Observation of Joining Phenomena in Friction Stage and Improving Friction Welding Method*

Masaaki KIMURA**, Kenji SEO**,
Masahiro KUSAKA** and Akiyoshi FUJI***

This report describes the observation result of joining phenomena in the friction stage, and an improvement of the conventional friction welding method with similar materials. The materials used were carbon steels and a brake type (direct drive) friction welding machine was used for joining. As the improving friction welding method, relative speed was instantaneously rendered to zero at the end of each friction time. The wear of both surfaces started at periphery portion (outer surface) of the joint and moved to center portion (center axis). Seizure and joining began at center portion and then extended toward periphery portion. The friction torque reached to initial peak torque when the welded interface was joined completely and upsetting of both base metals started. It was determined that friction welded joints with 100% joint efficiency and good bend ductility could be obtained by using only the friction stage up to initial peak torque and without the need for the forging (upsetting) stage. As a conclusion, friction welded joints made without using the forging stage has the same mechanical properties as those welded by the conventional friction welding process including that stage. The friction welding method without forging stage has the advantages of less burn-off (axial shortening) and less burr.

Key Words: Welding, Welded Joint, Tensile Properties, Friction Welding, Relative Speed, Initial Peak Torque, Tensile Strength, Burn-off

1. Introduction

Friction welding process, one of them, is widely used in the automobile industry, and it is applied to fabricate important parts such as drive shafts, engine valves, and so on.

Hasui et al.[1] concluded that the welding cycle could be divided into four stages on the basis of the friction torque curve, as shown in Fig. 1. The first stage is the part of friction process in which friction torque increases from zero, i.e., weld faying surfaces of both base metals contact each other and initial peak torque is reached. The second stage is the one in which friction torque reaches steady state (steady equilibrium torque) after initial peak torque. The third stage is the one in which there is steady state equilibrium torque. The fourth stage, that is, the upsetting (forging) stage, it is the one in which friction torque increases as a brake is applied and then drops to zero when rotation stops. Most research reported on joining phenomena of the third and fourth stages in the friction welding process[2)-(7]. Some research reported on the friction welding mechanism of the first and second stages[8),(9]. However, the phenomena of the first and second stages are very complicated and difficult to understand because of their unstable thermal conditions. Therefore, detailed mechanisms have not yet been clarified. When friction welding is applied to join advanced materials or dissimilar materials, it is necessary to clarify the joining mechanism during the first and second stages in the friction welding cycle.

This study presents results on joining phenomena in the friction stage, and an improvement of the

* Received 25th November, 2002 (No. 02-4256)

** Department of Mechanical Engineering, Graduate School of Engineering, Himeji Institute of Technology, 2167 Shosha, Himeji, Hyogo 671-2201, Japan. E-mail : mkimura@mech.eng.himeji-tech.ac.jp

*** Department of Mechanical Engineering, Faculty of Engineering, Kitami Institute of Technology, 165 Koen-cho, Kitami, Hokkaido 090-8507, Japan

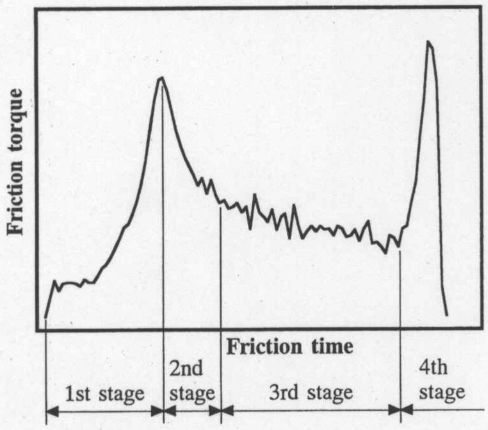


Fig. 1 Definition of stages on friction torque curve

conventional friction welding method. In this report, the authors describe the joining phenomena of the first stage, which include burn-off (axial shortening). They also present the results of tests on the joint tensile and bend properties of welded joints that were joined under various friction times without using the forging stage. In addition the authors propose a way to improve the conventional friction welding method.

