint between commercially pure titanium and low carbon steel using silver (Ag–34Cu–2Ti) and copper (Cu–12Mn–2Ni) based alloys have been characterized to determine the effect of brazing parameters and chemical composition on the strength of brazed joints. It is found that the shear strength of brazed joints strongly depends on the lap width. Furthermore, the fracture path and the value of shear strength significantly changed with the type of filler alloy. The two filler metals showed metallurgical interaction with steel and titanium forming different kinds of intermetallic compounds such as CuTi, Cu2Ti, and FeTi with silver based filler and Ti2Cu, FeTi and TiCuFe with copper based filler.

Introduction

The high strength to weight ratio and excellent corrosion resistance of titanium and titanium alloys [1–4] have led to a considerable interest in joining titanium to steel since there was a wide range of applications of this joint in aerospace, petrochemical industries, power generation and transportation industry [1, 5, 6].

Welding steel with titanium is very difficult due to the low solubility of iron in alpha titanium at room temperature. When titanium is welded with steel the intermetallic phases FeTi and Fe2Ti form, which are very hard and brittle and prevent the production of technically useable welds [7].

One of the most suitable ways to achieve strong joints of titanium to steel is brazing because it involves melting of the filler material only, thus eliminating problems that occur when dissimilar metals are fused. To avoid the intrusion of detrimental impurities such as oxygen and nitrogen, it is mandatory that titanium alloys are joined in an inert environment. Hence, titanium/steel joints are brazed in a vacuum furnace.

It has been reported that pure silver, silver base alloys, titanium base alloys, and copper base alloys have been used to braze titanium to steel [8–10]. The melting point of pure silver is 961 °C and it can be greatly decreased by alloying copper into the silver matrix. For instance, the melting point of Ag–Cu eutectic alloy is as low as 780 °C [11, 12]. A lower brazing temperature is preferred for most brazing processes, so the Ag–Cu eutectic braze alloy was chosen here as one filler metal for vacuum brazing of titanium to steel. Moreover, Cu–12Mn–2Ni was chosen as brazed filler metal because it provides good chemical compatibility in fusion reaction applications, it has good wettability to many materials, and it is suggested that the high percentage of Mn gave extra improvement for its wettability.

The objective of this investigation is focused in brazing of commercially pure titanium plate to a low carbon steel plate using Ag–Cu34–Ti2 and Cu–12Mn–2Ni filler alloys at various parameters to investigate the effects of these parameters on the joint strength and microstructure.

Experimental procedures

2 mm thick sheets of commercially pure titanium and low carbon steel were brazed together using silver base and

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copper base brazing filler alloys. The sheets were cut into $125 \times 28 \times 2$ mm strips for shear strength testing and $10 \times 10 \times 2$ mm strips for microstructural analysis. These specimens were then prepared using several stages of grinding papers and subsequently were ultrasonically cleaned by acetone before brazing. The filler alloys were a 100 μm Ag–34Cu–2Ti (wt.%) foil with melting range of 780–850 °C and Cu–12Mn–2Ni foil with melting range of 970–990 °C. The brazing foils were cleaned in acetone before brazing and then sandwiched between the overlapped areas of base metal.

The overlap width was changed from three times the thickness of parent metal (3t) to 6t to investigate its effect on joint strength. The joints were fixed with a stainless steel clamp, and then carefully placed into a vacuum furnace (SCHMETZ GmbH). Brazing experiments were carried out at 850–930 °C and 970–1000 °C when brazing with the silver base and copper base fillers respectively, to study the effect of brazing temperature on the metallurgical and mechanical properties of the joint. The soak time was kept at 15 min for all joints. The furnace vacuum was 2×10^{-5} Pa and the heating and cooling rate was adjusted at 15 °C/min.

The cross-sections of the bonded titanium/steel joints were prepared for metallographic analysis by standard polishing techniques and then etched by 5% HF, 20% HNO_3 and 75% glycerol for 60 s for the titanium side, 3% Nital solution for the steel side, and a solution of H_2O, NH_3, and $(NH_4)_2(CuCl_4)_2H_2O$ for 10 s for the copper base alloy. The microstructures were investigated using a NIKON–EPIPHOT optical microscope and the fracture surfaces were examined using a JEOL JXA-840 scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS).

