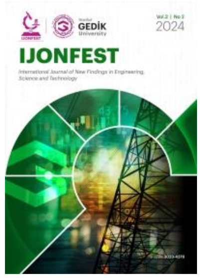
September 2024, Vol:2, Issue:2

International Journal of New Findings in Engineering, Science and Technology

journal homepage: *https://ijonfest.gedik.edu.tr/*



The Current Progress in the Application of Friction Stir Welding in Transportation Industries

Gürel Çam[a]

[a] *Iskenderun Technical University, Faculty of Engineering and Natural Sciences, Iskenderun, Hatay, TÜRKİYE e-mail:gurel.cam@iste.edu.tr*

Abstract

The use of the friction stir welding (FSW) process as a relatively new solid-state welding technology in the transport industries has pushed forward several developments in different related aspects of these strategic industries. Due to the geometric limitations involved in the conventional FSW process, many variants have been required in recent years to suit the different types of geometries and structures. As a result, numerous variants such as refill friction stir spot welding (RF-SSW), stationary shoulder friction stir welding (SS-FSW), and bobbin tool friction stir welding (BT-FSW) have been developed. The RF-SSW variant eliminates the hole left at the end of the weld line where the stirring tool is pulled out. This facilitates the use of FSW process in component welding. The SS-FSW is low heat input process compared to conventional FSW which offers several advantages such as narrower HAZ and reduced microstructural and mechanical variation across the weld region. Similarly, BT-FSW process eliminates weld root defects and penetration defects and achieves a full penetration weld. Thus, these developments have led to a wider application of FSW technology in various transport industries, such as automobile, shipbuilding, high-speed trains, and aerospace industries. The main aim of this review article is to summarize the state of knowledge regarding the application of the FSW process in the aerospace industry and to make suggestions for future work.

Keywords: Joining, friction stir welding, refill friction stir spot welding, stationary shoulder friction stir welding, bobbin tool friction stir welding.

1. INTRODUCTION

Welding is a unique manufacturing method that allows the production of complex parts from materials that are difficult to shape or not economical. In these cases, individual parts are manufactured separately and then assembled using a suitable joining technique. In addition, welding technology is generally a complementary process, not an alternative to other manufacturing methods. Weldability is therefore one of the most important factors determining the widespread application of new materials. In recent years, the demand for complex products that cannot be produced in one piece or are very costly to produce, especially in the transportation industry, has increased due to developing technology. Electric vehicles, high-speed trains, jumbo jets and cruisers (large passenger ships) where fuel consumption is important are examples of such products.

https://doi.org/10.61150/ijonfest.2024020208

The progress made in the weldability of materials used in engineering applications with the development of new welding technologies such as friction stir welding (FSW) further increases the importance of welding technology. FSW, which was developed and patented by The Welding Institute (TWI) in England in the early 1990s, is generally used in longitudinal welding processes of sheets and plates both in butt or overlap configurations [1]. The application of the friction stir welding method is shown schematically in Figure 1 [2]. FSW is still considered the most important development in the welding of materials in the last 30 years [2-26]. Nowadays, this welding technique is used commercially for joining Al-alloys in many industries such as the maritime industry [27-29], high-speed train manufacturing [27,29], and the aviation industry [27,30,31]. Standard length Al-extrusion panels used on high-speed cruise ships are currently joined by this method. In addition, this method is also used successfully in the welding of fuel tanks used in aviation applications [31]. This welding technique is also used to make the butt joining of hollow Al extrusions used in the construction of high-speed train carriages in Japan [30]. The method has recently begun to be widely used in battery carrier systems of electric vehicles. Additionally, some FSW variants have been developed in recent years to improve welded joint performance. For example, the recently developed friction stir spot welding (FSSW) is a candidate to replace the traditional resistance spot welding in overlap welding applications of Al-alloy sheets where sealing is not required [32]. As a matter of fact, this method is successfully used in overlap welding operations of Al-alloy sheets, which is difficult by resistance spot welding. Thus, this variant, together with conventional FSW, will enable the use of lightweight Al-alloys in the manufacture of electric vehicles. This technique is currently on the brink of industrial use in the lap jointing of Al alloy sheets in the automobile industry. The method also presents itself as a potential candidate to replace riveting.

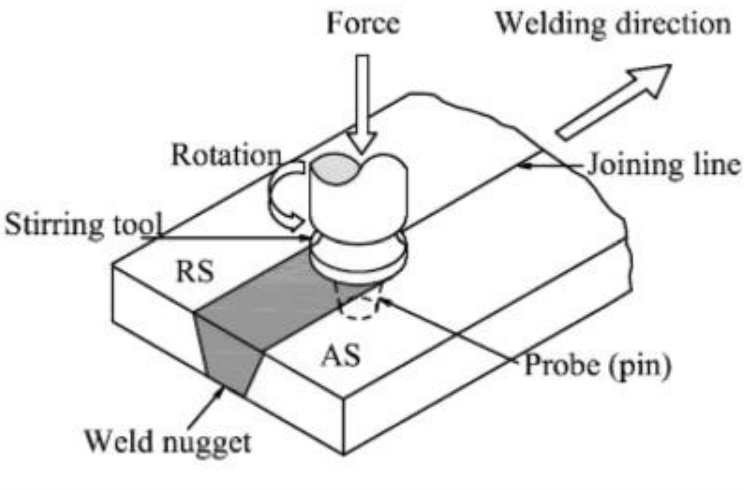


Figure 1. Schematic presentation of friction stir welding [2].
(AS: advancing side and RS: retreating side).

Although the FSW technique was initially developed for Al alloys [2-26,33-37], it also has great potential for use in the joining of Mg alloys [8,14,38-40], Cu alloys [8,41-43], Ti-alloys [8,17,18].], Al-alloy matrix composites [44-46], lead [47], steels [8,48-53], and thermoplastics [54-56]. In addition, it has also potential for joining different Al-alloys with similar behavior such as similar melting temperatures and hot workability [4,57-60] as well as for welding Al-alloys with Mg-alloys [61-64] and for joining different types of steel [65-70]. Various joint types such as butt, overlap, and T-joints can be produced with friction stir welding (Figure 2). However, cost-effective stirring tools are needed to join metal matrix composites and metals with high melting temperatures, such as steels and Ti-alloys, by friction stir welding [8, 12].