2. Experimental Procedures

The material used in experiments was low carbon steel (mild steel). The chemical composition and mechanical properties of the material used are given in Table 1. The dimension and configuration of the test specimens that were to be joined are shown in Fig. 2. The weld faying (contacting) surfaces of both base metals were polished by surface grinding machine before joining. The surface roughness of the weld faying surface was measured to the center line average asperities range of between 0.05 - 0.14 μm.

A brake type (direct drive) friction welding machine was employed for the joining. During friction welding operations, the following conditions were kept constant: friction speed was 27.5-revolution per second (1650-revolution per minutes); friction pressure was 30 MPa. The forging pressure was not loaded in order to clarify joining phenomena of the first stage. The joining behavior in the friction stage was recorded by a digital video camera. The friction torque during this time was recorded by personal computer through an A/D converter with sampling time of 0.05 s.

The joining slightly advances at the welded interface during braking (rotation stop) as for a brake type friction welding process. As the improving friction welding method, the following two kinds of experiments were carried out.

(1) The fixing side chuck was directly connected to the hydraulic cylinder, as shown in Fig. 3(a). The

Table 1 Chemical compositions and mechanical properties of materials used

(a) Chemical composition (mass%)

C	Mn	Si	P	S	Fe
0.15	0.41	0.29	0.012	0.019	Bal.

(b) Mechanical properties

T.S. (MPa)	Y.S. (MPa)	El. (%)	R.A. (%)
420	315	37	62

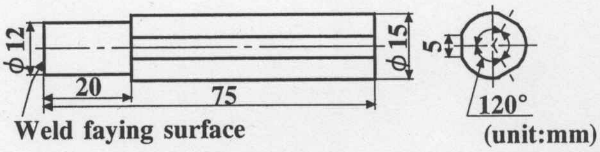
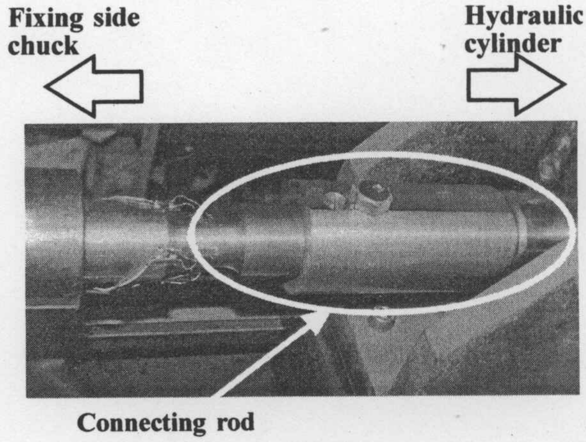
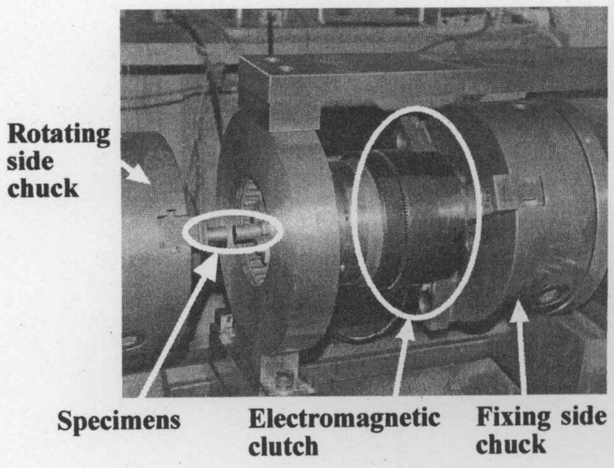


Fig. 2 Shape and dimension of the friction welding specimen



(a) Connection part



(b) Clutch part

Fig. 3 General view of simultaneous break system

fixing side specimen was simultaneously and forcibly separated from the rotating side specimen when friction time expired. The welded interfaces were separ-