Results and discussion

Vacuum brazing of Titanium/Ag–34Cu–2Ti/steel joint

Figure 1 displays microstructure features of the titanium/steel joint brazed at temperatures of 850–930 °C for 15 min. It is clear that the microstructure of brazed joints changed significantly by increasing the brazing temperature. Coarse grain structure, resulted from diffusional growth accompanied by recrystallization of steel substrate at high temperature, was formed at the steel interface in the case of the specimen brazed at 850 °C as shown in Fig. 1(a). This coarse structure changed at high temperature (930 °C) to a columnar structure as shown in Fig. 1(c). On the other hand, the titanium substrate did not show recrystallization and phase transformation at brazing temperatures of 850 °C and 880 °C while at a temperature of 930 °C the grains of titanium showed excessive grain growth after recrystallization, as shown in Fig. 1(c).

Observation with SEM revealed that several interaction layers were formed in the brazed area with different chemical analyses as shown in Fig. 2 and Table 1. At a brazing temperature of 850 °C, the titanium substrate showed no evidence of diffusion by elements of the brazed alloy since the analysis of region A in Fig. 2(a) showed pure Ti. A large amount of Ti was diffused from the titanium side to the brazed area close to the titanium substrate as shown from layers B and C. The ratios between Ti and Cu in layers B and C are close to CuTi and Cu2Ti phases respectively. Region D represents the eutectic Ag–Cu. However; the consumption of Cu by both CuTi and Cu2Ti phases resulted in a silver rich phase as indicated by region E in Fig. 2(a). These results are in agreed with those of previous research work [13, 14].

At high brazing temperature, area F in Fig. 2(b) represents a thick diffusion layer between the brazed alloy and titanium substrate. This layer contained mainly Ti with a high percent of Cu and little Ag, which corresponds to β-Ti. Layer G represents a thin layer of Ti2Cu, since the percentage of Ti is almost twice the amount of Cu. CuTi and Cu2Ti which formed at 850 °C continued to spread in the brazing area by increasing the temperature to 880 °C and reached their ultimate content at 930 °C, as shown in Fig. 2(b) by areas H and I respectively. Hence, most of the Cu in the eutectic Ag–Cu brazed foil is consumed to form CuTi and Cu2Ti and no eutectic structure remained at such a high temperature. Some islands of silver solid solution were isolated in the brazed region, as represented by areas J in Fig. 2(b). Based on the chemical analysis of area K, it is expected to contain FeTi + Cu or a FeTiCu intermetallic phase. van Beek et al. reported that nearly 38 at.% Cu could be dissolved in FeTi [15].

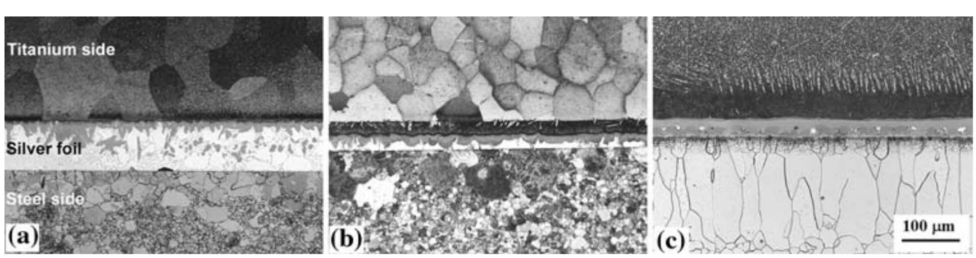

Fig 1 Microstructure of brazed joint at 850 °C (**a**), 880 °C (**b**), and 930 °C (**c**)

