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Mechanical properties of copper to titanium joined by friction welding

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This paper describes a fundamental investigation of friction welding pure copper to titanium. Friction welding was performed using a brake type friction welder. The effect of friction time and upset pressure on the mechanical and metallurgical properties were evaluated. Under constant upset pressure, the tensile strength made little difference with an increase in friction time, whereas at the constant friction time, the tensile strength increased with increasing upset pressure. Thus, the upset pressure plays a major role over the friction time and friction pressure on tensile strength. Though Cu_3Ti intermetallic compound is formed at the copper/titanium interface during welding, the tensile strength of welded joint is not affected. It may be due to the thickness of intermetallic compound layer at interface being very thin and scattered. The tensile fracture of the welded joint occurred in copper side near the interface. © *2003 Kluwer Academic Publishers*

1. Introduction

Recently, the major trend in material research is to make products more functional, powerful and reliable. As the trend towards functional and reliable materials continues, the introduction of more evironmental-friendly materials with wider variety of functions will bring more growth in the market. Material resources and environment have become the issues in industry with the development of technology. Thus, it is a serious problem to select materials within a limited range. Therefore, possible solutions should be found for the development of new material and modification of the existing materials. But, it takes too much time to develop new materials and it also requires multiple processes to test the reliability of them. Various methods of joining dissimilar materials has been introduced, both to meet the needs of users and to enhance the added value of new materials while keeping the merits of the existing materials intact. It is difficult to join dissimilar metals by fusion welding, such as TIG, MIG, and Brazing, due to the different characteristics of each material. Friction welding can be used to join metals of widely differing thermal and mechanical properties.

Friction welding is the only viable method in this field to overcome the difficulties encountered in the joining of dissimilar materials with a wide variety of physical characteristics. The advantages of this process are, among others, no melting, high reproducibility, short production time and low energy input [1]. The main factor of diffusion bonding is thermal energy, whereas the factors of friction welding are thermal energy by friction and axial force by forging [2]. Friction welding has advantage in materials that are hard to adopt fusion welding in that, it needs comparatively low thermal energy input in welding and causes minimal thermal degradation as base materials need not be fused for welding. Although a large amount of previous works in similar materials has been accumulated, mechanical properties of the copper to titanium joint by friction welding method has never reported except by Ruge *et al.* [1]. Thus, the objective of the present work is to examine the mechanical properties and optimal welding condition of friction welded joints of copper to titanium.

2. Experimental procedures

Friction welding was performed using a Brake type friction welder. During friction welding of copper and titanium, each deformation resistance differs greatly, in that the copper base metal deforms by plastic deformation during joining. Therefore, the diameter of the copper side was machined on a lathe, so that it was

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TABLE I Physical properties of materials used in the experiment

Materials	Density (g/cm^3)	Melting point (K)	Thermal conductivity ($W/cm \cdot K$)	Thermal expansion coefficient (293 K)
Cu	8.96	1357.6	4.01	16.5×10^{-6}
Ti	4.50	1943	0.219	8.35×10^{-6}

TABLE II Friction welding conditions

Friction time (t_1)	Friction pressure (P_1)	Upset pressure (P_2)	Upset time (t_2)	rpm
0.1–1.0 sec	100 MPa	100–325 MPa	6 sec	2000

larger than the diameter of the titanium side. In general, the difference in diameter provides more constraint in the softener material, thus compensate, in part, for the difference in the yield strength. The unalloyed base metals-titanium, 99.4 wt% and copper, 99.99 wt%-were available in the form of round bars with 16 and 20 mm diameter respectively. The physical properties of the base metals and experimental conditions are given in Tables I and II.

Fig. 1 shows the schematic illustration of friction welding. Friction welds are made by holding a nonrotating copper bar in contact with a rotating titanium bar under gradually increasing pressure until the interface reaches adherence and then the rotation was stopped to complete the weld. Microhardness measurements were made on the etched samples using a vickers indenter with a 50 gf load for 10 sec.