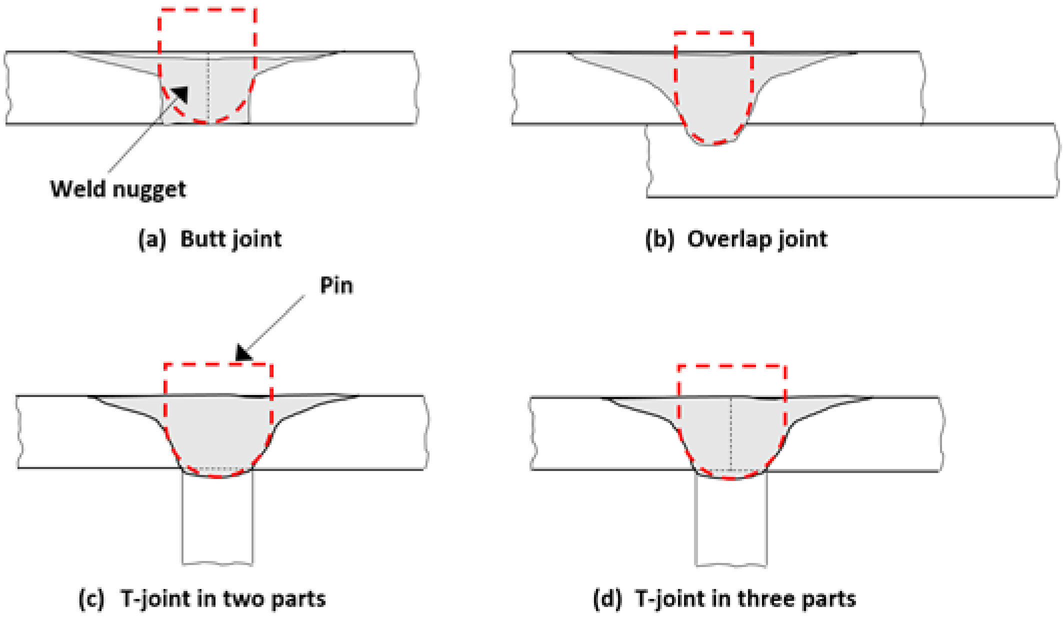


Figure 2. Joint types obtained by the FSW method: (a) butt joint, (b) overlap joint, (c) T-connection with two pieces of plate, and (d) T-connection with three pieces of plate [6].

The traditional FSW method does not give good results in cases where the mechanical properties of welded joints are inadequate as a result of high heat input, or to obtain joints that require high performance, especially in welding processes of different metals. For this reason, new FSW variants such as external cooling-assisted FSW [71-73] such as underwater FSW, and ultrasonic vibration-assisted FSW [74-77] have also been developed to reduce heat input thus to achieve high-performance joints and to prevent or minimize the formation of brittle intermetallic compounds in the welding of different metals, respectively. In recent years, in addition to external cooling-assisted and ultrasonic vibration-assisted FSW applications, new FSW variants have also been developed as a result of intensive research on the application of the method to different geometries and structure types. The most important of these new FSW variants are refill friction stir spot welding (RF-FSSW), stationary shoulder friction stir welding (SS-FSW), and bobbin tool friction stir welding (BT-FSW). These relatively new FSW variants will be discussed in the following section.

2. NEW FRICTION STIR WELDING VARIANTS

2.1 Refill Friction Stir Spot Welding

One of the new friction stir welding variants is friction stir spot welding (FSSW). The application of the friction stir spot welding technique is schematically illustrated in schematically in Figure 3 [4,78]. This joining process is done in three stages: plunging, stirring and tool withdrawal. After spot welding is achieved with this FSW variant, a gap is formed as a result of the tool withdrawal, as seen in Figure 3. In addition to the formation of voids, this process has other disadvantages such as a reduction in top plate thickness and hook-shaped joining [79]. As a result of efforts to prevent these weld defects, a new variant of this technique has also been developed in recent years. This new version of FSSW is called refill friction stir welding (RF-FSSW). Figure 4 schematically shows the refill friction stir spot welding process [3,80].

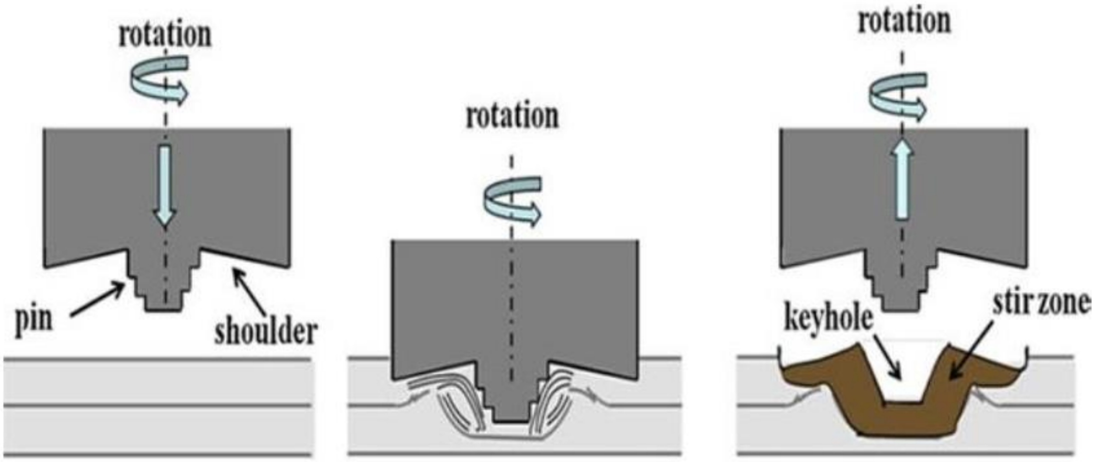


Figure 3. Schematic presentation of the stages of friction stir spot welding (FSSW) [78].

In the first stage of the RF-FSSW process, a preheating phase is initiated while the probe and shoulder are aligned at the same level on the top sheet surface. The friction effect at this stage softens the workpiece, allowing the stirring tool to rotate at high speed to begin plunging with alternating motion between the probe and the shoulder. In the second stage, the shoulder begins to plunge, causing further softening of the material so that the plasticized material is injected into the pin slot. In the third stage, the probe begins plunging to re-inject the displaced material. In the final stage, the shoulder and probe are again aligned parallel to each other on the top surface to create a void-free spot weld [81]. The RF-FSSW technique was successfully used by Boldsaikhan et al. [81] to weld sheets of aerospace aluminum alloys AA7075-T6 and AA2024-T3. In this study, AA2024-T3 was used as the lower plate representing the outer skin of the aircraft structure and AA7075-T6 was used as the upper plate representing the stiffener side of the aircraft's external skin-stiffening structure. Recently, this FSW variant has also been successfully employed to produce defect-free lap joints in Al-alloys such as Al 6061 for the production of cellular I-beams [82] and dissimilar joints such as between different Al-alloys for battery applications [83] and Al-Cu for battery tab-to-busbar applications [84].

