A Review on Friction Stir Spot Welding of Similar and Dissimilar Materials

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1 Introduction

The recent decrease of naturally available resources and increasing cost of the fuel lead to an increase in demand for lightweight materials in various aerospace and automobile industries. The lightweight materials reduce the consumption of fuel and enhance the performance of the automobiles. In this perspective, the utilization of lightweight material, such as aluminium and magnesium, has considered a great alternative of steel. The joining of lightweight materials is always a challenge to the research fraternity. Conventionally, riveting and resistance spot welding (RSW) is used for joining of aluminium and other lightweight materials of lesser thickness. However, these processes have many disadvantages such as high energy consumption and less production efficiency [1]. The friction stir welding (FSW) method was developed to overcome these limitations of the process, at The Welding Institute (TWI) in 1991. The FSW process has been successfully attempted for joining various non-ferrous, ferrous metals and polymers. The FSW set-up comprises of a tool, which rotates as well as moves along the seam. The relative motion amongst the tool and the workpiece material produces frictional heat, which tends to join the workpieces. A new process is derived from producing a weld on the spot named as friction stir spot welding (FSSW) by restricting the movement of the tool of the FSW process to rotation only. The cycle time of the FSSW process is less than the FSW process as it takes less time to produce spot weld than a seam weld [2].

The FSSW process joins the material in their solid state, i.e. the joining is done at a temperature, which is lesser than the melting point of the workpiece material to be weld and that too without any use of filler metal [3]. The process comprises of the three stages, namely plunging, stirring and retracting, as shown in Fig. 1. Initially, the

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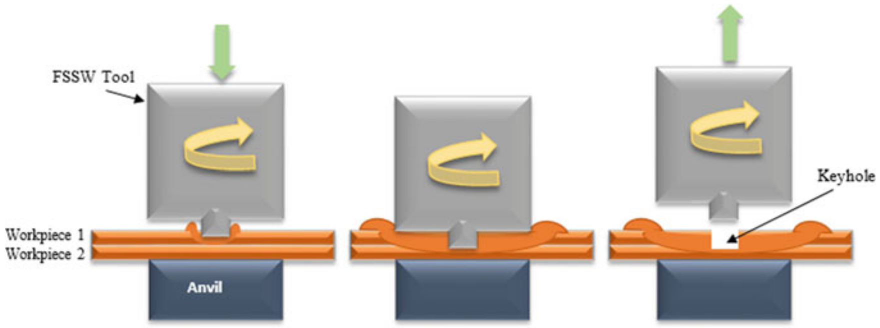

Fig. 1 Schematic diagram of FSSW process: **a** plunging, **b** stirring and **c** retracting

tool rotates and contact is made between the tool shoulder and the workpiece placed on top in lap position. After that, the tool penetrates the workpiece by applying a force to form spot weld. This stage is called plunging, and the material is expelled by the tool during this stage. When a predetermined depth is achieved, the stirring phase initiates. In the stirring step, the tool keeps on rotating in both workpieces. The material next to the tool is heated until it softens because of frictional heat, generated in both stirring and plunging phases and then mixed by stirring. At last, the tool is withdrawn or retracted from the workpieces, after a proper bonding is achieved [4]. The FSSW process is an intricate process which comprises of many process parameters such as rotation speed of the tool, plunge depth, dwell time and plunge rate and are defined as follows:

- Tool rotational speed: The term explains the rotational tool speed, and the direction of rotation is either counterclockwise or clockwise, as seen from the top.
- Plunge depth: The word used to explain the pin of the tool penetrates the workpiece.
- Plunge rate: Defined as the velocity at which the FSSW tool penetrates into the workpiece material.
- Dwell time: The term used for the time the FSSW tool remains in the workpiece.

The variation in the process parameters affects the various properties of the weld such as strength, hardness, microstructure and weld macrostructure. The macrostructure of the weld produced after FSSW process is categorized into four regions, i.e. stir zone (SZ), thermomechanically affected zone (TMAZ), heat-affected zone (HAZ) and parent material (PM).