Fig. 2 shows the shape and dimension of the tensile test specimen. Tensile tests were conducted on an Instron test machine at room temperature at a crosshead rate of 1.67×10^{-5} (m/sec) [3, 4]. Specimens were sectioned transversely in order to study the microstructural variations that exist from the center to the outside of the weld. Metallurgical polishing of the specimens was accomplished with a 0.3 micron alumina suspension. Chemical etching utilized Kroll's reagent (100 mL H_2O, 2 mL HNO_3 and 6 mL HF) for titanium and (25 mL NH_3, 25 mL H_2O, 10 mL H_2O_2) for copper. The microstructures of the joints were observed using optical and scanning electron microscopy (SEM). The phases and compositions were examined by X-ray diffractometer (XRD) and Electron probe microanalyzer (EPMA).

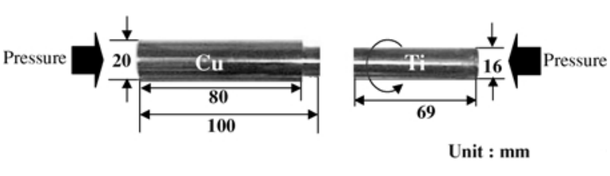

Figure 1 Schematic illustration of friction welding process.

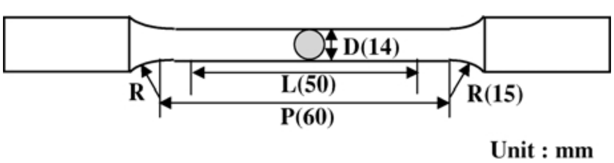

Figure 2 Dimension of tensile test specimen.

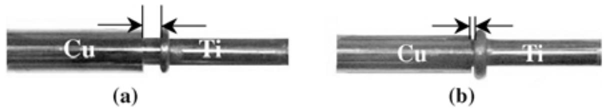

Figure 3 Appearance of copper-titanium joint. (a) Friction time (t_1) = 0.1 sec, Upset pressure (P_2) = 100 MPa and (b) Friction time (t_1) = 0.1 sec, Upset pressure (P_2) = 325 MPa.

3. Result and discussion

3.1. Appearance of joint

Fig. 3 shows the appearance of copper-titanium joint. Joint flash was formed at the copper side while the titanium side is not externally changed. It was also seen that the total length of the specimen decreased with increasing upset pressure. Hence, minimizing the loss of specimen without affecting the tensile strength is the derivative condition in friction welding [5].

3.2. Friction welding condition and joint efficiency

The tensile test specimens were prepared with a diameter of 14 mm and gauge length of 60 mm using a lathe, after friction welding. The conditions used were as follows: rotational speed; 2000 rev/min, friction pressure; 100 MPa, friction time; 0.1–1.0 sec, upset pressure; 100–325 MPa and upset time; 6 sec. Friction pressure, upset time and rotation speed was fixed in this work. The joint efficiency is the ratio of tensile strength of base metal that is not welded and tensile strength of welded joint.

Joint performance was evaluated by a joint efficiency (%) {(tensile strength of weld joint/tensile strength of softer metal) $\times$ 100 (%)} [6].

The joint efficiency of copper and titanium at each condition is plotted in Fig. 4. It shows the joint efficiency with increasing upset pressure for each friction time under a friction pressure of $P_1 = 100$ MPa and an upset time of $t_2 = 6$ sec.When the upset pressure is over 250 MPa, the joint efficiency rises to over 95%. But at a friction time of 0.1 sec, though the upset pressure increases, the joint efficiency is low. Also, if upset pressure becomes more than 250 Mpa, the gap of joint efficiency is narrowed regardless of friction time except at 0.1 sec.

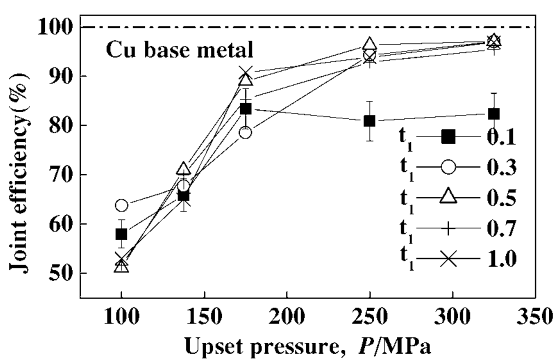

Figure 4 Variations of joint efficiency with increasing upset pressure (P_2) for each friction time (t_1).

