Mechanical and Electrical Characterization of Friction Stir Welded Copper and Aluminum Alloys

[1]Yugesh Anil Kharche, [2]Santosh Rama Shekokar

[1]Associate Professor, Department of Mechanical engineering, Padmashri Dr. V. B. Kolte College of Engineering Malkapur
[2]Assistant Professor, Department of Mechanical engineering, Padmashri Dr. V. B. Kolte College of Engineering Malkapur

Abstract: - Friction Stir Welding, often known as FSW, is a progressive solid state welding process that can be used to combine materials that are similar to one another as well as those that are completely unlike. The motivation behind this exploration is to provide an in-depth evaluation of FSW, with an accentuation on its applications in aluminum alloy welding. The fundamental ideas of FSW, the devices and hardware expected for the interaction, the benefits and drawbacks of FSW, and the different angles that effect weld quality will be generally explored. This paper covers a review that was directed to upgrade input boundaries to expand the rigidity, miniature hardness, and electrical resistivity. The micro hardness dissemination was most elevated in the weld joint's base zone, with lower readings in the center locale and middle readings on the top surface.
Keywords: Green welding, dissimilarmaterials, microhardness, and electrical resistivity

1. Introduction

The Welding Organization (TWI) of the United Realm developed the Friction Stir Welding (FSW) process in 1991, and since then it has become widely used as a strong state joining procedure that doesn't harm the environment to meet the rising demand for efficient and light-weight designs that cut down on both overall cost and weight [1]. FSW is separated by its capacity to weld a great many materials and composites, especially aluminum, by producing heat through grinding and plasticizing the material along the joint with a non-consumable turning tool.This process enjoys a few upper hands over conventional welding strategies, including the capacity to weld unique materials, like aluminum and copper, without the requirement for extra filler material, and a tight intensity impacted zone to forestall contortion and guarantee material property safeguarding. Aluminum combinations are broadly used in various enterprises because of their consumption obstruction and solidarity to-weight proportion. Nonetheless, because of their high intensity conductivity and low softening point, aluminum composites give welding difficulties. FSW has been demonstrated to be a viable approach for achieving high-quality welds with low distortion when bonding aluminium alloys. FSW has been shown to bond aluminum alloys with minimal deformation which is in the 1xxx, 2xxx, 3xxx, 4xxx, 5xxx, 6xxx, and 7xxx series. Several studies have been conducted to evaluate the impact of various factors. The form of the tool pin, the rate of rotation, the rate of travel, and the amount of axial force all have a role in the final weld quality. Mishra et al [2] proved that increasing the tool rotational and cross speed results in higher tensile strength and decreased porosity. Welding huge structural components, engine blocks, suspension components, hulls, and superstructures together with solid state welding (FSW) has been utilized in a wide number of manufacturing applications to combine aluminum alloys. These applications include the aerospace industry, locomotive industry, and marine industry. The FSW technique, which was initially utilized in the joining of aluminum alloys, has since been utilized in the joining of materials that are either same or dissimilar to one another [2]. Copper (Cu) is widely used in the electrical and structural industries due to its high strength, electrical and thermal conductivity; however, its density and high cost necessitate the development of a partial replacement material [3]. Aluminium (Al) has similar qualities to copper (Cu), and its substitution for copper delivers the same properties at a lower density and cost [1]. It is difficult to produce a dissimilar Al-Cu FSW joint of high quality using fusion welding due to differences in melting point, formation of brittle intermetallic mixtures (IMCs), porosity, and crack development [1]. These factors not only affect mechanical properties but also electrical resistivity and heat conduction [4]. Because the process temperature is lower than the melting temperature of the base material, the FSW technique may efficiently erase the aforementioned flaws and combine dissimilar Al-Cu in a solid state [5]. For welding, a non-consumable turning device with a pin and shoulder is used; the rotating device is inserted hooked on the adjoining boundaries of the weld specimen and then traversed alongside the weld bond line [6]. The heat generated by the rubbing between the shoulder surface and the plate outside, as well as the plastic distortion, softens the material surrounding the device pin. The material is mixed as the tool rotates, resulting in material migration from the front to the back of the tool pin [7]. During the friction stir welding process, the threaded pin profile results in increased levels of residual strain and stress [8]. The microstructures generated during the welding process, for example, had a considerable impact on the hardness and tensile strength of the precipitated phases in the nugget zone [9]. Welding done with the use of friction stir Because of the disparity in thermal characteristics between the two sides, the amount of heat that was expected to be produced by the aluminum side was more than that produced by the mild M.S. side [10]. In this study, the effect of FSW process parameters on joint quality is investigated. These elements include tool material, geometry, slope angle, sample position, offset, revolving speed, and cross speed [2]. Additionally, there is a paucity of research on FSW of electrical grade aluminum alloy and pure copper [11].

