Tensile Properties and Their Heterogeneity in Friction Stir Welded Joints of a Strain Hardened Aluminum Alloy†

LIU Huijie*, FUJII Hidetoshi**, MAEDA Masakatsu*** and NOGI Kiyoshi****

Abstract

A strain hardened aluminum alloy AA1050-H24 was friction stir welded in order to study the tensile properties and their heterogeneity of the joints. Experimental results showed that the tensile properties of the joints are significantly affected by the welding parameters. The optimum FSW parameters can be determined from the relation between the tensile properties and the welding parameters, and the maximum ultimate-strength of the joints is equivalent to 80% that of the base material. When the welding parameters deviate from the optimum values, a crack-like defect or serious softening is produced in the joints, thus the tensile properties of the joints deteriorate. In addition, the tensile properties of the joints are also heterogeneous. In the upper, middle and lower parts of each joint, the middle part is weakest and the upper part is strongest in tensile properties. On the two sides of the weld center, the tensile properties on the advancing side are inferior to those on the retreating side. These results are attributed to the different thermo-mechanical effects on the different component parts of the joints.

KEY WORDS: (Friction Stir Welding) (Tensile Properties) (Aluminum Alloy) (Welding Parameter) (Welded Joint) (Heterogeneity) (Strain Hardening)

1. Introduction

Friction stir welding (FSW) has been extensively and intensively investigated and is going into the commercial phase[1-5] since it was invented in 1991[6]. Recently, many studies on the microstructural characteristics and mechanical properties of the friction-stir welded joints have indicated that different types of aluminum alloys have different friction stir weldabilities.

Concerning the heat-treatable aluminum alloys such as 2014-T651[7], 2024-T6[8,9], 2195-T8[10], 6061-T5/T6[11-15], 6063-T5[16-18], 6082-T5[19,20], 7075-T651[21] and 7475-T76[22], FSW gives rise to a softened region in the joint because of the dissolution or growth of strengthening precipitates during the thermal cycle of welding, thus resulting in the degradation of the mechanical properties[18-22]. Fortunately, postweld ageing treatments can, to some extent, restore the loss of the mechanical properties of the softened region in these aluminum alloys[17-21].

With respect to the strain-hardened aluminum alloys such as 5754[23], 1100[24] and 1050[25,26], a softened region is also produced in the friction-stir welded joints because of the decrease in dislocation density in the weld and heat-affected zone (HAZ), but no better method has been found to compensate the deterioration in the mechanical properties for these aluminum alloys. In this case, it is quite important to study the effects of welding process parameters on the mechanical properties and their heterogeneity in order to obtain high-quality friction-stir-welded joints. Therefore, a strain-hardened and partially annealed aluminum alloy, AA1050-H24, is selected as the study object for FSW in the present paper, and the emphasis is placed on the tensile properties and their heterogeneity in the joints.

2. Experimental Procedure

The base material used in this study was a 5-mm-thick AA1050-H24 plate, and its chemical compositions and tensile properties are listed in Table 1. The plate was cut and machined into rectangular welding samples of 300 mm long by 80 mm wide, and the samples were longitudinally butt-welded using an FSW machine (Hitachi, SHK207-899). The designated welding tool size and welding parameters are showed in Table 2.

† Received on November 18, 2002

* Foreign Research Fellow, Associate Professor, NKLAWPT, Harbin Institute of Technology, Harbin 150001, P. R. China
** Associate Professor
*** Research Associate
**** Professor

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan

Table 1 Chemical compositions and tensile properties of AA1050-H24

Chemical compositions (wt%)							Tensile properties		
Al	Si	Fe	Cu	Mg	V	Ti	Ultimate strength	0.2% proof strength	Elongation
99.58	0.04	0.32	0.02	0.01	0.01	0.02	106.4 MPa	68.8 MPa	18.6 %

Table 2 Welding tool size and welding process parameters

Tool size (mm)			Welding parameters			
Shoulder diameter	Pin diameter	Pin length	Tool tilt	Rotation speed	Welding speed	Revolutionary pitch
15	6	4.7	3 °	1500 rpm	100-800 mm/min	0.07-0.53 mm/r

After welding, the joints were cross-sectioned perpendicular to the welding direction for the metallographic analyses and tensile tests using an electrical-discharge cutting machine. The cross-sections of the metallographic specimens were polished with alumina suspension, etched with Keller's reagent, and observed by optical microscopy.

