Effect of friction pressure on joining phenomena of friction welds between pure titanium and pure copper

M. Kimura*[1], Y. Saitoh[2], M. Kusaka[1], K. Kaizu[1] and A. Fuji[3]

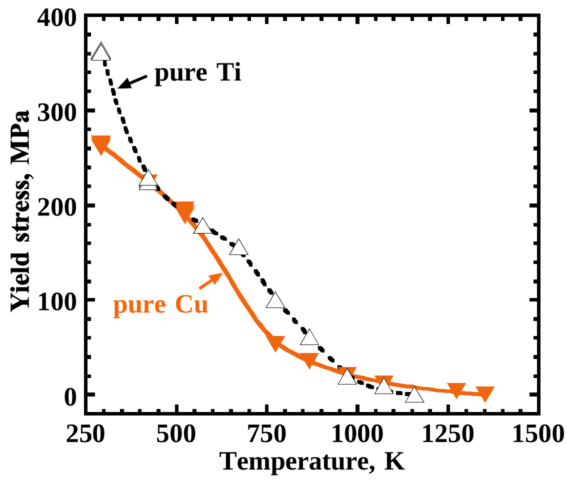
This paper describes the effect of friction pressure on the joining phenomena of friction welds between pure titanium (P-Ti) and pure copper (OFC). When the joint was made at a friction pressure of 60 MPa or lower, the OFC side had deformation from the contact of both weld faying surfaces. Then the joint had generated sparkle from the P-Ti side with increased friction time. The peripheral portion of the P-Ti side had large deformation and was intensely upset when the joint had sparkle. On the other hand, the joint did not have sparkle on the P-Ti side when it was made at a friction pressure of 75 MPa or higher. The deformation of the OFC side was large and was intensely upset, although the P-Ti side was hardly deformed. The joining phenomena had dissimilarity because the difference of the yield stress for each material depended on the temperature in the friction process.

Keywords: Friction welding, Titanium, Copper, Joining phenomena, Friction pressure, Deformation, Sparkle, Yield stress

Introduction

Friction welding, which is well known among solid state joining methods, can be applied to join dissimilar materials.[1] However, since its joining mechanism has not been fully clarified, to determine the friction welding conditions for material combinations are essential. In particular, the joining mechanism between dissimilar materials differs from that of similar materials because mechanical properties such as the tensile strength and thermal properties such as the thermal conductivity are different in their combinations. To theoretically determine the friction welding conditions, it is necessary to clarify the joining phenomena and the joint mechanical properties for various combinations of materials.

In previous works, the authors clarified the joining mechanism during the friction welding process for the joints of similar materials, and showed that the joint had 100% joint efficiency using only the first stage (up to the initial peak) of the friction process without increasing the forge pressure.[2-13] The authors also clarified the joining mechanism during the friction welding process and the mechanical properties for several joints made from dissimilar materials.[14-18] In addition, it was also indicated that the joining phenomena of dissimilar materials were affected by the differences between the yield stress of both base materials at a temperature on the weld interface during the friction process and the friction pressure to make the joint.[19] Figure 1 shows an excerpt from a previous report[19] of the relationships between temperature and the yield stress of pure titanium (Ti) and pure copper (Cu) base metals. In this case, the ultimate tensile strength of Ti and Cu base metals was 397 and 270 MPa, and the 0.2% yield strength of those was 362 and 262 MPa, respectively. In addition, the tensile test was carried out with a crosshead speed of 0.5 mm/min in atmosphere environment, and the yield stress of P-Ti at a temperature of 1,158 K was plotted as zero, since the P-Ti base metal intensely reacted with O_2 or N_2 under the high temperature condition.[20] When the temperature was below 950 K, the yield stress of pure Cu was lower than that of pure Ti, although they were similar at approximately 500 K. On the other hand, the yield stress of pure Cu was higher



1 Relationships between temperature and yield stress of pure Ti and pure Cu base metals[19]

[1]Department of Mechanical and System Engineering, Graduate School of Engineering, University of Hyogo, 2167 Shosha, Himeji, Hyogo 671-2280, Japan
[2]University of Hyogo, 2167 Shosha, Himeji, Hyogo 671-2280, Japan
[3]Department of Mechanical Engineering, National University Corporation–Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido, 090-8507, Japan

∗Corresponding author, email mkimura@eng.u-hyogo.ac.jp

than that of pure Ti over approximately 1,000 K. In case of the friction welding, it was able to be considered that the flash (burr or collar) was exhausted from the weld interface of the joint during the friction process when the yield stresses of the base materials with temperature raise by the friction were less than the loaded (maintained) friction pressure.[3,5,19] Hence, it will be able to estimate that pure Cu was easily deformed below approximately 950 K, and pure Ti was easily deformed over approximately 1,000 K. In this connection, when a joint between pure Ti and pure Cu was made at a friction pressure of 30 MPa, it was deformed and sparkled from the pure Ti side during the friction process, although the pure Cu side was slightly deformed at first.[19] Thus, it was considered that the joint had sparkle under a low friction pressure condition, i.e. it was made at high temperature. If a joint of pure Ti and pure Cu is made at low temperature, i.e. a high friction pressure condition, it will be expected that the pure Ti side will have only slight deformation. In this connection, some researchers[21-23] have reported that the pure Ti side deformed, although the friction welding condition differed. On the other hand, J. Ruge et al.[24] and S. Y. Kim et al.[25] showed that the pure Cu side had deformation. That is, it is considered that the joining phenomena will differ by applied friction pressure. Clarifications of the friction pressure effect for the joint are strongly required because the joint strength will be affected.[15]

Based on the above background, the authors investigate the joining phenomena during the friction process of friction welds of pure Ti and pure Cu, especially the effects of friction pressure on the friction torque, the joining behaviour, the transitional changes of the weld interface, and the cross-section of the joint. The authors also show the results of the joining phenomena by friction pressure and clarified the joining mechanism for those combinations.