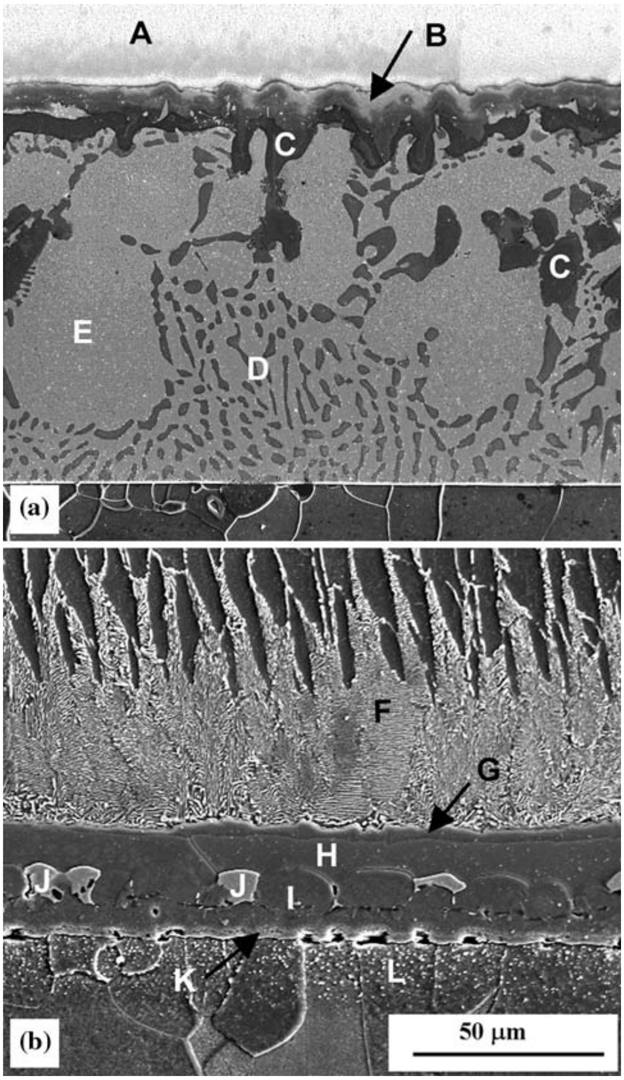

Fig 2 SEM microstructure of brazed joints at 850 °C (**a**) and 930 °C (**b**)

Table 1 Chemical analyses at points shown in Fig. 2

Symbol	Average chemical analyses, at.%			
	Ti	Fe	Cu	Ag
A	100	–	–	–
B	45.07	–	53.43	1.50
C	28.41	–	69.87	1.72
D	–	–	39.12	60.88
E	–	–	16.12	83.88
F	89.21	–	9.21	1.58
G	62.70	0.5	34.77	5.88
H	44.97	–	52.59	2.44
I	27.91	11.85	58.24	2.00
J	1.56	–	5.49	92.95
K	43.24	17.85	37.2	1.71
L	5.52	94.48	–	–

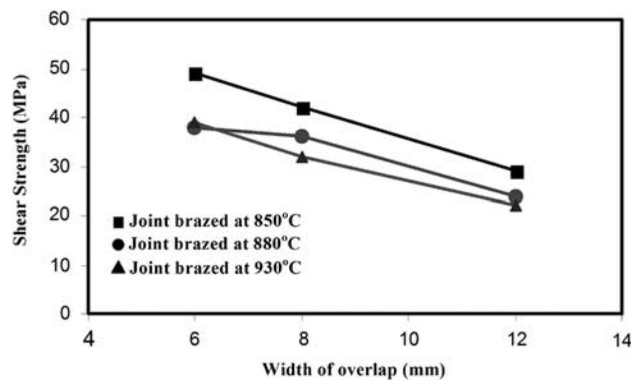

Fig 3 Relation between average shear strength of the joint, overlap width, and brazing temperature

It is clear that there was a high diffusion rate of Ti in the brazed joint, especially at high temperature, such that titanium could react with the steel substrate at the interface and form scattered FeTi phase extended along the interfacial region as represented by region L in Fig. 2(b).

The average shear strength of the joint showed a general tendency to decrease with increasing lap width as clearly shown in Fig. 3. This phenomenon has been discussed elsewhere [16, 17]. A literature review indicates that Von Mises stress was successfully utilized to demonstrate the decrease of the average shear stress in the lap joint with the increase of the overlap width [18]. As the overlap-length of joint increases, the Von Mises stress distribution becomes less and less uniform. The middle portion of the overlap contributes less and less to the overall load-carrying capacity of the joint, whereas the ends of the joint become overloaded. The non-uniform stress distribution in the lap joint causes the decreasing of the shear strength. On the other hand, Fig. 3 also represents the effect of temperature on the average shear strength. Increasing the temperature also led to a decrease in the shear strength, since the microstructure contained thick and different intermetallic compound which impair the joint. In comparison, the brazed joint at low temperature contained thin and few types of intermetallic compounds. The maximum shear strength of the joints was 54 MPa for the specimen brazed at 850 °C for 15 min at 3t.