The global-section specimens used for assessing the tensile properties of the global joints were prepared with reference to JIS Z2201, and their dimensions were 100 mm long, 12.5 mm wide and 5 mm thick. The partial-section specimens used for assessing the heterogeneity of the tensile properties of the joints were prepared in two steps. The joints were firstly cut into the global-section specimens, and every global-section specimen was finally cut perpendicular to the thickness direction into three partial-section specimens of 1.4 mm thick, and they were marked as upper, middle and lower parts of the joint.

Prior to the tensile tests, the Vickers hardness profiles across the weld, HAZ and partial base material were measured under a load of 0.98 N for 10 s along the centerlines of the cross-sections of the tensile specimens using an automatic micro-hardness tester (Akashi, AAV-502), and the Vickers indents with a spacing of 1 mm were used to determine the fracture locations and strain distributions of the tensile specimens. The tensile tests were carried out at room temperature at a crosshead speed of 1 mm/min using a screw-driven testing machine (Baldwin, SS-207D-UAD), and the tensile properties and their heterogeneity in each joint were evaluated through three tensile specimens.

3. Results and Discussion

3.1 Tensile properties of global joints

3.1.1 Effect of welding parameters on tensile properties

Fig. 1 shows the tensile properties of the global joints welded at different revolutionary pitches. It can be seen from this figure that, although the 0.2% proof strength monotonically increases as the revolutionary pitch increases, all the tensile properties of the joints are lower than those of the base material (see Table 1) except the elongation.

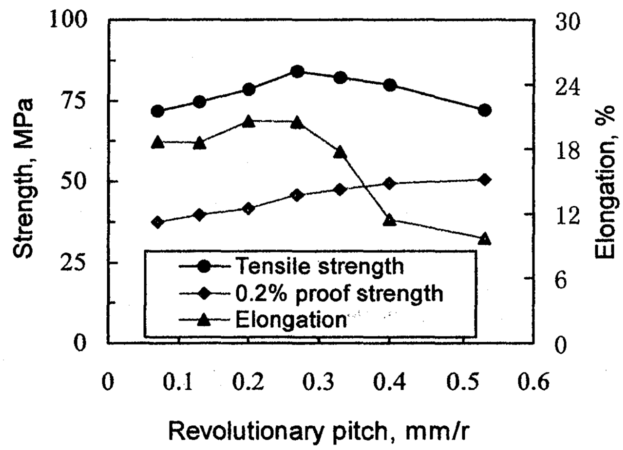

Fig. 1 Tensile properties of the global joints welded at different revolutionary pitches.

When the revolutionary pitch is smaller than or equal to 0.27 mm/r, the ultimate strength increases with the revolutionary pitch, and the elongation remains almost at the same level as that of the base material. When the revolutionary pitch is greater than 0.27 mm/r, the ultimate strength decreases with increasing revolutionary pitch, and the elongation dramatically decreases to a considerably low level.

These results indicate that the FSW parameters have a significant effect on the tensile properties of the global joints, and the optimum FSW parameters can be determined from the relation between the tensile properties and the welding parameters. In respect to the ultimate strength, the revolutionary pitch of 0.27 mm/r, corresponding to the rotation speed of 1500 rpm and the welding speed of 400 mm/min, is optimum. In this case, the ultimate strength of the joint is up to 84 MPa, equivalent to 80% that of the base material.

3.1.2 Dominant factors affecting tensile properties

In fact, the tensile properties of the joints are dependent on the microstructures and defects of the joints, which are affected by the FSW parameters. As studied by Y. S. Sato[18], the microhardness of the joints, just like the microstructures of the joints, can reflect the mechanical behavior of the joints, thus the tensile test results of the joints can be explained by the microhardness and defects of the joints.