Experimental procedure

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%. On the other hand, two kinds of OFC having 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%. The ultimate tensile strengths of the OFC were 321 and 326 MPa, the 0.2% yield strengths were 309 and 311 MPa, and the elongations were 13.5 and 14.6%, respectively. Incidentally, the details of those materials differed with the experiment in Fig. 1, because they were also purchased at different times. The materials were machined to 12 mm diameters for the weld faying surface. Moreover, the temperature changes during the friction process at the centreline, the half-radius, and the periphery portions of the 1.0 mm longitudinal direction from the weld faying surface were measured using the P-Ti specimen. The details of the specimen shape for measuring the temperature changes have been described in previous reports.[14-17] All weld faying surfaces of the specimens were polished with a surface grinding machine before joining, and the centreline average height of the roughness of the P-Ti side specimen was about 0.34 μm, and that of the OFC side was about 0.30 μm.

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: friction speed of 27.5 s^{-1} (1650 rpm) and friction pressure of 60 and 75 MPa. To observe the joining phenomena, the authors carried out the following three experimental methods whose details were previously described.[1-12]

(1) The joining behaviour was recorded with a digital video camera. The friction torque was measured by a load-cell. A mineral insulated thermocouple with chromel-alumel was inserted into the drilled holes of the P-Ti specimen to measure the temperature change. The friction torque and temperature were recorded with a personal computer through an A/D converter with sampling times of 0.05 or 0.001 s.

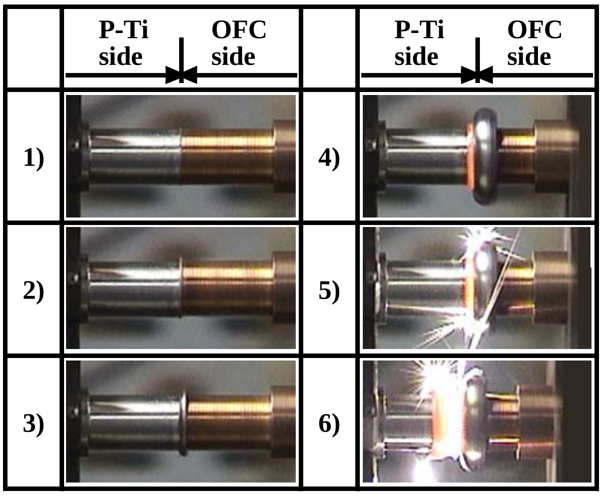
(2) The fixed (steady) side chuck was directly connected to a hydraulic cylinder. The fixed side specimen was simultaneously and forcibly separated from the rotating side specimen when the friction time expired. The weld interface was separated at each friction time and observed for the transitional changes of the weld interfaces.

(3) For observation of the cross-section of the joint, it was made with using of an electromagnetic clutch that was mounted on the fixed side specimen. When the clutch was released, the relative speed between both specimens instantly decreased to zero. In this case, friction pressure could be maintained (loaded), so that the deformation on the joint during the braking time was negligible. Also, as the braking time was smaller than 0.04 s, i.e., the time for one rotation of the specimen, its effect was negligible.

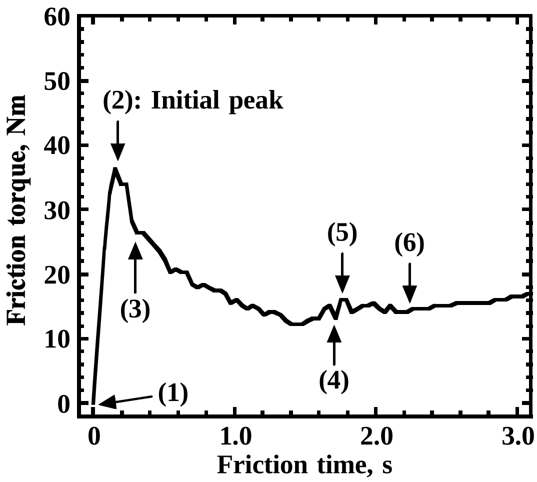
Results

Relationship between joining behaviour and friction torque

Figure 2 shows the relationship between the joining behaviour and the friction torque with a friction pressure of 60 MPa. Photos 1) to 6) in Fig. 2a correspond to the friction torque of (1) to (6) in Fig. 2b, respectively. Photo 1) shows the state at the weld faying surfaces as they contacted each other, then the friction torque was rapidly increased. When the friction torque reached the initial peak of (2), the OFC side was slightly upset (deformed) and exhausted the flash, as shown in Photo 2). The initial peak torque was approximately 40 Nm, and the elapsed time for the initial peak was about 0.2 s. Then the friction torque decreased with increasing friction time. The OFC flash increased with increasing friction time, although the P-Ti side was hardly upset, as shown in Photo 3). Thereafter, when the friction torque was rather rapidly increased of (4), the adjacent region of the P-Ti side was upset and its colour turned to red as shown in Photo 4), although the time of that behaviour had scatter. Immediately after that behaviour, the joint sparkled from the weld interface, as shown in Photo 5). Then the P-Ti side was intensely upset, even though the OFC side was hardly upset as shown in Photo 6). The friction torque