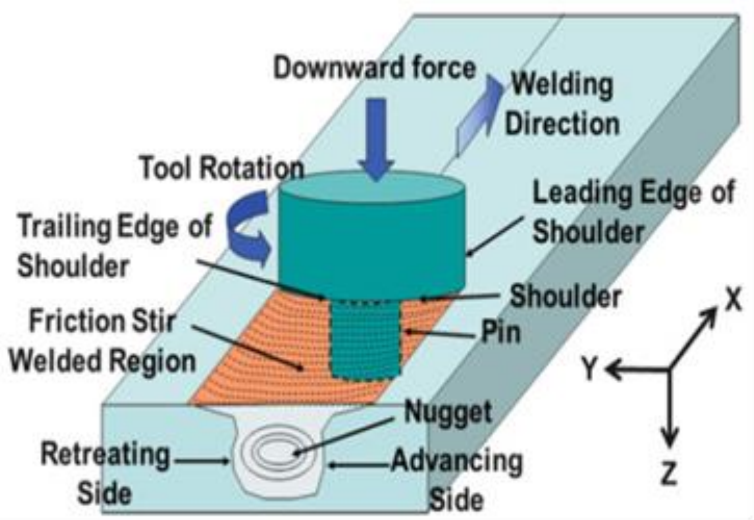


Fig 1: Basic principle of FSW

For joining 10 mm thick AA2024-T6 aluminum plates to overcome the fusion welding problems like softening in heat affected zone, lower joint efficiency, grain coarsening in fusion zone was solved friction stir welding process [12]. AA 2014 is hard to join using fusion welding process because of its properties and burning as well as porosity issues occurs. To overcome such effects friction, stir welding process used to join such materials [13]. Light weight combat aircraft structure was developed by friction stir welding process for replacing the riveting process for joining AA2014-T6 aluminum alloy [14]. AA7075-T651 plates of 10 mm thick butt joint developed by friction stir welding process to investigate the microstructure, tensile properties and fracture toughness of friction stir welded (FSW) butt joints [15]. As a consequence of this, the objective of this study is to evaluate the effect of FSW process parameters on the mechanical and electrical properties of the weld bond of electric grade aluminum alloy AA 6101-T64. and pure Cu in order to fill the research gap that has been identified. The past research [16-24] shows the application of RSM for welding processes. The RSM approach is most useful technique for analysis of welding charecteristics [25]. The heat treatment effect on joint is also carried out [26] with failure analysis and corrosion inestigations [27, 28] also the metallurgical effects and heat treatment effect on joint is carried out [29].

2. Experimentations

On a vertical milling machine, 150 mm long, 4 mm thick, and 75 mm wide plates of electric grade aluminium, pure copper, and alloy 6101 T64 were milled. The Cu specimen was located on the continuing flank and the Al plate on the receding side. A friction stir welding tool made of H13 tool steel (60 HRC) with a tapered cylindrical shape tool pin (tool size: shoulder diameter 20 mm, root diameter of pin 5 mm, small diameter of pin

4 mm, pin length 3.8 mm) and a flat, featureless shoulder was used. The tool was turned clockwise and skewed towards the softer substance Al side [12]. With a dwell time of 10 seconds, the tool shoulder was plunged by 0.1 mm. In order to analyze the mechanical and electrical properties, the welded samples were sliced at an angle that was perpendicular to the direction in which they were welded. In order to evaluate the mechanical qualities, tensile testing and micro hardness measurements were carried out. Electrical resistivity was used to evaluate the electrical property. The chemical composition of the foundational substance is presented in Table 1. The copper and aluminium plates' surfaces were polished and cleaned to facilitate weld joint formation.