3.3. Mechanical properties

Fig. 5 shows the microstructure of the interface of the as-welded specimen under a friction time of $t_1 = 0.1$ sec, upset time of $t_2 = 6$ sec, friction pressure of $P_1 = 100$ MPa and upset pressure of $P_2 = 175$ MPa. Since the metal is partially deformed by rapid heating and severe plastic flow, the recrystallized region, which is different from the microstructures of base metal (copper), is formed [7]. The change of microstructure was notably occurred in the copper.

Fig. 6 shows the hardness distribution in the direction perpendicular to the weld interface of the as-welded specimen. The hardness of the copper weld metal increases from around HV 65 at a position adjacent to the weld interface to the base metal hardness of around HV 110. On the titanium side, the hardness ranges between HV 170–190. The hardness of the recrystallized region is found to be lower than that of copper weld metal. This is the so-called heat softened zone. The distance that hardness is decreased in copper weld metal is consistent with that of the recrystallized region of the copper weld metal as shown in Fig. 5. Hence it is seen that, the higher the upset pressure, the narrower the recrystallized region, which is related to the increasing amount of upset. Microhardness analysis indicates that the width of recrystallized region is mainly affected by the upset pressure. Since the relative part of the velocity varies initially from zero at the center to a maximum of 1.67 m/sec at the outside of the joint, the heat generated during the welding process can vary locally along the bond line. As a result, the microhardness distribution of center and periphery is different [8].

Fig. 7a and b show the changes in the tensile strength and amount of upset with an increase in upset pressure. When the upset pressure is over 250 MPa, the tensile strength of welded joint increased slightly with an

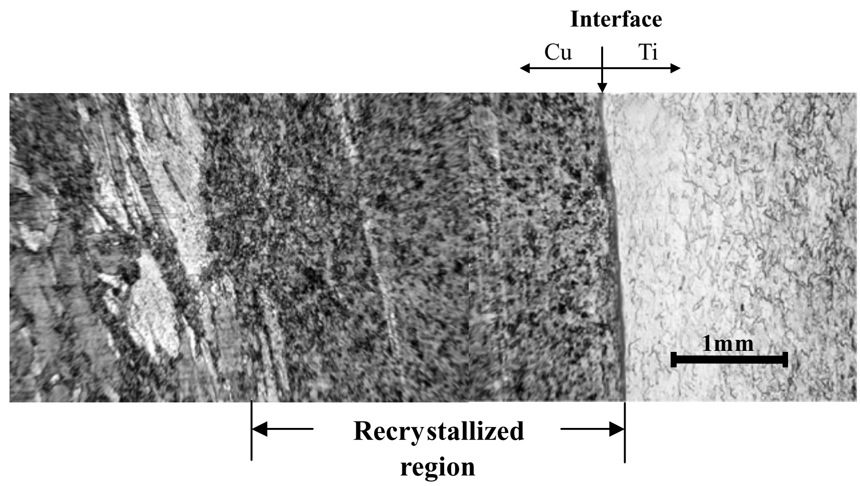

Figure 5 Microstructure of the interface of the as-welded specimen. (Friction time (t_1) = 0.1 sec, Upset time (t_2) = 6 sec, Friction pressure (P_1) = 100 MPa, and Upset pressure (P_2) = 175 MPa.)