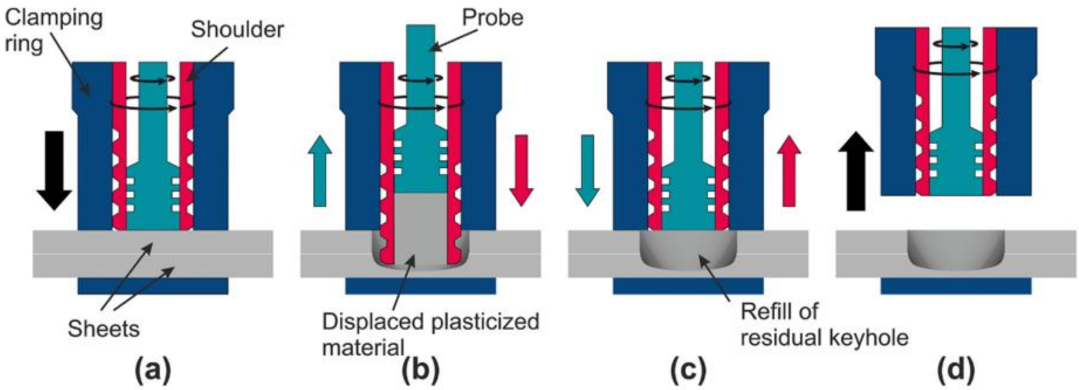


Figure 4. Schematic presentation of the stages of refill friction stir spot welding (RF-FSSW):

(a) clamping of sheets, (b) tool plunging and withdrawal of probe, (c) c) shoulder and probe reaching back to the sheet's surface and refilling the keyhole, and (d) release of the clamping force and tool withdrawal [3,80].

2.2 Stationary Shoulder Friction Stir Welding

The use of the FSW process in joining titanium-based alloys such as Ti-6Al-4V, which is widely used in aerospace applications, is limited due to their poor thermal conductivity. When using conventional FSW tools, heat is generated mainly at the top surface, resulting in a significant temperature gradient across the thickness of the welded plate, especially in thick plates. This problem, together with the limited but relatively high hot working range of alloys such as Ti-6Al-4V, makes it almost impossible to join titanium without defects with conventional FSW [85]. The Welding Institute (TWI) has developed the stationary shoulder friction stir welding (SS-FSW) variant to overcome this problem and weld titanium alloys using FSW [86]. The SS-FSW technique is shown schematically in Figure 5 [87]. In the SS-FSW process, the shoulder of the stirring tool moving along the weld does not rotate, only the pin of the stirring tool rotates within this fixed shoulder. Having the shoulder fixed significantly reduces the contribution of the shoulder to heat production and affects the heat distribution throughout the weld depth. Therefore, in the SS-FSW process, since the shoulder is stationary, a highly focused heat input is produced around the tool pin (i.e., probe) and excessive surface heating does not occur [88]. The SS-FSW technique was successfully applied by Russell et al. [88] in the welding of 6.35 mm thick Ti-6Al-4V plates and it was reported that the stationary shoulder provided more uniform heating throughout the thickness. As a result, it was observed that the microstructure was uniform throughout the entire weld cross-section. Additionally, the SS-FSW approach has also been used in welding aluminum alloys to develop uniform microstructure and crystallographic texture throughout the plate thickness [89].

In addition to porosity formation in fusion welding techniques, the most challenging obstacle in fusion welding and conventional FSW of high strength aerospace Al-alloys is extreme strength loss in the HAZ due to overaging resulting from the relatively high heat input [6-8,57,58,90-93]. The strength loss in the weld region is called strength undermatching and this leads to failure in this area [94-97]. Thus, it should be eliminated or at least minimized. The SS-FSW variant offers an advantage in this respect due to the stationary shoulder which reduces the heat input experienced by the workpieces during the joining process. For example, Wu et al. [87] conducted a detailed research to compare the SS-FSW method with the traditional FSW technique in welding high-strength aerospace Al-alloy AA7050-T765 sheets. In this study, they aimed to examine the effect of FSW welding parameters on power consumption by using the same stirring tool geometry in both conventional FSW and SS-FSW processes. The results obtained showed that the required heat input in the SS-FSW technique was 30% lower than in the traditional FSW technique. Additionally, the use of the SS-FSW technique has been determined to offer many advantages. These are:

- Formation of narrower and parallel heat affected zone (HAZ).

- Less variation in microstructure and other properties across the weld cross-section.
- Better cross-sectional tensile properties than traditional FSW method.
- Improvement in surface roughness due to the ironing effect of the non-rotating tool on the upper surface.

Similarly, the process has also been used to produce defect-free joints in Al-Li alloys (i.e., 2A97) in a recent study, and the best combination of strength and ductility was achieved at a rotational speed of 1000 rpm [98]. The SS-FSW process also offers an advantage in butt joining of dissimilar metals such as Al-alloys to Mg-alloys where a low heat input is required in order to reduce brittle intermetallic formation. However, the insufficient heat input may result in unfavorable material mixing in the weld zone which reduces the weld strength. Therefore, the process is usually used in combination with ultrasonic vibration, i.e. ultrasonic-assisted SS-FSW [99-102]. For instance, Hu et al. [101] employed an ultrasonic vibration and stationary shoulder-assisted hybrid FSW method to obtain dissimilar Al-Mg joints, and a maximum UTS of 161 MPa was achieved by this hybrid technology. Similarly, You et al [102] achieved a high-quality dissimilar Al-Cu joint by the ultrasonic vibration-assisted stationary shoulder FSW process.

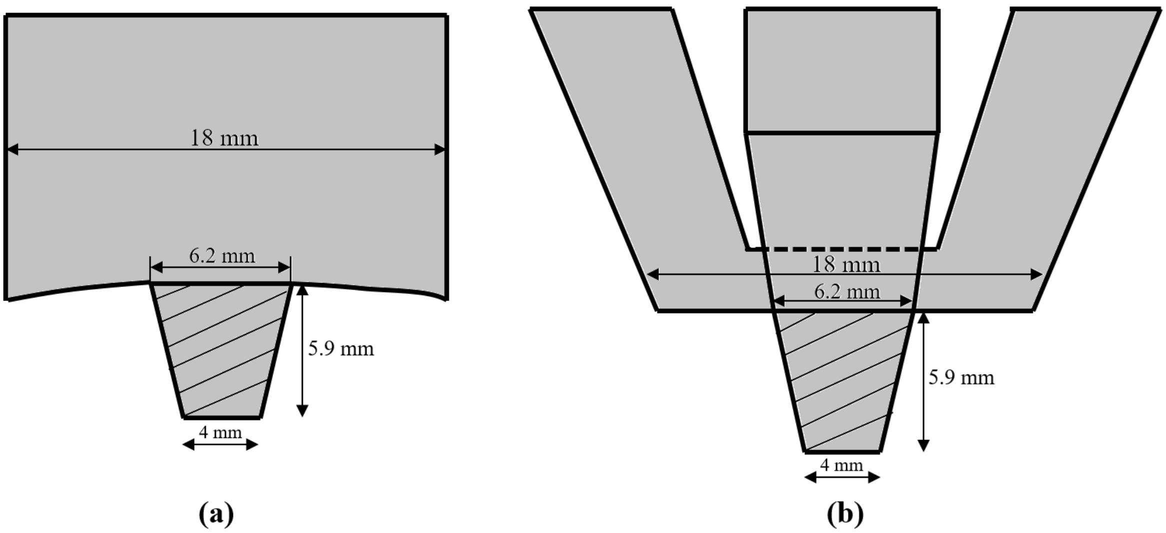


Figure 5. Comparison of the traditional FSW stirring tool and the stirring tool used in the SS-FSW method: (a) Traditional FSW and (b) SS-FSW [87].