The fracture path after performing shear test is shown in Fig. 4. It is noted that, at all brazing temperatures, the fracture took place at the interfacial region between the titanium substrate and the brazed alloy which means that the CuTi intermetallic compound is the most harmful phase at low brazing temperature and Ti2Cu and CuTi are the most harmful intermetallic phases at high temperature.

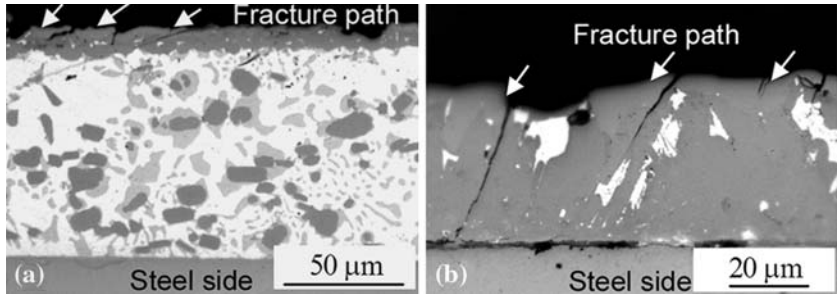

Fig 4 Cross section of fracture surface from steel side: (**a**) specimen brazed at 850 °C for 15 min and (**b**) specimen brazed at 930 °C for 15 min

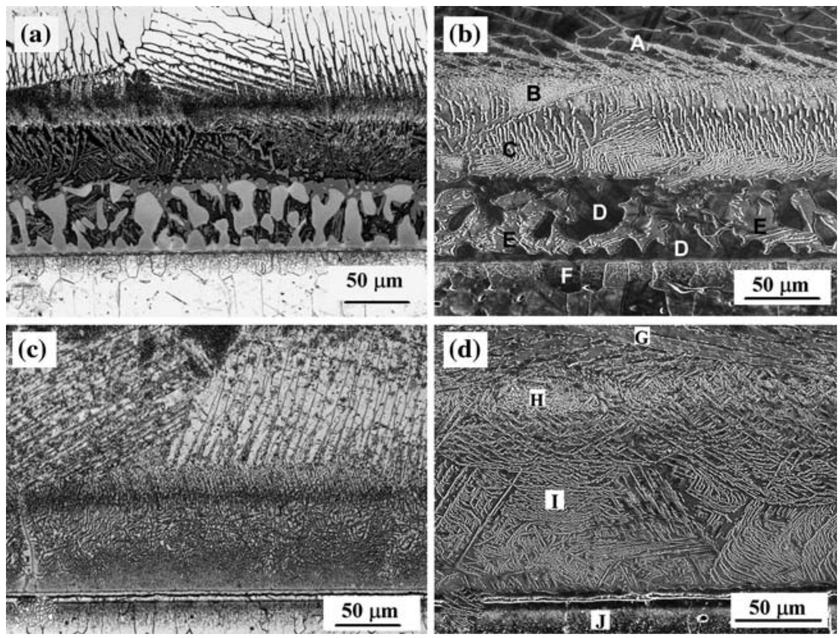

Fig 5 Microstructure of titanium/steel joint: (**a**) microstructure of joint brazed at 1000 °C, (**b**) SEM of the joint brazed at 1000 °C, (**c**) microstructure of joint brazed at 970 °C, (**d**) SEM of the joint brazed at 970 °C

Vacuum brazing of titanium/Cu–12Mn–2Ni/steel joint

The microstructural features of the titanium/steel joint using copper base brazing alloy at brazing temperatures of 1000 °C and 970 °C are shown in Fig. 5(a, c), respectively. At both brazing temperatures, several interaction layers occur between the copper based brazing alloy and the two substrates. The steel–copper bonding interface is planar in nature and a thin diffusion layer was revealed in contrast to the titanium–copper interface, which characterized by the presence of different interaction layers.