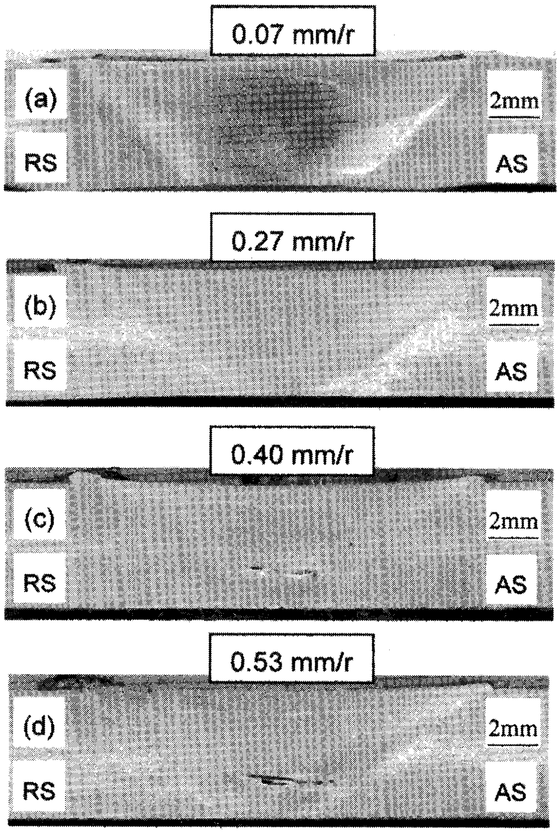

Fig. 2 Cross sections of the joints welded at different revolutionary pitches: (a) 0.07 mm/r, (b) 0.27 mm/r, (c) 0.40 mm/r, and (d) 0.53 mm/r.

Fig. 2 shows the typical cross-sections of the joints welded at different revolutionary pitches. Obviously, FSW can produce defect-free joints when the revolutionary pitch is smaller than or equal to the optimum value of 0.27 mm/r, and a crack-like defect can occur in the joints when the revolutionary pitch is greater than 0.27 mm/r. **Fig. 3** shows the microhardness profiles and strain distributions in the joints welded at different revolutionary pitches. In this figure, the minus horizontal coordinate means that the measured points are on the retreating side of each joint, and RS and AS denote retreating side and advancing side, respectively. These notations are also used in the other figures in the present paper. It can be seen from **Fig. 3a** that a hardness degradation region, i.e. softened region, located in the weld and HAZ has occurred in the joints, thus the tensile properties of the joints are all lower than those of the base material. It is easy to see from **Fig. 3b** that the tensile strain occurs only in a region corresponding to the weld and HAZ of the joint, and the maximum strain occurs at the fracture location of the joint. When the revolutionary pitch is smaller than or equal to the optimum value of 0.27 mm/r, the joint is fractured on the advancing side. Otherwise, when the revolutionary pitch is greater than 0.27 mm/r, the joint is fractured on the retreating side.