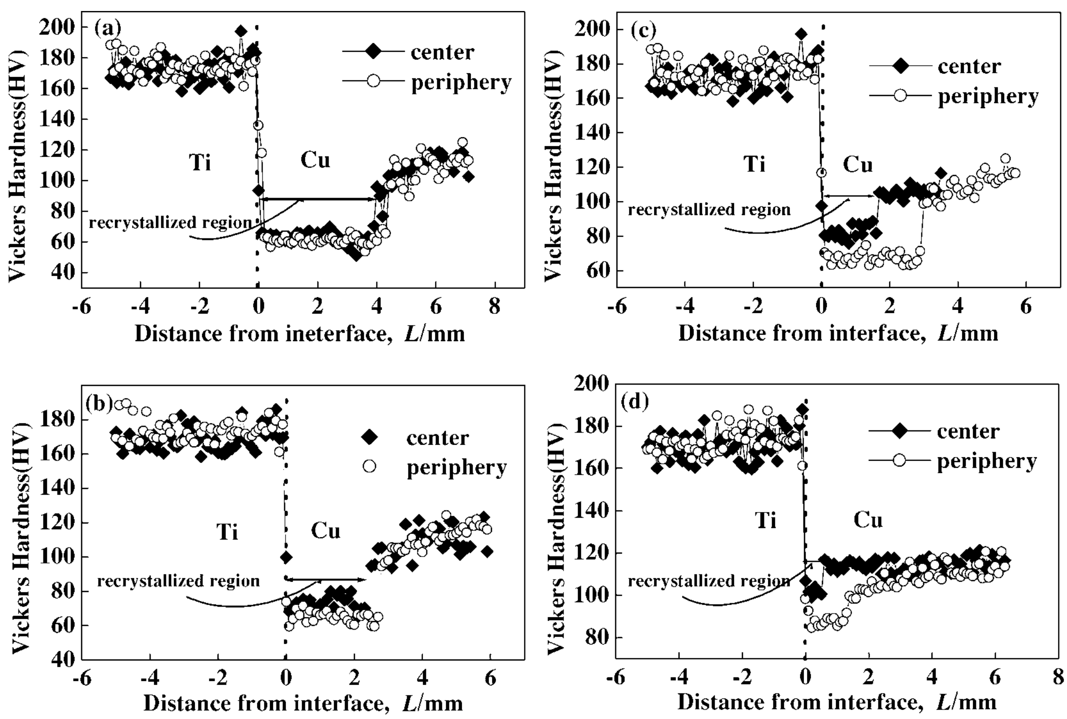

Figure 6 Hardness distribution in joint interface of as-welded specimen. (Friction pressure (P_1) = 100 MPa, Upset time (t_2) = 6 sec and Friction time (t_1) = 0.1 sec) (a) $P_2 = 100$ MPa, (b) $P_2 = 137.5$ MPa, (c) $P_2 = 175$ MPa, and (d) $P_2 = 325$ MPa.

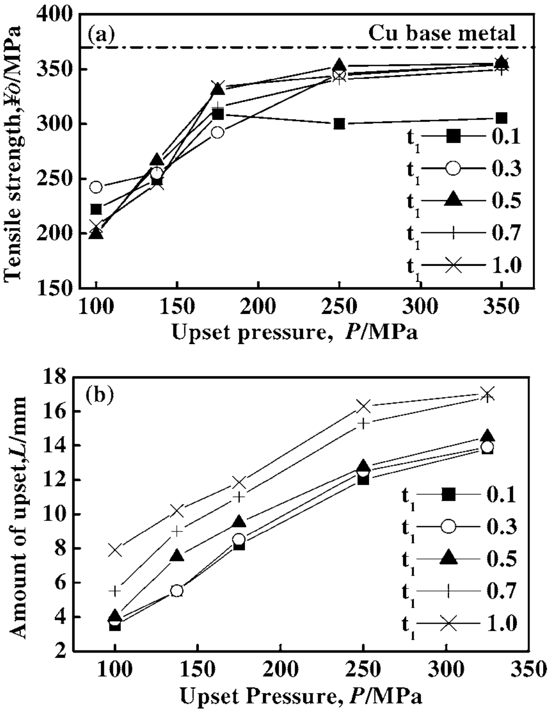

Figure 7 Variations of (a) tensile strength and (b) amount of upset with upset pressure (P_2).

