Analysing the Friction Stir Welded Joints of AA2219 Al-Cu Alloy in Different Heat-Treated-State

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Abstract. Aluminium alloy AA2219 is widely used in light weight structural applications where the good corrosion resistance and specific weight required. The fabrication of this alloy using friction stir welding process is gaining interest towards finding the characteristics of the weld metal properties, since this process involved in the welded materials does not melt and recast. In the present investigation, friction stir welding process was used for different heat treated conditions of 2219-T87 and 2219-T62 aluminium alloys to find the influence of base metal on characteristics of the joints. The experimental output results exhibited that, mechanical properties, weld metal characteristics and joint failure locations are significantly affected by the different heat treatment conditions of the substrate. The joints tensile and yield strength of the 2219-T87 welds was higher than the 2219-T62 welds. Hardness distribution in the stir zone was significantly varied between two different heat treated material conditions. The microstructural features of the 2219-T62 welds reveal the coarse grains formation in the thermo-mechanically affected zone and heat affected zone. The joint efficiency of the 2219-T82 welds is 59.87%, while that of 2219-T62 welds is 39.10%. In addition, the elongation of the joint also varied and the joints failure location characteristics are different for two different types heat treated condition joints.

1. Introduction
In recent years, friction stir welding became one of the prominent solid states joining technique. The welding institute (TWI) was invented the friction stir welding process in 1991, that offers the wide applications in fabrication industry and more advantages over the readily available fusion welding techniques [1,2]. In general, friction stir welding generates low heat input in the welds and the welded materials are being involved in absence of melting and solidification [3]. Friction stir welding produce the joints in solid phase where the substrates melting point maximum temperature below such as, it is approximately 0.8 times of the substrates original melting point. Friction stir welding, it is continuous, thermal shear and autogenous process with the use of non-consumable harder material rotation tool compared to the base materials [4]. Friction stir welding tool generates the heat during welding and base alloys are tend to occur phase transformations for the period of cooling and/or solidification of the weldments are of a welding condition of solid phase. Because of the deficiency of substrate metal melt and become softness, the newly developed friction stir welding process is perceived to offer a number of benefits than conventional fusion welding techniques [5-7]. While, in FSW consists a new...
set of four different regions such as thermo-mechanically affected zone (TMAZ), heat affected zone (HAZ), stir zone (SZ) and unaffected substrate. The seregions formations in welds are affected by the high speed rotation of the rotating tool in base metal, and material flow behaviour during FSW. The most important advantages of the FSW are its capable of join metals which are enormously hard to join through conventional arc welding methods, the materials such as aluminium alloys and dissimilar combinations. Moreover, FSW benefits includes less defects, low distortion and residual stress, no formation of intermetallic compounds formation and no filler wires deposition. In addition, because of low heat input produced in the welding, high quality welds with the formation of good microstructures and mechanical properties over conventional fusion welding processes [8]. Whereas, are conventional fusion welding process, during welding it is owing to the generation of high temperature which can cause to form defects such as porosity, cracks and burn through are certainly formed in the fusion zone. In addition, arc welding methods frequently occurred to deterioration of substantial strength in the weldments outstanding the microstructural changes in the fusion zone. To avoid these problems, new welding methods of solid state joining techniques such as diffusion bonding [9], friction welding (FRW) [10-18], explosive welding [19] friction stir welding [6, 20-23] and ultrasonic welding [24] processes are contemplated. Some of the dissimilar combinations are not successfully joined even though the solid state welding processes were applied. To overcome these issues bimetallic joints technique has been implemented using nickel [25-28], silver [29] and zinc [30] as a barrier between the substrates. However, solid state joining methods of FSW process indicates a valid choice in order to join high reliable welds without any problems for all materials combinations over other welding processes.