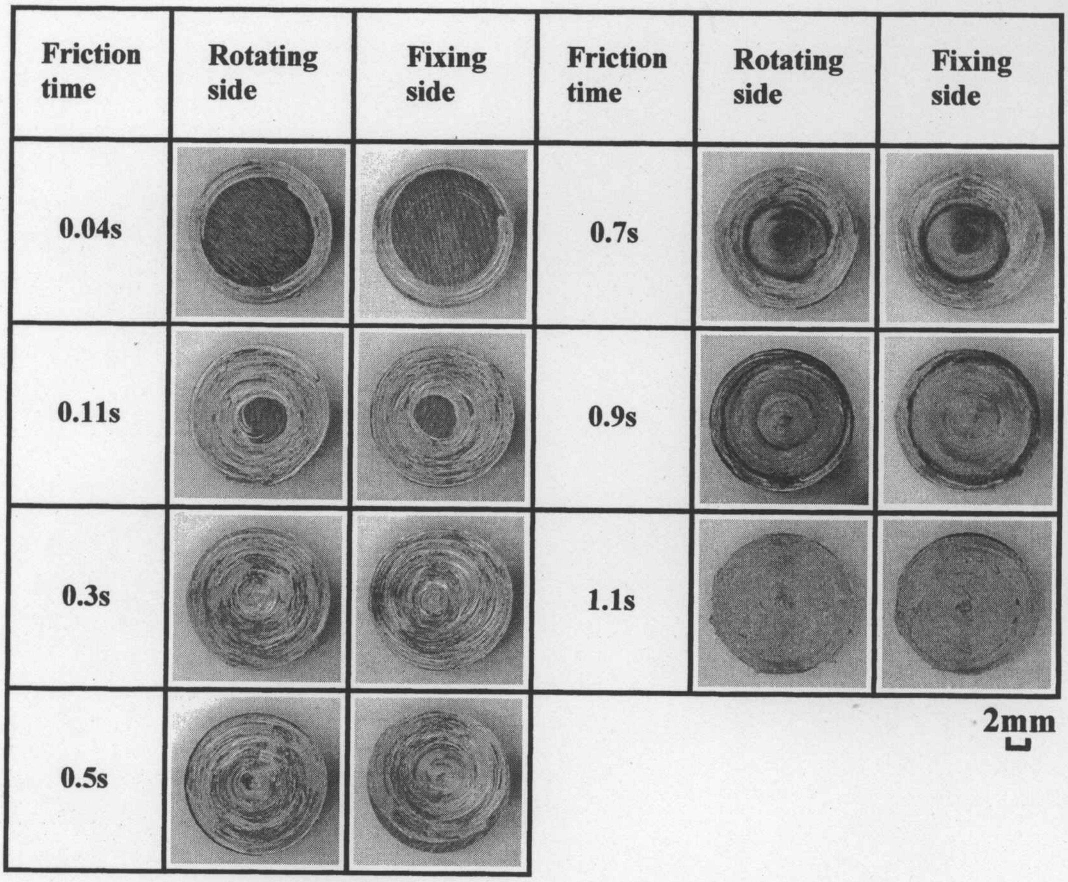


Fig. 4 Appearances of welded interfaces after welding in friction pressure 30 MPa and friction speed 27.5 s^{-1}

ated at each friction time and observed.

(2) The fixing side specimen was fixed with an electromagnetic clutch, as shown in Fig. 3(b). When the clutch was released, the relative speed between both specimens simultaneously decreased to zero. In this case, friction pressure was maintained (loaded). Braking time had a negligible effect on joining phenomena.

In experimental method (1), the transitional phenomena of the weld faying surfaces contacting each other at each applied friction time were clarified. In experimental method (2), the cross-sectional appearances of the welded interface regions of the welded joints were observed at each applied friction time and each burn-off was measured. Joint tensile tests were carried out on test specimens without burr. Joint bend tests were conducted by three-points bend test until 90 degrees. The test specimens used for these tests were also without burr. In bend test, the joint bend angle the bend specimen was bended without crack on the welded interface was measured.