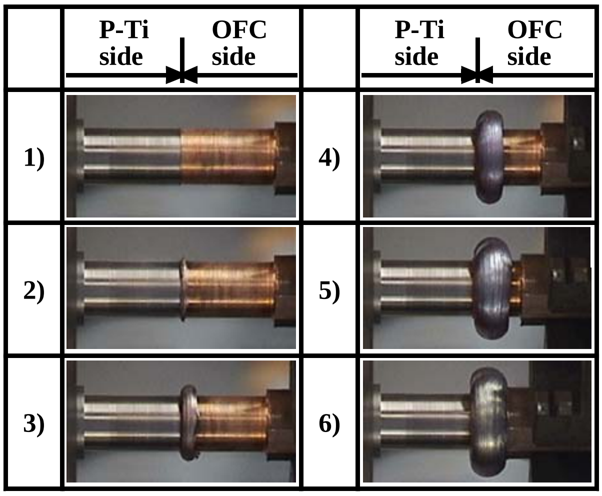


(a) Joining behaviour

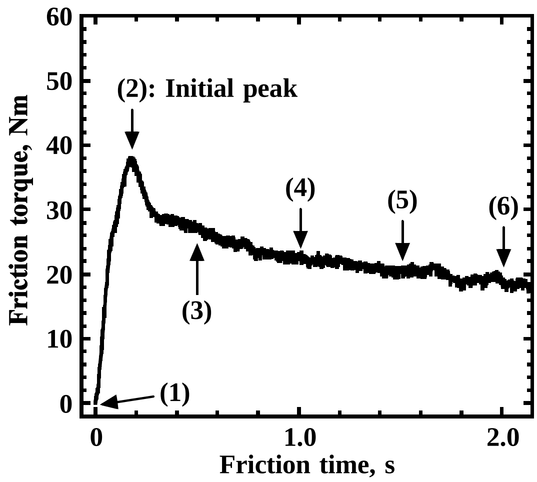


(b) Friction torque curve

2 Joining behaviour and friction torque curve during friction process; friction pressure of 60 MPa

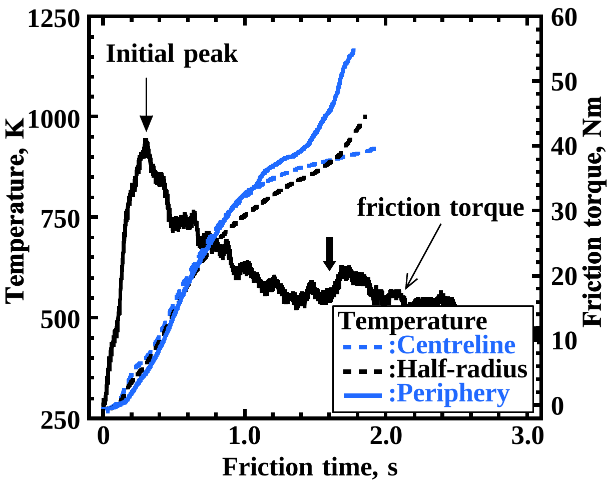


(a) Joining behaviour

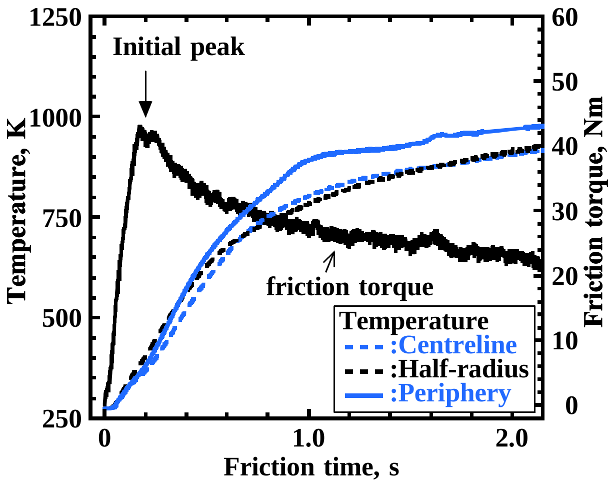


(b) Friction torque curve

3 Joining behaviour and friction torque curve during friction process; friction pressure of 75 MPa



4 Relationship between friction time and temperature changes at various measured portions of P-Ti side during friction process, in relation to friction torque curve; friction pressure of 60 MPa