The joining of aluminum alloys continuously increasing demand in the automotive and light weight structural industries. The aluminum alloy series of 2xxx and 7xxx alloys are determined as not feasible to weld using traditional arc welding techniques but these are having a prodigious benefit for a several advantages and aeronautic applications due to their specific strengths, good fracture toughness, excellent corrosion resistance and good cryogenic properties [26]. Among these, AA2219 alloys achieved a great interest in specific applications of liquid cryogenic rocket fuel tanks for launch vehicles and petroleum plants applications [8,31,32]. As the welding process of solid state joining methods, friction stir welding can avoid the weld defects and enhance the joint strength and other properties of the joints. A numerous researcher’s studies have revealed the great interesting things on microstructures, thermal histories, mechanical properties, corrosion resistance, weld metal flow behaviour and fatigue strength and its properties of the friction stir welding of AA2219 aluminum alloy sheets [33-35]. Arora et al.[35], have been deliberate the outcome of process conditions on mechanical strength and properties of the welds and reported that depletion of tensile strength and other mechanical properties is practised in circumstance of joints as comparison of the base substrates. The joint efficiency significantly varied with the change in weld travel speed, diameter of the shoulder and travel speed. Moreover, elongation of the joints is mostly exaggerated by welding travel speed. Because of the formation of second phase precipitate or intermetallic particles, the hardness values are lowered in the nugget zone. The lowest hardness profiles with an inclination of 0°-30° angle to the unaffected base metal microstructures in the HAZ. This inclination increases with decreasing the processing parameters of rotational tool speed which is increases with welding travel speed [1].Zhao et al. [36] reported the empirical relation between the welding processing parameters and tensile properties and its strength of the welded joints and found that the ultimate tensile load of the FSW joints was ominously pretentious by the welding travel speed and rotational speed and pinching gap exhibits less impact and it can be neglected. The additional increasing of welding speed leads in strength of the welds drops, while the gradual increase in rotational speed and pinching gap enhanced the linear growth in strength of the welds. Most of the studies focused on the AA2219-T87 alloys possessions of process conditions and tool pin profiles and tensile strength and mechanical properties of the joints. The efficiency of the AA2219-T87 FSW joints notice ably lesser, but it is relatively higher when the joint efficiency achieved by the arc welding techniques. There are very few studies are reported on other heat treatment condition of this AA2219 alloy and reported that the efficiency of
the AA2219-O condition has better joint efficiency that the AA2219-T87 condition [37]. However, it was not clear that the effect various heat treatment conditions of base metal on FSW joint properties. In the present study two different heat treatment conditions (T87 and T62) of AA2219 alloy has been selected to investigate the weld characteristics and joint properties, changes in microstructural formation and its effect on overall efficiency of the FSW joints. The adequacy of the set of same welding conditions for two different types of alloys is evaluating to understand the influence on properties of the FSW weldments.

2. Experimental Procedure

The materials which are rolled AA2219 aluminum alloy plates have thickness of 6 mm were cut into the dimensions of 160 mm in length and 50 mm wide by using bench power hacksaw and machined the edges of the plates to remove the burrs. The initial condition of the materials was selected AA2219-T87, and are subjected to annealing to recover the material to its original state. Then the material state was changed to AA2219-T62 condition by using heat treatment procedure of the material was kept in furnace at 525 °C for 8 hours and then quenched in salt water at room temperatures. After quenching again heat treated in furnace at 165 °C for 24 hours. The final form of AA2219-T62 and T87 condition materials are used for friction stir welding machine which is capable of various process parameters such as six types of spindle speeds, possible to change travel speed and 0-1000 psi variable pressure with least count of 10 psi. A non-consumable die steel tool with pin was used for FSW welding, its dimensions and illustration is exhibited in figure 1. The FSW tool entails of threaded pin which can easily moves the material not only from advancing side to retreating side but also provide up and down motion to the material which provide better mixing of abutting surfaces. The butt joint alignment was used for friction stir welding and plates were clamped firmly with the help of clamps to the backing plate as shown in figure 2. The substrates elemental chemical composition is provided in Table 1. FSW was performed in the longitudinal direction of the plates for both the heat treated conditions using same tool and welding parameters. The base materials, before welding were machined to avoid the misalignments and cleaned with steel wire brush to remove the oxide layers and finally cleaned with alcohol to remove the dirt, oil, grease, etc. FSW was carried out using low rotation speed to higher value conditions to understand the

![Figure 1](image1.png)  
(a) Schematic view (b) Display of the tool pin profile.  