3. Experimental Results

3.1 Transitional changes at welded interface

Examples of the appearance of welded interfaces that were obtained with experimental method (1) are shown in Fig. 4. When the friction time was 0.04 s, i.e., the specimen had been rotated once, the welded interface showed concentric structures generated at periphery portion (outer surface) on the fixing and rotating sides. This result indicates that wear of both base metals started from periphery portion. The state where weld faying surfaces were polished was indicated although center portion (center axis) of the welded interface was barely worn. The concentric structure had extended from periphery to center portion at the friction time of 0.11 s and had spread over the whole surface at the friction time of 0.3 s. The wear state in center portion of the welded interface changed to a torn state (seizure state), the color of which was pale black in Fig. 4 by the friction time of 0.7 s. The pale colored area at center portion had extended toward periphery at the friction time of 0.9 s. When the whole welded interface had changed to a seizure state, at the friction time of 1.1 s its color turned pale.

3.2 Relationship between the friction time, friction torque, and cross-sectional appearance of the welded interface region

According to Fig. 4, it could be considered that joining began at seizure state, i.e., at center portion of

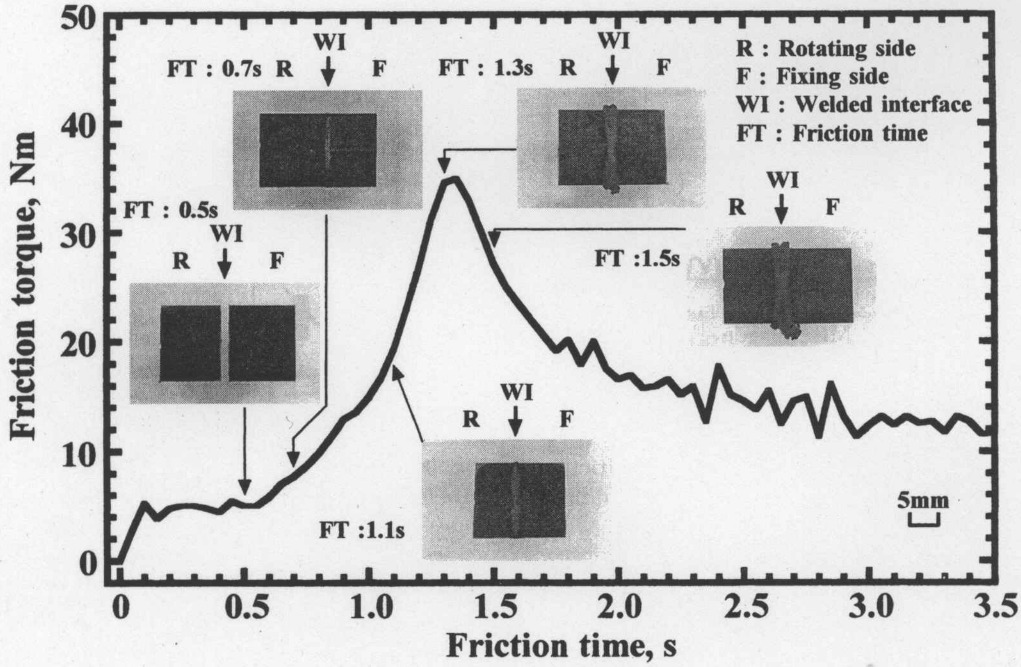


Fig. 5 Relationship between the friction time, friction torque, and cross-sectional appearance of the welded interface region in friction pressure 30 MPa and friction speed 27.5 s^{-1}

the welded interface. Figure 5 shows the relationship between the friction time, friction torque, and cross-sectional appearance of the welded interface region with experimental method (2). In order to clarify the joining process, each cross-sectional appearance is shown corresponding to the friction torque curve. At the friction time of 0.7 s, the whole welded interface was observed to be white in color, denoting the zone affected by friction heat. The boundary interfaces of both base metals at center portion were not clear, i.e., they were in a joined region. The heat affected zone and the joined region extended from center to periphery portion at the friction time of 1.1 s, and burr began to generate on the outer surface. The friction torque rapidly increased from the friction time of 0.7 s, at which time joining started at center portion of the welded interface. The friction torque reached to initial peak torque when the welded interface was joined completely and upsetting of both base metals started. Then, friction torque decreased with increasing friction time after initial peak torque.

