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Effect of Friction Welding Condition and Weld Faying Surface Properties on Tensile Strength of Friction Welded Joint between Pure Titanium and Pure Copper*

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Abstract

This paper describes the effect of the friction welding condition and the weld faying surface properties on the tensile strength of the friction welded joint between pure titanium (Ti) and pure copper (OFC). The joint strength of the joint, which was made with the weld faying surface of the Ti side specimen finished with a surface grinding machine, was investigated. The joint did not have 100% efficiency and OFC side fracture regardless of the friction welding conditions. When the joint was made with a friction pressure of 75 MPa, the joint efficiency was approximately 64% regardless of the forge pressures, and all joints fractured at the weld interface, although that efficiency exceeded that of the joints made with other friction pressures. To improve the joint efficiency, one was made with a Ti side specimen whose weld faying surface was finished by buff polishing. The joint efficiency was increased to approximately 85%, although the joint fractured at the weld interface. Moreover, a joint at a friction pressure of 75 MPa with a forge pressure of 270 MPa or higher was obtained with an OFC side fracture, although it did not achieve 100% efficiency. The fact that the joint did not fracture at the OFC base metal was due to the mechanically mixed layer at the weld interface that depended on the maximum height of the Ti side weld faying surface. To clarify the reason why the joint did not achieve 100% joint efficiency, the tensile strength of the OFC base metal with the addition of various compressive stresses was investigated. When the compressive stress was higher than the yield stress of the OFC base metal, its tensile strength was lower than that without a compressive load. Moreover, the tensile strength along the radial direction of the OFC base metal was also slightly lower than that of the longitudinal direction. Hence, the fact that the joint did not also achieve 100% efficiency was due to the decrease in the tensile strength of the OFC base metal by the Bauschinger effect and the difference of the anisotropic property with as-manufactured condition.

Key words : Friction Welding, Titanium, Copper, Joint Efficiency, Friction Welding Condition, Roughness, Bauschinger Effect, Anisotropic Property

1. Introduction

Titanium (Ti) and its alloys (referred to as Ti-system material) are well-known materials with highly attractive characteristics in terms of mechanical and metallurgical properties, e.g.,

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high specific strength and excellent corrosion resistance. They are very widely used for the important structural components in architecture, automobiles, aerospace, and so on. Moreover, they are also useful as biomedical materials due to their low allergenic effect on the human body. On the other hand, fusion welding between Ti-system material and such other materials as steel, stainless steel, aluminum (Al), and copper (Cu) have poor mechanical properties due to the brittle intermetallic compound (IMC) layer produced at the joint interface.[(1),(2)] Therefore, a welding process for between Ti-system material and other material joints which will result in less degradation of the mechanical and metallurgical properties of the joint is urgently required.

The solid state joining methods such as diffusion welding, friction welding, and so on, can be applied to join between Ti-system material and other materials. Many researchers have reported that the mechanical and metallurgical properties of the friction welded joints of Ti-system material and other materials show desirable characteristics.[(3)−(18)] However, several friction welded joints, which were affected by the IMC that was generated at the weld interface, had brittle fractures themselves in the IMC.[(3)−(10),(12)−(15)] In addition, the joining mechanism of friction welding between dissimilar materials differs from that of similar materials because such mechanical properties as the tensile strength and such thermal properties as the thermal conductivity have different combinations. To determine the friction welding conditions theoretically, it is essential to clarify the joining phenomena and the joint mechanical properties. In particular, clarifications of the joining mechanism are strongly required concerning the weldability between the Ti-system materials and other material, because an expansion is expected in the use of Ti-system material.

In previous works, the authors clarified the joining mechanism during the friction welding process for similar or dissimilar materials joints.[(19)−(35)] In addition, the authors presented the joining phenomena during the friction stage at various friction pressures of friction welding between pure Ti and pure Cu.[(35)] However, the joint mechanical properties of that combination were not clarified. That is, clarification of the joint properties is indispensable. Based on the above background, the present paper focuses on the joint tensile properties between pure Ti and pure Cu friction welded joints under various friction welding conditions, especially on the effects of friction pressure, friction time, and forge pressure on the joint tensile strengths. The authors show the friction welding conditions for a joint that fractured on the pure Cu side with no crack at the weld interface. Furthermore, the authors also show the effect of the weld faying surface properties on the joint tensile strength and its influence on the base metal properties of pure Cu.

