Friction Stir Welding

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Friction stir welding is a method of materials processing that enables the joining of similar and dissimilar materials. The process, as originally designed by The Welding Institute (TWI), provides a unique approach to manufacturing—where materials can be joined in many designs and still retain mechanical properties that are similar to, or greater than, other forms of welding. This process is not free of defects that can alter, limit, and occasionally render the resulting weld unusable.

friction stir welding (FSW) nondestructive testing defect ultrasonic testing

1. Introduction

Friction stir welding (FSW) is a joining process that was first demonstrated by The Welding Institute (TWI) of Great Britain in 1991 [1]. Since that time, FSW use has soared, and by the end of 2007, TWI had issued 200 licenses for the process. Its applications continue to grow. In addition, approximately nineteen hundred patent applications have also been filed relating to aspects of FSW [2][3]. The popularity of the process can be related to the multiple advantages that FSW offers, when compared with other jointing modalities, including the ability to join vastly different metals, when performed correctly, achieve minimal defect creation, maintain much higher material strength along the bonds than typical for other joints, and provide smooth surfaces after joining.

In performing the FSW process it typically involves two metals clamped on a rigid surface that serves as an anvil together and a rotating shoulder, a mechanical "stirring" device that resembles a drill bit. The anvil serves to react the downward pressure, i.e., the plunge force, during the FSW process. By forcing the rotating shoulder into the materials along the weld interface, a frictional force is generated due to the high speeds and maintained downward pressure of the rotating shoulder against the metal plates. The resulting frictional heating creates a softened zone which is mechanically plasticized at the location of joining (**Figure 1**). The welding tool is simultaneously rotated and moved along the desired weld line, blending the materials along the path. The resulting weld is typically stronger than that given by traditional fusion welding methods because it is formed at a lower temperature, which minimizes a heat-affected zone and this also reduces distortion and resulting residual stress. In addition, FSW is an environmentally friendly process, as it does not use shielding gas or filler material and it involves minimal energy input.