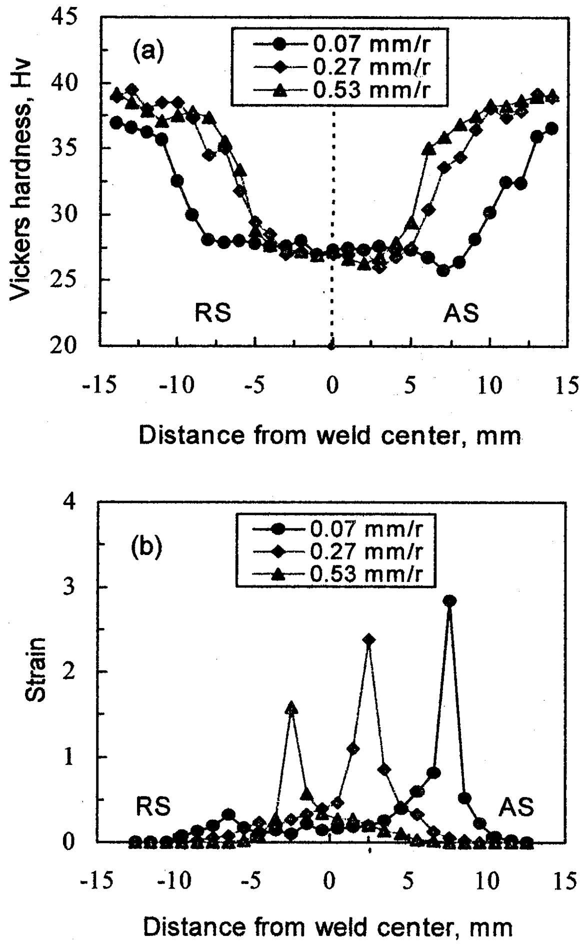

Fig. 3 Hardness profiles and strain distributions in the joints welded at different revolutionary pitches: (a) hardness profiles and (b) strain distributions.

When a joint is free of defects (see **Figs. 2a** and **2b**), the tensile properties and fracture locations of the joint are only dependent on the microhardness of the joint, especially the minimum hardness of the joint. There is a minimum-hardness zone on the advancing side of each joint (see **Fig. 3a**), therefore the joint is not fractured on the retreating side but on the advancing side. Moreover, the minimum hardness value of the joint increases as the revolutionary pitch increases, therefore both the ultimate strength and the 0.2% proof strength increase with the revolutionary pitch.

On the other hand, when a crack-like defect occurs in the joint (see **Figs. 2c** and **2d**), the tensile properties and fracture locations of the joint are significantly affected by the defects in the joint. In the tensile testing process, the mismatched deformation between the weld parts beneath and above the defect causes the joint to fracture part by part. First, the partial weld beneath the defect is fractured at the original interface between the two welding samples, and then the residual weld above the defect is fractured from the tip of the defect to the top surface of the joint. Because of the two-stages fracture, the elongation of the joint is at a considerably low level and the ultimate strength of the joint deteriorates. However, because the 0.2% plastic deformation is produced before the first-stage fracture, the 0.2% proof strength is almost not affected by the two-stages fracture and still increases with the microhardness as the revolutionary pitch increases. It can also be observed from **Figs. 2c** and **2d** that the crack-like defect slopes slightly from the retreating side to the advancing side, accordingly the joint tends to fracture on the retreating side.

From the viewpoint of heat input, the effect of the FSW parameters on the tensile properties of the joints is attributed to the different heat input to the joints. Because the softened level of the joint decreases with the heat input to the joint, the 0.2% proof strength monotonically increases with the revolutionary pitch. There is an optimum revolutionary pitch for the ultimate strength. When the FSW is performed at the optimum revolutionary pitch, the real heat input is just equal to the right heat input needed for producing a sound or defect-free joint. When the revolutionary pitch is greater than the optimum one, a welding defect occurs in the joint for lack of heat input to the joint, thus the joint is not qualified and accepted; when the revolutionary pitch is smaller than the optimum one, the softened level of the joint increases because of the excessive heat input to the joint although the defect-free joint can be produced, thus the tensile properties of the joint deteriorate.

3.2 Heterogeneity of tensile properties of joints

3.2.1 Tensile properties of different component parts of joints

Fig. 4 shows the tensile test results of the different component parts of the joints. It can be seen from **Fig. 4a** that the ultimate strength of the upper part of the same joint is the highest, while that of the middle part is the lowest. As the revolutionary pitch increases, the ultimate strength of the upper part increases, while that of the middle or lower part increases to the maximum at the revolutionary pitch of 0.27 mm/r.

