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Experience on Friction Stir Welding and Friction Stir Spot Welding at Universiti Teknologi Petronas

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Abstract: Friction Stir Welding (FSW) is a solid-state joining process where a non-consumable, rotating tool is rotated at a constant speed and fed at a constant traverse rate into the joint line between two pieces of sheet or plate material, which are butted together. Whereas, Friction Stir Spot Welding (FSSW) is a derivative of FSW without lateral movement of the tool during the process. Two plates of aluminum alloy 2011 in the dimension of 10 mm thickness was joint welded by using FSW and 1 mm thickness of Aluminum alloy 1100 sheets was spot welded by using FSSW. The strength of the welds was tested using Universal Tensile Machine and the microstructure evolution was observed using optical microscope. Three different regions of FSW and FSSW welds were characterized whereas the strengths of the FSW and FSSW welds were compared to the parent metal.

Key words: Friction stir welding, friction stir spot welding, microstructure, optical microscope, strength

INTRODUCTION

FSW is a solid-state joining process invented by Wayne Thomas and his colleagues at The Welding Institute (TWI) UK in December 1991 (Thomas *et al*., 1991). It has been widely used in joining aluminum alloys especially for production of fuel tank, engine cradles, and deck panels in automotive industry. In FSW, a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together. The parts have to be clamped onto a backing bar in a manner that prevents the abutting joint faces from being forced apart. Frictional heat is generated between the wear resistant welding tool and the material of the workpieces. This heat causes the latter to soften without reaching the melting point and allows traversing of the tool along the weld line. The plasticized material is transferred from the leading edge of the tool to the trailing edge of the tool probe and is forged by the intimate contact of the tool shoulder and the pin profile. It leaves a solid phase bond between the two pieces. The process can be regarded as a solid phase keyhole welding technique since a hole to accommodate the probe is generated, then filled during the welding sequence (Yuh and Xinhai, 1999). Figure 1 depicts schematically the friction stir welding process.

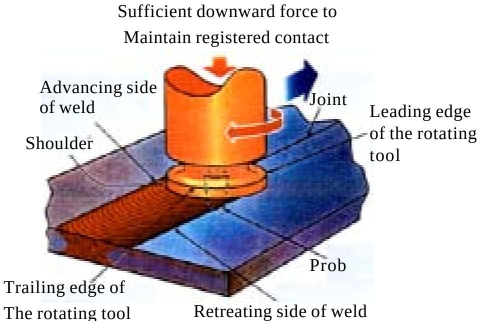

Fig. 1: Schematic diagram of FSW process (Thomas *et al*., 1991)

FSSW is a derivative of the FSW without lateral movement of the tool during welding process. It has been used in the production of aluminum doors, engine hoods, and deck lids in automotive industry. The FSSW are created by the combined action of frictional heating and mechanical deformation due to a rotating tool. The probe penetrates the work piece whereas the shoulder rubs with the top surface (Badeshia, 2003). The FSSW process consists of three phases; plunging, stirring and retraction as shown in Fig. 2. It starts with tool spinning and slowly plunge the tool into a weld spot until the shoulder contacts the top surface of the work piece. The stirring phase enable the materials of two-work pieces mix together. Once a predetermined

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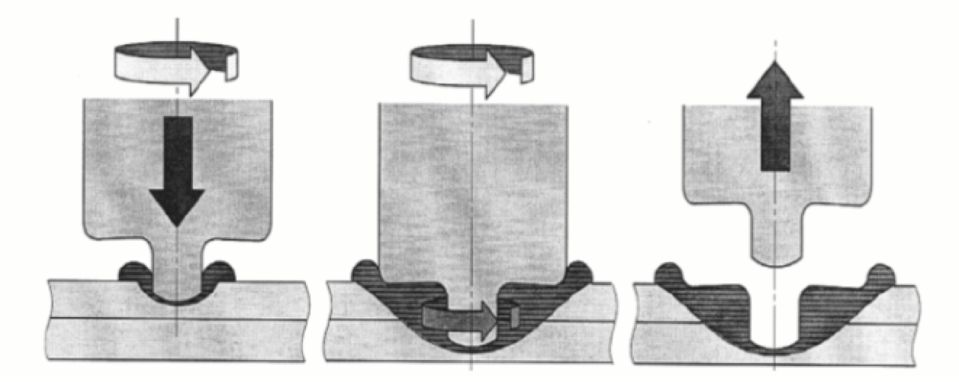