![Figure 2](image2.png)  
Figure 2 FSW welding setup and clamping of the plates.
Figure 3 Dimensions of the FSW joints tensile testing specimen.

Table 1 Base metal elemental composition used in present study

|   | Al  | Cu  | Mn  | Ti  | V   | Zr  | Mg  | Si  | Zn  |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|   | 93.0| 6.3 | 0.3 | 0.06| 0.10| 0.18| 0.02| 0.2 | 0.1 |

Welding parameters range. With the results of preliminary experiments a set of welding parameters were optimized. The FSW was performed at the tool traverse speed was 30 mm/min, rotation of the tool speed was 708 rpm with the tool in clockwise rotational direction, tool force of 4 KN and pin length is 6mm.

The FSW joints after joining have been sliced in abrupt to the direction of the welding using electrical discharge cutting machine for macro-structural studies and tensile tests. The samples which are cross-sectioned were arranged for microstructural analysis as per the ASTM E3-11 standard metallographic procedure. The tensile samples were arranged as per the standard procedure of ASTM E8, as shown in figure 3. The polished surfaces were etched with Keller’s reagent (HNO₃ 2.5 ml, H₂O 95 ml, HCl 1 ml and HF 1.5 ml) for 15 minutes to reveal the microstructural features and followed by washed with running water and alcohol, and air dried. The hardness was measurements for the samples which are cross-sectioned were arranged for microstructural analysis as per the ASTM E3-11 standard metallographic procedure. The tensile samples were equipped as per the standard procedure of ASTM E8, as shown in figure 3. The polished surfaces were etched with Keller’s reagent (HNO₃ 2.5 ml, H₂O 95 ml, HCl 1 ml and HF 1.5 ml) for 15 minutes to reveal the microstructural features and followed by washed with running water and alcohol, and air dried. The hardness was measurements for the welds with the help of Vickers’s hardness tester. The micro hardness of Vickers’s hardness (HV) test was conducted across the microstructures of the samples, at three different positions in welds with the load of 0.2 kg. The mechanical properties of the welded joints were assessed under universal testing machine of India make Instron5892, India. The tensile test was conducted normally at room temperature, cross-head speed of 2 mm/min, and the tension test results of individually every joint were assessed using five tensile samples selected from the one weld joint. After completion of tensile tests, optical and scanning electron microscope was used to analyse the microstructural features of the welds. The fracture paths and failure locations of the welded joints of each state of the welding materials are evaluated to find the effect of base materials heat treatment conditions.

3. Results and Discussions
Friction stir welding of aluminum alloys are free from defects when compared to the fusion welding techniques, the defects like porosity, solidification cracks and inclusion formations are not involved due to the absence of melting during welding. However, there are other defects found in FSW joints like tunnel defects, kissing bond, piping defects, pin holes and cracks formation, etc., due to inappropriate material flow and inadequate mixing of materials in stir zone region. However, very few defects are encountered for FSW of AA2219 alloys which are most influential factors of cracks, tunnel defects and pin holes on strength of the joints. There are only two types of major defects found over the effects of wide range of processing parameters on FSW joints are tunnel defects and pin holes [1]. Most of the defects which are affected by material flow, owing to the unacceptable range of processing parameters i.e. the material experiences too hot at higher rotational speed and cold at low rotational speed. These two conditions are not enough to form good joints and considered to be defects
formation. The FSW trails done at wide range of parameters to optimize the processing conditions and it was observed that the tensile stress of the base substrates and FSW joints of AA2219 T87 and T62 alloys.

![Figure 4 Tensile stress of the base substrates and FSW joints of AA2219 T87 and T62 alloys.](image1)

![Figure 5 Yield stress of the FSW joints of AA2219 T87 and T62 alloys.](image2)

The hot processing defects are starts to form over 1000 rpm rotational speed and groove like defects were generated in the friction stir processing (FSP) region. Whereas, tunnel defects are observed below the 690 rpm and large number of defects found at 500 rpm rotational speed, it is owing to the inappropriate mixing of weld material in the FSP zone. The tensile strength of the both substrates (AA2219 T87 & T62) and FSW joints produced at optimum process parameters are depicted in figure 4. It is perceived that the mechanical strength of the AA 2219 T87 base metals higher than the T-62 alloys with the minor difference. Whereas, the variation in strength of the FSW joints is quite higher and T-87 joints has higher strength compared to T62 joints. The defects free microstructural observations of the joints produced at optimum processing conditions are determines the prevention of defects associated with flow occur at an improver temperature where material stick and slip spreading flow, and the material flow from pin is precisely composed with that back flowing and fill the freed region other side of the tool pin.