2. Experimental procedures

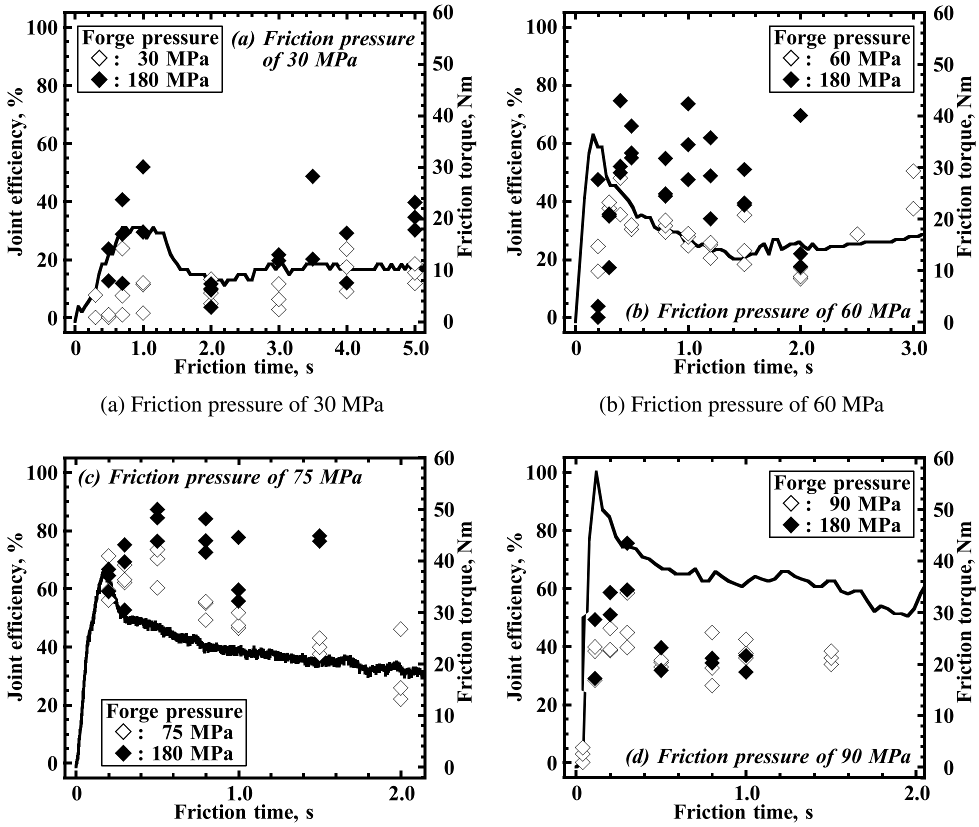
The materials used were commercially pure Ti (referred to as P-Ti) and oxygen free copper (referred to as OFC) in 16 mm diameter rods. The chemical composition of the P-Ti was 0.01H-0.1O-0.01N-0.01C-0.07Fe in mass%, the ultimate tensile strength was 478 MPa, the 0.2% yield strength was 353 MPa, and the elongation was 26.5%. Two kinds of OFCs with slightly different tensile properties were used for this experiment because they were purchased at different times. The chemical composition of both OFCs was 99.99Cu in mass%. Their ultimate tensile strengths were 321 and 326 MPa, their 0.2% yield strengths were 309 and 311 MPa, and their elongations were 13.5 and 14.6%. The materials were machined to 12 mm diameters for the weld faying surfaces. All weld faying surfaces were finished with a surface grinding machine before joining, because its surface roughness influenced the mechanical properties of dissimilar materials joint.[(4),(8),(15),(36)−(37)] In this case, the centerline average height of the roughness of the P-Ti side specimen was about 0.34 μm, and the OFC side specimen was about 0.30 μm. All specimens were used without heat treatment after mechanical processing. The used materials and specimen shapes were identical to those in a previous report.[(35)]

A continuous (direct) drive friction welding machine, which had an electromagnetic clutch to prevent braking deformation during the rotation stop, was used for the joining. During the friction welding operations, the friction welding condition was set to the following combinations: a friction speed of 27.5 s^{-1} (1650 rpm), friction pressures of 30, 60, 75, and 90 MPa, a range of friction times from 0.04 to 5.0 s, a range of forge pressures from 30 to 320 MPa, and a forge time of 6.0 s. The friction torque was measured with a load-cell, and recorded with a personal computer through an A/D converter with sampling times of 0.05 or 0.001 s. All joint tensile test specimens were machined to 12 mm diameters and 66 mm in parallel length. That is, all flash (burr or collar), which was exhausted from the weld interface during the friction welding process, were removed from the joint for joint tensile test specimen. Then, the joint tensile test was carried out with as-welded condition at room temperature. The details of the joining method were previously described.(35) Moreover, analysis via EDS was carried out to analyze the chemical composition in the weld interface region. Vickers hardness distribution at the half-radius and peripheral locations across the weld interface region was measured with a load of 9.81 N (1 kgf).

3. Results

3.1. Joint tensile strength

Figure 1 shows the relationship between the friction time and the joint efficiency of the joint at various friction pressures, in relation to the friction torque curves. The joint efficiency was defined as the ratio of the joint tensile strength to the ultimate tensile strength of the OFC base metals. When the joint was made with friction and forge pressures of 30 MPa, the joint efficiency was approximately 10% at all friction times, which is indicated by open rhombus symbols in Fig. 1a. The joint did not achieve 100% efficiency, as indicated by the solid



(a) Friction pressure of 30 MPa

(b) Friction pressure of 60 MPa

(c) Friction pressure of 75 MPa

(d) Friction pressure of 90 MPa

Fig. 1 Relationship between friction time and joint efficiency for joint with finishing of P-Ti side weld faying surface by a surface grinding machine at various friction pressures, in relation to friction torque curves.

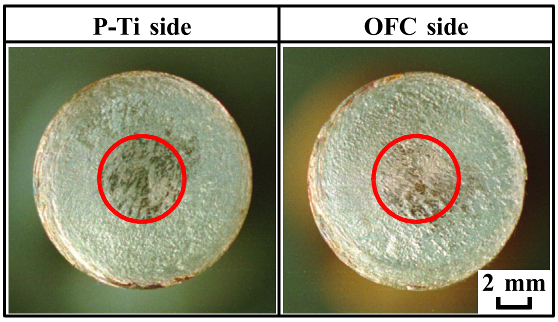


Fig. 2 Example of fractured surfaces of joint tensile test specimens after tensile testing under friction pressure of 90 MPa.

rhombus symbols, when it was made with a forge pressure of 180 MPa, although the joint efficiency slightly increased. All joints fractured at the weld interface, although they had a little OFC that adhered on the P-Ti side interface. The joint efficiency of the joint made with friction pressures of 60 and 75 MPa was higher than that of 30 MPa (Figs. 1b and 1c.). In addition, when the joint was made with a friction pressure of 75 MPa and a forge pressure of 180 MPa, the joint efficiency of several joints was approximately 80% or over (the solid rhombus symbols in Fig. 1c). However, the joint also fractured at the weld interface. When the joint was made at a friction pressure of 90 MPa, it did not achieve 100% efficiency and fractured at the weld interface (Fig. 1d). Also, the joint did not achieve 100% efficiency when it was made with a forge pressure of 180 MPa. The fact that the joint tensile strength differed at various friction pressures was caused by different joining phenomena during the friction process. That is, the joining phenomena during the friction process had differed by applied friction pressure, as indicated in a previous report.[35] The joint, which was made with a friction pressure of 60 MPa or lower, had such defects as a not-joined region at the weld interface. In addition, the P-Ti side did not have sparkle at a friction pressure of 75 MPa or higher although that had sparkle when the joint was made at a friction pressure of 60 MPa or lower. Consequently, the joint with high friction pressure such as 75 MPa had the flash of OFC although that with low friction pressure such as 60 MPa generated the flash of P-Ti and OFC. Therefore, the difference of the joint tensile strength seems to be a cause of the not-joined region and sparkle. Moreover, the central portion on the fractured surface at the P-Ti side of the joint with a friction pressure of 90 MPa had almost no OFC, which is indicated by circles as shown in Fig. 2. That is, this portion was not completely joined because the friction pressure was too high. Hence, to obtain higher joint efficiency, the joint should be made at a