SEM images of the transition joints at brazing temperatures of 1000 °C and 970 °C are shown in Fig. 5(b, d), respectively. Results of the chemical analyses for the different areas are listed in Table 2. It is worth noting that the migration of Cu, Fe, and Mn (strong β-stabilizer elements) in the titanium substrate lower the eutectoid transformation temperature of Ti and α-β phase aggregate forms by the decomposition of β-Ti during cooling [19, 20]. The α-β phase is shown at brazing temperatures 1000 °C and 970 °C in Fig. 5(b, d), respectively, represented by regions A and G. The β-Ti forms as bright needles with the composition shown in Table 2 while the α-Ti forms as dark platelike structures between the needles of β-Ti. The composition of regions B in Fig. 5(b) and H in Fig. 5(d) showed that these are enriched regions of β-Ti phase. Areas

Table 2 Chemical analyses at areas shown in Fig. 5

Symbol	Average chemical analyses, at.%			
	Ti	Fe	Cu	Mn
A	87.80	4.32	6.25	1.63
B	83.50	5.12	10.05	1.33
C	73.36	7.85	16.34	2.45
D	48.96	16.65	31.72	2.68
E	71.91	9.26	15.49	3.34
F	4.77	95.23	–	–
G	90.24	2.55	6.2	1.01
H	83.22	5.44	10.14	1.30
I	78.56	7.79	11.45	2.19
J	2.73	97.27	–	–

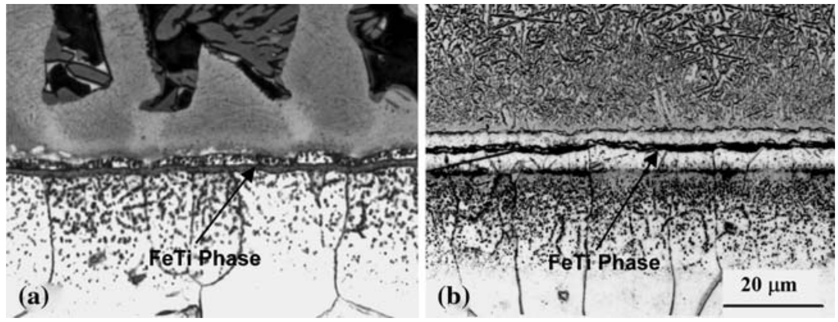

Fig 6 Microstructure at steel/copper brazed alloy: (**a**) joint brazed at 1000 °C and (**b**) joint brazed at 970 °C

C and I in Fig. 5(b, d) are phase mixtures of Ti2Cu and FeTi since Ti is present in high quantity in these areas and the Fe–Cu system has limited mutual solubility so copper does not form any intermetallics with iron [20].

The composition of the dark area represented by D in Fig. 5(b) has been found to lie within the TiCuFe phase range of composition, mostly close to Ti40Cu60–xFex; where $5 < x < 17$. The irregular phase which is represented by areas E is similar to area C but with higher percentages of Fe, which means that FeTi in this phase is higher than in area C.

It is obvious that the areas, which contain TiCuFe and FeTi at a brazing temperature of 1000 °C were not formed at temperature of 970 °C. This is probably due to the lower diffusion rate of Fe in the brazed alloy at low temperature. Areas F and J in Fig. 5(b, d) represents the diffusion layer on the steel side. A high percentage of Ti could reach these areas and form FeTi phase extended along the interfacial region. Figure 6 shows the extension of FeTi along the steel-copper brazed alloy interface for joints brazed at 1000 °C and 970 °C.

The average fracture load of the joint in the shear test showed similar tendencies to the joint brazed with silver base brazed alloy in respect of the relationship between shear strength and overlap width; the strength of the joint decreases with increasing overlap width as clearly shown in Fig. 7. In contrast to specimens brazed with silver base brazing alloy, specimens brazed with copper base alloy showed lower values of shear strength at a temperature 970 °C compared to at a temperature 1000 °C. This could be as a result of lack of fusion of the brazed alloy at some points of interfacial area since the brazing temperature was not enough to completely fuse the brazed alloy.

