JMEPEG (2011) 20:1419–1422
DOI: 10.1007/s11665-010-9787-x

# Homogeneity of Mechanical Properties of Underwater Friction Stir Welded 2219-T6 Aluminum Alloy

**H.J. Liu, H.J. Zhang, and L. Yu**

*(Submitted August 20, 2010; in revised form September 30, 2010)*

**Underwater friction stir welding (FSW) has been demonstrated to be available for the improvement in tensile strength of normal FSW joints. In order to illuminate the intrinsic reason for strength improvement through underwater FSW, a 2219 aluminum alloy was underwater friction stir welded and the homogeneity of mechanical properties of the joint was investigated by dividing the joint into three layers. The results indicate that the tensile strength of the three layers of the joint is all improved by underwater FSW, furthermore, the middle and lower layers have larger extent of strength improvement than the upper layer, leading to an increase in the homogeneity of mechanical properties of the joint. The minimum hardness value of each layer, especially the middle and lower layers, is improved under the integral water cooling effect, which is the intrinsic reason for the strength improvement of underwater joint.**

**Keywords** aluminum, mechanical testing, welding

## 1. Introduction

As a solid state joining process, friction stir welding (FSW) has been widely utilized to weld various aluminum alloys that were difficult to fusion weld owing to its high welding quality, low production cost, and low welding distortion (Ref 1-4). Regarding the FSW of precipitated hardened aluminum alloys, although the lower heat input generated during FSW does not melt the base metal, the thermal cycles can still exert negative effect on the mechanical properties of the joints through coarsening or dissolving the strengthening precipitates (Ref 5-9). Apparently, it is of interest and possible to improve the mechanical properties of normal friction stir welded joints by controlling the temperature level. In order to do this, external liquid cooling has been applied during FSW by several researchers. Benavides et al. (Ref 10) performed FSW experiment of 2024 aluminum alloy using liquid nitrogen cooling to decrease the initial temperature of plates to be welded from 30 to −30 °C. It was found that the hardness of the thermal mechanically affected zone (TMAZ) and the heat affected zone (HAZ) was remarkably improved, demonstrating the positive effect of external liquid cooling on joint properties. Fratini et al. (Ref 11, 12) considered in-process heat treatment with water flowing on the top surfaces of welding samples during FSW and the tensile strength of the joints was found to be improved to some extent. In order to take full advantage of the heat absorption effect of water, the present authors (Ref 13) conducted underwater FSW of 2219-T6 aluminum alloy, during which the whole workpiece was kept immersed in the water environment. The results demonstrated that this is a preferable method to improve the joint properties. In order to illuminate the intrinsic reason for strength improvement by underwater FSW, the underwater friction stir welded joint of 2219-T6 aluminum alloy was layered in this article and the mechanical characteristic of the layers was studied in detail.

## 2. Experimental Procedure

The base metal was a 7.5 mm thick 2219-T6 aluminum alloy plate (6.48 Cu, 0.32 Mn, 0.23 Fe, 0.06 Ti, 0.08 V, 0.04 Zn, 0.49 Si, 0.20 Zr, Al bal., in wt.%). The tensile strength and microhardness of the base metal are 432 MPa and 120-130 Hv, respectively. FSW experiments were performed under two kinds of conditions. One is in air, and the other is under water. For underwater FSW, the workpiece was entirely immersed in the water environment during the welding process, as shown in Fig. 1. The FSW joints obtained under the two conditions are called normal joint and underwater joint, respectively. The welding samples with dimension of 300 mm long by 100 mm wide were butt-welded using an FSW machine along the longitudinal direction. The welding tool and the parameters used for normal and underwater FSW were the same. The welding tool consisted of a 22.5 mm diameter shoulder and a conical right-hand screwed pin with the length of 7.4 mm and the median diameter of 7.4 mm. The rotation speed, welding speed, and axial pressure were 800 rpm, 100 mm/min, and 4.6 kN, respectively.

In order to investigate the homogeneity of mechanical properties of the joints in the thickness direction, the transverse rectangular specimens with dimension of 150 mm long by 15 mm wide were first cut perpendicular to the welding direction from the joints, and then each specimen was cut parallel to the weld surface into three layers, which were named as upper, middle, and lower layers of the joint. Prior to tensile tests, the cross sections of all the layers were polished with a diamond paste, and then Vickers hardness profiles were

---

**H.J. Liu, H.J. Zhang,** and **L. Yu**, State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin, China. Contact e-mail: liuhj@hit.edu.cn.