Table 1: Chemical Composition of AA6101-T64

Si	Fe	Zn	Mg	Sn	Ti	V	Pb	Cr	Sr	Al
0.374	0.167	0.025	0.482	0.003	0.002	0.008	0.019	0.06	0.004	98.87

Table 2: chemical composition of pure copper

Zn	Sn	Pb	P	Si	Fe	Cu	Balance
0.023	0.008	0.004	0.013	0.008	0.008	99.935	Al

Fig 2: FSW Tool

Fig 3: FSW set up with welding strategy

Table 3: FSW process parameters and their levels for experimentation.

Sr. No.	Input parameters	Notation	Unit	Levels		
				-1	0	1
1	Tool Rotational speed	A	rpm	900	1100	1300
2	Traverse speed	B	mm/min	30	50	70
3	Tool offset	C	mm	0.5	1	1.5

3. Results and discussions

In accordance with the requirements of the ASTM E8 standard, tensile tests were carried out in order to investigate how the characteristics of friction welding influence the overall quality of the weld joint. The influence that FSW process parameters have on the tensile strength of weld joints is outlined in Table 3. In terms of tool rotating speed, lesser rates yielded poorer tensile strength due to insufficient mixing of the copper components with the aluminium matrix.

However, the joint's ultimate tensile strength increased significantly with increasing rotating speed, reaching a maximum of 162 MPa at 1045 rpm, when sufficient copper mixing within the aluminium matrix was attained. Beyond 1045 rpm, tensile strength decreased, most likely due to increased contact time between the base material plate and the tool shoulder face, resulting in increased heat input and, as a result, thickening of the intermetallic compounds inside the stir zone [13]. Tensile strength was similarly reduced as the intermetallic compounds within the weld nugget zone grew [12].

3.1. Tool rotational speed effects

In the process of friction stir welding, the rotational speed of the tool is an extremely important factor. It has an effect on the temperature that is produced in the weld zone, as well as the quality of the welded connection and the rate of welding. Higher speeds result in higher temperatures and a faster welding rate, but they can also create flaws like porosity and cracks. When the weld speed is slowed down, the weld joint can become cooler, the weld quality can improve, and the welding process can be completed in less time. The tool's spinning speed should be determined by the material being connected and the desired weld quality.

The rotational speed is used to control the amount of heat in the weld zone, which effects the microstructure of the joint. A higher temperature input results from a faster revolving motion, which may soften the material and weaken the joint. A slower rotational speed, on the other hand, can cause the material to become overly hard and the joint to become overly weak. Low rotational speeds do not heat the material properly, and the joint does not have enough time to fully form, resulting in a weak joint. Higher rotating speeds warm the material, resulting in defects such porosity, cracking, and incomplete welds. FSW's optimal rotational speed produces a robust joint with a homogeneous microstructure.

The quantity of heat that is introduced into the weld zone is directly proportional to the feed rate of the tool, also known as the speed at which the device moves through the work piece. When the feed rate is increased, more heat is produced, but when the feed rate is decreased, less heat is produced. To obtain the appropriate level of heat input and joint quality, the rotating speed and feed rate must be utilized. Reduced tensile strength was reported at reduced tool rotational speed. It was caused by a lack of mixing of the copper elements in the aluminum matrix. The ultimate tensile strength of the weld bond increased progressively as the rotational speed increased. The greatest tensile strength of 162 MPa was reached at 1045 rpm due to adequate mixing of Cu in Al matrix at this speed. Tensile strength was also found to be declining starting at 1045 rpm.