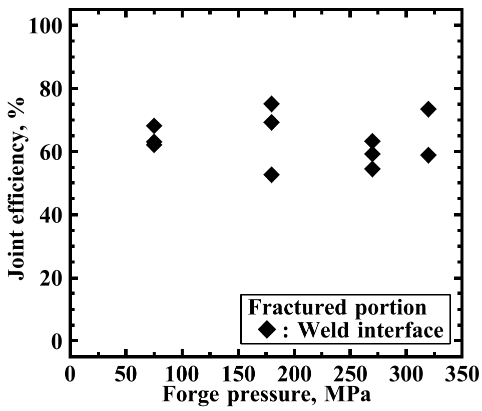


Fig. 3 Relationship between forge pressure and joint efficiency of joint with finishing of P-Ti side weld faying surface by a surface grinding machine; friction pressure of 75 MPa and friction time of 0.3 s.

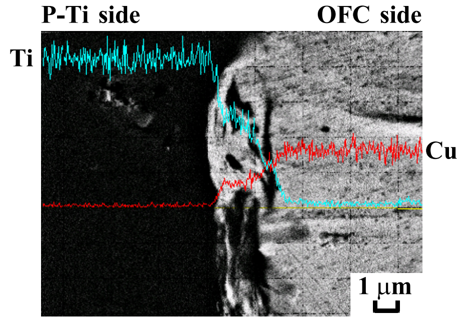


Fig. 4 SEM image and EDS analysis result at half-radius portion of weld interface region for joint with a surface grinding machine finishing at P-Ti side weld faying surface: friction pressure of 75 MPa, friction time of 0.3 s, and forge pressure of 270 MPa.

friction pressure of 75 MPa.

To improve the joint efficiency, a joint was made with higher forge pressure. Figure 3 shows the relationship between the forge pressure and the joint efficiency for a joint made under friction pressure of 75 MPa and friction time of 0.3 s. In this case, the friction time was set to 0.3 s, i.e. friction torque reached just after the initial peak, because this friction time was the opportune time for the OFC that was transferred to the entire weld interface on the P-Ti side at this friction pressure.[35] The joint efficiency was approximately 64% at all forge pressures, and the joint fractured at the weld interface. That is, the joint efficiency was not increased, and the fractured portion was not changed regardless of increased forge pressure. Figure 4 shows the SEM image and EDS analysis result at the half-radius portion of the weld interface region for joint with surface grinding machine finishing at P-Ti side weld faying surface, which was made with friction pressure of 75 MPa, friction time of 0.3 s, and forge pressure of 270 MPa. The distribution lines corresponding to Ti and Cu by EDS analysis had no plateau part of the weld interface, although the weld interface was not clear. That is, an IMC layer was not observed according to observation in SEM level. Hence, the weld interface fracture seems to be a cause of the weld faying surface properties of the specimens. Incidentally, the generating of IMC which had the width of about 0.1 μm or shorter was considered,[6] and further investigation is necessary to elucidate the detailed mechanical properties of the joints.

3.2. Improving joint properties

It is considered that the weld faying surface properties affected the joint tensile strength,

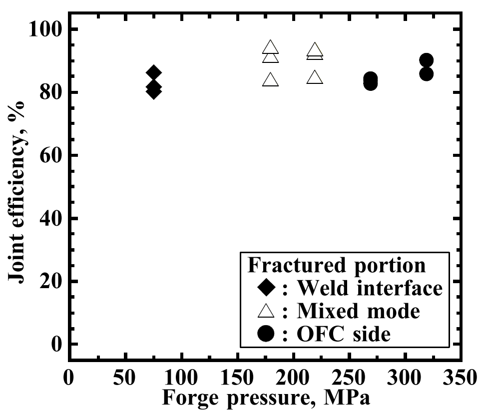


Fig. 5 Relationship between forge pressure and joint efficiency of joint with buff polishing at P-Ti side weld faying surface: friction pressure of 75 MPa and friction time of 0.3 s.

since the joint properties of several friction welded joints between the Ti-system material and other materials were improved using the weld faying surface finished by buff polishing.[4],[8],[15],[36] Hence, it was investigated how the surface finish condition of the weld faying surface by buff polishing affected on the joint efficiency of the joint. Figure 5 shows the relationship between the forge pressure and the joint efficiency of the joint, which was made with a weld faying surface finished by buff polishing under friction pressure of 75 MPa and friction time of 0.3 s. Figure 6 shows the examples of the appearances of the joint tensile test specimens for those joints after tensile testing. In this case, only the weld faying surface of the P-Ti side was finished by buff polishing with using the average particle diameter of 0.05 μm of alumina powder, and that of the OFC side was finished with a surface grinding machine. Because the deformation of the P-Ti side was smaller than that of the OFC side during the friction process, the finishing of the OFC side was ignored under this friction welding condition.[35] The joint efficiency, which was approximately 85% at all forge pressures, was increased by finishing the weld faying surface of the P-Ti side from a surface grinding machine to buff polishing (Figs. 2 and 5). The joints at forge pressures of 180 and 220 MPa were fractured between the OFC side and the weld interface (mixed mode fracture, Fig. 6b), although the forge pressure of 75 MPa had a weld interface fracture (Fig. 6a). In addition, the joint fractured on the OFC side with no