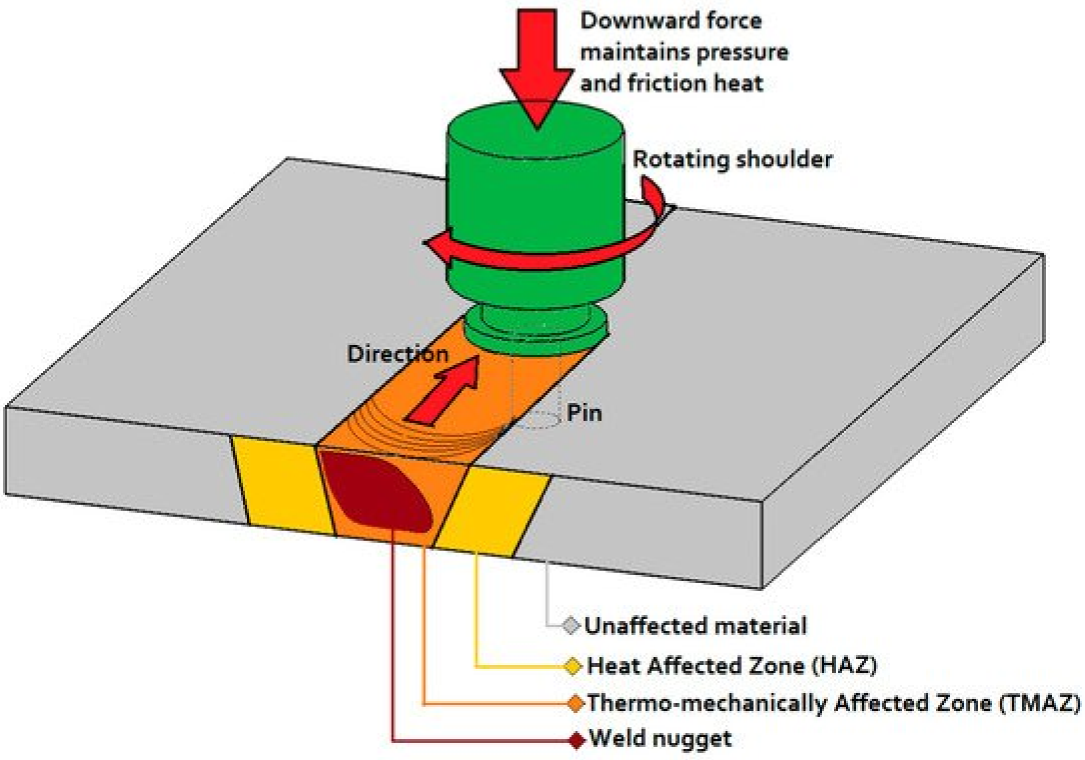

Figure 1. Friction Stir Welding (FSW) tool and system setup.

Since FSW is typically implemented in an automated process, when using correctly designed tools and parameters, defects should not occur. However, if the process is incorrectly controlled, the resulting quality of the weld can be degraded. For any material joining technique—No process is perfect, and defects can potentially occur. For FSW wormholes, kissing bonds, and defects caused by lack of penetration are the typical defects of current concern in industry [4][5]. With the use of FSW soaring, there is a need for nondestructive evaluation (NDE) processes that are superior to those currently available in the market [6] to provide adequate quality control [7], particularly for safety critical applications.

The nondestructive testing (NDT) demands by industry when FSW is used are that fast and cost-efficient methods are provided to assess the weld quality. Although welds are generally of high quality, some heterogeneity may arise due to the improper stirring of the parent material, lack of penetration of the tool pin, poor choice of tool pin design or improper choice of the process parameter window. When defects do occur, they are very different in form from those typically found in a conventional fusion welding process.

A further constraint, in terms of inspection needs, is that the FSW method is typically a high-end fabrication method. Destructive evaluation of such welds in most cases is not recommended for evaluating quality since they are costly, in terms of lost items, and time consuming to conduct [8]. When used destructive examination techniques generally involve bending tests and metallography/macrographs. In these techniques, the welded samples are removed from the original welding surface, but such samples only provide data for the region where measurements, such as micrographs, are taken. In general, evaluation of weld quality is most commonly performed post-weld using conventional non-destructive testing methods, such as X-rays, ultrasonic testing, eddy current and dye penetrant, although the later are limited to detecting surface defects. The specific type, size, shape and orientation of a defect all affect the detectability and characterization of the specific anomaly, and this depends on the specific nondestructive method used [7][9].

2. Applications of Friction Stir Welding

FSW is ideal for applications where higher strength properties are required along the welded seam. Examples of applications include those in the aircraft, marine, nuclear and the aero-space industries where extreme environments require welds to reliably have specific properties. Additionally, FSW welding typically creates stronger metallurgical bonds, it is also commonly a faster welding process, and can enable fabrication of designs that reduce the overall complexity of many components. In most cases, there is also a reduction in weight as no additional material was introduced. In the case of aircraft manufacturing, FSW is especially beneficial as the use of rivets and raised weld beads that can adversely impact the aerodynamics of the craft, can be avoided. This is especially important for supersonic craft, as the drag increases exponentially with surface roughness.

To take advantage of the benefits of using FSW, Eclipse Aerospace was one the first companies to utilize the process and implemented it on their 500 and 550 series business jets. A total of 128 m of friction stir welds was used on the jets and this replaced 60% of the rivets, resulting in a substantial reduction in materials used and hence overall weight. Additionally, the use of FSW saved time, as the welding process can be performed at a rate 10× faster than riveting, decreasing the time to build one airframe substantially compared to an original 5 h. As a result of the adoption of the use of this advanced welding process, the Eclipse 500 and 550 business jets were granted approval for double the service life, as compared with the earlier versions, with an increase to 20,000 pressurization cycles. This was due to the increased strength of the airframe, which was 3× stronger than those fabricated using conventional riveting [10]. Since Eclipse started using FSW, other companies including Spirit Aerosystems, Boeing, and Embraer have all begun production of components fabricated using FSW [11]. In addition to the aerospace industries, the possibility of improved fabrication of lightweight materials makes FSW a good candidate for applications in the automotive and rail transportation fields [12].