On the other hand, it has been reported that when very high tool traverse and rotation speeds are used, a negative effect such as "speed cracking", which is observed in hot extrusion, may occur [87]. Owing to relatively low heat input compared to conventional FSW, the SS-FSW method has also been widely used to join some different and similar aluminum alloy sheets with high strength employed in aerospace applications [103-108]. These results indicate that the SS-FSW technique is one of the promising FSW variants for aerospace applications.

2.3 Bobbin Tool Friction Stir Welding

The use of double-shoulder (top and bottom shoulder) FSW tools, known as bobbin tools, represents one of the new developments of FSW technology, which has many advantages in terms of welded joint quality as well as machine flexibility and capacity [109-116]. The advantages of the bobbin tool friction stir welding (BT-FSW) method are:

- Since full penetration weld is achieved, weld root defects and penetration defects do not occur.
- Low Z forces on fixture and machine.
- No support plate required due to lower shoulder use.
- Low distortion due to low Z forces applied.
- Thickness variation tolerance ability.
- Ability to join closed profiles such as hollow extrusions.
- More homogeneous mechanical properties throughout the thickness of the weld section.

Figure 6 (a) shows a schematic representation of FSW with two shoulder (upper and lower) bobbin tools and (b) shows an example of the fixture setup used in the BT-FSW process [115]. A support plate is not needed in the BT-FSW method. This feature makes the method ideal for welding hollow profiles, and at the same time, since the applied vertical forces are low, less buckling and less distortion occur in the welded parts.

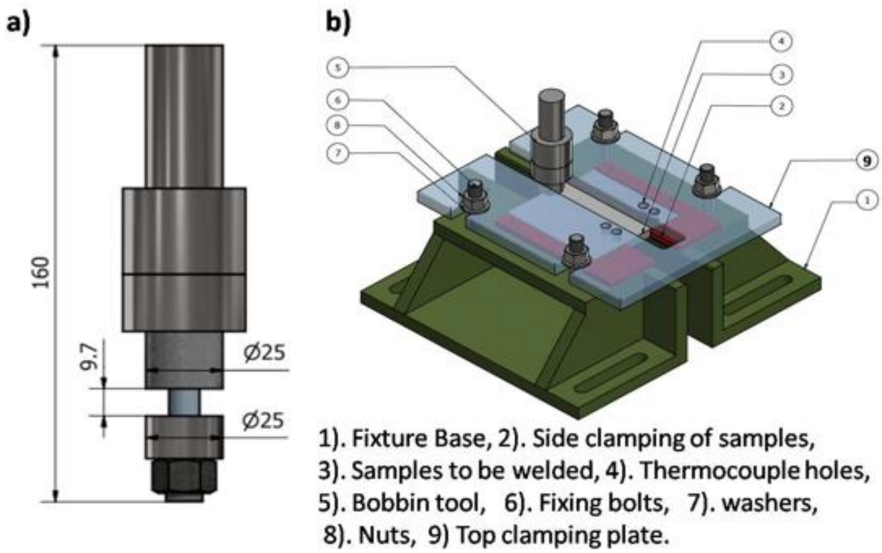


Figure 6. Schematic representation of the bobbin tool FSW technique: (a) an FSW bobbin tool used for welding 10 mm thick aluminum and (b) an example fixing setup used in the bobbin tool FSW process [115].

For example, Threadgill et al. [109] joined AA6082-T6 thick plates with FSW using both a bobbin tool and a conventional tool and reported that successful welded joints were obtained with both tools. However, they demonstrated that when the bobbin tool is used, the net axial force on the workpiece is almost zero, which has significant beneficial effects on machine design and cost. Similarly, Xu et al. [112,113] examined the welding of 12 mm thick AA7085-T7452 aluminum alloy sheets with both BT-FSW and conventional FSW and reported that successful joints were obtained in both methods. However, the joints obtained with the BT-FSW technique showed lower welding performance due to the presence of a Lazy S defect resulting from a larger amount of heat input [113]. On the other hand, Yang et al. [114] reported in a comparative study on AA6061-T4 sheets with BT-FSW and traditional FSW that similar welding performance values (approximately 93%) were obtained in both methods. Moreover, Wang et al. [110] investigated the weldability of 3.2 mm thick high-strength Al-alloy (AA2198) sheets used in aviation with BT-FSW and reported that strong welded joints (welding efficiency = 80%) were produced with different FSW parameters. Similarly, Ahmed et al. [116] conducted a study investigating the effect of tool pin profile and feed rate on the mechanical properties of aluminum alloy sheets welded by BT-FSW. The findings showed that the mechanical properties of the base plate can be preserved in the weld zone by optimizing the BT-FSW parameters.

However, the macrostructure of the stir zone obtained by the BT-FSW is governed by the refill behaviour of the plasticised metal. The refill occurs preferentially near the upper and lower shoulders, creating a triangular gap at the mid-thickness level. A recent study by Li et al [117] reported that tapering the stirring probe reduces the volume of displaced metal, leaving a smaller gap to be refilled during welding which leads to defect-free joints. More recently, a bobbin tool concept having one rotating and one stationary shoulder has been proposed [118]. This technique is known as semi-stationary shoulder bobbin-tool FSW. For instance, Goebel et al. [119] achieved flawless joints of AA2198 alloy by this variant and reported 30% less heat input and improved joint tensile properties as compared to conventional BT-FSW method. Similarly, Scupin [120] performed the semi-stationary shoulder BT-FSW to AA6082 alloy. They claimed that high welding speeds up to 2900 mm/min could be achieved, and the joint exhibited superior tensile properties close to those of the base metal. Furthermore, Li et al [121] very recently applied this technique to join AZ31B Mg-alloy. They reported that the use of semi-stationary BT-FSW method led to reduced forces as well as torque, enabling higher welding speeds up to 1500 mm/min.

3. GENERAL REMARKS

This review article clearly shows that defect-free butt joints can be obtained with the FSW process in Al-alloys and many other metals, particularly by employing the FSW variants. In addition, defect-free lap joints (spot welding) are readily achieved with refill FSSW while full penetration butt-joints can be obtained by the bobbin tool FSW process. However, the influence of welding conditions on joint performance has been determined to date only for Al-, Mg- and Cu-alloys. Today, friction stir welding (butt and lap welding applications) is currently used industrially to join Al alloys in the manufacture of ships, aircraft and space shuttles, trains and other vehicles. Although there is some work conducted particularly on SS-FSW of Ti-alloys and the application of the FSW variants such as SS-FSW in combination with ultrasonic vibration assistance to join Al-alloys with Mg-alloys, there is a need for further research on the applicability of the FSW variants in other structural alloys such as Mg-alloys and dissimilar metal combinations. The progress to be made in the welding of Al and Mg alloys in both similar and different combinations by friction stir welding variants will enable the mass production of light transportation systems, thus providing a significant reduction in fuel consumption. As a result, the application of this new welding method will increase in the coming days, especially in shipbuilding, aircraft and aerospace industry, automotive industry and other manufacturing sectors.