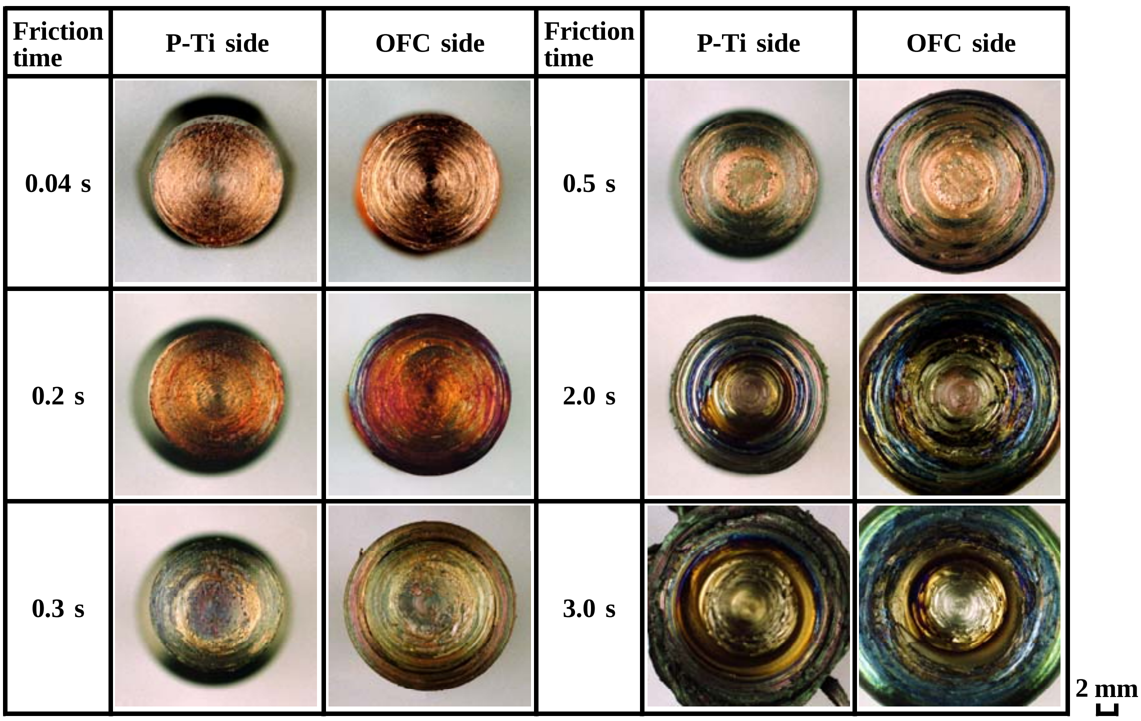
5 Relationship between friction time and temperature changes at various measured portions of P-Ti side during friction process, in relation to friction torque curve; friction pressure of 75 MPa

was maintained nearly constant between (5) and (6). The joining behaviour resembled the friction pressure result of 30 MPa, although the friction torque curve differed, as indicated in a previous report.[19]

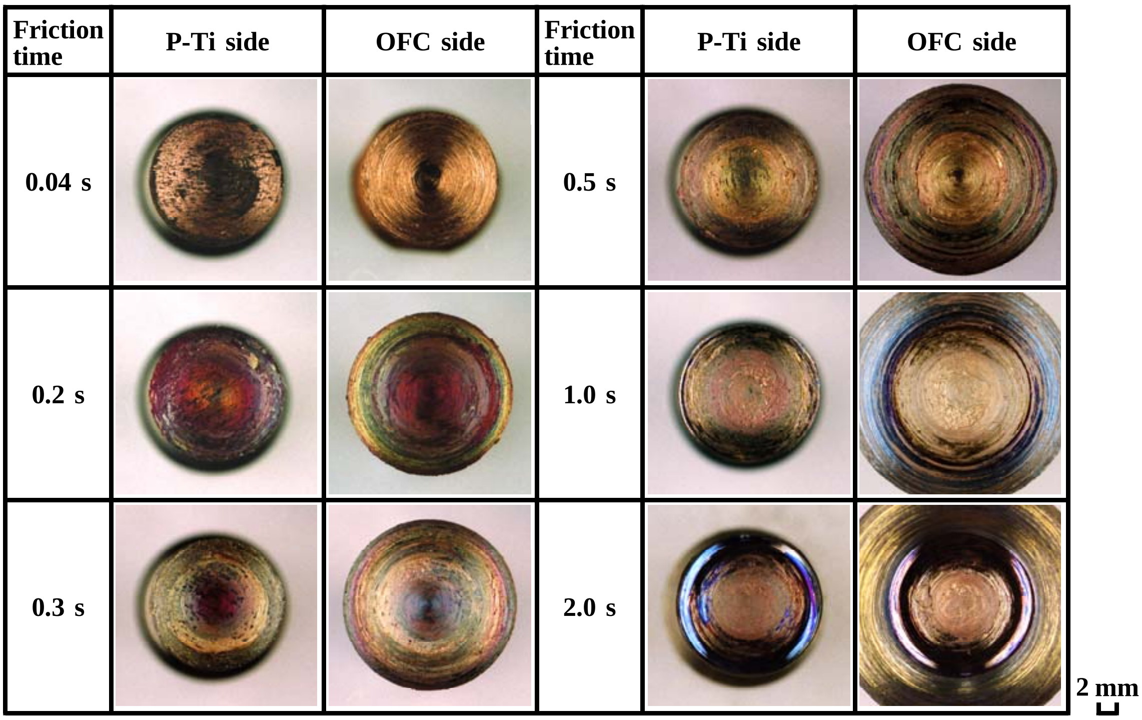
Figure 3 shows the relationship between the joining behaviour and the friction torque with a friction pressure of 75 MPa. Photos 1) to 6) in Fig. 3a correspond to the friction torque of (1) to (6) in Fig. 3b, respectively. Photo 1) shows the state at the weld faying surfaces that contacted each other, and the friction torque was also rapidly increased. The OFC side was slightly upset and pushed out the flash when the friction torque reached the initial peak of (2), as shown in Photo 2). The initial peak torque was approximately 40 Nm, and the elapsed time for the initial peak was about 0.2 s; i.e., the elapsed time for the initial peak resembled that at a friction pressure of 60 MPa (see Fig. 2a). Then the friction torque decreased with increasing friction time and remained nearly constant. The OFC side was intensely upset and the flash increased with increasing friction pressure, although the P-Ti side was hardly upset as shown in Photos 3) to 6). The joining behaviour was similar to the result at a friction pressure of 90 MPa, although the friction torque curve differed (data not shown due to space limitations). That is, the joint with a friction pressure of 60 MPa or under had sparkle at the weld interface, although the joint with 75 MPa or over did not have it. Hence, it could be clarified that the joining behaviour during the friction process had difference by the friction pressure.