Stir zone (SZ) was the region which is created underneath the shoulder and the tool pin when tool penetrated the workpiece, or it is a material which is in contact with the tool directly. HAZ is the region which is affected by the heat; however, there is not any deformation in the HAZ region. While the TMAZ region is affected by both deformation and heat [5]. Parent material (PM) is the base material which is away from the SZ and has experienced some heat; however, there is not any change in the microstructure of the material [6].

With the advancement in the process, researchers came out with various theories on different aspects of the process, and one of the main issues is the joining of dissimilar material. The objective of the paper is to present a literature review on FSSW of similar and dissimilar material and to provide some useful information that will be beneficial for future research.

2 Friction Stir Spot Welding of Similar Materials

2.1 Aluminium–Aluminium Joints

Due to the increasing environmental and global resource problems, reducing the weight of automotive bodies, high-speed cars, aerospace structures, etc., is gaining more attention and usage of lightweight material is found effective for the same. Aluminium alloys have many fine characteristics like lightweight, specific strength, corrosion resistance, high recycle and impact resistance [1]. Several researchers have considered the process of joining different aluminium alloys by FSSW over the years and some of them revealed that microstructural and mechanical properties of joints vary considerably with process parameters. Shen et al. [7] calculated the mechanical properties, failure mechanisms and microstructures of the weld produced by welding Al-6061 T4 sheets by FSSW process and reported that to obtain the desired appearance of the joint, the process should be done for a longer duration of time and at higher tool rotational speed. Tier et al. [8] stated that the foremost feature, which upsets the mechanical properties of welds that are made of aluminium alloys, is the Alclad distribution in the weld.

During the FSSW of aluminium alloys, the reasonable strain rate is generally complemented by a small rise in temperature, and it is the reason for the variations in the weld microstructure [9]. The experimental study of joining of Al-6082 and Al-7108 aluminium alloys by FSSW by Frigaard et al. [10] determined the strain rate during the process. The author reported the estimated values of the strain rate between 1.6 and 17 s^{-1}; it is seen that these values have a lower magnitude than those calculated during the FSW process. The researchers also suggested that there is slippage between contiguous material in the SZ and the tool periphery.

Tensile strength of aluminium alloys depends on the parameters of the welding and existence of imperfections in the welds [11]. Li et al. [11] observed joints with hook defect and without hook defect and recorded that a higher value of the tensile shear load, i.e. 12 kN, was obtained in joint without hook defect, while for joints with hook defect, the value obtained was 6.9 kN. It is observed that tensile strength obtained by refill FSSW process is higher than the welds having a keyhole. Uematsu et al. [12] examined Al 6061-T4 aluminium alloy sheets, welded by both conventional FSSW and refill FSSW process. The values of tensile strengths of the joints obtained by refill FSSW process was 3.458 kN, while for joints having a probe hole, it is

2.645 kN. It means the refill process improved the value of tensile strength of the joint by 30%.

2.2 Magnesium–Magnesium Joints

Magnesium takes sixth place amongst the most abundant elements on the earth's surface, and because of their lightweight properties, they have an excellent specific strength, hot formability, sound damping capabilities, recyclability and good castability [13]. Magnesium alloys have an essential application in industries where weight reduction is required because of its relation between strength and weight and also where it is essential to decrease inertial forces. On account of this, many denser materials like cast iron, steels, copper alloys and even aluminium alloys are also substituted by magnesium alloys in different structural and automotive applications [14]. The crystal structure of magnesium is hexagonal cubic packing, i.e. HCP with a restricted amount of operative slip systems at the room temperature. Shen et al. [15] increased the temperature to improve the plastic deformation of alloys of magnesium, which, therefore, improved the fluidity of magnesium alloy in the course of heating FSSW process. Thus, the voids count in the welded joint decreases, also there was an improvement in the tensile shear load of the joint due to an increase in the temperature. The researchers also witnessed that the width of the bonded region got enlarged with the rise in the temperature during the welding process.

Various factors influence the joint strength, such as stir tool, the thickness of the sheet and hybrid welding. Xu et al. [16] noted that the strength of the FSSW magnesium alloy joint could be enhanced by adding Zn interlayer. This improvement was seen because the addition of Zn interlayer lowered the reaction temperature of the interface, which advances the diffusion reaction among Mg substrate and Zn interlayer, creating a bonded region. Consequently, there was a decrease in the hook defect and an increase in the bonded region area, and thus, the tensile shear load of the weld joint was improved.