However, since high precision and high-quality part production is needed in the transportation industries, especially in the aviation industry, FSW variants suitable for the part geometry to be produced should be used and advanced NDT techniques such as special ultrasonic method (phased array ultrasonic method) must be employed to control the welded parts throughout production to determine whether the friction stir welded joints contain weld defects. Moreover, appropriate methods need to be developed in parallel to repair these defects to the highest standard and feasibility. Provided these shortcomings are overcome, the FSW technology in combination with the laser beam welding (LBW) process will enable significant weight savings in the aviation industry as well as in other transportation systems.

References

[1] Thomas, W.M., et al., International Patent Application No. PCT/GB92/02203 and GB Patent Application No. 9125978.8 and US Patent Application No. 5,460,317, Dec.1991.
[2] Ahmed, M.M.Z., El-Sayed Seleman, M.M., Fydrych, D., Çam G., A review on friction stir welding of dissimilar Al- and Mg-alloys: Scientometric analysis and strategies for achieving high-quality joints, Journal of Magnesium and Alloys, 2023, 11, 4082-4127.
[3] Ahmed, M.M.Z., El-Sayed Seleman, M.M., Fydrych, D., Çam G., Friction stir welding in the aerospace industry: The current progress and state-of-the-art review, Materials, 2023, Vol. 16, Article Number: 2971.
[4] Çam, G., Javaheri, V, Heidarzadeh, A., Advances in FSW and FSSW of dissimilar Al-alloy plates, J. Adhes. Sci. Technol., 2023, 37 (2), 162-194.
[5] Khaliq, U.A., Yusof, F., Chen, Z., Mohd Isa, M.S., Çam, G., A comprehensive review on friction stir welding of aluminum with magnesium: A new insight on joining mechanisms by interfacial enhancement, J. Mater. Res. Technol., 2023, 27, 4595-4624.
[6] Kashaev, N., Ventzke, V., Çam, G., Prospects of laser beam welding and friction stir welding processes for aluminum airframe structural applications, J. Manuf. Proces., 2018, 36, 571-600
[7] Çam, G. and İpekoğlu, G., Recent developments in joining of aluminium alloys, Int. J. Adv. Manuf. Technol., 2017, 91 (5-8), 1851-1866.
[8] Çam, G., Friction stir welded structural materials: Beyond Al-alloys, Int. Mater. Rev., 2011, 56 (1), 1-48.
[9] Mishra, R.S. and Ma, Z.Y., Friction stir welding and processing, Mater. Sci. Eng. R, 2005, 50, 1-78.
[10] 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.
[11] Nandan, R., Debroy, T., Bhadeshia, H.K.D.H., Recent advances in friction-stir welding – Process, weldment structure and properties. Prog. Mater. Sci., 2008, 53, 980-1023.
[12] 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.
[13] Mishra, R.S. and Mahoney, M.W., Eds., 'Friction Stir Welding and Processing', ASM International, Materials Park, Ohio, USA, 2007.
[14] Singh, K., Singh, G., Singh, H., Review on friction stir welding of magnesium alloys, J. Magnes. Alloy., 2018, 6 (4), 399-416.
[15] Padhy, G.K., Wu, C.S., Gao, S., Friction stir based welding and processing technologies – process, parameters, microstructures and applications – A review, J. Mater. Sci. Technol., 2018, 34 (1), 1-38.
[16] Wahid, M.A., Khan, Z.A., Siddiquee, A.N., Review on underwater friction stir welding: A variant of friction stir welding with great potential of improving joint properties, Transactions of Nonferrous Metal Society of China, 2018, 28 (2), 193-219.
[17] Mironov, S., Sato, Y.S., Kokowa, H., Friction-stir welding and processing of Ti-6Al-4V titanium alloy: A review, J. Mater. Sci. Technol., 2018, 34 (1), 58-72.
[18] Gangwar, K. and Ramulu, M., Friction-stir welding of titanium alloys: A review, Materials & Design, 2018, 141 (5), 230-255.
[19] Venkatesh, K.M., Arivarsu, M., Manikandan, M., Arivazhagan, N., Review on friction stir welding of steels, Materials Today: Proceedings, 2018, 5 (5), 13227-13235.
[20] Liu, F.C., Hovanski, Y., Miles, M.P., et al., A review of friction stir welding of steels: Tool, material flow, microstructure, and properties, J. Mater. Sci. Technol., 2018, 34, 39-57.
[21] Yang, X.W., Fu ,T., Li, W.Y., Friction stir spot welding: A review on joint macro- and microstructure, property, and process modelling, Adv. Mater. Sci. Eng., 2014, 1, 1-11.
[22] İpekoglu, G. and Çam, G., Farklı Al-alaşımı levhaların (AA6061/AA7075) sürtünme karıştırma kaynağına temper durumunun etkisi', Mühendis ve Makina, 2012, 53 (629), 40-47.
[23] İpekoglu, G., Akçam, Ö., and Çam, G., Farklı kalınlıktaki AA6061-T6 levhaların sürtünme karıştırma kaynağı için uygun kaynak parametrelerinin belirlenmesi, Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi, 2018, 18 (1), 324-335.
[24] Çam, G., Sürtünme karıştırma kaynağı (SKK) – Al-alaşımları için geliştirilmiş yeni bir kaynak teknolojisi, Mühendis ve Makina, 2005, 46 (541), 30-39.
[25] Yavuz, H. and Çam, G., Yeni bir kaynak teknolojisi: Sürtünme karıştırma kaynağı, Endüstri ve Otomasyon, 2001, 51, 18-20.
[26] Çam, G., Al-alaşımları için geliştirilen yeni kaynak yöntemleri, Kaynak Teknolojisi III. Ulusal Kongresi ve Sergisi, 19-20 October 2001, İstanbul, 2001, 267-277.
[27] Thomas, W.M. and Nicholas, E.D., Friction stir welding for the transportation industries, Mater. Des., 1997, 18 (4-6), 269-273.
[28] Dawes, C.J. and Thomas, W.M., Friction stir process welds aluminum alloys, Weld. J., 1996, 75, 41-45.
[29] Kallee, S.W., Davenport, J., Nicholas, E.D., Railway manufacturers implement friction stir welding, Weld. J., 2002, 81, 47-50.
[30] Johnsen, M.R., Friction stir welding takes off at Boeing, Weld. J., 1999, 78, 35-39.
[31] Ding, J., Carter, R., Lawless, K., et al., Friction stir welding flies high at NASA, Weld. J., 2006, 85, 54-59.
[32] Kawasaki Heavy Industries, Ltd., 'A new method for light alloy joining - Friction spot joining, 2006-2014. www.kawasakirobot.com.