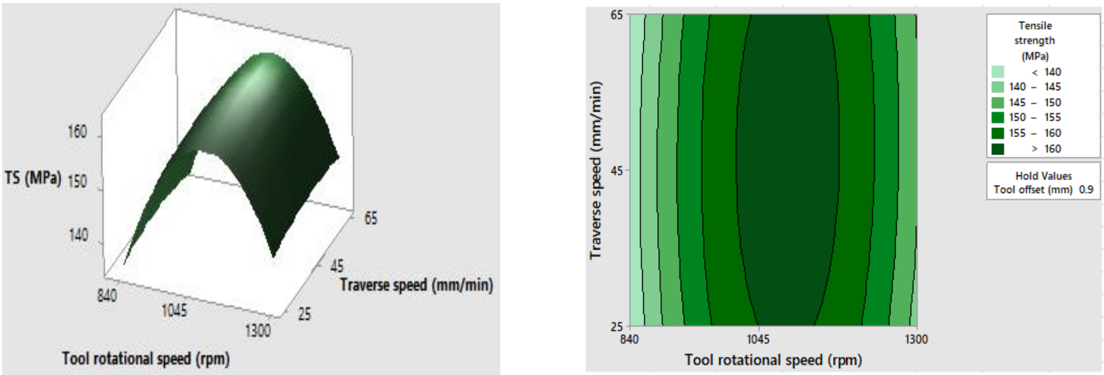
This was happening because there was increased contact time between the base substantial and the device shoulder face, resulting in more heat input. This greatly promotes IMC thickening in the stir zone [14]. Tensile strength decreased when IMCs in the weld nugget zone increased [13].

3.2 Traverse speed effects

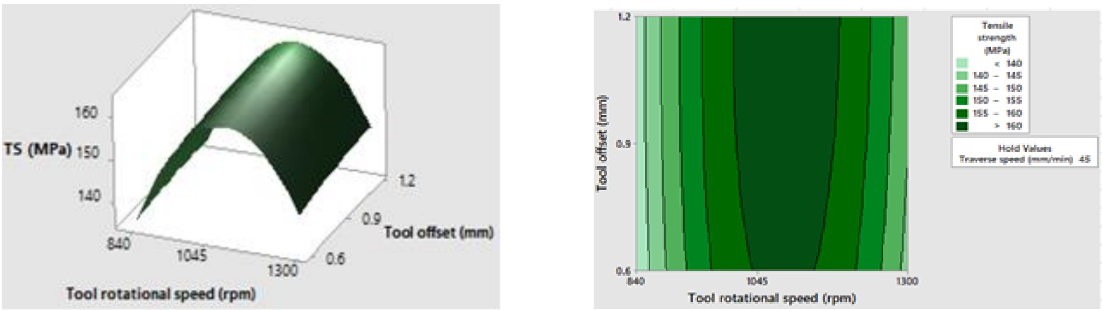
The traversal speed of friction stir welding (FSW) has a substantial effect on the quality and characteristics of the weld bond. Traverse speed is the rate at which the tool moves sideways of the bond and is usually measured in millimetres per minute. Increasing the cross speed raises the temperature input into the material, which increases the amount of plastic deformation and the duration of that deformation. This can increase the weld strength and joint integrity, particularly for thicker materials. High traverse rates can also aid to prevent weld porosity and oxidation. When raising the traversal speed, there are some technical difficulties to consider. Higher traverse rates put more pressure on the tool and the weldment, which can cause more vibration and, as a result, lower weld quality. Faster traverse speeds can also increase the danger of tool wear and breakage, especially when welding heavier materials. As a result, it is critical to choose a traverse speed that is acceptable for the material thickness and weld joint geometry. Due of the intense heat input and movement stress transition between Al-Cu in the nugget zone, reduced cross speed of 25 mm/min caused in lower tensile strength. The reduced strength was caused by the turbulent material flow. Microcracks generated at high heat input, causing the weld connection to fracture. In addition, thick brittle intermetallic complexes formed, lowering tensile strength. The desired heat participation increased the tensile strength as the cross speed improved to 45 mm/min. At this point, the recrystallized fine grain size decreased, expanding the grain boundary. The turbulent flow returned to normal. When the traverse speed was improved to 65 mm/min, the heat input decreased, reducing the rate of plasticization and inappropriate material mixing. This meant that at lower tensile strengths, the weld joint failed less frequently.

3. 3 Tool offset Effects

The ultimate tensile strength of a device pin displaced by 0.6 mm towards the aluminum side was lower. It effects in weak bonding and canceled defects. More Cu atoms are in the stir zone, resulting in brittle IMC [15]. The tensile strength was reduced by these IMCs. The tensile strength improved when the device offset rose to 1mm and 1.2mm. When there are less Cu atoms in the stir zone, they react with Al atoms. As a result, fewer IMCs form and tensile strength increases.



a. Interface effects of tool rotational speed and traverse speed on tensile strength.



b. Interface effects of tool rotational speed and tool offset on tensile strength.