Temperature change during friction process

Figures 4 and 5 show the relationship between the friction time and the temperature changes at various measured portions of the P-Ti side during the friction process, in relation to the friction torque curves. When friction pressure was 60 MPa as shown in Fig. 4, the temperatures at all the measured portions on the weld interface of the P-Ti side were almost equal before a friction time of about 1.0 s. The periphery temperature rapidly increased to over 1,100 K when the friction torque rather rapidly increased at a friction time of about 1.6 s, indicated by the thick arrow. Then the half-radius temperature rapidly increased to approximately 1,000 K. That is, the temperature at the half-radius and the periphery portions of the weld interface exceeded 1,000 K at this friction time. Incidentally, the temperature at all portions was not measured after a friction time of about 2.0 s because the thermocouples were broken by the flash, which was exhausted from the P-Ti side. On the other hand, when the friction pressure was 75 MPa as shown in Fig. 5, the temperatures at all the measured portions were almost equal before a friction time of about 1.0 s. The temperature at the periphery portion was higher than that of the centreline and half-radius portions when the friction time was about 1.0 s or longer. However, the temperature difference was approximately 100 K or less. Moreover, the temperatures at the centreline and the half-radius portions were almost equal when friction time was about 1.0 s or longer. The maximum temperatures with a friction pressure of 75 MPa were lower than those of 60 MPa, although the friction torque slightly varied. Although further investigation is necessary to elucidate the detailed the temperature at the weld interface, the difference of the maximum temperature was considered to depend on the loaded friction pressure, because the flash was exhausted from the weld interface of the joint during the friction process when the yield stresses of the base materials were less than the loaded friction pressure.[3,5,19] That is, this result was due to the difference of the yield stress for the P-Ti and OFC base metals that depended on the temperature in the friction process (see Fig. 1). The fact that the temperature at low friction pressure was higher than that of high friction pressure was also similar



6 Appearances of weld interfaces after welding at various friction times; friction pressure of 60 MPa



7 Appearances of weld interfaces after welding at various friction times; friction pressure of 75 MPa

to the result in other materials combinations.[6,15,17]