2.3 Copper–Copper Joints

Welding of copper to copper by FSSW welding process has got less attention and has limited literature. Sansui et al. [17] joined commercially pure copper of 3 mm thickness by FSSW. The researchers scrutinized the microstructure of the joint and then conducted a corrosion test. The study was conducted at three different tool rotation speed, and a completely metallurgical bonded region was witnessed in stir zone with equiaxed and fine grains having their size bigger than those of base metal. Hook defect was observed, which showed that there was an inadequate flow of material during the stirring process. Some residuals were detected in the energy dispersive spectrometer (EDS) analysis which was supposed to come from the tool which could negatively affect the corrosion property of the workpiece. It was witnessed that the joint made at 1200 rpm had the least potential to corrode, and also it performed worse than joints produced at 1600 rpm and 2000 rpm. Finally, the corrosion property of the joint was enhanced by processing the workpiece in 3.5% NaCl.

2.4 Steel–Steel Joints

Initially, only aluminium alloy was welded by FSSW process because of the trouble in choosing the suitable tool materials, which can survive the elevated temperature, produced while welding of steels by FSSW. Moreover, this procedure can be applied now to the steels after advancements in the tool materials [18]. Steel is essential for the structure of the body of all mass-produced, high-volume cars. The customers emphasize on safety and protection from corrosion, and this has increased the usage of galvanized steel [19]. Baek et al. [19] produced galvanized steel joints and considered the impact of tool penetration depth; also, the microstructure of the nugget was analysed. The researchers concluded that there was not any mechanically blended layer between the bottom and top workpiece plates at the nugget, and this was because of less tool penetration and small height of the tool as compared to the thickness of the steel plate. Sun et al. [20] scrutinized the mechanical properties and microstructure of joints made of mild steel with flat FSSW technique. The researchers performed a lap shear test, and interfacial mode of failure of the weld was observed. After failure, the load fell to zero in very less time.

On the other hand, when the fracture happened through plug mode, the load applied started to fell after the crack initiated. Researchers in their another study [21] carried out on FSSW of low carbon steel (LCS) plates and used a supplementary heat source in the form of high-frequency induction and stated that strong welds could be achieved with a small load and low tool rotation speed after preheating. Also, a maximum of 12.4 kN of the tensile shear load was achieved.

2.5 Polymer–Polymer Joints

With the advancement in the technology, the polymers are now taking the place of various metals due to their low cost and lightweight such as polycarbonate (PC), acrylonitrile butadiene styrene (ABS) and high-density polyethylene (HDPE). Lambiase et al. [22] joined polycarbonate sheets and analysed the effect on rotational speed of the tool, dwell time, waiting time, preheating and plunge rate on mechanical properties of the workpiece, while Arici et al. [23] joined polypropylene sheets and optimized the tool penetration depth for maximizing the tensile strength of the weld. Bilici [24] also welded polypropylene sheets by FSSW process and observed the effect of the tool geometry on the weld formed. The author stated that the variation in the tool geometry affected the development of the SZ and the strength of the weld.

3 Friction Stir Spot Welding of Dissimilar Materials

Dissimilar material welding is the need of many industries to produce a structure with properties of different materials by joining them with different methods (Fig. 2). Joining dissimilar materials is the difficult task because of the variance in the melting temperature of the materials, development of intermetallic compounds (IMCs), poor solubility of the materials in each other, variance in coefficient of thermal expansion of the materials and corrosion in the intermetallic zone [25]. The main issue in welding of dissimilar materials is the development of brittle intermetallic compounds (IMCs). IMCs help in the propagation of cracks and thus lead to failure, also corrosion can occur in that region. The formation of IMCs occurs when two different materials melted and joined, which is common in various fusion welding processes. Joining of dissimilar material is made easy with the introduction of solid-state joining processes, which is lesser than the temperature of melting point of the material. FSSW is proved to be an efficient process for joining dissimilar materials. The following section provides a detailed study on different materials joined with FSSW and general trends in the joining of dissimilar materials.