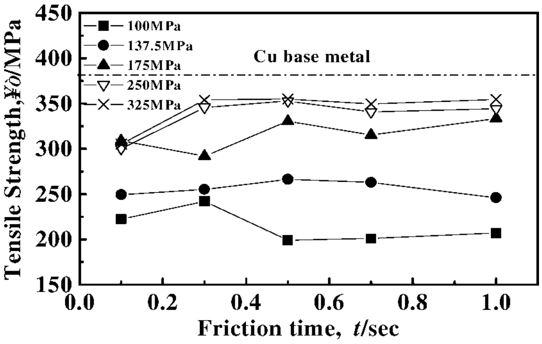

Figure 8 Variations of the tensile strength with friction time (t_1) for each upset pressure (P_2).

increase in upset pressure, whereas the amount of upset increased steadily with increasing upset pressure. That is, upset pressure of more than 250 MPa does not contribute to tensile strength elevation regardless of friction time. Hence, the optimal joint performance was attained at a friction time (t_1) of 0.7 sec and an upset pressure (P_2) of 325 MPa. The tensile fracture of welded joint occurred in the copper side near the interface. The maximum tensile strength was 355 MPa which was near 95% that of the copper base metal.

Fig. 8 shows the changes in the tensile strength with friction time for each upset pressure. When the upset pressure is 100 MPa, which is the lowest pressure in this experiment, though the friction time increases, the tensile strength of welded joint is low. That is, though the thermal degradation region increase with friction time, the low upset pressure cannot discharge thermal degradation region from the interface totally. Thus it is considered that the upset pressure plays a major role over the friction time and friction pressure on tensile strength, which is mainly under the control of upset pressure (P_2). The above experimental result shows that the tensile strength of the welded joint mainly increases with an increase in the upset pressure. Because the friction and wear help to get rid of contaminants like oxide on the surface, a new face will be surfaced. At the same time, the upset pressure sets in to bring the new face within the scope of the attraction range [2].

3.4. Microstructural observations of welded joint

Fig. 9 shows the microstructural features of the interfaces with increasing upset pressure. With an increase of upset pressure, the amount of burr increases and the shape of the burr tilts toward copper from its original axis-symmetric form. The center of faying surface has a flat shape regardless of upset pressure, the outside of joint is a mechanical mixture of copper and titanium. This is because the outside of the joint is faster than

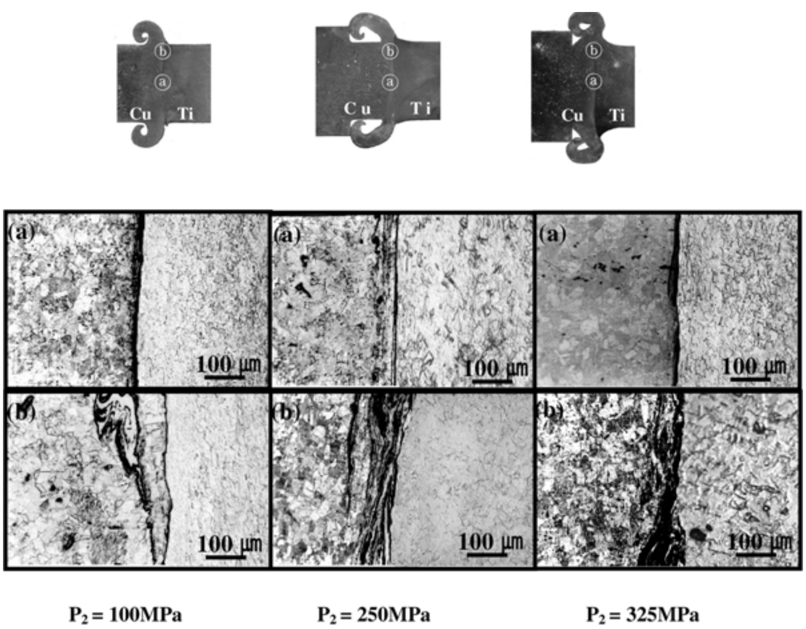

Figure 9 Microstructure of joint ($t_2 = 6$ sec and $P_1 = 100$ MPa, $t_1 = 0.7$ sec) (a) Central interface and (b) peripheral interface.