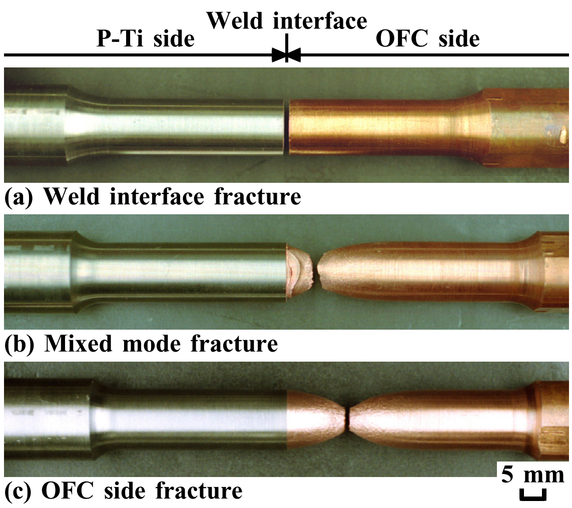


Fig. 6 Example of appearances of joint tensile test specimens after tensile testing.

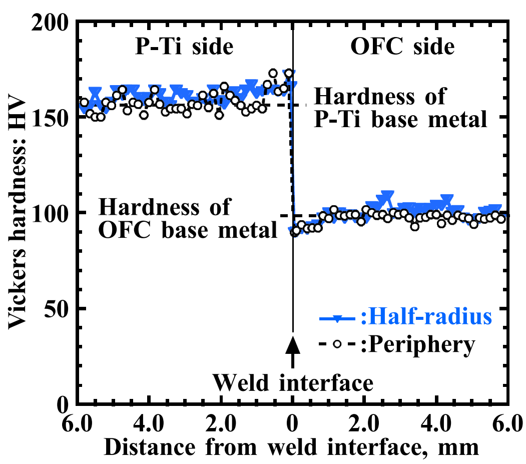


Fig. 7 Vickers hardness distribution across weld interface region of joint with buff polishing at P-Ti side weld faying surface: friction pressure of 75 MPa, friction time of 0.3 s and forge pressure of 270 MPa.

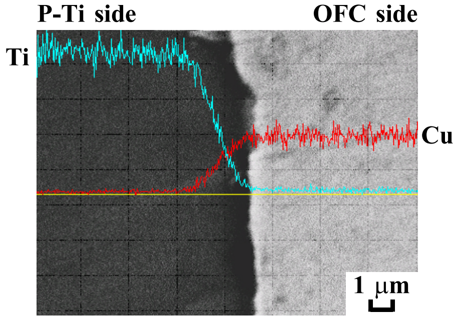


Fig. 8 SEM image and EDS analysis result at half-radius portion of weld interface region for joint with buff polishing at P-Ti side weld faying surface: friction pressure of 75 MPa, friction time of 0.3 s, and forge pressure of 270 MPa.

cracking at the weld interface when it was made with a forge pressure of 270 MPa or higher (Fig. 6c). That is, the joint with the OFC side fracture was obtained with the P-Ti side faying surface finished by buff polishing. Moreover, this joint had scarcely the softened region at the adjacent region to the weld interface of the OFC side as shown in Fig. 7. Furthermore, the distribution lines corresponding to Ti and Cu had no plateau part at the half-radius portion of the weld interface as shown in Fig. 8, i.e. this joint did not also have an IMC layer according to observation in SEM level. Incidentally, the flash quantity and the axial shortening (burn-off) of the joint, which was made with the P-Ti side weld faying surface finished by buff

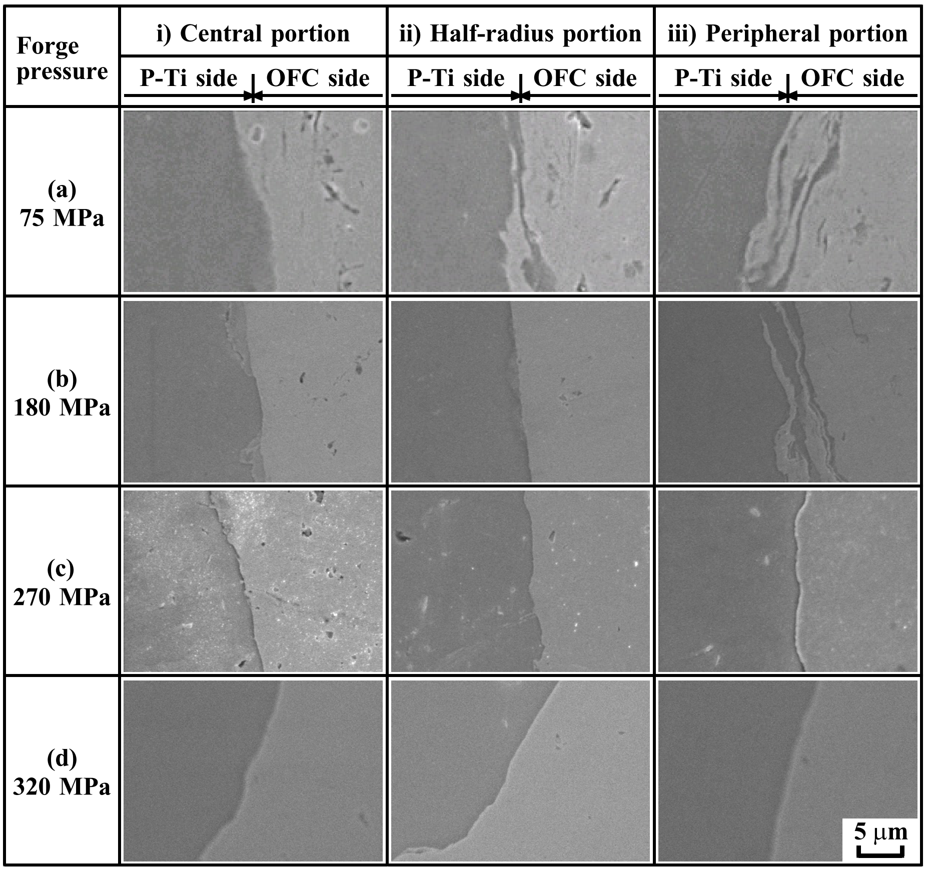


Fig. 9 SEM micrographs of cross-section of weld interface region for joint with P-Ti side weld faying surface of buff polishing at various forge pressures: friction pressure of 75 MPa and friction time of 0.3 s.

polishing, had almost same values compared to the joint with a surface grinding machine finishing. Hence, the fact that the joint did not achieve 100% efficiency seems to be a cause of the decrease of the tensile strength of the OFC base metal.