Suhuddin et al. [26] joined AZ31 magnesium alloy and AA5754 aluminium alloy and analysed the microstructure of the joint. The author reported that the factors that affect the development of the grain arrangements in the SZ are grain boundary diffusion, dynamic recrystallization and interfacial diffusion, which results in the fine equiaxed grains in the weld centre. The author also analysed similar Al-Al and Mg-Mg welds and concluded that both similar welds had higher mechanical and microstructural properties as compared to dissimilar Al–Mg weld. Chowdhury et al. [27] studied the joint produced by welding AA5754-O aluminium alloy and

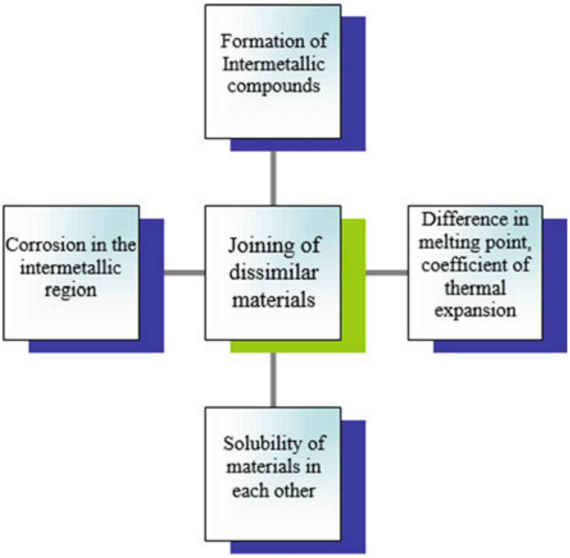

Fig. 2 Factors affecting joining of dissimilar materials

commercial AZ31B-H24 magnesium alloy by FSSW process. The author studied both Al–Mg and Mg–Al adhesive joint and observed that there was a unique interfacial layer containing intermetallic compounds in both joints. It was observed that either Al–Mg or Mg–Al adhesive welds had greater failure energy and lap shear strength that the Al–Mg weld without adhesive. While Sun et al. [28] welded a commercial 1 mm thick aluminium alloy 6061 and mild steel of the same thickness and had witnessed no evident IMCs layer present along the interface. Bozzi et al. [20] studied the formation of IMCs layer after welding AA 6016 aluminium alloy with a galvanized IF-steel sheet. The author witnessed that with the rise in the penetration depth and tool rotational speed, the thickness of the intermetallic compound (IMCs) layer increases. In addition, it is perceived that the presence of intermetallic compounds (IMCs) appeared to be essential to improve the strength of the weld, but in case the thickness of the intermetallic compound layer is large then the crack could propagate simply through that IMCs layer. Lee et al. [29] joined low carbon steels to Al–Mg alloy to scrutinize the influence of penetration depth of the tool on the development of IMCs. The author observed that the area in which IMCs are formed grew with the increase in the penetration depth of the tool. Table 1 shows the fssw process of dissimilar materials.

4 Conclusion and Future Scope

The FSSW process is suitable for producing joints of both similar and dissimilar metals as well as polymers. This paper is leading the way to the work done until now on FSSW of similar and dissimilar joints. FSSW belonging to a class of solid-state joining processes is a feasible mode of joining similar and dissimilar material. The process is attracting more researchers because of its many advantages like mass production, low energy utilization, cost reduction, etc. Earlier the FSSW method was used for welding aluminium alloys, but with time many more materials have also taken the interest of researchers like copper, steel, magnesium, polymers, etc. After an extensive literature survey, it is perceived that there are many studies related to FSSW of similar materials, but the field of dissimilar material joining still needs more attention. Polymers are gaining the interest of researchers, and its application can be seen in various fields like automobile, aerospace, etc. Also, polymer–metal dissimilar welding has been reported by various researchers by different technologies and their joining by FSSW still needs consideration. Copper is also least reported in the research. The difficulty in welding of the copper is that the metal gets corrode soon and when it is welded with dissimilar material, the formation of IMCs is more. Researchers can consider the material for future research and eliminate the shortcomings of the weld. The FSSW process is an efficient process for industrial use; innovation in the process can help to improve the production rate by FSSW process to increase its utility in industries.