The yield stress of the FSW joints obtained from two different heat treatment conditions of the AA2219 alloys, are illustrated in figure 5. The yield stress also shows similar observations like tensile stress of the joints, welds of T62 condition showing lower values of strength compared to welds of T87 condition. The reduction in tensile stress of the welds owing to either the presence of defects or precipitates formation. There is no evidence of defects formation in both the conditions, and precipitates formation are the key reason for variation in strength of the FSWed joints. The state of the AA2219-T87 is a heat treatable alloy which is more prone to gains strength from the formation of second phase precipitates. During friction stir welding due to high rotational speed, temperature in the weld metal raises to above 450 °C. It is noticed that the welding conditions have great impact on tensile strength and elongation of the welded joints. The presence of such a high temperature cause to dissolution of precipitates in the FSW welds [35]. During FSW, due to the high frictional contact heat input rises with increasing of rotational tool speed thus resulted in proportional increase in large amount of diffusion advancing and over aging. The turbulence in the weld joint due to higher rotational speed can lead to scarce formation of the plasticized zone and reduction in strength of the joints. Zhang et al. [38], described the numerical simulation of friction stir welding joints have moreover exhibited deprivation of quality of the welded joint with rising of rotational speed owing to the large amount of weld flash formation. On the other hand it is shown that decrease in heat input consequences in improving the strength of the joints due to the rising of welding speed by means of the interaction time among substrates and tool is condensed and therefore the generated frictional heat for a particular constant length of the FSWed also decreased, hence the improving in welds strength.
Most of the studies reported that the strength of the welds varying with process conditions of tool pin profile and force, tool speed and welding travel speed. It is envisaging that the large variation in

![Figure 6 Joints efficiency of the FSW joints of the AA2219 T87 and T62 alloys.](image)

![Figure 7 Microhardness of the FSW joints of AA2219 T87 and T62 alloys.](image)

Strength of the both heat treated conditioned joints owing to influence of welding parameters on different heat treatment conditions of the joints. The selected welding parameters in this study are more suitable for T87 temper condition than the T62 condition of the material. The joint quality is related to the material flow in friction stir welding and based on these three types of material flow characteristics are defined such as deficient material flow, equilibrium material flow and extreme material flow [39]. There are no defects formations in the equilibrium material flow welds; it could be attained by a proper speed and plunge depth. Whereas, inadequate and surplus material flow conditions are in general comes from the higher speed and rotational rate. Both of the heat treated conditions have balanced material flow, since there is no evidence of formation of defects in the welds, except changes in the microstructural formation (the details of the microstructures are explained in next section). It is clear that the obtained welding conditions are not suitable for T62 temper condition compared to the T87 temper condition. It is hypothesis that the second phase precipitates formation is more in the T62 temper condition over the T87 temper condition, which are affecting on strength due to this, destruction in tensile strength and mechanical properties of the friction stir welded joints.