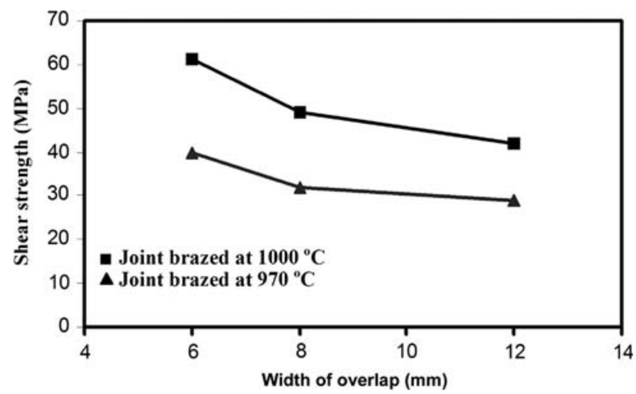

Fig 7 Relation between average shear strength of the joint, overlap width, and brazing temperature

It is worth noting that joints brazed with copper base brazed alloy at 1000 °C achieved higher shear strength compared to joints brazed with silver base brazed alloy at 850 °C, as can be seen by comparing Figs. 3–7. This result could be explained by the fact that copper base alloy has higher strength compared to silver base alloy.

The fracture path after performing shear testing is shown in Fig. 8. On contrarily to the joint brazed with silver base brazed alloy, at both brazing temperatures, the fracture took place close to interfacial region between the steel and the brazed alloy. The fracture took place at the TiCuFe and FeTi phases in the joints brazed at 1000 °C and the FeTi phase in the joints brazed at 970 °C.

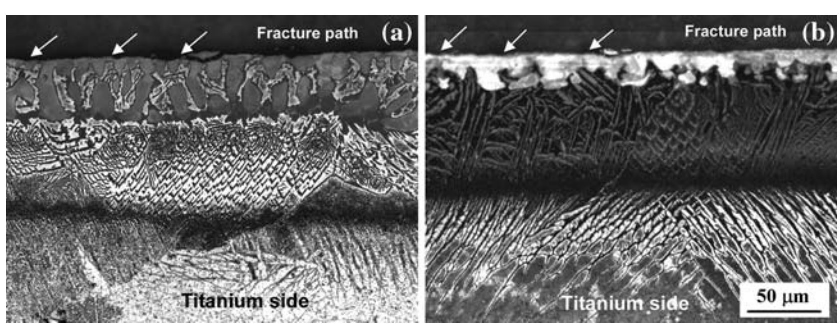

Fig 8 Cross section of fracture surface from titanium side: (**a**) specimen brazed at 1000 °C for 15 min and (**b**) specimen brazed at 970 °C for 15 min

Conclusions

The microstructural evolution and shear strength of the vacuum brazed titanium and steel using Ag–34Cu–2Ti and Cu–12Mn–2Ni filler alloys were extensively evaluated in this study. Important conclusions are summarized below:

1. For the specimen brazed with silver based alloy, interaction layers containing α-βTi, CuTi and Cu2Ti were formed at the titanium/silver alloy interface while no interaction layers were formed at steel/silver alloy interface in case of brazing at 850 °C. Increasing the brazing temperature led to an increase in thickness of both CuTi and Cu2Ti which consumed much of the copper from the eutectic Ag–Cu brazed alloy. At a brazing temperature of 930 °C, there was no eutectic structure remaining in the brazed area and a solid solution of silver separated islands was formed. Moreover, a reaction layer consisting of FeTi is formed at the steel/silver alloy interface.
2. For the specimen brazed with copper based foil, interaction layers containing α-βTi, Ti2Cu, FeTi and TiCuFe were formed.
3. The average fracture load of the joint in the shear tests showed a general tendency to decrease with increasing lap width and temperature in case of specimen brazed with silver alloy; joints brazed with copper alloy showed a general tendency to decrease in average shear strength with increasing overlap width and decreasing temperature.
4. For the specimen brazed with silver based alloy, at all brazing temperatures, fracture took place at the interfacial region between the titanium substrate and the silver alloy owing to the formation of intermetallic compounds of CuTi at low temperature and CuTi with Ti2Cu at high temperature. On the other hand, for the specimen brazed with copper alloy, fracture took place close to interfacial region between the steel substrate and the silver alloy owing to the formation of intermetallic compounds of TiCuFe and FeTi at a brazing temperature of 1000 °C and FeTi at a brazing temperature of 970 °C.

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