Fig 4 (a, b): Response surface and contour plots for tensile strength

3.4 Microhardness test

The micro hardness test was carried out from the Al side to the Cu side at three separate places namely 2 mm (middle), 3.5 milimeters (bottom), and 0.5 mm (top), and variations in micro hardness were noted in the different sections. Because of the presence of intermetallic compounds (IMCs) at the bottom of the weld nugget area, a highestmicro hardness was observed. Increased heat input in the bottom stir zone produced thickening of the IMCs and hence an increase in micro hardness.

A substantial increase in micro hardness was detected in the thermomechanically damaged region of the Cu side at the weld nugget region. This was owing to the complicated structure that emerged near the shoulder region as aeffect of the improved heat input. In the weld nugget zone, a wave pattern of micro hardness distribution was found. The difference in characteristics between the two materials influenced this, resulting in shorter thermal mechanisms affected zones (TMAZ) and heat affected zones on the Copper specimen side compared to wider TMAZ and HAZ on the aluminium side. The production of dispersions and the aggregation of IMCs caused the abrupt increase in micro hardness at the Cu side TMAZ.

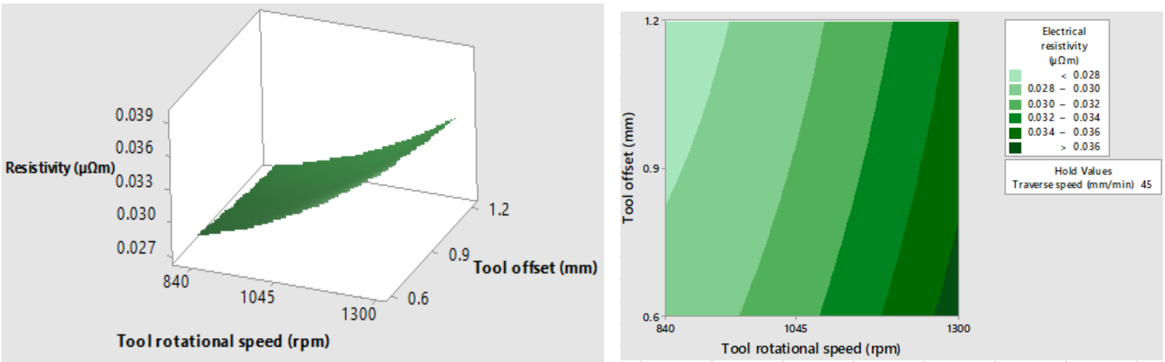
3.5 Micro hardness at the top

The micro hardness of the Cu basis material was approximately 90 HV, while the micro hardness of the Al base material was approximately 40 HV. The complicated distribution of micro hardness was observed in the mixingregion. It was initiated by the growth of IMCs in the agitated region. As a result, hard intermetallic compounds were observed in the soft aluminium material, growing the micro hardness. The changes in micro hardness in the TMAZ and SZ were caused by mixing the IMCs in the basic components, which increased the micro hardness. The micro hardness in the HAZ of Al side was in the range of 80 to 100 HV. The micro hardness of the TMAZ increased dramatically.