Figure 6 illustrates the efficiency of the welds of both the heat treated conditions of AA2219 T87 and T62 aluminum alloys. The difference in efficiency of the welded joints is around 20%, which is almost similar to the variation of the base metal strength. Whereas, the larger difference in strength of the welds is owing to the microstructural difference. Vickers micro hardness values have taken across the joint interface at the centre of the welds to identify the difference in microstructural formation of various zones. The micro hardness distribution of the AA2219 T87 and T62 temper condition welds are depicted in figure 7. The hardness distribution of the welded joints was considerably lesser than that of the base metal hardness in two sides of the weld centre of retreating (RS) and advancing side (AS). The lower hardness regions of the joints on RS side lower than that on the AS. The hardness distribution shows that, in case of T87 welds highest hardness values 86 HV are recorded in the stir zone, whereas 79 to 81 HV was recorded for the T62 welds condition. The large difference in hardness distribution in overaged region (TMAZ and stir zone) cause to the variation in joint efficiency of the friction stir welds. It is also observed that the increase in hardness of the HAZ and TMAZ of the T62 condition welds over T87 condition welds shows that the formations of secondary strengthen precipitates in the stir zone is higher. Stir zone microstructure is more influential factor in welds to determine the strength of the welds. The lower hardness zones in HAZ and TMAZ for the T87 temper condition owing to the coarse grains formation. Therefore the inferior secondary precipitation
weakening resulted in the formation of lower hardness in both sides of the stir zone. Whereas, low hardness regions of the T62 state welds are unlikely as T87 and shows the weakest region in stir zone.

Figure 8 Microstructures of the (a) Base metal, (b) HAZ, (c) TMAZ and (d) Stir zone of the FSW joints of AA2219 T87 alloys.

It is also confirmed that the fracture of the T62 joints occurred at the stir zone centre of the welds. Whereas, the joint failure occurred in HAZ/TMAZ region for the T87 welds. The microstructures are also evident that the grain size variation between the various zones of the joints and two different conditions of the welds.

The macrostructures of the friction stir welds produced at various processes parameters were revealed the no presence of defects at the optimum welding conditions. Whereas, nugget size started to decrease with further rising of welding speed over 30 mm/min, which is ascribed to the reduction of the total of material flow all over the tool pin. Figure 8 shows the microstructures of the various zones of AA2219 T87 alloys and base substrate. It is observed that the grain size in HAZ much advanced than the base substrate grain size and coarsen almost twice of the base metal grain size. The elongated and larger grains are observed in the TMAZ which are thermally affected by heat and rotational pin. The stir zone characterized by very fine equi-axed grains; these are very smaller compared to the HAZ and TMAZ grain size owing to the dynamic recrystallization through friction stir welding. The stir zone grain size varies vastly by altering the welding speed and plunge depth. From the observations, it is found that as the increase in welding speed resulted in gradual increasing of grain size owing to the changes in heat input and ensued from the relative causes of material flow or material deformation in the nugget zone. It is fact that the lowering of degree of material flow deformation usually initiates to improving in the recrystallized grain size. Consequently, the adequate tool rotational and welding speeds produce proper material flow and fine grain structure, as shown in figure 8(d) and figure 9(d).
The morphology of TMAZ entirely different from the other zones and due to the high tool rotational speed and welding speed, grains in the TMAZ would experience to more plasticized and disintegration.

Figure 9 Microstructures of the (a) Base substrate, (b) heat affected zone, (c) thermos mechanically affected zone and (d) Stir zone of the FSW joints of AA2219 T62 alloys.

can be happen as illustrated in figure 8(c) and figure 9(c). During FSW, the occurrence of shear force action of the rotational speed cause to form extended grains in TMAZ owing to the dynamic recovery variations in the weld microstructural morphologies. Whereas, the material zone which is with the tool pin contains the grains per unit area covered by petite extruded severe braking force leads to a more amount of large crystals formation in weld metal microstructure of the stir zone [40-45]. Figure 9 (a-d) illustrates the microstructures of the AA2219-T62 condition base metal and weld metal microstructure of HAZ, TMAZ and stir zone respectively. The base substrates microstructures and HAZ looks similar and contains the same size of the grain size. In the HAZ and the TMAZ, the variation of microstructures clearly indicates the size and orientation of the grains are illustrated in figure 9 (b & c). The observations also found that the grain size of HAZ and TMAZ significantly varied with the rise of welding speed. The microstructure of the AA2219-T62 condition of TMAZ is different from the AA2219-T87 condition of TMAZ. The grains in the TMAZ of AA2219 T62 welds show the highly extruded and elongated on the advancing side. The interface between the TMAZ and stir zone also shows very sharp (see figure 9(c)) and different grain structure formation, whereas the TMAZ/SZ interface of AA2219-T87 welds is unclear and the grains size and orientation distributed across the interface. It seems to be that, HAZ experienced only by welding thermal cycles and no evidence of occurrence of plastic deformation. The variations of the weld microstructural formation between AA2219-T87 and T62 conditions are owing to the effect of heat treatment conditions. Therefore, the strength of the welds are significantly affected by microstructural formation in various zones of the FSW welds. The raise in hardness of the HAZ and TMAZ of the AA2219-T62 welds is due to the
formation of fine grain size formation compared to the AA2219-T87 welds. The base metal heat treatment conditions have greatly effect on the microstructural and strength of the welds.