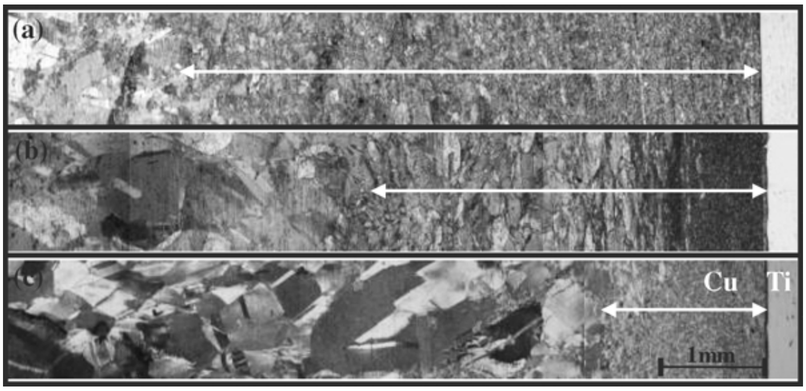

Figure 10 Microstructures of friction-welded joint of copper and titanium. (Friction pressure $(P_1) = 100$ MPa, Upset time $(t_2) = 6$ sec and Friction time $(t_1) = 0.7$ sec) (a) $P_2 = 100$ MPa, (b) $P_2 = 250$ MPa, and (c) $P_2 = 325$ MPa.

the central part, so the frictional heat of the outside of the joint is larger than the central part. Therefore, at the outside of the joint plastic flow is easier than in central part. This produces an increase of surface area and is considered to contribute to joint strength increase.

Fig. 10 shows the microstructures of friction-welded joint at the friction time of 0.7 sec under the upset pressure of 100, 250 and 325 MPa respectively. In Fig. 10a, the recrystallized region is found to be broad. As a result of tensile test, the fracture occurred at the joint interface. The recrystallized region of Fig. 10b decreases compared to that of Fig. 10a, and the fracture occurred in faying surface. As shown in Fig. 10c, the recrystallized region decreases to a large extent. The tensile fracture of joint did not occur in the faying surface but in the copper base material. This means that the decrease in recrystallized region caused by high upset pressure contributes to the tensile strength increase. Consequently, the increase of tensile strength is due to the exposure and contact of material that is not deformed by upset pressure.

When similar materials are welded, heat flow direction is axis-symmetric into each of the parts. In dissimilar metal combinations, however, heat flow occurs preferentially into the material with the greatest thermal conductivity. Due to the different thermal conductivities between copper and titanium, the specific heat is so large, and hence most of the frictional heat generated during welding is dissipated in copper [1, 7]. Generally, the peak temperature at the weld interface is about 2/3 of the melting point of the lowest melting material. The difference in thermal conductivity explains the microstructural changes which occur preferentially in the copper. For titanium, no evidence of microstructural variations was seen in the vicinity of the interface; neither grain growth nor grain boundary precipitation was observed. Little deformation was observed in the titanium side.

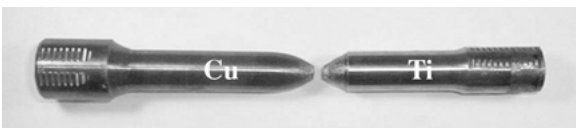

Figure 11 Base metal fracture after tensile test. (Uupset time $(t_2) = 6$ sec, Friction pressure $(P_1) = 100$ MPa, Friction time $(t_1) = 0.7$ sec and Uupset pressure $(P_2) = 325$ MPa.)

Fig. 11 shows the base metal fracture under a friction time of $t_1 = 0.7$ sec and an upset pressure of $P_2 = 325$ MPa. The fracture surfaces under the same conditions are shown in Fig. 12, which displays a typical dimple a pattern.

Fig. 13 shows the X-ray diffraction pattern at the faying surface of copper/titanium weld under a friction time of $t_1 = 0.5$ sec, and an upset pressures of $P_2 = 100$ and 325 MPa respectively.