[33] Von Strombeck, A., Çam, G., dos Santos, J.F., et al., ‘A comparison between microstructure, properties, and toughness behavior of power beam and friction stir welds in Al-alloys’, Proc. of the TMS 2001 (Louisiana, USA, February 12-14, 2001), eds: S.K. Das, J.G. Kaufman, and T.J. Lienert, pub.: TMS, Warrendale, PA, 2001, pp. 249-264.
[34] İpekoğlu, G., Erim, S., Gören Kıral, B., Çam, G., Investigation into the effect of temper condition on friction stir weldability of AA6061 Al-alloy plates, Kovove Mater., 2013, 51 (3), 155-163.
[35] İpekoğlu, G., Gören Kıral, B., Erim, S., Çam, G., Investigation of the effect of temper condition friction stir weldability of AA7075 Al-alloy plates, Mater. Tehnol., 2012, 46 (6), 627-632.
[36] Çam, G., Güçlüer, S., Çakan, A., Serindağ, H.T., Mechanical properties of friction stir butt-welded Al-5086 H32 plate, Mat.-wiss. u. Werkstofftech., 2009, 40 (8), 638-642.
[37] İpekoğlu, G., Akçam, Ö., Çam, G., AA6061-T6 Al-alaşımı levhaların sürtünme karıştırma kaynağında levha kalınlığının kaynak hızına etkisi, Kaynak Teknolojisi X. Ulusal Kongre ve Sergisi (KAYKON 2017), 17-18 Kasım 2017, Ankara, 63-75.
[38] Lee, W.B., Yeon, Y.M., Jung, S.B., Joint properties of friction stir welded AZ31B-H24 magnesium alloy, Mater. Sci. Technol., 2003, 19 (6), 785-790.
[39] Afrin, N., Chen, D.L., Cao, X., Jahazi, M., Microstructure and tensile properties of friction stir welded AZ31B magnesium alloy, Mater. Sci. Eng. A, 2008, 472 (1-2), 179-186.
[40] Xie, G.M., Ma, Z.Y., Geng, L., Effect of microstructural evolution on mechanical properties of friction stir welded ZK60 alloy, Mater. Sci. Eng. A, 2008, 486 (1-2), 49-55.
[41] Çam, G., Serindağ, H.T., Çakan, A., et al., The effect of weld parameters on friction stir welding of brass plates, Mat.-wiss. u. Werkstofftech., 2008, 39 (6), 394-399.
[42] Çam, G., Mistikoglu, S., Pakdil, M., Microstructural and mechanical characterization of friction stir butt joint welded 63%Cu-37%Zn brass plate, Weld. J., 2009, 88 (11), 225-232.
[43] Küçükömeroğlu, T., Şentürk, E., Kara, L., et al., Microstructural and mechanical properties of friction stir welded nickel-aluminum bronze (NAB) alloy, J. Mater. Eng. Perform., 2016, 25 (1), 320-326.
[44] Avettand-Fenoel, M.-N. and Simar, A., A review about friction stir welding of metal matrix composites, Mater. Charact., 2016, 120, 1-17.
[45] Nami, H., Adgi, H., Sharifitabar, M., Shamabadi, H., Microstructure and mechanical properties of friction stir welded Al/Mg2Si metal matrix cast composite, Mater. Des., 2011, 32, 976-983.
[46] Ceschini, L., Boromei, I., Minak, G., et al., Effect of friction stir welding on microstructure, tensile and fatigue properties of the AA7005/10 vol.% Al2O3p composite, Compos. Sci. Technol., 2007, 67, 605-615.
[47] Günen, A., Kanca, E., Demir, M., et al., Microstructural and mechanical properties of friction stir welded pure lead, Indian J. Eng. Mater. Sci., 2018, 25 (1), 26-32.
[48] Küçükömeroğlu, T., Aktarer, S.M., İpekoğlu, G., Çam, G., Investigation of mechanical and microstructural properties of friction stir welded dual phase (DP) steel, IOP Conf. Series: Materials Science and Engineering, 2019, 629, 012010.
[49] İpekoğlu, G., Küçükömeroğlu, T., Aktarer, S.M., et al., Investigation of microstructure and mechanical properties of friction stir welded dissimilar St37/St52 joints, Materials Research Express, 2019, 6 (4), 046537.
[50] Reynolds, A.P., Tang, W., Gnaupel-Herold, T., Prask, H., Structure, properties, and residual stress of 304L stainless steel friction stir welds, Scr. Mater., 2003, 48 (9), 1289-1294.
[51] Meran, C., Kovan, V., Alptekin, A., “Friction stir welding of AISI 304 austenitic stainless steel, Mat.-wiss. u. Werkstofftech., 2007, 38 (10), 829-835.
[52] Çam, G., İpekoğlu, G., Küçükömeroğlu, T., Aktarer, S.M., Applicability of friction stir welding to steels, J. Achiev. Mater. Manuf. Eng. (JAMME), 2017, 80 (2), 65-85.
[53] Çam, G. and Meran, C., Çeliklerin sürtünme karıştırma kaynağı, Mühendis ve Makina, 2009, 50, (599), 24-32.
[54] Forcellese, A., Mancia, T., Pieralisi, M., Vita A., Friction stir welding of additively manufactured blanks in thermoplastic polymer, Procedia CIRP, 2022, 112, 448-453.
[55] Pirizadeh, M., Azdast, T., Ahmadi, S.R., et al., Friction stir welding of thermoplastics using a newly designed tool, Mater. & Des., 2014, 54, 342-347.
[56] Jaiganesh, V., Maruthu, B., Gopinath, E., Optimization of process parameters on friction stir welding of high density polypropylene plate, Procedia CIRP, 2014, 97, 1957-1965.
[57] İpekoğlu, G. and Çam, G., Effects of initial temper condition and postweld heat treatment on the properties of dissimilar friction-stir-welded joints between AA7075 and AA6061 aluminum alloys, Metall. Mater. Trans. A, 2014, 45A (7), 3074-3087.
[58] Çam, G., İpekoğlu, G., Tarık Serindağ, H., Effects of use of higher strength interlayer and external cooling on properties of friction stir welded AA6061-T6 joints, Sci. Technol. Weld. Join., 2014, 19 (8), 715-720.
[59] Ouyang, J.H. and Kovacevic, R., Material flow and microstructure in the friction stir butt welds of the same and dissimilar aluminum alloys, J Mater Eng Perform., 2002, 11, 51-63.
[60] Zhang, C., Cao, Y., Huang, G., et al., Influence of tool rotational speed on local microstructure, mechanical and corrosion behavior of dissimilar AA2024/7075 joints fabricated by friction stir welding, J. Manuf. Processes, 2020, 49, 214-226.
[61] Shah, L.H., Othman, N.H., Gerlich, A., Review of research progress on aluminium-magnesium dissimilar friction stir welding, Sci. Technol. Weld. Joining, 2018, 23, 256-270.
[62] Kwon, Y.J., Shigematsu, I., Saito, N., Dissimilar friction stir welding between magnesium and aluminum alloys, Mater. Lett., 2008, 62, 3827-3829.

[63] Firouzdor, V. and Kou, S., Al-to-Mg friction stir welding: effect of material position, travel speed, and rotation speed, Metall. Mater. Trans. A, 2010, 41, 2914-2935.