Figure 9 shows SEM micrographs of a cross-section of the weld interface region for the joint at various forge pressures. The half-radius and periphery portions of the weld interface for the joint at a forge pressure of 75 MPa demonstrated lamellar structures between P-Ti and OFC, i.e., these had the mechanically mixed (mechanical mixing) layers (Fig. 9a). When the joint was made at a forge pressure of 180 MPa, the periphery portion also had a mechanically mixed layer, although the half-radius portion of the joint did not (Fig. 9b). However, the joint at a forge pressure of 270 MPa had no mechanically mixed layer at any of the observed portions (Fig. 9c). In addition, when the joint was made at a forge pressure of 320 MPa, the mechanically mixed layer was not observed (Fig. 9d). Similar mechanically mixed layers were also observed in several dissimilar friction welded joints.(5),(11)−(14),(38)−(45) Hence, the difference of the fractured portion for the joint seems to be a cause of the existence on the mechanically mixed layer.

4. Discussion

4.1. Influence of weld faying surface properties

Based on the above results, the joint, which was made with the weld faying surface of the P-Ti side specimen finished by buff polishing and with the same friction welding condition, was fractured at the OFC side, even though it did not achieve 100% efficiency. Incidentally, the joining phenomena during the friction process resembled the joint with the weld faying surface of the P-Ti side specimen finished by buff polishing. That is, the initial peak torque and elapsed time for the initial peak had almost same values as shown in Fig. 1c, and the friction torque curve did not have difference. Moreover, the flash quantity and the axial shortening of the joint also had almost same values, and joint appearance did not have difference. To clarify the cause that buff polishing improved the joint efficiency, it was investigated how the finishing type of the P-Ti side weld faying surface affected that efficiency. Figure 10 shows the result of the joint efficiency for the joints at various finishing types of P-Ti side weld faying surfaces. These joints were made under a friction pressure of 75 MPa, a friction time of 0.3 s, and a forge pressure of 270 MPa. The joint efficiency of the joints made with the P-Ti side weld faying surface finished with a surface grinding machine (referred to as surface grinding machine joint), was approximately 60%, and the joint fractured at the weld interface. When the joints were made with the P-Ti side weld faying surface finished with a #2000 grit size emery paper (referred to as #2000 emery paper joint), the joint efficiency was approximately

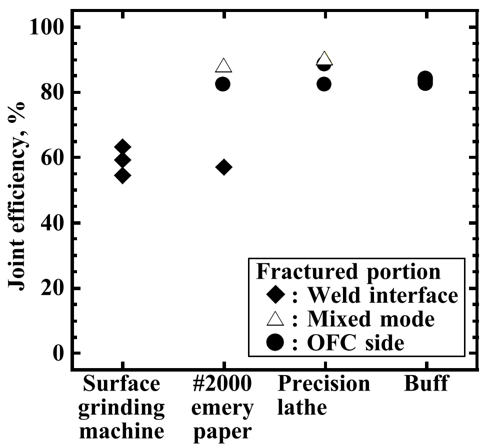


Fig. 10 Result of joint efficiency for joints at various finishing types of P-Ti side weld faying surface: friction pressure of 75 MPa, friction time of 0.3 s and forge pressure of 270 MPa.

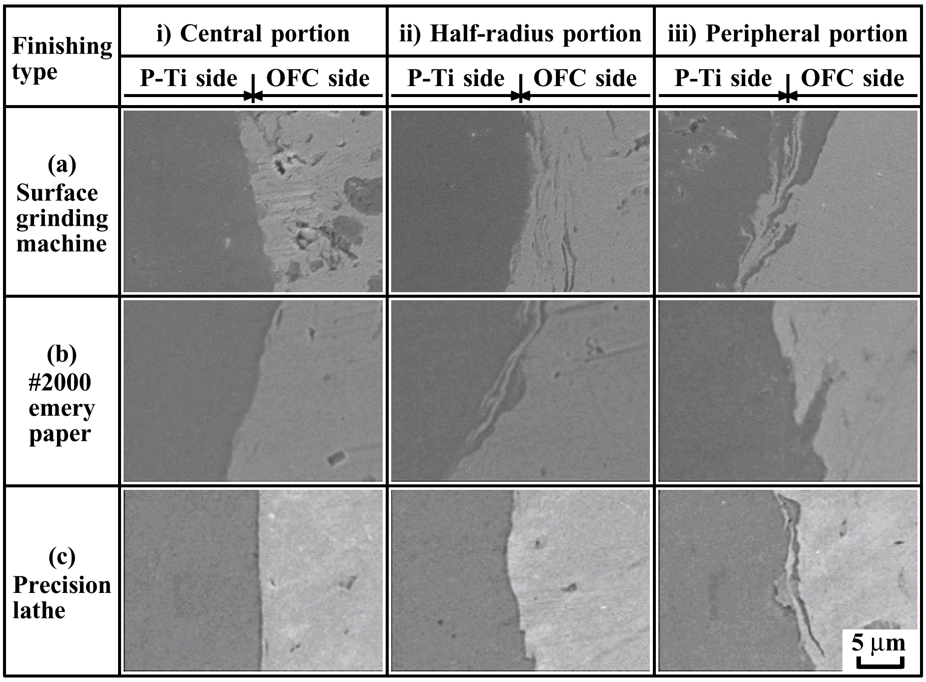


Fig. 11 SEM micrographs of cross-section of weld interface region for joint at various finishing types of P-Ti side weld faying surface: friction pressure of 75 MPa, friction time of 0.3 s and forge pressure of 270 MPa.