(a) Plunging (b) Stirring (c) Retracting

Fig. 2: Three stages of FSSW process (Pan *et al*., 2004)

penetration is reached, the process stops and the tool retract from the work piece (Badeshia, 2003).

As the rotating tool is plunged into the upper and lower sheets, it extrudes material sideways. It is logically hypothesized that analogously to the FSW process; a Thermo-mechanically Affected Zone (TMAZ) and a heat affected zone are created around the pin. However, the micro structural details of both zones are yet to be elucidated in open literature. There has been a recent series of conference proceedings concerning the mechanics or heat transfer in FSSW. There are also current works regarding pin insertion depth on failure mode of the lap shear specimens with its microstructure but not all process parameters has been studied their effect on weld joint strength (Mitlin *et al*., 2006).

FSW has made a significant impact on the welding industries in a short time and will continue to grow in both research and commercial application. Early years of FSW, many researchers believed it is a relatively simple process. However, the metallurgical fundamentals that results in this remarkable post weld properties have found to be quite complex. Most data in many research and literatures provide empirical observation but not an understanding of the process itself. A concerted effort is needed to address the basic components of the process to integrate them into a complete process description (Mishra and Mahoney, 2007). Therefore, in the first part of this research, using fabricated FSW tool, which operated, produced FSW welds of aluminum alloy 2011 by CNC milling machine.

The region occurred on weld was characterized based on the microstructure examination by using optical microscope and Scanning Electron Microscopy (SEM) whereas the strength of the FSW welds was tested using Universal Tensile Machine to compare with the strength of the parent metal. For the second part of this research, spot welds of FSSW on 1100 Aluminum alloy was produced by using fabricated FSSW tool which operated by CNC milling machine. The region occurred on weld was characterized based on the microstructure examination whereas the strength of the FSW welds was tested to compare with the parent metal.

MATERIALS AND METHODS

A tool for FSW was fabricated by Mazak Integrex 200-III CNC Turning Machine from 50 mm diameter and 200 mm long AISI H13 tool steel to a length of 8 mm with a diameter of shaft around 62 mm. The design of the tool is attached in the Appendix. A tube furnace to prevent tool wear then heated the tool. Two plates of 100×100 mm of aluminum alloy 2011 with thickness of 10 mm was butted joint together and clamped on the backing support (127 mm×280 mm×25 mm of aluminum block) by vise jaw of CNC Milling Machine.

The two workpieces were friction stir welded by using Mazak Variaxis 630 5-X CNC milling machine. The rotating tool speed was in the range of 550 to 3500 rpm, the transverse speed was 100 mm/min and the depth of penetration was 8 mm. The FSW welds were then prepared by metallographic techniques to characterize by optical microscopy. Transverse tensile tests were performed according to the ASTM E8-00b Standard Test Methods for Tension Testing of Metallic Materials. A Universal Testing Machine was used to conduct the pull-to-break test method at 1.27 mm min^{-1} to determine the tensile strength of the weld.

A 25 mm diameter and 305 mm long AISI H13 tool steel was fabricated by using CNC Turning Machine to

100 mm length and 25 diameter of FSSW tool steel. The design of FSSW tool steel is attached in the Appendix . A tube furnace to prevent tool wear then heated the tool. Two sheets of 200×30 mm of 1100 Aluminum with thickness of 10 mm was butted joint together and clamped on the backing support (127 mm×280 mm×25 mm of aluminum block) by vise jaw of CNC Milling Machine. A 200 mm×30 mm sheet 1100 Aluminum with the same thickness was put under on the sheet to be joined in order to make a spot weld.