4. Discussion

4.1 Division of the first stage

Although Hasui et al.[1] divided the friction torque curve into four stages, we clarified that the first stage could be divided into two further stages, i.e., wear and seizure stages. Figure 6 schematically shows the wear and seizure stages of the first stage. In the wear stage, the friction torque is kept almost

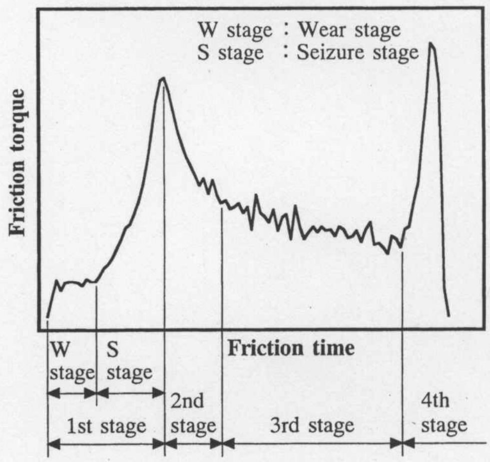


Fig. 6 Division of sub-part in the first stage on friction torque curve

constant and both weld faying surfaces are rubbed against each other. A fresh surface can be repeatedly created from periphery toward center portions of the welded interface, so that heat generation is estimated to be small in this stage. Following on from the wear stage, the seizure stage is when friction torque rapidly increases to reach initial peak torque. The temperature of the fresh surface is high enough to generate seizure. The seizure is generated from center portion where the relative speed of both base metals is slow. The joined region (seizure region) extends with increasing friction torque. This process occurred repeatedly. When a fresh surface generated the sei-

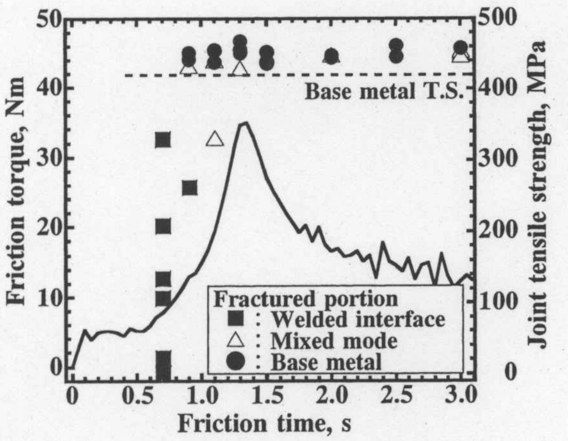


Fig. 7 Relationship between the friction time, friction torque, and joint tensile strength in friction pressure 30 MPa and friction speed 27.5 s^{-1}

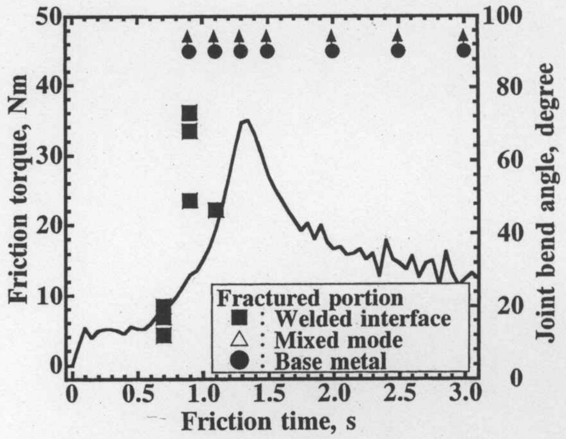


Fig. 9 Relationship between the friction time, friction torque, and joint bend angle in friction pressure 30 MPa and friction speed 27.5 s^{-1}