The aforementioned is just one of the multitudes of uses for FSW in today's industries. The ability to weld dissimilar metals and composites [7] with relative ease has now driven the process to be adopted across various industries. The fact that this technique is superior in many ways compared to traditional processes is why it has been so popular and rapidly adopted in a relatively short time. FSW is a one of a kind material joining technique, which provided a new technology with significant potential for improved joining of materials. The following sections describe the most common applications of the FSW. However, it should be noted that there are a variety of other applications, which are developed for FSW such as friction stir spot welding, multi-pass FSW, tandem stir welding and bobbin welding. In this paper, the types of defects, mechanism of generation, and methods of NDT used for defect detection is discussed. For more advanced application of FSW, such as mentioned above, the NDT techniques might need to be adjusted accordingly.

2.1. Welding of Conventional Metals

FSW is a solid-state process that can provide improvements over conventional welding in terms of both quality and performance for a wide range of materials, specifically those which are difficult-to-weld, such as aluminum [13][14], and for cases involving steel [15] where mechanical properties of the FSW material compare favorably with the properties of the parent metal. Furthermore, FSW provides a lower-cost and more environmentally friendly process with less energy consumption and a more repeatable performance when compared with conventional joining [16].

2.2. Welding of Dissimilar Materials

One of the main advantages of FSW is its ability to join dissimilar metals and alloys where the combination might not be compatible in terms of chemical and mechanical properties when considering conventional welding techniques. This is possible because FSW does not involve bulk melting of the materials that are joined [17][18]. Joining dissimilar alloys has many different applications including in the automotive, aerospace and shipbuilding industries where FSW can be a solution to cases where there are no alternative conventional welding method available [19][20][21]. An example of a configuration for joining dissimilar materials with a butt joint using a friction stir welding process, representing the importance of tool offset on FSW of dissimilar materials is shown in **Figure 2**.

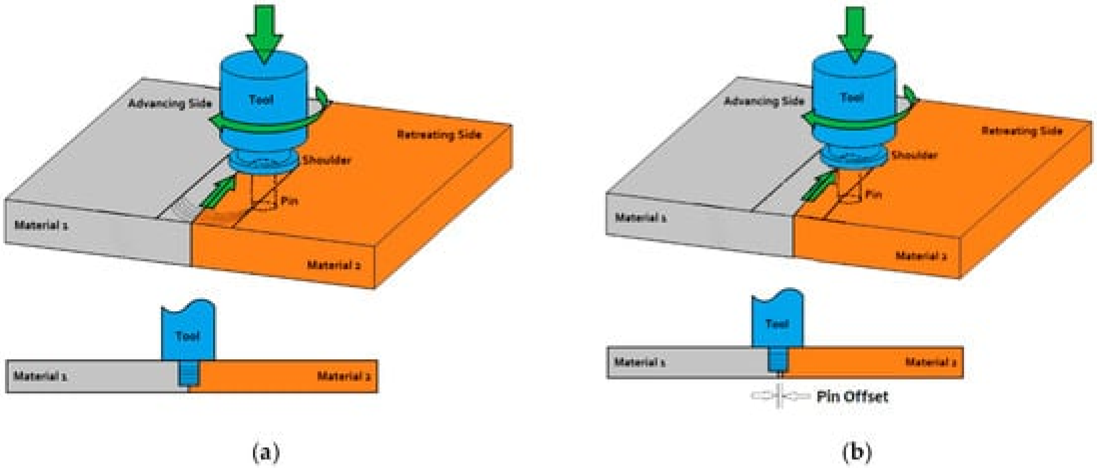

Figure 2. Schematic showing configuration for joining dissimilar materials using a friction stir welding process. (**a**) No tool offset, (**b**) Existence of tool offset.