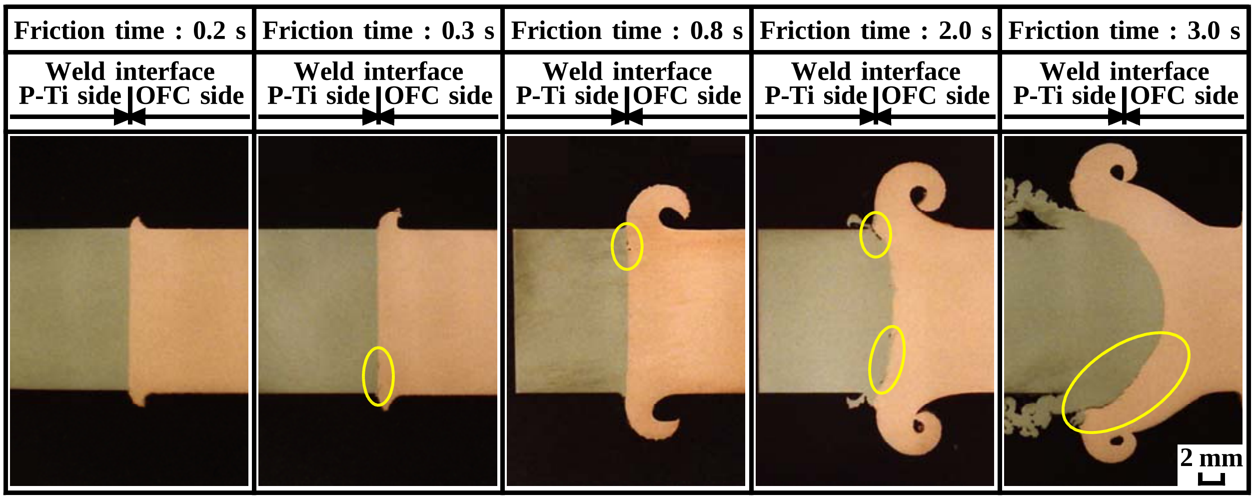
Transitional changes of weld interface

Figure 6 shows the examples of the appearances of the weld interfaces after welding at a friction pressure of 60 MPa. When the friction time was 0.04 s, OFC transferred on almost the whole weld interface without the central region on the P-Ti side. The concentric rubbing marks were observed at those regions of the weld interface on the OFC side. The transferred OFC of the weld interface on the P-Ti side increased although the central region did not have its OFC when the friction time was 0.2 s, i.e. the friction torque just reached the initial peak. Also, the concentric rubbing marks were observed on the whole weld interface of the OFC side, and the flash from the OFC side was exhausted. When the friction time was 0.3 s, OFC was transferred to the entire weld interface on the P-Ti side. In addition, the transferred OFC on the P-Ti side and the weld interface of the OFC side also became colorful. Then the flash from the OFC side was increased at a friction time of 0.5 s, although the P-Ti side was hardly deformed. When the friction time was 2.0 s, the peripheral portion of the P-Ti side deformed and flash was generated from its portion. Moreover, the weld interface of the P-Ti side was demonstrated as a convex shape, and the peripheral portion of the OFC side just had a little transferred P-Ti. The peripheral portion of the P-Ti side had large deformation, and the flash and the transferred P-Ti on the OFC side were increased at a friction time of 3.0 s. The transitional changes of the weld interfaces at a friction pressure of 30 MPa resembled those of 60 MPa.[19] That is, large deformation of the P-Ti side and the transferred P-Ti of the weld interface on the OFC side were observed at a friction pressure of 60 MPa or lower.

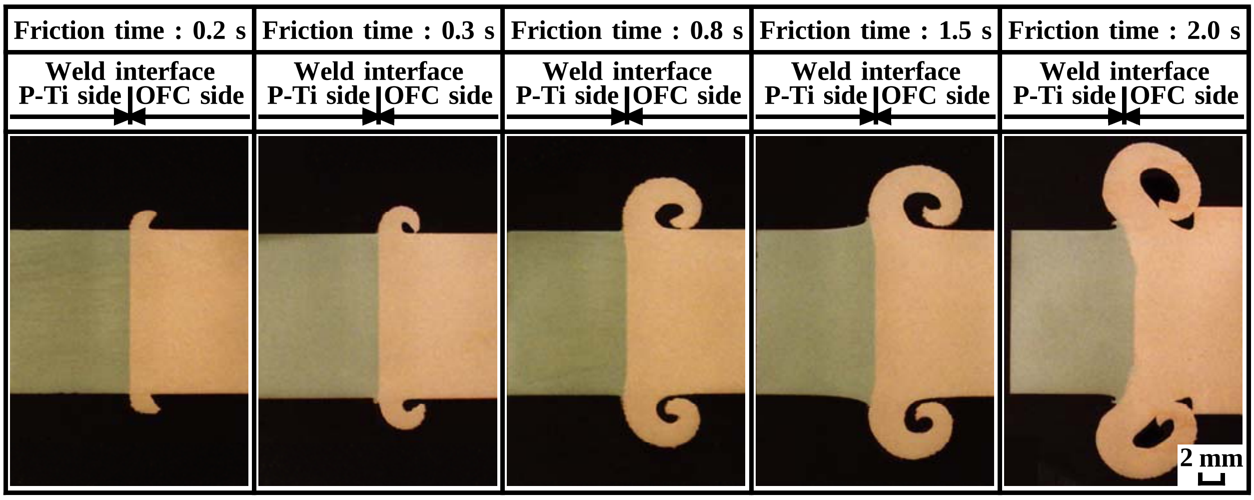
Figure 7 shows the examples of the appearances of the weld interfaces after welding at a friction pressure of 75 MPa. When the friction time was 0.04 s, OFC was transferred at the half-radius and the peripheral portions on the P-Ti side. The concentric rubbing marks were also observed at those regions of the weld interface on the OFC side. The transferred OFC of the weld interface on the P-Ti side increased, and the flash from the OFC side was exhausted, although its central region did not have OFC when the friction time was 0.2 s, i.e. friction torque was close to the initial peak. The concentric rubbing marks were also observed at the whole weld interface of the OFC side, and the transferred OFC on the P-Ti side and the weld interface on the OFC side turned red. When the friction time was 0.3 s, OFC was transferred to the entire weld interface on the P-Ti side. In addition, the transferred OFC on the P-Ti side and the weld interface of the OFC side also became colorful. Then the flash from the OFC side increased with increasing friction time, although the P-Ti side was hardly deformed. Thereafter, when the friction time was 2.0 s, the peripheral portion of the P-Ti side slightly deformed and flash was generated from its portion. However, the OFC side did not have transferred P-Ti. The transitional changes of the weld interfaces at a friction pressure of 90 MPa resembled those of 75 MPa. That is, large deformation of the P-Ti side and the transferred P-Ti of the weld interface on the OFC side were not observed at a friction pressure of 75 MPa or higher.