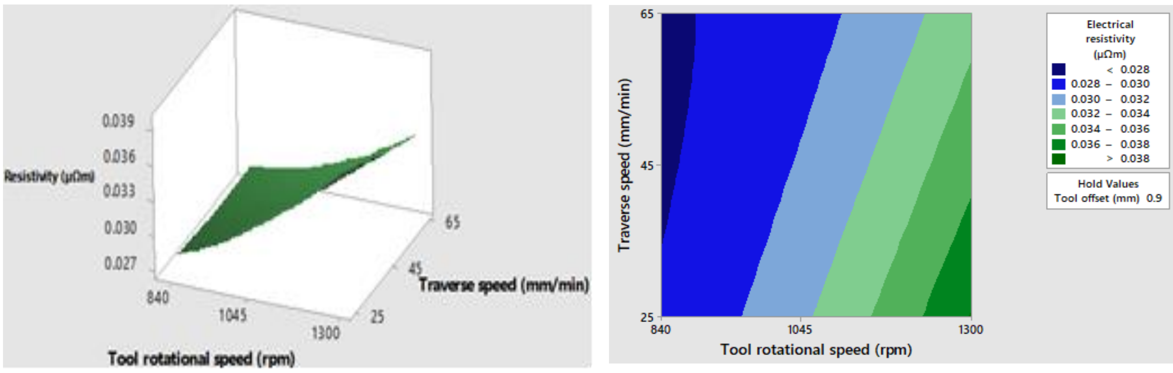
The addition of Intermetallic Mixtures (IMCs) in the base materials enhanced the micro hardness at the Al region of the Heat Affected Zone (HAZ) to 80 HV. As IMCs were incorporated, similar changes in microhardness were found in the Thermo-Mechanically Affected zones (TMAZ) and Stir region (SZ). The addition of hard and brittle IMCs to the microhardness distribution increased the microhardness in the HAZ of the Copper plate by up to 100 HV. Furthermore, the grain size of the bond material was greater in the HAZ of copper region than in the base material. This is due to copper's higher melting temperature, which resulted in the production of coarse granules. Because the hardness of the material is based on the grain size, this can result in greater hardness values in the HAZ of copper region. Furthermore, the high grain size in the Cu side HAZ can contribute to the low microhardness of the Al side HAZ by inducing plastic deformation in the Al material, which further reduces the microhardness.

3.6 Electrical resistivity

Variations in heat input, material mixing, and microstructure change all contribute to resistivity fluctuations. Influence of device rotating speed: It was discovered that the higher the tool rotational speed, the higher the level resistivity. Because of the considerable heat input at this temperature, IMC thickening occurs, resulting in increased electrical resistance [22]. As the minimum heat input and thickness of the IMCs were not raised much, the least electrical obstruction was seen at the most reduced device rotational speed. Variation in electrical resistivity was also detected as aoutcome of welding current. Because of the increased heat input, a higher electrical resistivity was attained at a higher current level [12].



a. Interface effects of tool rotational speed and tool offset on electrical resistivity



b. Interface effects of tool rotational speed and tool offset on electrical resistivity

Fig 5 (a, b): Response surface and contour plots for electrical resistivity.

The reason for this is that higher current levels result in higher heat input, which promotes the creation of intermetallic compounds and hence increases electrical resistance. The effect of flux and flux-cored wire mixing ratio: The joint electrical resistivity is also affected by the mixing ratio of flux and flux-cored wire. The electrical resistivity reduces as the flux mixing ratio increases. This is because a higher flux level aids in weld pool cooling while also enhancing weld pool cleaning efficiency. This reduces the joint electrical resistivity by inhibiting the generation of intermetallic compounds. The effect of microstructure: The microstructure of the welded bond has an effect on the joint electrical resistivity. The electrical resistance increases with the concentration of intermetallic compounds. Because IMCs have higher electrical resistivity than base metals, the overall electrical resistivity of the welded bond increases. Cross speed impacts not only the amount of heat input during welding but also the size and distribution of intermetallic compounds (IMCs) that form as a result of welding. As heat input increases, higher resistance is noticed at lower traversal speeds, resulting in thicker and tougher IMCs. Lower electrical resistivity is observed at higher traverse speeds when heat input decreases and IMCs drop. The number of copper particles that blend with the aluminiummedium is determined by the dvice pin offset, which effects welding performance. At lower offsets towards the Al side, more copper particles mix with the Alumunium matrix to create thick, rigid IMCs. As a result, resistance increases. As the tool pin offset grows, the amount of copper particles that mix with the Aluminium matrix reduces, resulting in smaller size IMCs and lower resistance. This detailed thought process and technical understanding of the influence of cross speed and tool pin offset on welding performance can help welders optimise the welding process for better results.

4. Conclusions

The welding parameters that are employed, the composition of the materials that are being joined, and the microstructure of the joint all have an effect on the mechanical and electrical properties of a joint that has been treated by friction stir welding (FSW). The following major inferences were drawn from the present research.