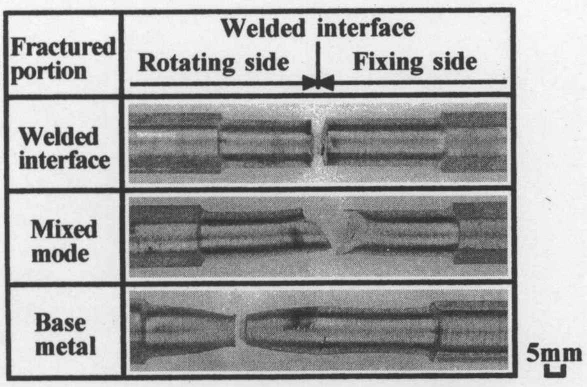


Fig. 8 Appearance of joint tensile test specimens after testing in friction pressure 30 MPa and friction speed 27.5 s^{-1}

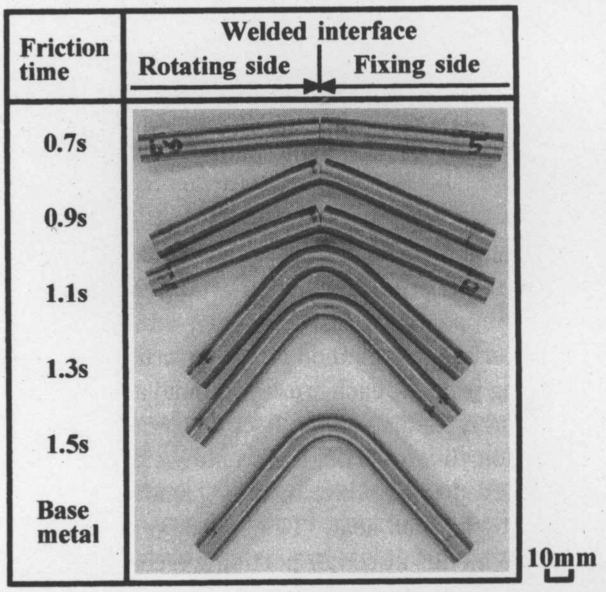


Fig. 10 Appearance of joint bend test specimens after testing in friction pressure 30 MPa and friction speed 27.5 s^{-1}

zure toward periphery portion, friction torque was reached to initial peak torque. After the first stage, friction torque decreased with reducing yield strength of base metals due to the increasing temperature of the welded interface in the second stage. Friction pressure forces the hot metal, oxides and surface impurities out of the joint as burr.

4.2 Results of tensile tests

It can be considered that joining was completed when friction torque reached initial peak torque. In other words, friction welded joints, which have 100% joint efficiency in a tensile test, can be obtained with no forging stage. A friction welded joint with 100% joint efficiency can be obtained by optimal friction time, which was derived from tensile tests of joints made with experimental method (2). Figure 7 shows the relationship between the friction time, friction torque, and joint tensile strength. Figure 8 shows the appearance of joint tensile test specimens after testing. At the friction time of 0.7 s, that is, the seizure stage of the first stage, the joint tensile strengths scattered and fractures occurred at the welded interface, as shown in Fig. 8. When friction times were 0.9 s and 1.1 s, the joint tensile strength increased and scatter decreased. The joint tensile strengths were close to that of the base metal, and fractures occurred from welded interface to mixed mode including the base metal. The fracture occurred in the base metals (not at the welded interface) in all welded joints when friction time was 1.3 s (close to initial peak torque) or longer.