Like FSW, the 1100 Aluminum sheets was friction stir spot welded by using Mazak Variaxis 630 5-X CNC Milling machine. The rotating tool speed was varied from 4000 to 6000 rpm, the plunge rate of 45 to 75 mm min^{-1} and the plunge depth of 1.7 mm. The FSSW spot welds were then prepared by metallographic techniques to characterize by optical microscopy. Transverse tensile tests were performed according to the ASTM E8-00b Standard Test Methods for Tension Testing of Metallic Materials. Universal Testing Machine was used to conduct the pull-to-break test method at 1.27 mm min^{-1} to determine the tensile strength of the weld.

RESULTS AND DISCUSSION

Figure 3 shows the top surface of the welds joined by FSW at 2500 rpm with a 100 mm min^{-1} and plunge depth of 8 mm. Even though the top surface of the welds has good surface finish, the radiography examination shows that there are defect and hole along the weld line.

Figure 4 shows the hole produced by FSW along the weld line. Data in Table 1 and 2 shows the parameters of FSW that joined the two plates of aluminum alloy 2011 but all of them produce defect along the weld line.

Colligan *et al.* (2001) reported that the hole along the weld line FSW can be characterized as common FSW defect which is called wormhole or tunnel defect. This defect is a result of insufficient material transport around the tool pin to the advancing side. It occurs when the tool advance per revolution is too high. The defect in this research possibly occurs because of insufficient dwell time during the plunging of FSW tool in order to give steady state heat input to the material before it travels along the line.

Figure 5 shows the different welded region generated from FSW process. The finest grain structure in the welded region is called the nugget zone. This zone-undergone recrystallization by direct rubbing of the tool pin and the tool shoulder without exceed the solidus temperature, T_s. This region undergoes extreme levels of plastic deformation that leads to a very fine recrystallized grain structure being formed in the center of the weld. The finer grain structure with little porosity in the welded region is called the Thermos-Mechanically-Affected Zone (TMAZ). In this region, the FSW tool has plastically deformed the material and the heat from the process will also exerted some influence on the material. In aluminum,

Table 1: FSW parameters

Run no	Spindle speed	Transverse speed	Weld penetration	Weld defect
1	2500	100	8.0	Tunnel
2	2500	100	8.5	Tunnel
3	2500	100	8.2	Tunnel
4	3500	100	8.1	Tunnel