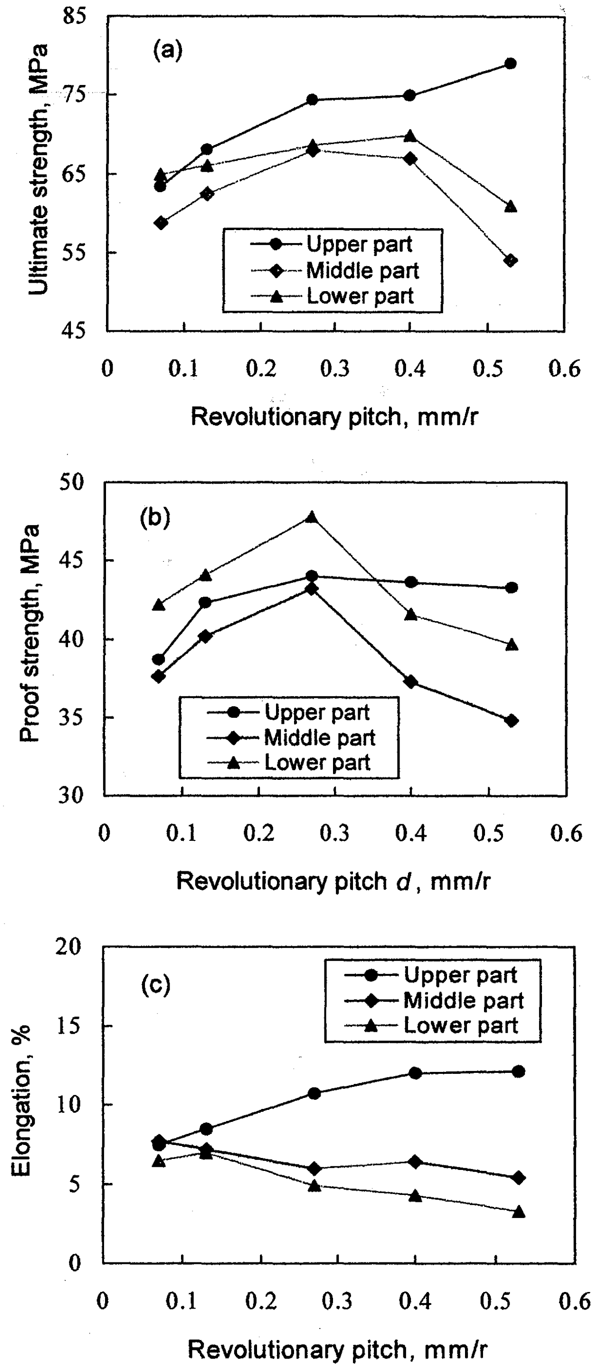

Fig. 4 Tensile properties of the different component parts of the joints: (a) ultimate strength, (b) 0.2 % proof strength, and (c) elongation.

As shown in **Fig. 4b**, in the three component parts of the same joint, the middle part always possesses the lowest proof strength. When the revolutionary pitch is smaller than 0.27 mm/r, the proof strength of the lower part is higher than that of the upper part; when the revolutionary pitch is greater than 0.27 mm/r, the proof strength of the lower part becomes lower than that of the upper part.

It's easy to observe from **Fig. 4c** that the elongation of the upper part is always the highest, while that of the lower part is always the lowest. As the revolutionary pitch increases, the elongation of the upper part increases and that of the middle or lower part decreases.

These results clearly indicate that the different component parts of the joint possess different tensile properties, and the welding parameters have different effects on the tensile properties of these different component parts. In the three component parts of the joint, the middle part is weakest and the upper part is strongest in ultimate strength. This is very interesting and useful information for improving the tensile properties of the global joint of such aluminum alloy as AA1050-H24 because a two-side welding process can be adopted to make one joint possess two "upper parts".

3.2.2 Decisive factors dominating heterogeneity of tensile properties

Like the global joint, the tensile properties of the component parts of each joint are also dependent on the welding defects and hardness profiles. **Fig. 5** shows the strain distributions and microhardness profiles in the different component parts of the joints welded at different revolutionary pitches. It can be seen from **Figs. 5a** and **5b** that the upper and middle parts are always fractured on the advancing side, and the lower part is fractured on the advancing side or at the weld center. This implies that the tensile properties of the joints are heterogeneous on the two sides of the weld center and the tensile properties on the advancing side are inferior to those on the retreating side.