Observation of weld interface region

Figure 8 shows the cross-sectional appearances of the weld interface region of the joint at a friction pressure of 60 MPa. When the friction time was 0.2 s, i.e. the friction torque just reached the initial peak, the weld interface was clear and flat. Also, the OFC was exhausted as flash from the peripheral portion of the weld interface. The weld interface remained almost flat, and the P-Ti side was not deformed with increasing friction time, although the



8 Cross-sectional appearances of weld interface region of joints at various friction times; friction pressure of 60 MPa



9 Cross-sectional appearances of weld interface region of joints at various friction times; friction pressure of 75 MPa

quantity of the flash at OFC increased at a friction time of 0.3 s. In addition, this joint had such defects as a not-joined region at the peripheral portion, indicated by an oval line. The peripheral portion of the P-Ti side slightly deformed and was exhausted as flash when the friction time was 0.8 s. This joint also had a not-joined region. Thereafter, the P-Ti side was deformed to a convex shape, i.e. the weld interface was not flat, and the flash of both sides increased, which was indicated as the joint of a friction time of 2.0 s. That is, it was considered that a convex shape deformation of the P-Ti side was generated at a friction time of about 1.8 s (see Fig. 2). Then, the P-Ti side intensely deformed, and its flash increased with increasing friction time, which was shown as the joint of a friction time of 3.0 s. These joints had a not-joined region at the peripheral portion. These changes of the weld interfaces resembled the result at a friction pressure of 30 MPa.[19] That is, the joint had large deformation and flash of the P-Ti side.

Figure 9 shows the cross-sectional appearances of the weld interface region of the joint at a friction pressure of 75 MPa. When the friction time was 0.2 s, i.e. the friction torque was close to the initial peak, the weld interface was clear and flat. This joint also did not have a not-joined region, and the OFC was exhausted as flash from the peripheral portion of the weld interface. The weld interface remained almost flat, and the P-Ti side was not deformed with increasing friction time, although the quantity of the flash at the OFC side was increased. Thereafter, the flash of the OFC side intensely increased with increasing friction time, although the peripheral portion of the P-Ti side had slight deformation as shown in joints of 0.8 s or longer because the OFC flash was contacted with the holding part edge of the OFC specimen, and its deformation was constrained. In particular, the P-Ti side deformation of the joint at a friction pressure of 75 MPa was smaller than that of the joint of 60 MPa. That is, the joint did not have a large amount of flash of the P-Ti side. These changes of the weld interfaces were also similar to the result in a friction pressure of 90 MPa.

Discussion

According to the above results, the joining phenomena can be divided into two groups by the friction pressure under this experimental condition. At first, the weld faying surfaces of both materials are rubbed against each other from its contact, and then the concentric rubbing marks can be repeatedly created from the peripheral portion toward the central portion of the weld interface. In addition, OFC flash is generated because the yield stress of the base metal is lower than that of the P-Ti base metal. Thereafter, the friction torque reaches the initial peak after the entire weld interface on the P-Ti side has transferred the OFC. When the joint is made at such relatively low friction pressure as 60 MPa or lower, it has sparkle at the P-Ti side during the friction process, because the yield stress of the P-Ti base metal is becoming lower than that of the OFC by the increasing temperature during the friction process (see Figs. 1 and 2). Moreover, the peripheral part at the weld interface of the P-Ti reacts with O_2 or N_2 in air because the temperature of that interface was high over 1,150 K (see Fig. 4). Consequently, the P-Ti side is intensely upset, even though the OFC side is only slightly upset. On the other hand, the OFC side is intensely upset because the yield stress of its base metal is continuously lower than that of the P-Ti base metal when the joint is made at such relatively high friction pressure as 75 MPa or higher (see Figs. 1 and 3). In addition, the peripheral part at the weld interface of the P-Ti does not react with O_2 and N_2 in air because the temperature of that interface could estimate to approximately 1,000 K (see Fig. 5). Therefore, the joint does not obtain sparkle and the upsetting of P-Ti. That is, the fact that the joining phenomena had dissimilarity was due to the difference of the yield stress for each material depended on the temperature in the friction process. Further investigation must elucidate the detailed mechanical properties of the joints because that phenomenon may be changed by friction pressure.[15] Moreover, the dissimilarity of the joining phenomena by friction pressure is expected for material combinations, especially the combination of Ti or its alloys and other materials. Therefore, to make joints between Ti or its alloys and other materials should be necessary to note, because that may be generating a sparkle at the weld interface by the setting friction pressure.

Conclusions

This report described the effect of friction pressure on the joining phenomena of friction welds between pure titanium (P-Ti) and pure copper (OFC). The following conclusions are provided.

1. When the joint was made at a friction pressure of 60 MPa or lower, the OFC side had deformation from the contact of both weld faying surface. Then the joint had generated sparkle from the P-Ti side with increased friction time. The peripheral portion of the P-Ti side had large deformation and was intensely upset when the joint had sparkle. Consequently, the P-Ti side became convex shape. In addition, the joint had a not-joined region at the weld interface.

2. When the joint was made at a friction pressure of 75 MPa or higher, it did not have sparkle of the P-Ti side. The deformation of the OFC side was large and intensely upset, although the P-Ti side was hardly deformed. That is, the weld interface remained almost flat. The joint also did not have a not-joined region.