[64] Sameer, M.D. and Birru, A.K., Mechanical and metallurgical properties of friction stir welded dissimilar joints of AZ91 magnesium alloy and AA 6082–T6 aluminium alloy, J. Magnesium Alloys, 2019, 7 (2), 264-271.

[65] Küçükömeroğlu, T., Aktarer, S.M., İpekoğlu, G., Çam, G., Mechanical properties of friction stir welded St 37 and St 44 steel joints, Materials Testing, 2018, 60 (12), 1163-1170.

[66] İpekoğlu, G., Küçükömeroğlu, T., Aktarer, S.M., et al., Investigation of microstructure and mechanical properties of friction stir welded dissimilar St37/St52 joints, Mater. Research Express, 2019, 6 (4), 046537.

[67] Jafarzadegan, M., Feng, A.H., Abdollah-Zadeh, A., et al., Microstructural characterization in dissimilar friction stir welding between 304 stainless steel and st37 steel, Mater. Charact., 2012, 74, 28-41.

[68] Logan, B.P., Toumpis, A.I., Galloway, A.M., et al., Dissimilar friction stir welding of duplex stainless steel to low alloy structural steel, Sci. Technol. Weld. Joining, 2016, 21, 11-19.

[69] He, B., Cui, L., Wang, D., et al., The metallurgical bonding and high temperature tensile behaviors of 9Cr-1W steel and 316L steel dissimilar joint by friction stir welding, J. Manuf. Processes, 2019, 44, 241-251.

[70] İpekoğlu, G., Küçükömeroğlu, T., Aktarer, S.M., et al., Sürtünme karıştırma kaynağıyla birleştirilen St37/St52 levhaların mikroyapı karakterizasyonu ve mekanik özellikleri, Fen ve Müh. Dergisi, Dokuz Eylül Üniv., 2018, 20 (59), 471-480.

[71] Mehta, K.P., Carlone, P., Astarita, A., et al., Conventional and cooling assisted friction stir welding of AA6061 and AZ31B alloys, Mater. Sci. Eng. A, 2019, 759, 252-261.

[72] Zhao, Y., Lu, Z., Yan, K., Huang, L., Microstructural characterizations and mechanical properties in underwater friction stir welding of aluminum and magnesium dissimilar alloys, Mater. Des., 2015, 65, 675-681.

[73] Zhao, Y., Jiang, S., Yang, S., et al., Influence of cooling conditions on joint properties and microstructures of aluminum and magnesium dissimilar alloys by friction stir welding, Int. J. Adv. Manuf. Technol., 2016, 83, 673-679.

[74] Liu, Z., Meng, X., Ji, S., et al., Improving tensile properties of Al/Mg joint by smashing intermetallic compounds via ultrasonic-assisted stationary shoulder friction stir welding, J. Manuf. Processes, 2018, 31, 552-559.

[75] Ji, S., Meng, X., Liu, Z., et al., Dissimilar friction stir welding of 6061 aluminum alloy and AZ31 magnesium alloy assisted with ultrasonic, Mater. Lett., 2017, 201, 173-176.

[76] Lv, X., Wu, C., Yang, C., Padhy, G.K., Weld microstructure and mechanical properties in ultrasonic enhanced friction stir welding of Al alloy to Mg alloy, J. Mater. Process. Technol., 2018, 254, 145-157.

[77] Jiang, X.Q., Liu, Y.Y., Yuan, T., et al., Enhanced mechanical properties of dissimilar Al and Mg alloys fabricated by pulse current assisted friction stir welding, J. Manuf. Proces., 2022, 76, 123-137.

[78] Patrick, M.M., Akinlabi, E., Makhatha, M.E., 'Microstructure and electrical resistivity properties of copper and aluminium friction stir spot welds', 8th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT), Feb. 2017, 42-47.

[79] Sun, Y., Fujii, H., Zhu, S., Guan, S., Flat friction stir spot welding of three 6061-T6 aluminum sheets, J. Mater. Process. Tech., 2019, 264, 414-421.

[80] De Castro, C.C., Shen, J., Plaine, A.H., et al., Tool wear mechanisms and effects on refill friction stir spot welding of AA2198-T8 sheets, J. Mater. Res. Technol., 2022, 20, 857-866.

[81] Boldsaikhan, E., Fukada, S., Fujimoto, M., et al., Refill friction stir spot welding of surface-treated aerospace aluminum alloys with faying-surface sealant, J. Manuf. Process., 2019, 42, 113-120.

[82] Derlatka, A. and Lacki, P., Experimental study and numerical simulation of cellular I-beam manufactured using refill friction stir spot welding technology, Thin–Walled Structures, 2024, 200, 111890.

[83] Gera, D., Fu, B.-L., Suhuddin, U.F.H.R., et al., Microstructure, mechanical and functional properties of refill friction stir spot welds on multilayered aluminum foils for battery application, Journal of Materials Research and Technology, 2021, 13, 2272-2286.

[84] Kim, D.-J., Baek, S.-Y., Nishijima, M., et al., Toward defect-less and minimized work-hardening loss implementation of Al alloy/high-purity Cu dissimilar lap joints by refill friction stir spot welding for battery tab-to-busbar applications, Materials Science & Engineering A, 2024, 892, 146089.

[85] Wynne, B.P., Threadgill, P.L., Davies, P.S., et al., Microstructure and texture in static shoulder friction stir welds, In Proceedings of the 7th International Friction Stir Welding Symposium; TWI, Awaji Island, Japan, 2008, pp. 1-8.

[86] Russell, M.J. and Blignault, C., In Proceedings of the Proc 6th Int. Symp. on Friction Stir Welding; P L Threadgill, Ed., TWI, Saint Sauveur, Quebec, Canada, 2007.

[87] Wu, H., Chen, Y., Strong, D., Prangnell, P., Stationary shoulder FSW for joining high strength aluminum alloys, J. Mater. Process. Tech., 2015, 221, 187-196.

[88] Russell, M.J., Threadgill, P.L., Thomas, M.J., Wynne, B.P., Static Shoulder Friction Stir Welding of Ti-6Al-4V: Process and Evaluation, In Proceedings of the 11th World Conference on Titanium (Ti-2007), (JIMIC - 5); Kyoto, Japan, 2007.

[89] Ahmed, M.M.Z., Wynne, B.P., Rainforth, W.M., Threadgill, P.L., Through-thickness crystallographic texture of stationary shoulder friction stir welded aluminium. Scr. Mater., 2011, 64, 45-48.

[90] İpekoğlu, G. and Çam, G., Formation of weld defects in cold metal transfer arc welded 7075-T6 plates and its effect on joint performance, IOP Conf. Series: Materials Science and Engineering, 2019, 629, 012007.

[91] Çam, G., Prospects of producing aluminum parts by wire arc additive manufacturing (WAAM), Materials Today: Proceedings, 2022, 62(1), 77-85.

[92] Çam, G. and Günen, A., Challenges and opportunities in the production of magnesium parts by directed energy deposition processes, Journal of Magnesium and Alloys, 2024, 12, 1663-1686.