2.3. Friction Stir Additive Manufacturing

Friction stir welding as a solid-state joining process can be used for fabrication of multilayer metal parts. This process works by joining metals layer-by-layer until the desired shape and thickness of the part is achieved [22][23]. The advantage of this method is that each previously added layer acts as a support for the next pass so that the structure is self-supported during the manufacturing process [23][24]. Investigations show that mechanical properties of multilayer FSW formed materials are comparable to those of the corresponding base metal. In addition, there are potentially improved mechanical properties in the weld zone' when compared to those for the base metal [23].

3. Friction Stir Welding Process

FSW differs in many ways from a traditional welding process and other jointing processes that employ an external heat source. All heating that occurs with FSW is generated from the joining process itself. In the analysis of this process there are many variables that are related to the heat generation and input into the part during FSW such as traverse speeds, rotation speed, downward force, pin design, and the tilt angle of the pin. These variables have a dependence on the properties of the material being welded. This combination of parameters and material properties all interact and the interplay of the relationships all affect the resultant weld properties in different ways. Through the optimization of these parameters, FSW welds can exhibit high strengths, but may not always be defect free. When the process is correctly designed, the optimum parameters allow for a stick-slip wiping flow where the material flowing into the region ahead of the pin is balanced by the material flowing into the space behind the tool [25].

3.1. Heat Generation

FSW differs greatly from other welding processes in that there is no external heat source and all of the heat involved in the joining process is generated through the tool-material interaction. The tool action on the workpiece generates considerable stress and strain at the tool-workpiece interface. The heat is primarily generated by high shear stresses and strain rates in the material at the tool/workpiece interface [2]. For a given alloy and plate thickness with a particular tool, the primary operating process variables which affect the heat generation phenomena are the pin geometry and then the downward force, tool plunge depth, rotation speed, and traverse speed. The downward force is a preset variable (if welding is not accomplished under position control), while the tool plunge depth needed is defined by sample thickness. This leaves rotation speed and traverse speed as the undefined process variables. Increased rotation speed leads to higher levels of heating and hence temperatures induced in the material (**Figure 3**). Tang et al. (1998) performed a test in which the tool rotation speed was varied and the resulting temperature of the weld in a 6061-T6 aluminum plate was measured for various speeds; all other parameters were kept constant. At a tool rotation speed of 300 rpm, a temperature of 425 °C was recorded. An increase to 650 rpm resulted in a 40 °C increased to 465 °C, and a further increase in speed to 1000 rpm resulted in a further increase of 20 °C to 485 °C [26]. Variation in the second key parameter, the transverse speed, is found to directly impact weld quality. There is an optimal set of speed conditions with degraded welds occurring when the speed is either too slow or too fast. When the transverse speed is too fast, occurrence of defects is common because the pin moves too fast to give the time needed to properly mix the material and to generate the needed level of heat input. A slow traverse speed will create too much heat within the weld and lead to different forms of defects, knows as flash or voids [27].