1. The use of this joints allowed for successful preparation due to the increased strength and ductility of the alloys when heated. The setting of the tool offset near the aluminum side provided sound weld joint due to the increased control of heat input and the ability to accurately control the temperature of the weld.
2. Positioning of aluminum on the retreating side also gave sound weld joint because of the increased surface area of contact between the two metals and the ability to control heat input more accurately.
3. The minimum and maximum tensile strength obtained was 135 to 162 MPa due to the increased strength of the aluminum alloy and the increased amount of heat input.
4. The minimum and maximum resistance obtained was 0.02 to 0.03 μΩm due to the increased electrical conductivity of the copper and the formation of thinner IMCs.
5. Higher tool rotational speed and lower traverse speed caused a high heat input and formation of thick IMCs, thus lowering the tensile strength and increasing the resistivity of the joint.

Refrences

[1] V. Pedroand W. Thomas, Friction stir welding technology in Structural Connections for Lightweight Metallic Structures (Berlin, Heidelberg: Springer Berlin Heidelberg, 2011), pp. 85-124.

[2] R.S. Mishra and P.S. De, Friction stir welding and processing: science and engineering, (Springer international publishing Switzerland, ISBN 978-3-319-07042-1), pp. 259-296.

[3] H. Singh and H. S. Arora, Friction stir welding-Technology and future potential In Proceeding of National conference on advancements and futuristic trends in mechanical and materials engineering.

[4] X. W. Li, D. T. Zhang, Q. I. U. Cheng and W. Zhang, Microstructure and mechanical properties of dissimilar pure copper/1350 aluminum alloy butt joints by friction stir welding, Trans. Nonferrous Met. Soc. China. 22(6) (2012), pp. 1298-1306.

[5] P. Sadeesh, M. V. Kannan, V. Rajkumar, PAvinash, N. Arivazhagan, K. D. Ramkumar and S. Narayanan, Studies on friction stir welding of AA 2024 and AA 6061 dissimilar metals. Procedia Engineering 75 (2014), pp. 145-149.

[6] T. K. Bhattacharya, H. Das and T. K. Pal, Influence of welding parameters on material flow, mechanical property and intermetallic characterization of friction stir welded AA6063 to HCP copper dissimilar butt joint without offset, Trans. Nonferrous Met. Soc. China 25(9) (2015), pp. 2833-2846

[7] M. N. Avettand-Fenoel R. Taillard G. Ji and D. Goran, Multiscale study of interfacial intermetallic compounds in a dissimilar Al 6082-T6/Cu friction-stir weld, Metall. Mater. Trans. A 43 (2012), pp.4655-4666.

[8] R. Butola, R. Singh, Fabrication of FSW Tool Pins through Turning of H13 Tool Steel: A Comparative Analysis for Residual Stresses, world sci.21 (2022), pp.351-366.

[9] I. Karagoz, R. Cakir, Friction Stir Butt Weldability of Dissimilar Alloys AA5754 AND AA1050, World sci. online

[10] R. Tharmaraj, N. Rajesh, Investigation on the Thermal Behavior of Friction Stud Welding of Dissimilar Aluminum/Mild Steel Joints, World Sci. 29 (2022), 2250093.

[11] W. B. Lee and S. B. Jung, Void free friction stir weld zone of the dissimilar 6061 aluminum and copper joint by shifting the tool insertion location. Mat. Res. Innovat. 8(2) (2016), pp. 93-96

[12] T Sonar., et al. Investigating the Effect of PWHT on microstructural features and fatigue crack growth behavior of friction stir welded AA2024-T6 aluminum alloy joints." Forces in Mechanics 8 (2022): 100107.

[13] T Sonar., et al. Investigation of shoulder diameter to sheet thickness (D/T) ratio on tensile properties friction stir welded AA2014-T6 aluminum alloy joints." Advances in Materials and Processing Technologies 8.3 (2022): 3440-3453.

[14] Parasuraman, Prabhuraj, Tushar Sonar, and Selvaraj Rajakumar. Microstructure, tensile properties and fracture toughness of friction stir welded AA7075-T651 aluminium alloy joints." Materials Testing 64.12 (2022): 1843-1850.