[93] Güler, S., Serindağ, H.T., Çam, G., Tel ark eklemeli imalat: Son gelişmeler ve değerlendirmeler, TMMOB Makina Mühendisleri Odası, Kaynak Teknolojisi 12. Ulusal Kongre ve Sergisi (KAYKON 2021), 19-20 Kasım 2021, Ankara, S. 9-40.
[94] Çam, G., Ventzke, V., dos Santos, J.F., et al., Characterization of laser and electron beam welded Al-alloys, Prakt. Metallogr., 1999, 36 (2), 59-89.
[95] Çam, G., Koçak, M., Dobi, D., et al., Fracture behaviour of diffusion bonded bimaterial Ti-Al joints, Sci. Technol. Weld. Join., 1997, 2 (3), 95-101.
[96] Çam, G., Sürtünme karıştırma kaynağındaki gelişmeler, TMMOB Makina Mühendisleri Odası, Kaynak Teknolojisi IV. Ulusal Kongre ve Sergisi, 24-26 Ekim 2003, Kocaeli, S. 47-64.
[97] Çam, G., Sürtünme karıştırma kaynağı ve uygulamaları, 9. Malzeme Sempozyumu Bildiriler Kitabı, 8-10 Mayıs 2002, Pamukkale Üniversitesi, Denizli, 2002, S. 450-458.
[98] Sun, G.D., Zhou, L., Liu, Y.N., et al., Microstructure characterization and evaluation of mechanical properties in 2A97 aluminum-lithium alloys welded by stationary shoulder friction stir welding, Journal of Materials Research and Technology, 2022, 16, 416-432.
[99] Sen, M. and Puri, A.B., Formation of intermetallic compounds (IMCs) in FSW of aluminum and magnesium alloys (Al/Mg alloys) - A review, Materials Today Communications, 2022, 33, 105017.
[100] Song, Q., Wang, H., Ji, S., et al., Improving joint quality of hybrid friction stir welded Al/Mg dissimilar alloys by RBFNN-GWO system, J. Manuf. Process., 2020, 59, 750-759.
[101] Hu, W., Ma, Z., Ji, S., et al., Improving the mechanical property of dissimilar Al/Mg hybrid friction stir welding joint by PIO-ANN, J. Mater. Sci. Technol., 2020, 53, 41-52.
[102] You, J.-Q., Zhao, Y.-Q., Dong, C.-L., Su, Y.-H., Improving the microstructure and mechanical properties of Al-Cu dissimilar joints by ultrasonic dynamic-stationary shoulder friction stir welding, Journal of Materials Processing Tech., 2023, 311, 117812.
[103] Hammad, A.S., Ahmed, M.M.Z., Lu, H., et al., An investigation on mechanical and microstructural evolution of stationary shoulder friction stir welded aluminum alloy AA7075-T651, Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci., 2022, 236, 6665-6676.
[104] Barbini, A., Carstensen, J., dos Santos, J.F., Influence of a non-rotating shoulder on heat generation, microstructure and mechanical properties of dissimilar AA2024 / AA7050 FSW joints, J. Mater. Sci. Technol., 2018, 34, 119-127.
[105] Li, D., Yang, X., Cui, L., et al., Investigation of stationary shoulder friction stir welding of aluminum alloy 7075-T651, J. Mater. Process. Tech., 2015, 222, 391-398.
[106] Sun, T., Roy, M.J., Strong, D., et al., Weld zone and residual stress development in AA7050 stationary shoulder friction stir T-joint weld, J. Mater. Process. Tech., 2019, 263, 256-265.
[107] Sun, Z., Yang, X., Li, D., Cui, L., The local strength and toughness for stationary shoulder friction stir weld on AA6061-T6 alloy, Mater. Charact., 2016, 111, 114-121.
[108] Ji, S.D., Meng, X.C., Liu, J.G., et al., Formation and mechanical properties of stationary shoulder friction stir welded 6005A-T6 aluminum alloy, Mater. Des., 2014, 62, 113-117.
[109] Threadgill, P.L., Ahmed, M.M.Z., Martin, J.P., et al., The use of bobbin tools for friction stir welding of aluminium alloys, Mater. Sci. Forum, 2010, 642, 1179-1184.
[110] Wang, F.F., Li, W.Y., Shen, J., et al., Effect of tool rotational speed on the microstructure and mechanical properties of bobbin tool friction stir welding of Al-Li alloy, Mater. Des., 2015, 86, 933-940.
[111] Wang, G.Q., Zhao, Y.H., Tang, Y.Y., Research progress of bobbin tool friction stir welding of aluminum alloys: A review, Acta Metall. Sin. (English Lett.), 2020, 33 (1), 13-29.
[112] Xu, W.F., Luo, Y.X., Fu, M.W., Microstructure evolution in the conventional single side and bobbin tool friction stir welding of thick rolled 7085-T7452 aluminum alloy, Mater. Charact., 2018, 138, 48-55.
[113] Xu, W.F., Luo, Y.X., Zhang, W., Fu, M.W., Comparative study on local and global mechanical properties of bobbin tool and conventional friction stir welded 7085-T7452 aluminum thick plate, J. Mater. Sci. Technol., 2018, 34, 173-184.
[114] Yang, C., Ni, D.R., Xue, P., et al., A comparative research on bobbin tool and conventional friction stir welding of Al-Mg-Si alloy plates, Mater. Charact., 2018, 145, 20-28.
[115] Lohwasser, D., Friction stir welding of aerospace alloys, In Proceedings of the Proc. 4th Int. Symp. on 'Friction stir welding; TWI, Park City, UT, USA, 2003; Vol. 48, pp. 37-46.
[116] Ahmed, M.M.Z., Habba, M.I.A., El-Sayed Seleman, M.M., et al., Bobbin tool friction stir welding of aluminum thick lap joints' properties, Materials, 2021, 14 (16), 4584.
[117] Li, G.-H., Gao, S.-K., Luo, S.-F., et al., Tailoring macrostructure and texture in bobbin-tool friction stir weld via manipulation of deformation behaviour of plasticised metal during welding enabled by modifying tool profile, International Journal of Machine Tools & Manufacture, 2024, 201, 104198.
[118] Russell, M.J., Nunn, M.E., Martin, J., Recent developments in the stationary shoulder FSW of titanium alloys. In: Proceedings of Seventh Int. Symp. on Friction Stir Welding. 2008, TWI, Japan.
[119] Goebel, J., Reimann, M., Norman, A., dos Santos, J.F., Semi-stationary shoulder bobbin tool friction stir welding of AA2198-T851, J. Mater. Process. Technol., 2017, 245, 37-45.
[120] Scupin, P., Semi-stationary shoulder bobbin tool (S3BT): A new approach in high speed friction stir welding, Ph.D. Thesis, Helmholtz-Zentrum Geesthacht, Germany, 2015.
[121] Li, G.-H., Chen, T., Fu, B.-L., et al., Semi-stationary shoulder bobbin-tool: A new approach in tailoring macrostructure and mechanical properties of bobbin-tool friction stir welds in magnesium alloy, Journal of Materials Processing Tech., 2023, 317, 117984.