4.3 Results of bending tests

Figure 9 shows the relationship between the friction time, friction torque, and joint bend angle. Figure 10 shows the appearance of joint bend test specimens after testing. The joint bend angle scattered at the friction time of 0.7 s (seizure stage). The

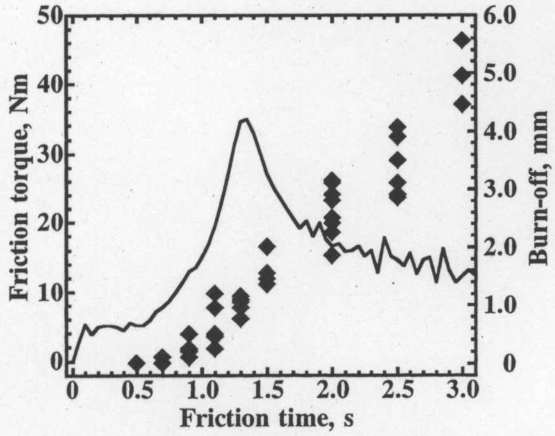


Fig. 11 Relationship between the friction time, friction torque, and burn-off in friction pressure 30 MPa and friction speed 27.5 s^{-1}

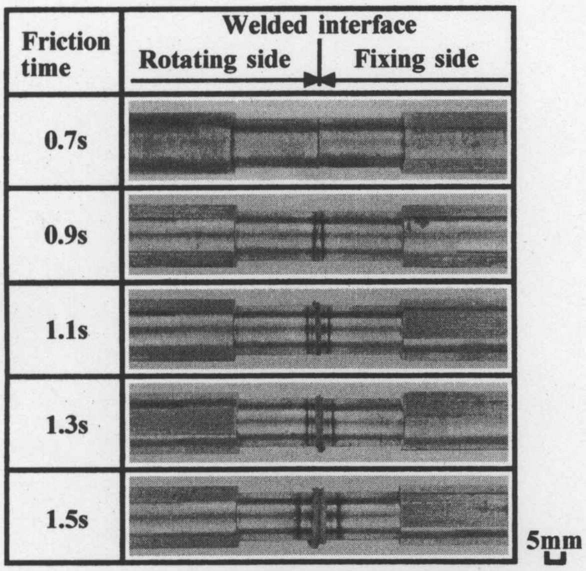


Fig. 12 Appearances of welded joints after welding in friction pressure 30 MPa and friction speed 27.5 s^{-1}

bend specimen fractured at the welded interface, as shown in Fig. 10. When friction times were 0.9 s and 1.1 s, the joint bend angle increased and scatter decreased. The bend angle was 90 degrees with no crack in all bend specimens when friction time was 1.3 s (close to initial peak torque) or longer. The bend angles of the joints were close to that of the base metal. According to joint tensile and bend test results, it can be concluded that friction welded joints with 100% joint efficiency and good bend ductility can be obtained by using only the friction stage up to initial peak torque without forging stage.

4.4 Burn-off of the welded joints

Figure 11 shows the relationship between the friction time, friction torque, and burn-off. Figure 12 shows the appearance of the welded joints after

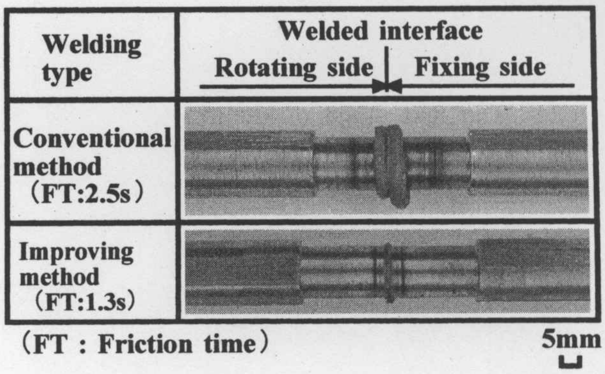


Fig. 13 Appearances of welded joints after welding by the conventional method and experimental method (2) in friction pressure 30 MPa and friction speed 27.5 s^{-1}

welding. At the friction time of 0.7 s (seizure stage), the color of periphery part at the welded interface did not change. At the friction time of 0.9 s, the color of periphery part at the welded interface changed to a pale color (black in Fig. 11). No burr was generated at these friction times. The amount of burr increased with increasing friction time and reached about 1 mm at 1.3 s (close to initial peak torque). Thus burr increases with increasing friction time, that is, at the second and the third stages. However, the quantity of burr obtained from experimental method (2) is less than that obtained from the conventional friction welding process.