77%, and the joints had three types of fractured modes (Fig. 6). The joint efficiency was approximately 85% and the joint had a mixed mode fracture or an OFC side fracture, when they were made with the P-Ti side weld faying surface finished with a precision lathe (referred to as precision lathe joint). When the joint was made with the P-Ti side weld faying surface finished by buff polishing (referred to as buff joint), all joints fractured from the OFC side, although the joint efficiency was the same as the joints finished with a precision lathe. Figure 11 shows SEM micrographs of the cross-section of the weld interface region for the joints. The surface grinding machine joint had a mechanically mixed layer at the half-radius and periphery portions of the weld interface (Fig. 11a). The #2000 emery paper joint had a mechanically mixed layer at the half-radius and periphery portions, and the precision lathe joint had it at the periphery portion (Figs. 11b and 11c). In addition, the mechanically mixed layer was decreased in polishing order, i.e., with a surface grinding machine, a #2000 grit size emery paper, and a precision lathe. However, the buff joint obtained no mechanically mixed layer at any observed portions (Fig. 9c). Thus, it was clarified that the fractured portion of the joint was affected by the mechanically mixed layer at the weld interface.

Figure 12 shows SEM micrographs of the weld faying surface of the P-Ti side specimens and its roughness curves for various finishing types. The surface roughness with a surface grinding machine was very rough, and the undulation of the roughness curve greatly changed (Fig. 12a). When the surface was finished with a #2000 grit size emery paper, the roughness was rough and its undulation was slightly small (Fig. 12b). The roughness of the precision lathe was slightly flat (Fig. 12c). The undulation of the roughness curve was very flat (Fig. 12d); the surface roughness of the buff polishing was very smooth. Table 1 summarizes the measured results of the surface roughness for the P-Ti side specimens at various finishing types. In this case, the centerline average height was measured with a contact type surface roughness machine, and the maximum height was measured with a not-contact type one. The surface roughness of the surface grinding machine finishing was larger than that of the others. The surface roughness decreased in polishing order: with a surface grinding machine, a #2000 grit size emery paper, a precision lathe, and a buff. In particular, the maximum height by buff

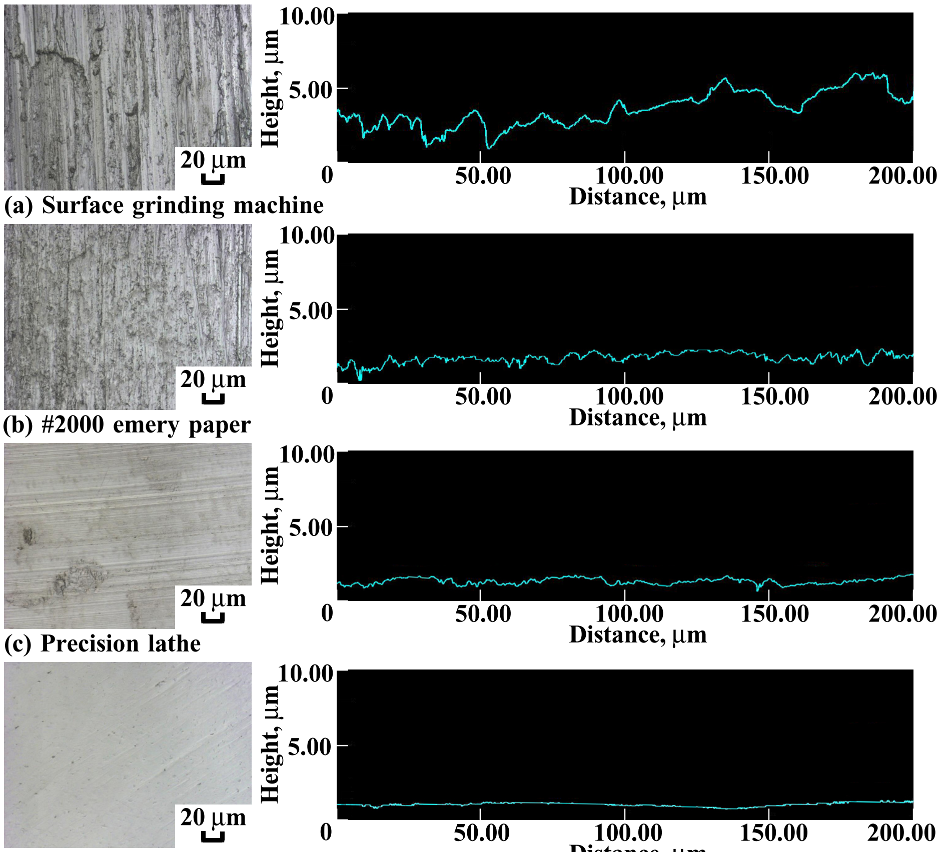


Fig. 12 SEM micrographs of weld faying surface of P-Ti side specimens and its roughness curves for various finishing types.

Table 1 Measured results of surface roughness of P-Ti side specimen at various finishing types.

Finishing type	Centerline average height, μm		Maximum height, μm	
	Range	Average	Range	Average
Surface grinding machine	0.15 - 0.53	0.34	1.940 - 6.622	4.131
#2000 emery paper	0.10 - 0.15	0.13	0.864 - 2.526	1.661
Precision lathe	0.03 - 0.05	0.03	0.692 - 0.974	0.813
Buff	0.03 - 0.04	0.03	0.187 - 0.686	0.428

polishing was lower than that of a precision lathe, although their centerline average heights were about 0.03 μm. Hence, it was considered that the mixture fraction between P-Ti and OFC decreased with decreasing the maximum height by decreasing of the contact resistance of the initial surface at the weld faying surface. Even though further investigation is necessary to elucidate the detailed characteristics of the joints by finishing types, the difference of the fractured portion of the joint seems to cause the maximum height of the P-Ti side weld faying surface.