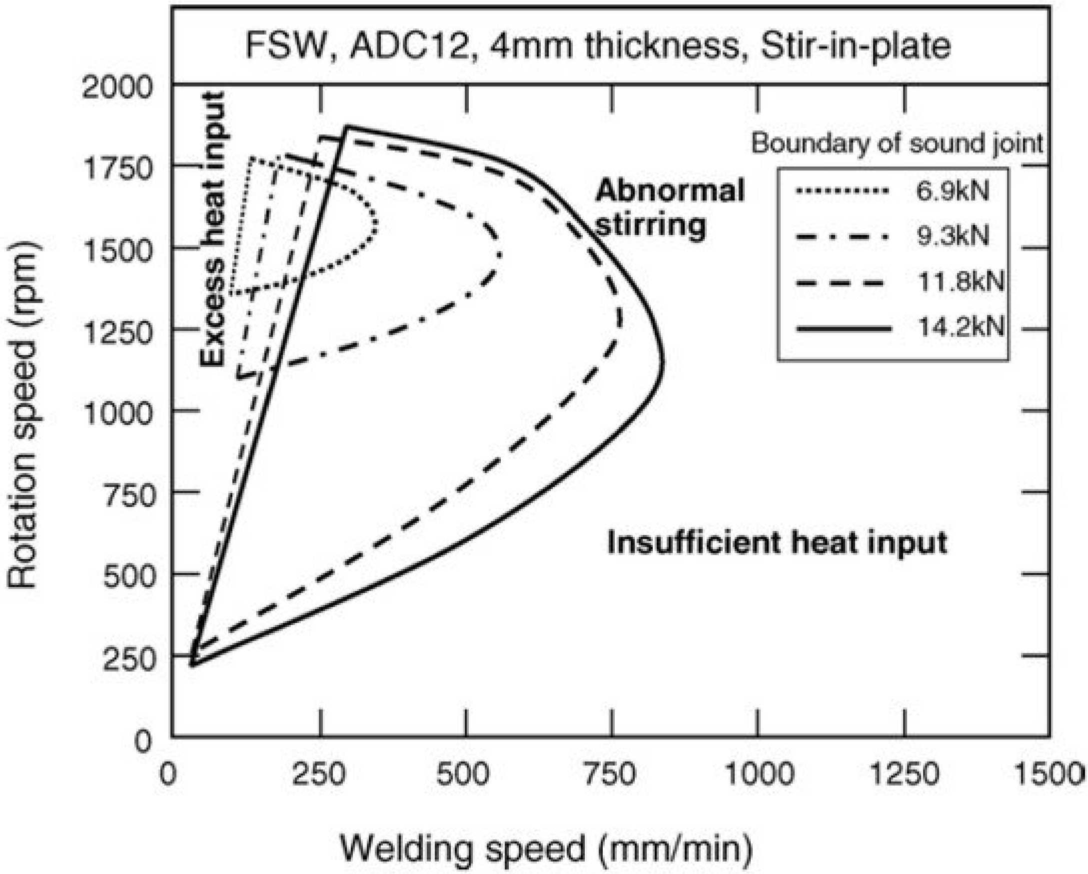

Figure 3. Tool rotation versus traverse welding speed showing heat generation. Reproduced with permission from [28], Elsevier, 2006.

3.2. Tool Properties

Tool properties such as geometry play a critical role in determining material flow and it controls what is the optimal transverse speed for good quality weld formation [29][30]. The tool is designed with a shoulder and a pin, as shown in **Figure 1** and it has two main functions: to control the material flow and generate heat. The pin and shoulder can be any one of multiple designs which have been developed to encourage the formation of the desired microstructure and resulting mechanical properties. More modern tools are designed so as to reduce displaced volume. For example the MX Triflute pin reduces displaced volume by 60% when compared to earlier conventional pins [31]. The advances in design of this tool reduces welding force, enables easier flow of plasticized material, creates downward auguring, and decreases the interface area between the pin and the plasticized material [31]. Additional tool designs have been investigated so as to be able to perform various functions during welding [32][33]. In producing a tool design a combination of life and performance parameters also need to be considered for a FSW processes so as to minimize the equipment costs associated with the process [34].

3.3. Effect of Anvil Back Plate

Anvil back plates have a significate effect of properties of FSW due to the interaction with the plunge force as well as influence on heat dissipation of the process. The influence on heat dissipation will affect the microstructure evolution in the weld nugget and thermomechanically affected zone. For example, the conventional steel anvil back plates have a high thermal conductivity, which increases the dissipation of the generated heat [35].