Table 1 Research contribution in FSSW of dissimilar materials

Authors	Material/thickness	Findings
Piccini and Svoboda [30]	AA6063-T6/2 mm and an LCG-S/0.7 mm	Stirring and forging of the top sheet into the bottom sheet was improved by welding with the tools having shorter pins
Reilly et al. [31]	AA6111-T4/ 0.93 mm, DC04 (ungalvanized)/1 mm and DX54Z (galvanized) low carbon steel sheet/1 mm	Used fluted tools and observed that metal flow is circumferential, and it was seen that the tool and the central region of the workpiece stick to each other
Fereiduni et al. [32]	Al-5083/3 mm and St-12/1 mm	The joint strength or tensile shear strength of the weld first enhanced and then a depreciation was seemed with a rise in the dwell time and with this intermetallic layer was formed, and also there was growth in aluminium grains adjoining the exit-hole of the weld. So, the improvement in the optimum tensile shear strength was seen by increasing the rotational tool speed and decreasing the dwell time
Shen et al. [33]	ZEK 100 magnesium Alloy/1.5 mm and galvanized DP600 automotive steel sheets/0.9 mm	Mg-steel welds have higher effective bonded areas than Mg-Mg welds because of zinc brazing and presence of incomplete bonding about the periphery of the Mg-steel weld
Aliasghari et al. [34]	AA 5052 and propylene/2 mm	Polypropylene failed due to ductile failure having fibrous behaviour. Joints made using pretreated alloy have approx. 40% decrease in the crystallinity of the polypropylene whereas it is approx. 10% when the untreated alloy is used
Siddharth and Senthilkumar [35]	Al5083 and C10100/1.5 mm	Considered the influence of variations in plunge depth on the flow of materials within the weld zone

(continued)

Table 1 (continued)

Authors	Material/thickness	Findings
Ravi et al. [36]	Al6082-T6/15 mm and HDPE/0.8 mm	Used different tool profiles and determined that the tool with square pin was good for both tri-metallic and sandwich sheets, and also it was seen that joints of tri-metallic sheets performed better with every type of tool profile
Siddharth and Senthilkumar [37]	Al 5086 and C10100/1.5 mm	Found out the optimized values of the process parameters as 2.05 mm plunge depth, 1100 rpm tool rotational speed, 11.5 s dwell time, 2.234 kN of a maximum tensile shear failure load and 90.9 HV of minimum interface hardness
Rana et al. [38]	AA5052-H32/2 mm and HDPE/1 mm	It was observed that sandwich sheets than bimetallic sheets because of smaller peak temperature exhibited finer grain structure, and the size of grain increased after the rotational tool speed was increased because of the larger generation of heat

References

1. Zhang Z, Yang X, Zhang J, Zhou G, Xu X, Zou B (2011) Effect of welding parameters on microstructure and mechanical properties of friction stir spot welded 5052 aluminum alloy. Mater Des 32(8–9):4461–4470. https://doi.org/10.1016/j.matdes.2011.03.058
2. Badarinarayan H, Shi Y, Li X, Okamoto K (2009) Effect of tool geometry on hook formation and static strength of friction stir spot welded aluminum 5754-O sheets. Int J Mach Tools Manuf 49:814–823. https://doi.org/10.1016/j.ijmachtools.2009.06.001
3. Mathers G (2002) The welding of aluminium and its alloys. Woodhead Publishing
4. Yang XW, Fu T, Li WY (2014) Friction stir spot welding: a review on joint macro-and microstructure, property, and process modelling. Adv Mater Sci Eng 2014. https://doi.org/10.1155/2014/697170
5. Threadgill PL (2007) Terminology in friction stir welding. Sci Technol Weld Joining 12(4):357–360. https://doi.org/10.1179/174329307X197629
6. Mubiayi MP, Akinlabi ET (2014) Friction stir spot welding of dissimilar materials: an overview. Lecture Notes in Engineering & Computer Science, 2214
7. Shen Z, Yang X, Zhang Z, Cui L, Yin Y (2013) Mechanical properties and failure mechanisms of friction stir spot welds of AA 6061–T4 sheets. Mater Des 49:181–191. https://doi.org/10.1016/j.matdes.2013.01.066
8. Tier MD, dos Santos JF, Olea CW, Rosendo T, Mazzaferro CP, Mazzaferro JAE, Strohaecker TR, da Silva AAM, Isakovic JT (2008) The influence of weld microstructure on mechanical