Generally, the intermetallics are brittle and are weak in tension, fatigue and bending properties. Thus, the formation of intermetallic compound at the interface during welding, causes a reduction in strength [1, 9, 10]. In this experiment, although Cu_3Ti intermetallic compound is formed at the copper/titanium interface during welding, the tensile strength of welded joint is not affected as shown in Fig. 7. This is because the thickness of intermetallic compound layer at interface is very thin and scattered. Also, most intermetallic compounds are

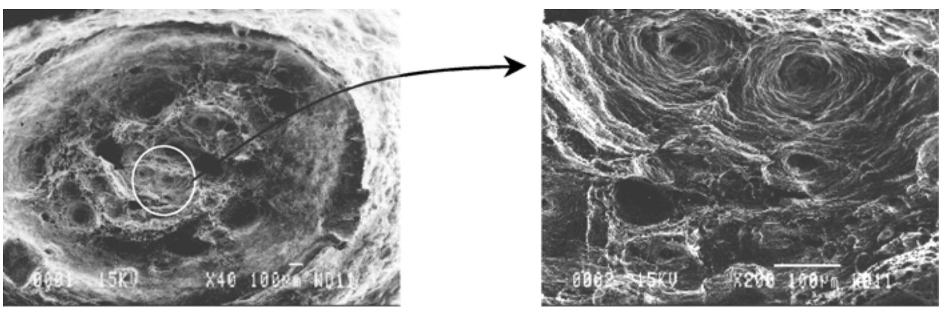

Figure 12 Microfractographs of tensile fracture surfaces. (Upset time $(t_2) = 6$ sec, Friction pressure $(P_1) = 100$ MPa, Friction time $(t_1) = 0.7$ sec, Upset pressure $(P_2) = 325$ MPa.)

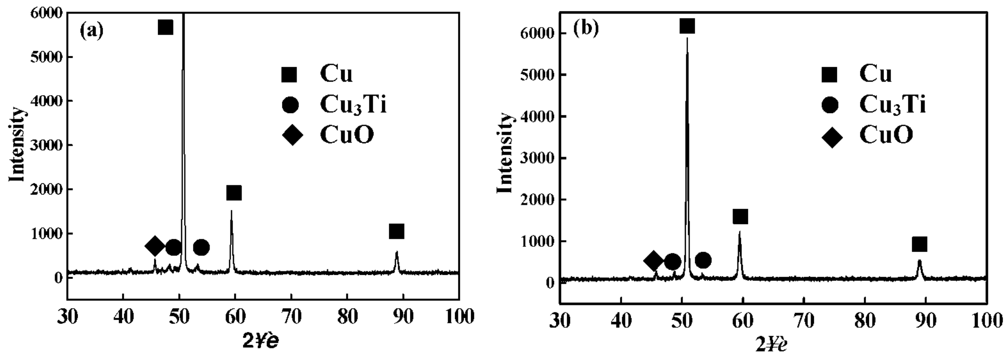

Figure 13 X-ray diffraction pattern on interface of copper/titanium joint. (Friction pressure (P_1) = 100 MPa, Upset time (t_2) = 6 sec and Friction time (t_1) = 0.5 sec) (a) P_2 = 100 MPa and (b) P_2 = 325 MPa.

discharged from the interface by upset pressure and the centrifugal force. And hence, the Cu_3Ti intermetallic compound may not affect the tensile strength of welded joint. The formation and growth of this phases can be controlled by varying the friction welding process parameters, such as lower speed and higher upset pressure during the friction welding [11]. It is also known from other reports that maximum tensile strength was not reached as faying surface was imperfect [1, 5]. The reasons for the generation of imperfect interface are (i) the insufficient friction time prevented temperature from reaching optimal value and (ii) regardless of friction time, low upset pressure could not bring these materials within the attraction range. These factors affect the situation separately or collectively. As shown in Fig. 8, increased friction time when coupled with low upset pressure will result in low tensile strength. In the case of short friction time with high upset pressure, the result will be the same.