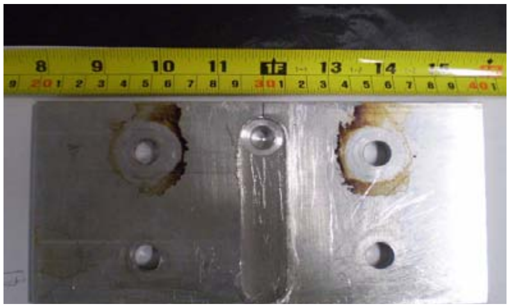


Fig. 3: FSW of Aluminum Alloy 2011

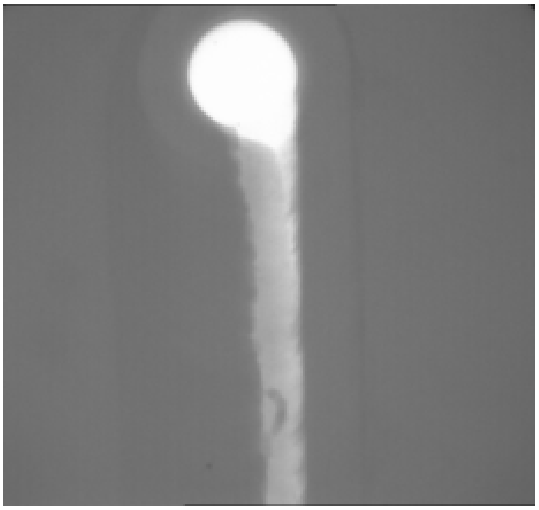


Fig. 4: Wormhole defects along weld line of Aluminum Alloy 2011

Table 2: FSW Parameters and their Tensile Strength

Sample	Spindle speed(rmp)	Depth (mm)	Load (KN)	UTS(MPa)
1	2500	8.1	16.76	57.92
2	3000	8.1	19.4	63.28
3	3000	8.1	20.48	72.91
4	3500	8.1	15.52	53.64
5	3000	8.1	21.58	76.80
6	2500	8.1	26.89	106.71

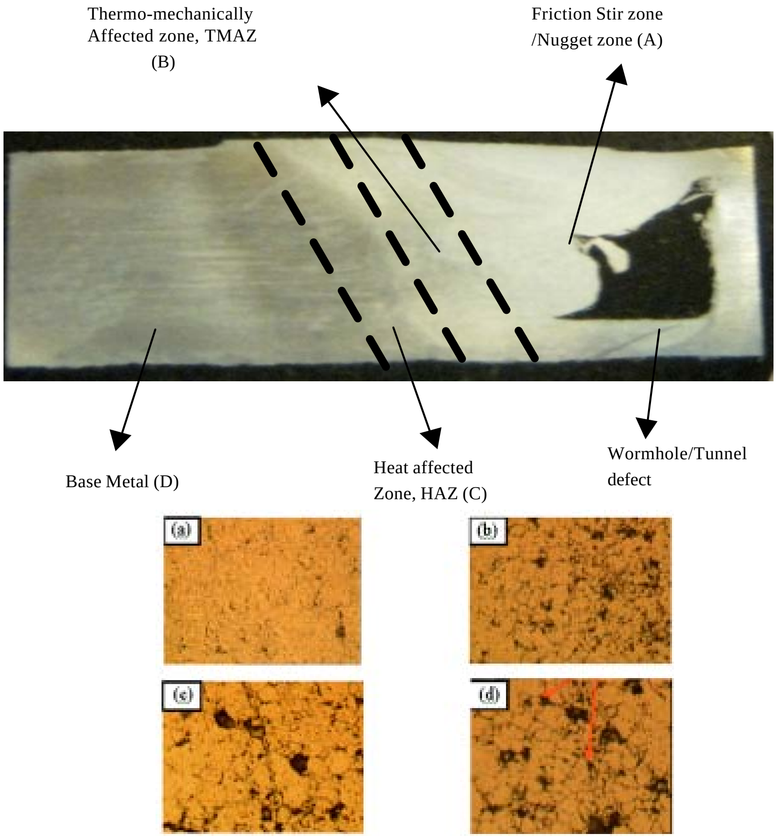


Fig. 5: Cross section area indicating different welded region generated from FSW process. (a) Friction stir processed zone or Nugget. (b) Thermo-mechanically affected zone (TMAZ). (c) Heat affected zone (HAZ). (d) Base metal. All optical microscopic images are taken at 20X magnification. Etching reagent: 25mL NH_4OH, 20mL distilled water and 8-25mL of H_2O_2 (3%)

there is generally a distinct boundary between recrystallized zone and the deformed zones of TMAZ.

The region, which has fine grain structure with porosity, is called Heat-Affected Zone (HAZ). It is a zone that clearly lies closer to the weld centre. The material has experienced a thermal cycle, which has modified the microstructure and the mechanical properties. However, there is no plastic deformation occurred in this area. Whereas the region with least fine grain structures with large porosity is the base metal. This part is remote from the weld and not been deformed. It might have experience a thermal cycle from the weld but not affected the microstructure or mechanical properties.