When a joint is free of defect (see **Figs. 2a** and **2b**), the tensile properties and fracture locations of the component parts of the joint are only dependent on their hardness profiles. There is a minimum-hardness zone on the advancing side of each component part of the joint (see **Fig. 5c**), therefore the fracture occurs on the advancing side during the tensile tests. In the three component parts of the same joint, the minimum hardness value of the middle part is slightly smaller than

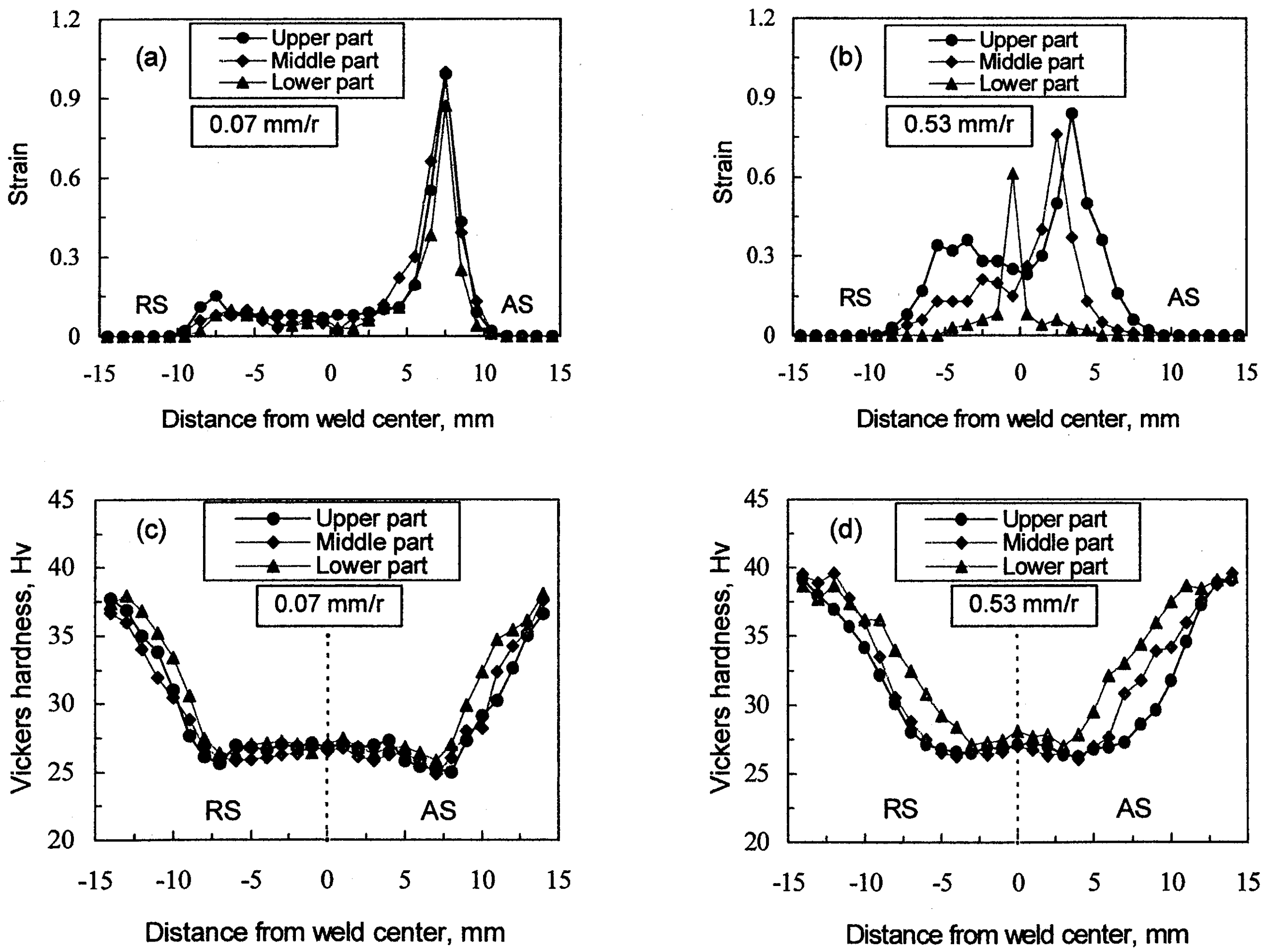

Fig. 5 Strain distributions and hardness profiles in the different component parts of the joints: (a) and (b) strain distributions, (c) and (d) hardness profiles.