Figure 13 shows the appearance of welded joints after welding with the conventional method and experimental method (2). The friction welded joints obtained with experimental method (2) were close to the joint tensile strength of those obtained with the conventional method. However, the friction welded joints of experimental method (2) had less burr compared with those of the conventional method, as shown in Fig. 13. The friction welded joints of experimental method (2) had less burn-off (about 1 mm) compared with those of the conventional method (about 6 mm). In conclusion, the friction welded joints made without using the forging stage have the same mechanical properties as those welded by the conventional friction welding process including that stage.

5. Conclusions

This report described the observation results of joining phenomena in friction stage and an improvement of the conventional friction welding method with similar materials. The following results are concluded.

(1) The wear of both weld faying surfaces started at periphery portion of the joint and extended to

center portion. Then seizure and joining began at center portion and extended towards periphery portion.

(2) The first stage of the friction stage was composed of wear and seizure stages.

(3) The friction torque reached initial peak torque when the welded interface was joined completely and upsetting of both base metals started.

(4) The joints obtained only in the first stage (up to initial peak torque) had 100% joint efficiency and 90 degrees bend ductility with no crack.

(5) As a conclusion, the friction welded joints without using the forging stage have the same mechanical properties as those welded by the conventional friction welding process including that stage. The friction welding method without forging stage has more advantages, i.e., less burn-off and less burr.

Acknowledgments

The authors wish to thank the staff of the Machine and Workshop Engineering at Graduate school of Engineering of Himeji Institute of Technology as well as to their former students of Mr. Takashi Matsumoto and Mr. Yasutomo Takeuchi for their devoted contribution to this research project.

References

(1) Hasui, A. and Fukushima, S., On the Torque in Friction Welding, Journal of the Japan Welding Society, (in Japanese), Vol. 44, No. 12 (1975), pp. 1005-1010.

(2) Shinoda, T., Tanada, K., Katoh, Y. and Shimizu, T., Study on Thermal Phenomena during Friction Welding and the Mechanical Properties of Aluminium Alloy, Journal of the Light Metal Welding & Construction, (in Japanese), Vol. 31, No. 10 (1993), pp. 462-467.

(3) Kobayashi, A., Machida, M. and Matsuda, T., Friction Welding Characteristics of SC Steel Based on Thermal Hysteresis, Journal of Japan Friction Welding Association, (in Japanese), Vol. 4, No. 3 (1997), pp. 6-12.

(4) Hasui, A., Fukushima, S. and Kinugawa, J., Experimental Studies in Friction Welding Phenomenon, Transactions of National Research Institute of Metals, (in Japanese), Vol. 11, No. 2 (1968), pp. 209-227.

(5) Fukakusa, K., On Real Rotational Contact Plane in Friction Welding of Different Diameter Materials and Dissimilar Materials, Quarterly Journal of the Japan Welding Society, (in Japanese), Vol. 14, No. 3 (1996), pp. 483-488.

(6) Bendzsak, G.J. and North, T.H., Modelling of Friction Joining Through the Equations of Fluid Mechanics, International Symposium on Theoretical Prediction in Joining and welding 1996 JWRI Osaka University, pp. 207-223.

(7) Ogawa, K., Yamaguchi, H., Kaga, S. and Sakaguchi, K., Optimization of Friction Welding Condition for S45C Carbon Steel, Quarterly Journal of the Japan Welding Society, (in Japanese), Vol. 11, No. 1 (1993), pp. 24-29.

(8) Rao, M. and Hazlett, T.H., A Study of the Mechanisms Involved in Friction Welding of Aluminum Alloys, Welding Journal, Vol. 49 (1970), pp. 181-s-188-s.

(9) Hasegawa, M. and Ieda, T., Effect of Friction Welding Condition on Initial Joining Phenomena, Quarterly Journal of the Japan Welding Society, (in Japanese), Vol. 17, No. 1 (1999), pp. 24-34.