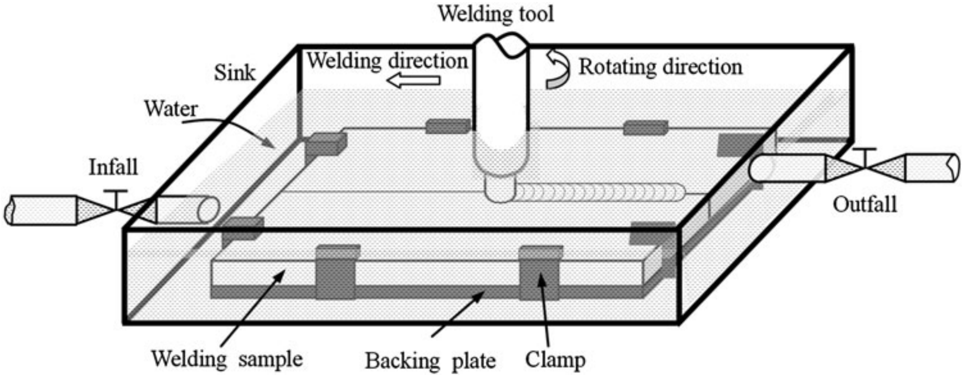

**Fig. 1** The schematic view of underwater FSW

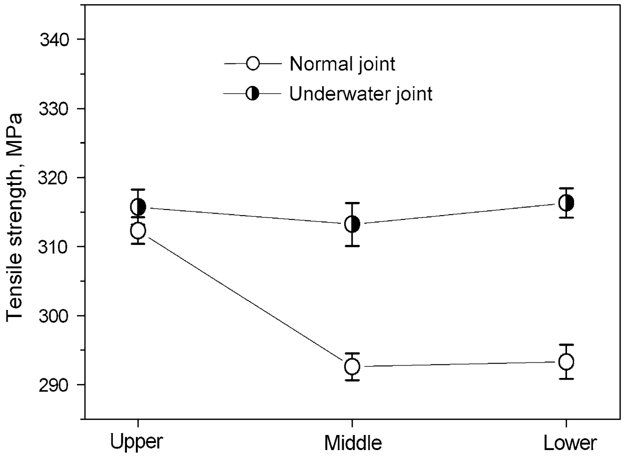

**Fig. 2** Tensile property of each layer in the joints

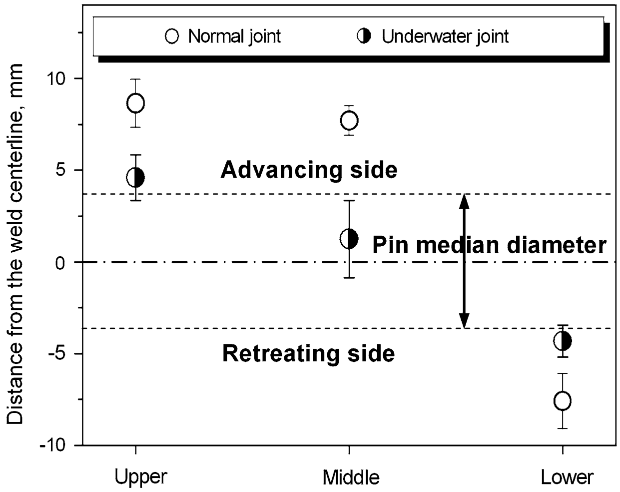

**Fig. 3** Fracture location of each layer in the joints

measured at the mid-thickness across weld nugget zone (WNZ), TMAZ, HAZ, and partial base metal. The load was 4.9 N for 10 s, and the Vickers indents with a spacing of 1 mm were also used to determine the fracture locations of the layers during tensile test. The room temperature tensile test was carried out at a crosshead speed of 1 mm/min. The tensile properties of each layer were evaluated through three tensile specimens.

## 3. Results and Discussion

Figure 2 shows the tensile properties of different layers of normal and underwater joints. As observed in the literatures (Ref 14-16), a heterogeneity of mechanical properties exists in the thickness direction of normal joint. The upper layer has a tensile strength of 312 MPa, while the middle and lower layers have relatively low tensile strength, only 292 and 293 MPa, respectively. This means that the middle and lower layers are the intrinsic weak locations of the joint. Compared with the normal joint, the underwater joint exhibits strength improvement in all the three layers, but the improved levels are different. There is only a slight improvement of tensile strength in the upper layer, but larger extent of strength improvement occurs in the middle and lower layers. The strength improvement in each layer finally causes a 6% increase in tensile strength of underwater joint (Ref 13). Furthermore, the tensile properties of the three layers of underwater joint are nearly the same, indicating an increase in homogeneity of mechanical properties of the joint.