that of the other parts, therefore the middle part always possesses the lowest strength, including ultimate strength and proof strength. In addition, the minimum hardness value of each component part of the joint increases as the revolutionary pitch increases, consequently the ultimate and proof strengths of the component parts of the joint increase with the revolutionary pitch.

On the other hand, when a defect occurs in the joint (**see Figs. 2**c and **2d**), the tensile properties and fracture locations of the component parts of the joint are affected by the defect. Because the defect occurs in the middle and lower parts, the tensile properties of these two parts seriously deteriorate although the minimum hardness value of the lower part is higher (see **Fig. 5d**). However, there is no defect in the upper part, therefore the tensile properties of the upper part remain at high levels.

In nature, the heterogeneity of the tensile properties of friction stir welded joints is attributed to the different thermo-mechanical actions on the different component pars of the joints. In the three component parts of the same joint, the upper part is frictionized and stirred not only by the tool pin, but also by the tool shoulder, therefore it is different from the middle and lower parts in microstructural characterizations. Even if the FSW is carried out at a comparatively high revolutionary pitch, the heat input to the upper part is still sufficient to produce a defect-free weld, thus the upper part has the highest ultimate strength. The middle and lower parts are frictionized and stirred only by the tool pin, therefore the heat input to them is lower than that to the upper part. However, the heat output from the middle part is lower than that from the upper part or the lower part, and then the effective heat absorbed by the middle part may be higher than that absorbed by the upper part or the lower part, thus the middle part is seriously softened and is weakest in tensile properties. The effect of the friction heat on the lower part is not as remarkable as that on the upper and lower parts because the lower part is characterized by the lowest heat input and the highest heat output. When the revolutionary pitch is comparatively low, e.g. 0.07 mm/r, the lower part possesses comparatively high tensile properties; but when the revolutionary pitch is over a certain value, i.e. 0.27 mm/r, a welding defect occurs in the lower part for lack of heat input, thus the tensile properties of the lower part seriously deteriorate.

4. Conclusions

A softened region, composed of the weld and HAZ, has clearly occurred in the friction stir welded joints of AA1050-H24 aluminum alloy. The softened levels and tensile properties of the joints are significantly affected by the welding parameters. The optimum FSW parameters can be determined from the relation between the tensile properties and the welding parameters, and the maximum ultimate-strength of the joints is equivalent to 80% that of the base material. When the welding parameters deviate from the optimum values, a crack-like defect or serious softening is produced in the joints, thus the tensile properties of the joints deteriorate and the fracture locations of the joints change.

The tensile properties of the friction stir welded joints of AA1050-H24 are quite heterogeneous, especially when a defect occurs in the joints. In the upper, middle and lower three component parts of each joint, the middle part is weakest and the upper part is strongest in tensile properties. On the two sides of the weld center, the tensile properties on the advancing side are inferior to those on the retreating side. The reason for this is that the different component parts of the joints undergo different thermo-mechanical effects during the FSW.