properties of alclad AA2024-T3 friction spot welded (No. 2008–01–2287). SAE Technical Paper. https://doi.org/10.4271/2008-01-2287
9. Rosendo T, Parra B, Tier MAD, Da Silva AAM, Dos Santos JF, Strohaecker TR, Alcântara NG (2011) Mechanical and microstructural investigation of friction spot welded AA6181-T4 aluminium alloy. Mater Des 32(3):1094–1100. https://doi.org/10.1016/j.matdes.2010.11.017
10. Frigaard Ø, Grong Ø, Hjelen J, Gulbrandsen-Dahl S, Midling OT (1999) Proceedings of 1st international symposium on friction stir welding, Thousand Oaks, CA, TWI, Great Abington, Cambridge, UK
11. Li W, Li J, Zhang Z, Gao D, Wang W, Dong C (2014) Improving mechanical properties of pinless friction stir spot welded joints by eliminating hook defect. Mater Des 1980–2015(62):247–254. https://doi.org/10.1016/j.matdes.2014.05.028
12. Uematsu Y, Tokaji K, Tozaki Y, Kurita T, Murata S (2008) Effect of re-filling probe hole on tensile failure and fatigue behaviour of friction stir spot welded joints in Al–Mg–Si alloy. Int J Fatigue 30(10–11):1956–1966. https://doi.org/10.1016/j.ijfatigue.2008.01.006
13. Singh K, Singh G, Singh H (2018) Review on friction stir welding of magnesium alloys. J Magnesium Alloys 6(4):399-416. Luo AA (2013) Magnesium casting technology for structural applications. J Magnesium Alloys 1(1):2-22. https://doi.org/10.1016/j.jma.2018.06.001
14. Trojanová Z, Král R, Chatey A (2007) Deformation behaviour of an AJ50 magnesium alloy at elevated temperatures. Mater Sci Eng A 462(1–2):202–205. https://doi.org/10.1016/j.msea.2005.12.108
15. Shen J, Min D, Wang D (2011) Effects of heating process on the microstructures and tensile properties of friction stir spot welded AZ31 magnesium alloy plates. Mater Des 32(10):5033–5037. https://doi.org/10.1016/j.matdes.2011.05.046
16. Xu RZ, Ni DR, Yang Q, Liu CZ, Ma ZY (2015) Influencing mechanism of Zn interlayer addition on hook defects of friction stir spot welded Mg–Al–Zn alloy joints. Mater Des 69:163–169. https://doi.org/10.1016/j.matdes.2014.12.045
17. Sanusi KO, Akinlabi ET, Muzenda E, Akinlabi SA (2015) Enhancement of corrosion resistance behaviour of frictional stir spot welding of copper. Mater Today: Proc 2(4–5):1157–1165. https://doi.org/10.1016/j.matpr.2015.07.027
18. Lakshminarayanan AK, Annamalai VE, Elangovan K (2015) Identification of optimum friction stir spot welding process parameters controlling the properties of low carbon automotive steel joints. J Mater Res Technol 4(3):262–272. https://doi.org/10.1016/j.jmrt.2015.01.001
19. Baek SW, Choi DH, Lee CY, Ahn BW, Yeon YM, Song K, Jung SB (2010) Microstructure and mechanical properties of friction stir spot welded galvanized steel. Mater Trans 51(5):1044–1050. https://doi.org/10.2320/matertrans.M2009337
20. Sun YF, Fujii H, Takaki N, Okitsu Y (2013) Microstructure and mechanical properties of dissimilar Al alloy/steel joints prepared by a flat spot friction stir welding technique. Mater Des 47:350–357. https://doi.org/10.1016/j.matdes.2012.12.007
21. Sun YF, Shen JM, Morisada Y, Fujii H (2014) Spot friction stir welding of low carbon steel plates preheated by high frequency induction. Mater Des 1980–2015(54):450–457. https://doi.org/10.1016/j.matdes.2013.08.071
22. Lambiase F, Paoletti A, Di Ilio A (2015) Mechanical behaviour of friction stir spot welds of polycarbonate sheets. Int J Adv Manuf Technol 80(1–4):301–314. https://doi.org/10.1007/s00170-015-7007-4
23. Arici A, Mert Ş (2008) Friction stir spot welding of polypropylene. J Reinf Plast Compos 27(18):2001–2004. https://doi.org/10.1177/0731684408089134
24. Bilici MK (2012) Effect of tool geometry on friction stir spot welding of polypropylene sheets. Express Polymer Lett 6(10). https://doi.org/10.3144/expresspolymlett.2012.86
25. https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=152
26. Suhuddin UFH, Fischer V, Dos Santos JF (2013) The thermal cycle during the dissimilar friction spot welding of aluminum and magnesium alloy. Scripta Mater 68(1):87–90. https://doi.org/10.1016/j.scriptamat.2012.09.008
27. Chowdhury SH, Chen DL, Bhole SD, Cao X, Wanjara P (2012) Lap shear strength and fatigue life of friction stir spot welded AZ31 magnesium and 5754 aluminum alloys. Mater Sci Eng A 556:500–509. https://doi.org/10.1016/j.msea.2012.07.019