The fracture locations of different layers of the joints are shown in Fig. 3. The three layers of normal joint are all fractured in the HAZ, far from the weld center. Regarding the underwater joint, the fracture locations of all the layers are closer to the weld center, lying in the interior or periphery of the WNZ. This means that the weakest locations of all the layers, including the middle layer that does not directly contact with water during FSW, are moved toward the weld center by the water cooling action.

With respect to a defect-free FSW joint, the tensile strength is mainly dependent on the hardness distributions. The hardness profiles of all the layers are shown in Fig. 4. A softening region having lower hardness value than the base metal is created by the welding thermal cycles in both normal and underwater joints. Furthermore, the softening regions of the layers in underwater joint are much narrower than those in normal joint. Such a result suggests a reduced effect of welding thermal cycles on joint properties, which contributes to the strength improvement via underwater FSW. Comparing Fig. 3 with 4, it is found that the layers tend to fail at or adjacent to the lowest-hardness zone for both normal and underwater joints. The hardness profiles of the layers in normal joint show a "W" type with minimum hardness lying in the HAZ (Fig. 4a), while the

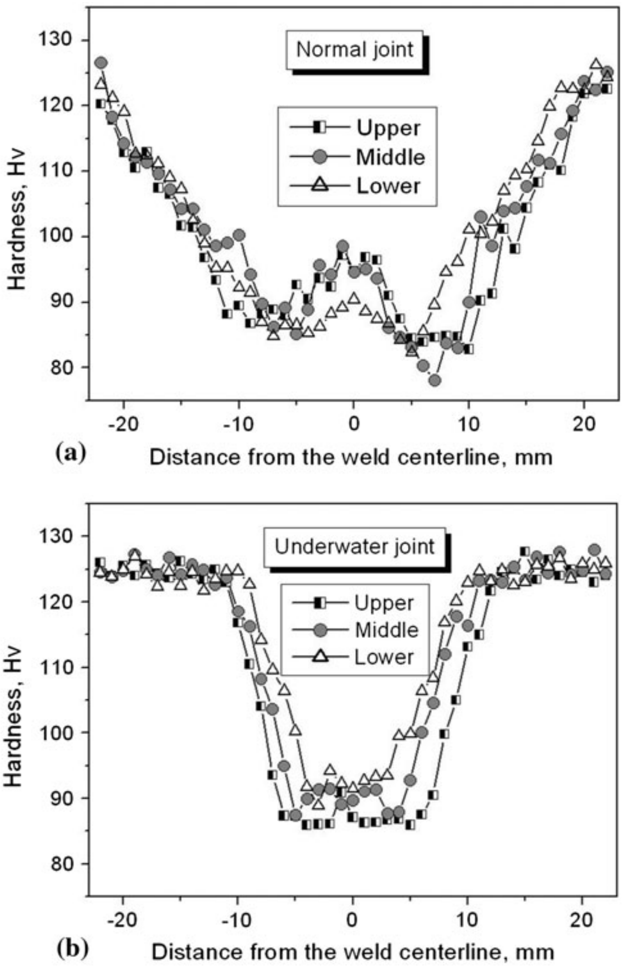

**Fig. 4** Microhardness distributions in the joints: (a) normal joint; (b) underwater joint

hardness profiles of the layers in underwater joint exhibit a "U" type and the minimum hardness is located at the interior or periphery of the WNZ (Fig. 4b). The minimum hardness value of each layer in underwater joint is improved in contrast to the normal joint. The improved level is lowest in the upper layer and relatively high in the middle and lower layers. The increase in the minimum hardness value of the three layers, especially in the middle and lower layers, is the intrinsic reason for the strength improvement of underwater joint.

A great advantage of underwater FSW is that the heat absorption effect of water can be fully utilized by immersing the whole workpiece in the water environment during the welding process. A large amount of heat can be dissipated not only from the top surface but also from the lateral and bottom surfaces of the workpiece. Consequently, the properties of the weak locations (i.e., the middle and lower layers) of the joint can be effectively strengthened under this integral water cooling effect, leading to an improvement in the tensile strength of underwater joint.