Besides having microstructure evolution, Table 2 also illustrates the value of tensile strength of FSW welds is near to the tensile strength of the parent metal. The most optimum set of parameters from the experiment was at 3000 rpm, travelling speed of 40 mm min^{-1} and penetration depth of 8 mm. The lower tensile strength was expected because of the material did not has high composition of alloy and not being tempered to give more influences to alloy response. The high thickness of the material also results in low cooling rate, which affect the properties of the material.

Figure 6 shows the base metal which is not affected by the FSSW. The microstructure has very coarse grains with lots of small pores. The porosity might be because of the inclusions of Copper in the 1100 Aluminum alloy or oxide stringers that interrupted during the manufacturing process of 1100 Aluminum alloy. Whereas the TMAZ shows the microstructure at this region has coarse grains with small pores but quite less than the base metal. These might happened because of the force from the stirring tool gives more compaction to the grains. For the finest grain structure in the spot welded region is called the stir zone. Even though it has large size porosity, the porosity formed is quite less than base metal region and TMAZ zone. The

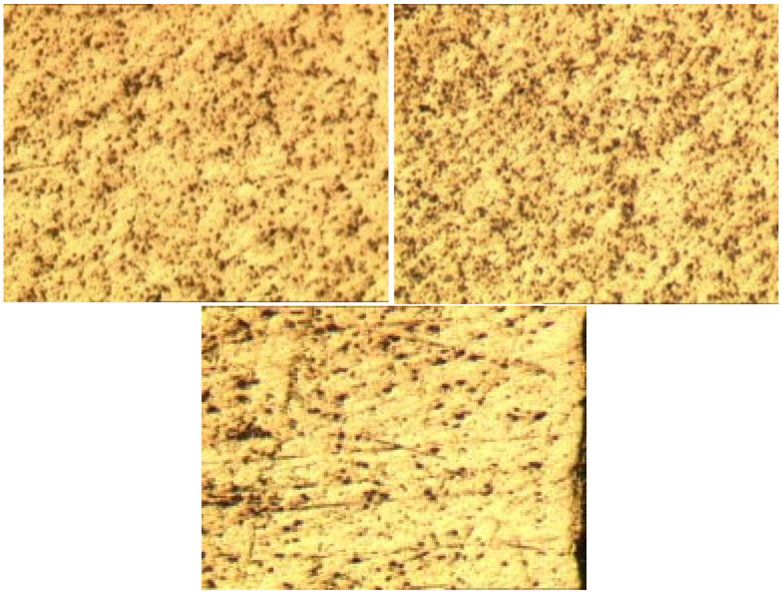


Fig. 6: (a) Micrograph view of base metal region (b) region affected by the tool shoulder (c) region affected by the tool pin. All optical microscopic images are taken at 10X magnification

Table 3: FSSW parameters and their tensile strength

Sample no	Spindle speed (rpm)	Penetration rate (mm/min)	Maximum load applied (N)
1	2000	55	1905.0
2	2000	70	2182.8
3	2000	85	2181.3
4	4000	55	1967.7
5	4000	70	1994.8
6	4000	85	2041.6
7	6000	55	1810.5
8	6000	70	1859.5
9	6000	85	1874.4

large size of porosity might happen because of the higher force from the stirring tool pin that gives more compaction to the grains of inclusions of copper or oxide stringers in the metal.

The tensile test in Table 3 illustrates the maximum load withstand by FSSW spot welds at different parameters. The optimum parameter for FSSW is 2000 rpm rotational speed with penetration rate of 75 mm/min which results maximum load which is 2182.8 N. The area proportional to the force is 0.00006 m^2. Thus, the maximum tensile strength of FSSW spot weld in this experiment is 36.38 MPa. The tensile strength of 1100 Aluminum alloy is 110 MPa (Davis, 1993). Thus, the friction stir spot welded tensile strength is closed to 1100 Aluminum alloy by 33.1%. The lower tensile strength was expected because of the material has no high alloy composition and not being tempered to give more influences to alloy response.