3. The maximum temperatures with a friction pressure of 75 MPa were lower than those of 60 MPa, although the friction torque slightly varied. The joining phenomena had dissimilarity because the difference of the yield stress for each material depended on the temperature in the friction process.

Acknowledgements

A part of this research was partially supported by the Ministry of Education, Culture Sports, Science and Technology, Grant-in-Aid for Young Scientists (B), 20760496, 2008. We wish to thank the staff members of the Machine and Workshop Engineering at the Graduate School of Engineering, University of Hyogo. We also wish to thank the alumnus Mr Tomoya Ura in Himeji Institute of Technology (present, University of Hyogo) for his devoted contributions to this research project.

References

1. American Welding Society: "WELDING HANDBOOK, Eighth Edition, Vol. 2", 739-763; 1991, Miami, FL, American Welding Society.
2. M. Kimura, H. Mioh, M. Kusaka, K. Seo and A. Fuji: *Q. J. Jpn. Weld. Soc.*, 2002, **20**, (3), 425-431 (in Japanese).
3. M. Kimura, M. Kusaka, K. Seo and A. Fuji: *Q. J. Jpn. Weld. Soc.*, 2002, **20**, (3), 432-438 (in Japanese).
4. M. Kimura, M. Kusaka, K. Seo and A. Fuji: *Q. J. Jpn. Weld. Soc*., 2002, **20**, (4), 559-565 (in Japanese).
5. M. Kimura, Y. Ohtsuka, G. B. An, M. Kusaka, K. Seo and A. Fuji: *Q. J. Jpn. Weld. Soc*., 2003, **21**, (4), 615-622 (in Japanese).
6. M. Kimura, G. B. An, M. Kusaka, K. Seo and A. Fuji: *Q. J. Jpn. Weld. Soc*., 2005, **23**, (3), 460-468 (in Japanese).
7. M. Kimura, M. Kusaka, K. Seo and A. Fuji: *JSME Int. J.(Series A)*, 2003, **46**, (3), 384-390.
8. M. Kimura, M. Kusaka, K. Seo and A. Fuji: *Sci. Technol. Weld. Joining*, 2005, **10**, (3), 378-383.
9. M. Kimura, Y. Ohtsuka, M. Kusaka, K. Seo and A. Fuji: *Q. J. Jpn. Weld. Soc*., 2005, **23**, (4), 577-586 (in Japanese).
10. M. Kimura, M. Kusaka, K. Seo and A. Fuji: *JSME Int. J.(Series A)*, 2005, **48**, (4), 399-405.
11. M. Kimura, M. Choji, M. Kusaka, K. Seo and A. Fuji: *Sci. Technol. Weld. Joining*, 2005, **10**, (4), 406-412.
12. M. Kimura, M. Choji, M. Kusaka, K. Seo and A. Fuji: *Sci. Technol. Weld. Joining*, 2006, **11**, (2), 209-215.
13. M. Kimura, M. Kusaka, K. Seo and Y. Muramatsu: *Sci. Technol. Weld. Joining*, 2006, **11**, (4), 448-454.
14. M. Kimura, S. Nakamura, M. Kusaka, K. Seo and A. Fuji: *Sci. Technol. Weld. Joining*, 2005, **10**, (6), 666-672.
15. M. Kimura, M. Kusaka, K. Kaizu and A. Fuji: *J. Solid Mech. Mater. Eng.*, 2009, **3**, (2), 187-198.
16. M. Kimura, H. Ishii, M. Kusaka, K. Kaizu and A. Fuji: *Sci. Technol. Weld. Joining*, 2009, **14**, (5), 388-395.
17. M. Kimura, K. Kasuya, M. Kusaka, K. Kaizu and A. Fuji: *Sci. Technol. Weld. Joining*, 2009, **14**, (5), 404-412.
18. M. Kimura, H. Ishii, M. Kusaka, K. Kaizu and A. Fuji: *Sci. Technol. Weld. Joining*, 2009, **14**, (7), 655-661.
19. M. Kimura, M. Kusaka, K. Seo and A. Fuji: *Q. J. Jpn. Weld. Soc*., 2003, **21**, (3), 481-488 (in Japanese).
20. American Welding Society: "Welding Handbook, Seventh Edition, Vol. 4", 434-443; 1982, Miami, FL, American Welding Society.
21. M. Aritoshi, K. Okita, T. Enjo, K. Ikeuchi, F. Matsuda and T. Tomita: *Q. J. Jpn. Weld. Soc*., 1991, **9**, (4), 481-488 (in Japanese).
22. H. Yamaguchi, K. Ogawa, H. Ochi, T. Sawai, G. Kawai, Y. Yamamoto and R. Tsujino: *J. Jpn. Res. Inst. Adv. Copper-Base*

Mater. and Technol., 2003, **42**, (1), 132-136 (in Japanese).
23. S. D. Meshram, T. Mohandas and G. M. Reddy: *J. Mater. Process. Technol.*, 2007, **184**, 330-337.
24. J. Ruge, K. Thomas, C. Eckel and S. Sundaresan: *Weld. J.*, 1986, **65**, (8), 28-31.
25. S. Y. Kim, S. B. Jung, C. C. Shur, Y. M. Yeon and D. U. Kim: *J. Mater. Sci.*, 2003, **38**, (6), 1281-1287.