References

1. Thomas, W.M.; Murch, M.G.; Nicholas, E.D.; Temple-Smith, P.; Needham, J.C.; Dawes, C.J. Improvements Relating to Friction Welding. Google Patents EP 0653265 A2, 17 May 1995.
2. Threadgill, P.L.; Leonard, A.J.; Shercliff, H.R.; Withers, P.J. Friction stir welding of aluminium alloys. Int. Mater. Rev. 2009, 54, 49–93.
3. Thompson, J.M. Friction Stir Welding Machine and Method. U.S. Patent 6302315 B1, 16 October 2001.
4. Podrzaj, P.; Jerman, B.; Klobčar, D. Welding defects at friction stir welding. Metalurgija 2015, 54, 387–389.
5. Kah, P.; Rajan, R.; Martikainen, J.; Suoranta, R. Investigation of weld defects in friction-stir welding and fusion welding of aluminium alloys. Int. J. Mech. Mater. Eng. 2015, 10, 1–10.
6. Kinchen, D.G.; Martin, L.; Space, M.; Orleans, N.; Aldahir, E. NDE of friction stir welds in aerospace applications. Insp. Trends 2002, 1, 1–7.
7. Cerniglia, D. A Case Study on the Evaluation of Friction Stir Welds by Ultrasonic Inspection Technique. In Proceedings of the 14th International Symposium on Nondestructive Characterization of Materials (NDCM 2015), Marina Del Rey, CA, USA, 22–26 June 2015; p. 308.
8. Sagar, S.P.; Miyasaka, C.; Ghosh, M.; Tittmann, B.R. NDE of friction stir welds of Al alloys using high-frequency acoustic microscopy. Nondestruct. Test. Eval. 2012, 27, 375–389.
9. Bond, L.J.; Baquera, M. Ultrasonic sizing and imaging. In ASM Metals Handbook; ASM International: Materials Park, OH, USA, 2018; pp. 291–321.
10. Mehta, M.; Reddy, G.M.; Rao, A.V.; De, A. Numerical modeling of friction stir welding using the tools with polygonal pins. Def. Technol. 2015, 11, 229–236.
11. Dubourg, L.; Merati, A.; Jahazi, M. Process optimisation and mechanical properties of friction stir lap welds of 7075-T6 stringers on 2024-T3 skin. Mater. Des. 2010, 31, 3324–3330.
12. Elatharasan, G.; Kumar, V.S.S. Modelling and optimization of friction stir welding parameters for dissimilar aluminium alloys using RSM. Procedia Eng. 2012, 38, 3477–3481.
13. Rhodes, C.G.; Mahoney, M.W.; Bingel, W.H.; Spurling, R.A.; Bampton, C.C. Effects of friction stir welding on microstructure of 7075 aluminum. Scr. Mater. 1997, 36, 69–75.
14. Mahoney, M.W.; Rhodes, C.G.; Flintoff, J.G.; Spurling, R.A.; Bingel, W.H. Properties of friction-stir-welded 7075 T651 aluminum. Metall. Mater. Trans. A 1998, 29, 1955–1964.