References

1. H. OKAMURA, K. AOTA, and M. EZUMI: *J. Jpn. Inst. Light Met.*, 2000, **50**, 166-171.
2. G. CAMPBELL and T. STOTLER: *Welding J.*, 1999, **78**, 45-47.
3. M. R. JOHNSEN: *Weld. J.*, 1999, **78**, 35-39.
4. K. E. KNIPSTROM and B. PEKKARI: *Weld. J.*, 1997, **76**, 55-57.
5. C. J. DAWES and W. M. THOMAS: *Weld. J.*, 1996, **75**, 41-45.
6. W. M. THOMAS, E. D. NICHOLAS, J. C. NEEDHAM, M. G. MURCH, P. TEMPLE- SMITH, and C. J. DAWES: *International Patent Application PCT/GB92/02203 and GB Patent Application 9125978.8*, UK Patent Office, London, December 6, 1991.
7. M. G. DAWES, S. A. KARGER, T. L. DICKERSON, and J. PRZYOATEK, *Proceedings of the 2nd International Symposium on Friction Stir Welding*, Gothenburg, Sweden, June 2000, Paper No. S2-P1.
8. S. BENAVIDES, Y. LI, L. E. MURR, D. BROWN, and J. C. MCCLURE: *Scripta Mater.*, 1999, **41,** 809-815.
9. T. HASHIMOTO, S. JYOGAN, K. NAKATA, Y. G. KIM, and M. USHIO: *Proceedings of the 1st International Symposium on Friction Stir Welding*, California, USA, June 1999, Paper No. S9-P3.
10. D. G. KINCHEN, Z. X. LI, and G. P. ADAMS, *Proceedings of the 1st International Symposium on Friction Stir Welding*, California, USA, June 1999, Paper No. S9-P2.
11. M. KUMAGAI and S. TANAKA, *Proceedings of the 1st International Symposium on Friction Stir Welding*, California, USA, June 1999, Paper No. S3-P2.

12. H. OKAMURA, K. AOTA, M. SAKAMOTO, M. EZUMI, and K. IKEUCHI: *Q. J. Jap. Weld. Soc.*, 2001, **19**, 446-456.
13. G. LIU, L. E. MURR, C. S. NIOU, J. C. MCCLURE, and F. R. VEGA: *Scripta Mater.*, 1997, **37**, 355-361.
14. L. E. MURR, G. LIU, and J. C. MCCLURE: *J. Mater. Sci.*, 1998, **33**, 1243-1251.
15. Y. NAGANO, S. JOGAN, and T. HASHIMOTO: *Proceedings of the 3rd International Symposium on Friction Stir Welding*, Kobe, Japan, September 2001, Paper No. Post-12.
16. Y. S. SATO, H. KOKAWA, M. ENOMOTO, and S. JOGAN: *Metall. Mater. Trans. A*, 1999, **30**, 2429-2437.
17. Y. S. SATO, H. KOKAWA, M. ENOMOTO, S. JOGAN, and T. HASHIMOTO: *Metall. Mater. Trans. A*, 1999, **30**, 3125-3130.
18. Y. S. SATO and H. KOKAWA: *Metall. Mater. Trans. A*, 2001, **32**, 3023-3031.
19. J. HAGSTROM and R. SANDSTROM: *Sci. Technol. Weld. Join.*, 1997, **2**, 199-208.
20. L. E. SVENSSON, L. KARLSSON, H. LARSSON, B. KARLSSON, M. FAZZINI, and J. KARLSSON: *Sci. Technol. Weld. Join.*, 2000, **5**, 285-296.
21. M. W. MAHONEY, C. G. RHODES, J. G. FLINTOFF, R. A. SPURLING, and W. H. BINGEL: *Metall. Mater. Trans. A*, 1998, **29**, 1955-1964.
22. L. MAGNUSSON and L. KALLMAN: *Proceedings of the 2nd International Symposium on Friction Stir Welding*, Gothenburg, Sweden, June 2000, Paper No. S2-P3.
23. H. JIN, S. SAIMOTO, M. BALL, and P. L. THREADGILL: *Mater. Sci. Technol.*, 2001, **17**, 1605-1614.
24. O. V. FLORES, C. KENNEDY, L. E. MURR, D. BROWN, S. PAPPU, B. M. NOWAK, and J. C. MCCLURE: *Scripta Mater.*, 1998, **38**, 703-708.
25. Y. S. SATO, M. URATA, H. KOKAWA, and K. IKEDA: *Proc.7th Int. Weld. Symp.*, Kobe, Japan, Nov. 2001, JWS, 633-638.
26. Y. S. SATO, M. URATA, H. KOKAWA, K. IKEDA, and M. ENOMOTO: *Scripta Mater.*, 2001, **45**, 109-113.