28. Lee CY, Choi DH, Yeon YM, Jung SB (2009) Dissimilar friction stir spot welding of low carbon steel and Al–Mg alloy by formation of IMCs. Sci Technol Weld Joining 14(3):216–220. https://doi.org/10.1179/136217109X400439
29. Bozzi S, Helbert-Etter AL, Baudin T, Criqui B, Kerbiguet JG (2010) Intermetallic compounds in Al 6016/IF-steel friction stir spot welds. Mater Sci Eng A 527(16–17):4505–4509. https://doi.org/10.1016/j.msea.2010.03.097
30. Piccini JM, Svoboda HG (2015) Effect of pin length on friction stir spot welding (FSSW) of dissimilar aluminum-steel joints. Procedia Mater Sci 9:504–513. https://doi.org/10.1016/j.mspro.2015.05.023
31. Reilly A, Shercliff H, Chen Y, Prangnell P (2015) Modelling and visualisation of material flow in friction stir spot welding. J Mater Process Technol 225:473–484. https://doi.org/10.1016/j.jmatprotec.2015.06.021
32. Fereiduni E, Movahedi M, Kokabi AH (2015) Aluminum/steel joints made by an alternative friction stir spot welding process. J Mater Process Technol 224:1–10. https://doi.org/10.1016/j.jmatprotec.2015.04.028
33. Garg A, Bhattacharya A (2017) Strength and failure analysis of similar and dissimilar friction stir spot welds: influence of different tools and pin geometries. Mater Des 127:272–286. https://doi.org/10.1016/j.matdes.2017.04.084
34. Piccini JM, Svoboda HG (2017) Tool geometry optimization in friction stir spot welding of Al-steel joints. J Manuf Processes 26:142–154. https://doi.org/10.1016/j.jmapro.2017.02.004
35. Zhou L, Zhang RX, Li GH, Zhou WL, Huang YX, Song XG (2018) Effect of pin profile on microstructure and mechanical properties of friction stir spot welded Al-Cu dissimilar metals. J Manuf Processes 36:1–9. https://doi.org/10.1016/j.jmapro.2018.09.017
36. Ravi KK, Narayanan RG, Rana PK (2019) Friction stir spot welding of Al6082-T6/HDPE/Al6082-T6/HDPE/Al6082-T6 sandwich sheets: hook formation and lap shear test performance. J Mater Res Technol 8(1):615–622. https://doi.org/10.1016/j.jmrt.2018.05.011
37. Siddharth S, Senthilkumar T (2018) Development of friction stir spot welding windows for dissimilar Al5086/C10100 spot joints. Mater Today: Proc 5(2):6550–6559. https://doi.org/10.1016/j.matpr.2017.11.310
38. Rana PK, Narayanan RG, Kailas SV (2018) Effect of rotational speed on friction stir spot welding of AA5052-H32/HDPE/AA5052-H32 sandwich sheets. J Mater Process Technol 252:511–523. https://doi.org/10.1016/j.jmatprotec.2017.10.016