According to these results, the fractured portion of the joint at various forge pressures, in relation to the surface roughness of the P-Ti side weld faying surface, was considered as follows. Figure 13 shows schematic illustrations of the fractured portion of the joint at various forge pressures, in relation to the surface roughness at the weld faying surface of the P-Ti side specimen. The joint with large maximum height of the P-Ti side specimen was generated by many mechanically mixed layers at the weld interface due to the large height at the weld faying surface of its specimen (Fig. 13a), since it was estimated that the contact resistance

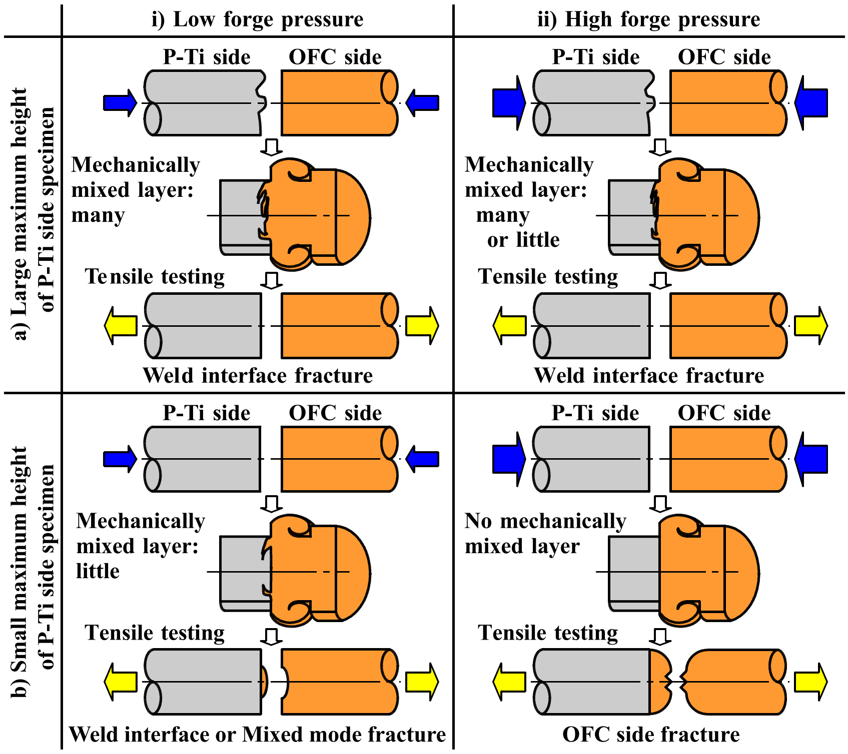


Fig. 13 Schematic illustrations of fractured portion of joint at various forge pressures, in relation to surface roughness at weld faying surface of P-Ti side specimen.

of the initial surface at the weld faying surface was large. Moreover, the mechanically mixed layer was not pushed out as flash enough, because the forge pressure was low (Fig. 13a-i). Hence, the joint fractured at the weld interface (Fig. 6a). The joint made with high forge pressure also fractured at the weld interface, although the mechanically mixed layer decreased (Fig. 13a-ii). On the other hand, the joint with small maximum height slightly generated a mechanically mixed layer at the weld interface (Fig. 13b), since it was estimated that the contact resistance of the initial surface at the weld faying surface was small. When the joint was made at low forge pressure, the mechanically mixed layer was not completely pushed out as flash (Fig. 13b-i). Hence, the joint obtained weld interface or mixed mode fractures (Figs. 6a and 6b). However, the joint made with high forge pressure did not obtain any mechanically mixed layer at the weld interface, because the layer was almost completely exhausted as flash. Thus, the joint had an OFC side fracture (Fig. 6c), although it did not achieve 100% efficiency (Fig. 13b-ii). To obtain higher joint efficiency and OFC side fracture, the joint should be made by a P-Ti side weld faying surface polished with a buff, opportune friction pressure, and higher forge pressure.

4.2. Consideration about OFC base metal properties

As shown in Fig. 6c, the joint, which was made with buff polishing at the P-Ti side weld faying surface and a forge pressure of 270 MPa or higher, were fractured from the OFC metal although it did not achieve 100% joint efficiency. In addition, the joint had scarcely the softened region at the adjacent region to the weld interface of the OFC side (see Fig. 7). To clarify the reason why the joint did not achieve 100% joint efficiency, the tensile strength of the OFC base metal with the addition of various compressive stresses was investigated, since the Bauschinger effect(32) and the difference of the anisotropic properties with as-manufactured condition(29) of the OFC base metal were considered. First, we investigated the tensile strength of the OFC base metal at various compressive loads, because the joint with the OFC side fracture was made with a high forge pressure condition. Figure 14 shows

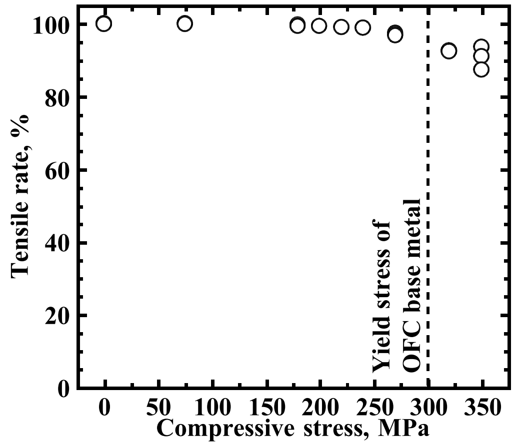


Fig. 14 Relationship between compressive stress and tensile rate of OFC base metal.