[15] S. Celik, and R. Cakir, Effect of friction stir welding parameters on the mechanical and microstructure properties of the Al-Cu butt joint, Metals 6(6) (2016), pp.133

[16] Kakade, S. P., et al. Experimental investigations and optimisation of Ni-Cr-B-Si hardfacing characteristics deposited by PTAW process on SS 410 using response surface method." Advances in Materials and Processing Technologies (2022): 1-17.

[17] Deshmukh, D. D., & Kalyankar, V. D. (2019). Deposition Characteristics of Multitrack Overlayby Plasma Transferred Arc Welding on SS316Lwith Co-Cr Based Alloy–Influence ofProcess Parameters. High Temperature Materials and Processes, 38(2019), 248-263.

[18] Kalyankar, V., Bhoskar, A., Deshmukh, D., & Patil, S. (2022). On the performance of metallurgical behaviour of Stellite 6 cladding deposited on SS316L substrate with PTAW process. Canadian Metallurgical Quarterly, 61(2), 130-144.

[19] Deshmukh, D. D., & Kalyankar, V. D. (2021). Analysis of deposition efficiency and distortion during multitrack overlay by plasma transferred arc welding of Co–Cr alloy on 316L stainless steel. Journal of Advanced Manufacturing Systems, 20(04), 705-728.

[20] Deshmukh, D. D., & Kalyankar, V. D. (2019). Evaluation of surface characteristics of PTAW hardfacing based on energy and powder supplied. In Advances in Micro and Nano Manufacturing and Surface Engineering: Proceedings of AIMTDR 2018 (pp. 547-558). Singapore: Springer Singapore.

[21] Kakade, S. P., Thakur, A. G., Deshmukh, D. D., & Patil, S. B. (2022). Experimental investigations and optimisation of Ni-Cr-B-Si hardfacing characteristics deposited by PTAW process on SS 410 using response surface method. Advances in Materials and Processing Technologies, 1-17.

[22] Deshmukh, D. D., & Kharche, Y. (2023). Influence of processing conditions on the tensile strength and failure pattern of resistance spot welded SS 316L sheet joint. International Journal on Interactive Design and Manufacturing (IJIDeM), 1-13.

[23] Kakade, S., Thakur, A., Patil, S., & Deshmukh, D. (2023). Experimental evaluation and correlation of plasma transferred arc welding parameters with hardfacing defects. In Recent Advances in Material, Manufacturing, and Machine Learning (pp. 326-331). CRC Press.

[24] Yugesh Kharche, Neeraj Kumar, B. B. Ahuja, M. Dhanvijay, Mathematical Modelling of Material Removal Rate and Diameter of Overcut for Sodalime glass through Pressurized Flow ECDM Process

by Response Surface MethodologyInternational Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-8, Issue-5S3 July 2019

[25] Deshmukh, D. D., & Kalyankar, V. D. (2018). Recent status of overlay by plasma transferred arc welding technique. International Journal of Materials and Product Technology, 56(1-2), 23-83.

[26] Naik, H. V., Deshmukh, D. D., & Kalyankar, V. D. (2019). Study of heat treatment effect on microstructure of PTA weld deposited surface of SS 316L steel. In Advances in Additive Manufacturing and Joining: Proceedings of AIMTDR 2018 (pp. 597-607). Singapore: Springer Singapore.

[27] Kalyankar, V. D., & Deshmukh, D. D. (2017, December). Failure investigations of failed valve plug SS410 steel due to cracking. In IOP Conference Series: Materials Science and Engineering (Vol. 282, No. 1, p. 012007). IOP Publishing.

[28] Chaudhari, A. Y., & Deshmukh, D. D. (2020, March). Metallurgical investigations on corrosion behavior of simple and heat treated duplex stainless steel 2205 exposed to corrosive media. In IOP Conference Series: Materials Science and Engineering (Vol. 810, No. 1, p. 012048). IOP Publishing.

[29] Bhoskar, A., Kalyankar, V., & Deshmukh, D. (2023). Metallurgical characterisation of multi-track Stellite 6 coating on SS316L substrate. Canadian Metallurgical Quarterly, 62(4), 665-677.