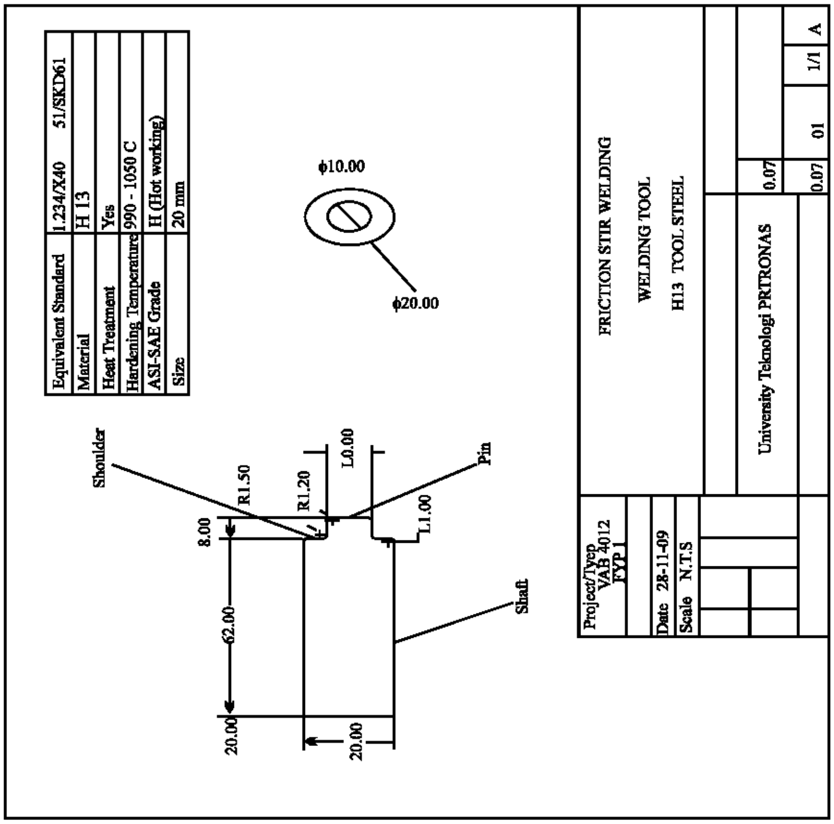
CONCLUSIONS

For FSW, there are four different regions appeared from the welds, which are friction stir nugget zone, TMAZ, HAZ and the base metal or unaffected material. The tensile strength of friction stir welds is closer to the tensile strength of the aluminum alloy 2011. Heat treatment to the material could increase the tensile strength of FSW welds. Heat treatable aluminum alloy such as 2, 6 or 7 xxx series are preferable to give closer tensile strength of welds to the parent metal tensile strength. Whereas the tunnel defect occurred in the weld can be avoided by choosing suitable welding process parameters for aluminum alloy such as rotational speed, transverse speed or stirring time during the plunging.

In the FSSW, there are three different regions formed by the spot welds which are base metal or non-affected region, stir zone and TMAZ. The tensile strength of the spot welds is closer to the tensile strength of the 1100 Aluminum Alloy. The porosity of the material could be avoided by using high strength aluminum alloy and by increasing the dwell time of the welding process.

For future works, two plates of Aluminum Metal Matrix Composite with composition of 242 Aluminum alloy and 30% volume percent of reinforced particle of Alumina, Al_2O_3 will be jointed using FSW and will be compared with conventional welding, Gas Tungsten Arc Welding (GTAW) on the same material in the scope of microstructure evolution and tensile strength of both welds.