15. Thomas, W.M.; Threadgill, P.L.; Nicholas, E.D. Feasibility of friction stir welding steel. Sci. Technol. Weld. Join. 1999, 4, 365–372.
16. Lohwasser, D.; Chen, Z. Friction Stir Welding: From Basics to Applications; Woodhead Publishing Ltd.: Cambridge, UK, 2009.
17. DebRoy, T.; Bhadeshia, H.K.D.H. Friction stir welding of dissimilar alloys—A perspective. Sci. Technol. Weld. Join. 2010, 15, 266–270.
18. Kumar, N.; Yuan, W.; Mishra, R.S. A framework for friction stir welding of dissimilar alloys and Materials. In Friction Stir Welding of Dissimilar Alloys and Materials; Kumar, N., Yuan, W., Mishra, R.S., Eds.; Butterworth-Heinemann: Oxford, UK, 2015; pp. 15–33.
19. Murr, L.E. A review of FSW research on dissimilar metal and alloy systems. J. Mater. Eng. Perform. 2010, 19, 1071–1089.
20. Okamura, H.; Aota, K. Joining of dissimilar materials with friction stir welding. Weld. Int. 2004, 18, 852–860.
21. Kumar, N.; Yuan, W.; Mishra, R.S. Friction stir welding of dissimilar alloys. In Friction Stir Welding of Dissimilar Alloys and Materials; Kumar, N., Yuan, W., Mishra, R.S., Eds.; Butterworth-Heinemann: Oxford, UK, 2015; pp. 43–69.
22. Palanivel, S.; Nelaturu, P.; Glass, B.; Mishra, R.S. Friction stir additive manufacturing for high structural performance through microstructural control in an Mg based WE43 alloy. Mater. Des. 2015, 65, 934–952.
23. Lim, Y.C.; Sanderson, S.; Mahoney, M.; Wang, Y.; Chen, J.; David, S.A.; Feng, Z. Fabrication of thick multilayered steel structure using A516 Grade 70 by multipass friction stir welding. Sci. Technol. Weld. Join. 2016, 21, 564–569.
24. Taendl, J.; Nambu, S.; Inoue, J.; Enzinger, N.; Koseki, T. Friction stir welding of multilayered steel. J. Sci. Technol. Weld. Join. 2012, 17, 244–253.
25. Aditya, A.V.; Arora, H.S.; Mukherjee, S. Corrosion behavior of ZrTiCuNiBe bulk metallic glass subjected to friction stir processing. J. Non. Cryst. Solids 2015, 425, 124–129.
26. Tang, W.; Guo, X.; McClure, J.C.; Murr, L.E.; Nunes, A. Heat input and temperature distribution in friction stir welding. J. Mater. Process. Manuf. Sci. 1998, 7, 163–172.
27. Imam, M.; Biswas, K.; Racherla, V. On use of weld zone temperatures for online monitoring of weld quality in friction stir welding of naturally aged aluminium alloys. Mater. Des. 2013, 52, 730–739.
28. Kim, Y.G.; Fujii, H.; Tsumura, T.; Komazaki, T.; Nakata, K. Three defect types in friction stir welding of aluminum die casting alloy. Mater. Sci. Eng. A 2006, 415, 250–254.

29. Reza-E-Rabby, M.; Tang, W.; Reynolds, A.P. Effect of tool pin features on process response variables during friction stir welding of dissimilar aluminum alloys. Sci. Technol. Weld. Join. 2015, 20, 425–432.

30. Costa, M.I.; Verdera, D.; Costa, J.D.; Leitao, C.; Rodrigues, D.M. Influence of pin geometry and process parameters on friction stir lap welding of AA5754-H22 thin sheets. J. Mater. Process. Technol. 2015, 225, 385–392.

31. Mishra, R.S.; Ma, Z.Y. Friction stir welding and processing. Mater. Sci. Eng. R Rep. 2005, 50, 1–78.

32. Thomas, W.M.; Johnson, K.I.; Wiesner, C.S. Friction stir welding-recent developments in tool and process technologies. Adv. Eng. Mater. 2003, 5, 485–490.

33. Thomas, W.M.; Staines, D.G.; Norris, I.M.; de Frias, R. Friction stir welding tools and developments. Weld. World 2003, 47, 10–17.

34. Thompson, B.T. Tool Degradation Characterization in the Friction Stir Welding of Hard Metals. Master's Thesis, Ohio State University, Columbus, OH, USA, 2010.

35. Chu, W.S. Influence of different anvil back plates on heat dissipation velocity of the micro-friction stir welding process. Appl. Mech. Mater. 2015, 786, 415–420.