## 4. Conclusions

From this investigation, the conclusions of significance are drawn as follows:

(1) Underwater FSW can be utilized to improve the mechanical properties of the normal joint. The middle and lower layers possess higher improved levels than the upper layer, leading to an increase in the homogeneity of mechanical properties of the joint.
(2) Compared with the normal joint, the softening regions of the layers in underwater joint are significantly narrowed and the weakest locations are closer to the weld center, indicating a reduced effect of welding thermal cycles on joint properties in water cooling case.
(3) The reason for the strength improvement via underwater FSW is that the minimum hardness value of the weak locations of the normal joint (i.e., the middle and lower layers) can be effectively improved under the integral cooling effect of water.

## Acknowledgments

The authors are grateful to be supported by the National Basic Research Program of China (973 Program, 2010CB731704) and by the National Science and Technology Major Project of China (302010ZX04007-011).

## References

1. M.R. Johnsen, Friction Stir Welding Takes Off at Boeing, *Weld. J.*, 1999, **78**, p 35–39
2. D. Joelj, The Friction Stir Welding Advantage, *Weld. J.*, 2001, **80**, p 30–34
3. W.B. Lee, Y.M. Yeon, and S.B. Jung, The Improvement of Mechanical Properties of Friction-Stir Welded A356 Al Alloy, *Mater. Sci. Eng. A*, 2003, **355**, p 154–159
4. R.S. Mishra and Z.Y. Ma, Friction Stir Welding and Processing, *Mater. Sci. Eng. Rep.*, 2005, **50**, p 1–78
5. R.W. Fonda and J.F. Bingert, Microstructural Evolution in the Heat-Affected Zone of a Friction Stir Weld, *Metall. Mater. Trans. A*, 2004, **35**, p 1487–1499
6. L.E. Svensson, L. Karlsson, H. Larsson, B. Karlsson, M. Fazzini, and J. Karlsson, Microstructure and Mechanical Properties of Friction Stir Welded Aluminum Alloys with Special Reference to AA 5083 and AA 6082, *Sci. Technol. Weld. Join.*, 2000, **5**, p 285–296
7. M.J. Starink, A. Seschamps, and S.C. Wang, The Strength of Friction Stir Welded and Friction Stir Processed Aluminum Alloys, *Scripta Mater.*, 2008, **58**, p 377–382
8. K. Elangovan, V. Balasubramanian, and S. Babu, Developing an Empirical Relationship to Predict Tensile Strength of Friction Stir Welded AA2219 Aluminum Alloy, *JMEPEG*, 2008, **17**, p 820–830
9. V. Dixit, R.S. Mishra, R.J. Lederich, and R. Talwar, Influence of Process Parameters on Microstructural Evolution and Mechanical Properties in Friction Stirred Al-2024 (T3) Alloy, *Sci. Technol. Weld. Join.*, 2009, **14**, p 346–355
10. S. Benavides, Y. Li, L.E. Murr, D. Brown, and J.C. McClure, Low-Temperature Friction-Stir Welding of 2024 Aluminum, *Scripta Mater.*, 1999, **41**, p 809–815
11. L. Fratini, G. Buffa, and R. Shivpuri, In-Process Heat Treatments to Improve FS-Welded Butt Joints, *Int. J. Adv. Manuf. Technol.*, 2009, **43**, p 664–670
12. L. Fratini, G. Buffa, and R. Shivpuri, Mechanical and Metallurgical Effects of in Process Cooling during Friction Stir Welding of AA7075–T6 Butt Joints, *Acta Mater.*, 2010, **58**, p 2056–2067
13. H.J. Liu, H.J. Zhang, Y.X. Huang, and L. Yu, Mechanical Properties of Underwater Friction Stir Welded 2219 Aluminum Alloy, *Trans. Nonferrous Met. Soc. China*, 2010, **20**, p 1387–1391
14. S.B. Lin, Y.H. Zhao, and L. Wu, Integral and Layered Mechanical Properties of Friction Stir Welded Joints of 2014 Aluminum Alloy, *Mater. Sci. Technol.*, 2006, **22**, p 995–998

15. H.J. Liu, H. Fujii, M. Maeda, and K. Nogi, Heterogeneity of Mechanical Properties of Friction Stir Welded Joints of 1050–H24 Aluminum Alloy, *J. Mater. Sci. Lett.*, 2003, **22**, p 441–444

16. W.F. Xu, J.H. Liu, G.H. Luan, and C.L. Dong, Temperature Evolution, Microstructure and Mechanical Properties of Friction Stir Welded Thick 2219-O Aluminum Alloy Joints, *Mater. Des.*, 2009, **30**, p 1886–1893