APPENDIX



Equivalent Standard	1.234/X40 51/SKD61
Material	H 13
Heat Treatment	Yes
Hardening Temperature	990 - 1050 C
ASI-SAE Grade	H (Hot working)
Size	20 mm

Fig. A1: Detailed design of FSW tool

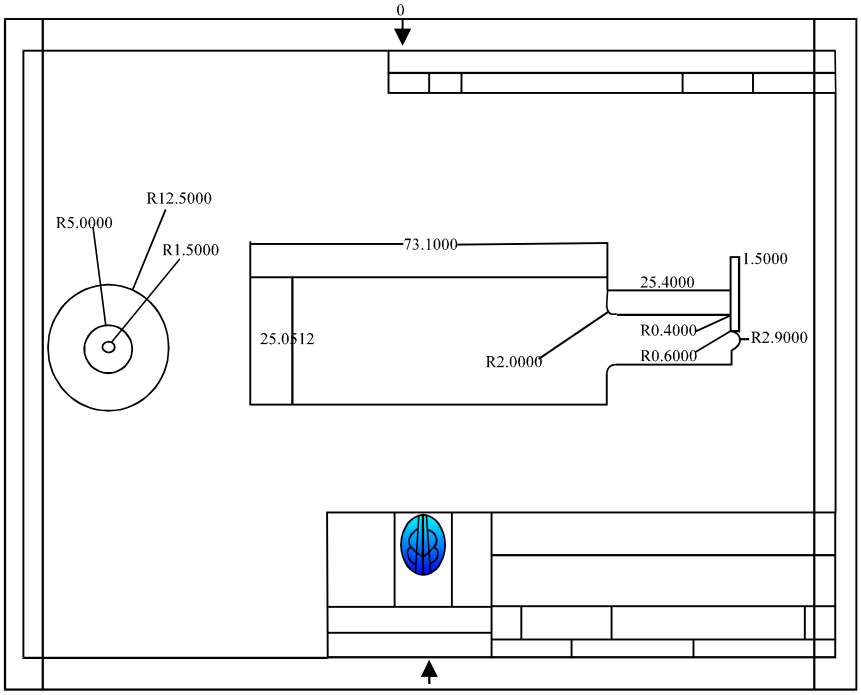


Fig. A2: Detailed design of FSSW

Fig. A3: FSW tool

Fig. A4: FSSW tool

REFERENCES

Badeshia, H.K.D.H., 2003. Major review on friction stir welding. Proceedings of the International Conference on Aluminum (INCAL 2003).

Colligan, K., I. Ucok, K. McTernan, P. Konkol and J.R. Pickens, 2001. Friction stir welding of thick section 5083-h131 and 2195-t8p4 aluminum plates. Proceedings of the 3rd International Symposium on Friction Stir Welding, Kobe Exhibition Center, Port Island, Kobe, Japan, September 2001 (Distributed by TWI on CD).

Mishra, R.S. and M.W. Mahoney, 2007. Friction stir welding and processing. ASM Int., pp: 35.

Mitlin, D., V. Radmilovic, T. Pan, J. Chen, Z. Feng and M.L. Santella, 2006. Structure-properties relations in spot friction welded (also known as Friction Stir Spot Welded) 6111 Aluminum. Mater. Sci. Eng. A, 441: 79-96.

Pan, T.Y., A. Jouquin, D.E. Wilkosz, L. Reatherford, J.M. Nicholson, Z. Feng and M.L. Santella, 2004. Spot friction welding for sheet aluminum joining. Proceedings of the 5th International Symposium of Friction Stir Welding, Sept. 14-16, Metz, France, pp: 1-7.

Thomas, W.M., E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith and C.J. Dawes, 1991. Friction -stir butt welding. GB Patent No. 9125978.8, International Patent No. PCT/GB92/02203.

Yuh, J.C. and Q. Xinhai, 1999. Heat transfer and thermo-mechanical analysis of friction stir joining of aluminum alloy 6061-T6 plates. Proceedings of 1st International Symposium on Friction Stir Welding, June 1999 (Thousand Oaks, CA), TWI.

Davis, J.R., 1993. Aluminum and Aluminum Alloys: ASM Specialty Handbook. Illustrated Edn., ASM International, NY, ISBN-10: 087170496X, pp: 784.