the relationship between the compressive stress and the tensile rate of the OFC base metal. In this experiment, the material was machined to a 12 mm diameter and 12 mm in parallel length to prevent buckling of the parallel part of the tensile test specimen during compressive loads. The specimens were set on the tensile testing machine and processed under various compressive loads. Then the specimen was remachined to a 12 mm diameter to its parallel part after compression. The tensile test was carried out under room temperature. The detailed specimen shape and experimental method were previously described.[32] In this case, the tensile rate was defined as the ratio of the tensile strength to the ultimate tensile strength of the OFC base metal with no compressive loads (as-received). When the compressive stress was 270 MPa, the tensile rate was approximately 97%: not have 100% (Fig. 14). Then the tensile rate decreased with increasing compressive stress and became approximately 90% when the compressive stress was 350 MPa. That is, it was clarified that the tensile rate was lower than that without a compressive load, when the compressive stress was higher than the yield stress of the OFC base metal. Therefore, one of the reasons for the decrease in the tensile strength of the OFC base metal by higher compressive stress was due to the Bauschinger effect. Incidentally, the decreasing of the tensile rate could estimate at other temperature, since the Bauschinger effect at various temperatures was also observed in the friction welded joint between pure Al and low carbon steel in a previous report.[32] Consequently, the joint was not achieved 100% efficiency, because of the higher compressive load to the OFC base metal

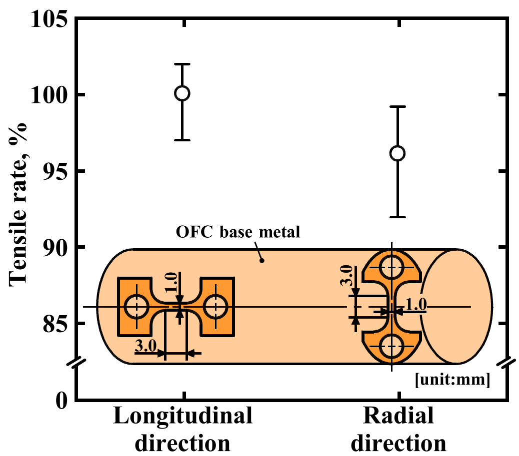


Fig. 15 Tensile rate of OFC base metal at longitudinal and radial directions.

during the forging process. However, high forge pressure is necessary for the joint since it fractured at the OFC side when it was made at a lower forge pressure (see Fig. 5).

Second, we investigated the difference of the tensile strength of the OFC base metal at the longitudinal and radial directions, because the flash of the OFC of the joint was exhausted to the radial directions from the longitudinal directions at the adjacent region to the weld interface,[35] and the fractured portion of the joint was not the softened region of the OFC side (see Figs. 6c and 7). Incidentally, the grain flow of the OFC base metal with corresponding to the longitudinal direction was confirmed by the optical microscope observation, because the OFC base metal was joined with as-manufactured condition. Figure 15 shows the tensile rate of the OFC base metal at the longitudinal and radial directions. This experiment was carried out with tensile specimens that were cut along the longitudinal and radial directions from the OFC rod in 16 mm diameter by machining. The width, length, and thickness of the parallel parts were 1.0, 3.0, and 1.0 mm, respectively (see Fig. 15). The tensile test was carried out with as-machined condition at room temperature. The details of the specimen shape and the experimental method were also previously described.[29] In this case, the tensile rate was defined as the ratio of the tensile strength of the radial direction to the average tensile strength of the longitudinal direction. The tensile rate of the radial direction was slightly lower than that of the longitudinal direction (Fig. 15). That is, the tensile strength of the radial direction was approximately 96% to that of the longitudinal direction. Consequently, the joint was not achieved 100% efficiency, and one of the reasons was also the difference of the anisotropic properties with as-manufactured condition of the OFC base metal. Similar anisotropic properties were also observed in the friction welded joint of the Al alloys described in a previous report.[29] Based on the above results, the fact that the joint did not achieve 100% efficiency was due to the decrease in the tensile strength of the OFC base metal by the Bauschinger effect and the difference of the anisotropic properties with as-manufactured condition that depended on the longitudinal and radial directions. That is, it is considered that the joint had approximately 85% efficiency by both influences of the Bauschinger effect and the anisotropic properties. Further investigation is necessary to elucidate the detailed mechanical properties of the joints and the tensile properties of the OFC base metal.

5. Conclusions

This report described the effect of the friction welding condition and the weld faying surface properties on the tensile strength between pure titanium (P-Ti) and pure copper (OFC) friction welded joints. In particular, we investigated the joint tensile strength under various friction welding conditions and finishing types of the P-Ti side specimen. We also investigated the cause of the decreasing of the joint strength. The following conclusions are provided.

(1) When the weld faying surface of the P-Ti side specimen was finished with a surface grinding machine, the joint did not have 100% efficiency and the OFC side fracture regardless of the friction welding conditions. The joint efficiency of the joints with a friction pressure of 75 MPa was approximately 64% regardless of the forge pressures, and all joints fractured at the weld interface, although such efficiency was higher than that of the joints made with other friction pressures.

(2) To improve the joint efficiency, a joint was made with P-Ti whose weld faying surface was finished by buff polishing. The joint efficiency increased to about 85%, although the joint fractured at the weld interface. The joint at a friction pressure of 75 MPa with a forge pressure of 270 MPa or higher obtained an OFC side fracture, although it did not achieve 100% efficiency.

(3) The mechanically mixed layer at the weld interface of the joint decreased in polishing order at the P-Ti side weld faying surface: with a surface grinding machine, a #2000 grit size emery paper, and a precision lathe. However, the joint at a forge pressure of 270 MPa obtained no mechanically mixed layer according to observation in SEM level. Therefore, the joint did not fracture at the OFC base metal because of the mechanically mixed layer at the weld interface that depended on the maximum height of the P-Ti side.

(4) The tensile strength of the OFC base metal was lower than that without compressive load, when the compressive stress was higher than the yield stress of the OFC base metal. In addition, the tensile strength along the radial direction of the OFC base metal was slightly lower than that of the longitudinal direction. Hence, the fact that the joint did not achieve 100% efficiency was due to the decrease in the tensile strength of the OFC base metal by the Bauschinger effect and the difference of the anisotropic property with as-manufactured condition.

In conclusion, to obtain higher joint efficiency and OFC side fracture, the joint should be made by a P-Ti side weld faying surface polished with a buff, opportune friction pressure, friction time, and high forge pressure.

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