Fig. 14 shows EPMA line profiles of Cu/Ti friction-welded joint under $t_1 = 0.7$ sec, $P_1 = 100$ MPa and $t_2 = 6$ sec. It is assumed that SEM photo and line profile of specimen tested at the lowest pressure ($P_2 =$ 100 MPa) and highest pressure ($P_2 = 325$ MPa) showed there is no intermetallic compound and this means thickness of intermetallic compound layer is thin and distribution is not balanced. Thus, EPMA could not secure clear result.

Therefore, Further work is required to fully characterize the intermetallic compound. Because of the spatial and limitation of SEM and EPMA, other techniques such as TEM (Transmissions electron microscopy) and SAM (Scanning auger microscopy) could provide more accurate information.

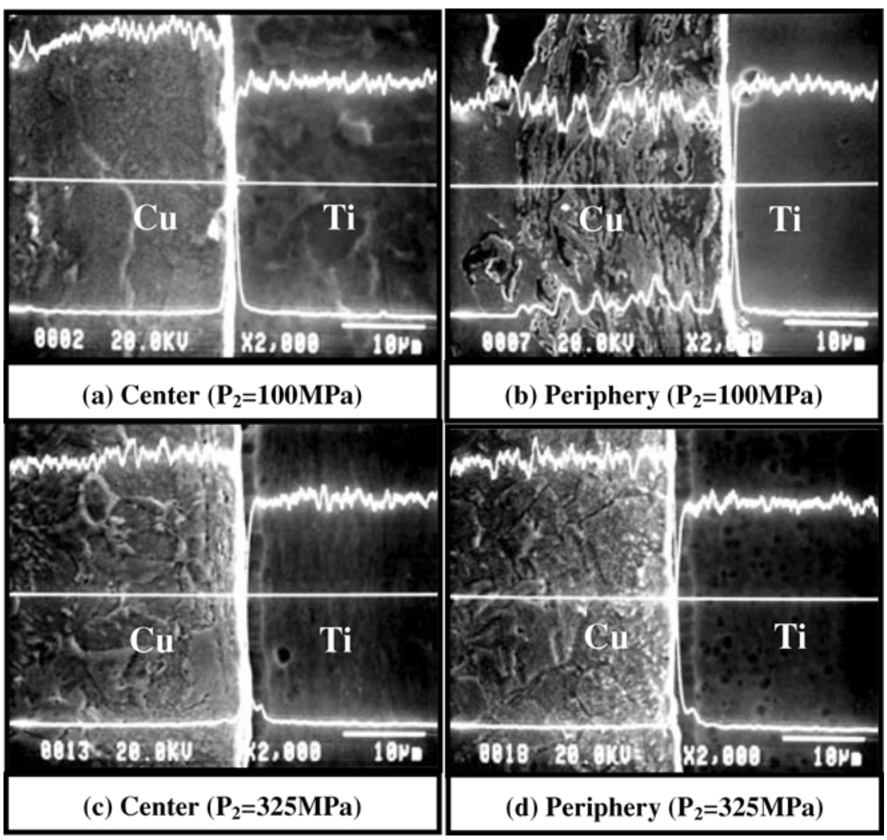

Figure 14 EPMA line profiles of Cu/Ti joint (Friction time (t_1) = 0.7 sec, Friction pressure (P_1) = 100 MPa and Upset time (t_2) = 6 sec).

4. Conclusion

This study investigates some factors affecting the joint performance of friction-welded joint of copper to titanium. The tensile and microhardness test were carried out under various test conditions to evaluate the joint performance. Based on the results, the following conclusions were obtained.

1. The tensile strength of friction-welded joint of copper and titanium increased with increasing upset pressure.
2. The center of faying surface has a flat shape while the outside of faying surface wrinkled with a mechanical mixture of copper and titanium.
3. The microstructure of joint interface is finer than that of base metal in the copper.
4. The width of recrystallized region is mainly affected by the upset pressure.
5. The optimal joint performance was attained at a friction pressure of 100 MPa, upset time of 6 sec, friction time of 0.7 sec and upset pressure of 325 MPa.

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