4. Conclusions
The effect of base metal heat treatment state of AA2219-T87 and T62 conditions are investigated on the mechanical properties and microstructural characterizations of the FSW welds. The conclusions of significance of the observations revealed that the FSW joints tensile strength considerably varied with the base metal heat treatment condition. The tensile and yield strength of the AA2219-T87 FSW joints achieved higher strength than the T62 state of the welds. The level of heat input which is generated in the weld metal during welding is not adequate for both the heat treated conditions. The result of this shows the different microstructural formation for the two different base metal conditions. The HAZ and TMAZ grain size of the AA2219-T87 welds elongated and coarser than the T62 welds. The hardness in the stir zone also varied between these base metal conditions. The hardness gradually increased from stir zone to TMAZ and HAZ regions in the AA2219-T62 welds. Although the microstructural changes and coarse grains formation in the T87 welds over the T62, the strength of the welds shows higher than the T62 welds which have finer grain microstructure. The formation of secondary precipitates in the FSWed weld stir zone leads to the major difference between two heat treatment conditions of the AA2219 alloys. The adequate welding conditions for two different alloys are needed to be developed to improve the strength of the welds.

References
[1] Lakshminarayanan A K, Malarvizhi S and Balasubramanian V 2011 Developing friction stir welding window for AA2219 aluminum alloy Trans. Nonferrous Met. Soc. China.21 2339-47.
[2] Venkateswarlu D, Rao PN, Mahapatra MM, Harsha SP and Mandal NR 2015 Processing and optimization of dissimilar friction stir welding of AA 2219 and AA 7039 alloys J. Mater. Eng. Perform.24(12)4809-24.
[3] Radisavljevic I Z, Zivkovic A B, Grabulov V K and Radovic N A 2015 Influence of pin geometry on mechanical and structural properties of butt friction stir welded 2024-T351 aluminum alloy Hem. Ind.69(3) 323-30.
[4] Dawes C J 1995 An introduction to friction stir welding and its development Weld. Met. Fabr.63(1) 13-5.
[5] Yigezu B S, Venkateswarlu D, Mahapatra M M, Jha P K and Mandal N R 2014 On friction stir butt welding of Al + 12Si/10 wt% TiC in situ composite Mater. Des.54 1019-1027.
[6] Cao G and Kou S 2005 Friction stir welding of 2219 aluminum: behavior of 0 (Al2Cu) particles Weld. J.1-s-8-s.
[7] Devuri V, Mahapatra M M, Harsha S P and Mandal N R 2014 Effect of shoulder surface dimension and geometries on FSW of AA7039 J. Manuf. Sci. Prod.14 183-194.
[8] Mishra RSand Ma Z Y 2005 Friction stir welding and processing Mater. Sci. Eng. R.50 1-78.
[9] Chen H, Cao J, Tian X, Li R and Feng J 2013 Low-temperature diffusion bonding of pure aluminum Appl. Phys. A.113(1) 101-4.
[10] Muralimohan C H, Haribabu S, Reddy Y H, Muthupandi V and Sivaprasad K 2015 Joining of AISI 1040 steel to 6082T6 aluminium alloy by friction welding J. Adv. Mech. Eng. Sci.1(1) 57-64. http://dx.doi.org/10.18831/james.in/2015011006
[11] Muralimohan C H, Muthupandi V and Sivaprasad K 2014 The influence of aluminium intermediate layer in dissimilar friction welds Inter. J. Mater. Res.105 350-57.
[12] Tabana E, Gould J E and Lippold J C 2010 Dissimilar friction welding of 6061-T6 aluminum and AISI 1018 steel: Properties and microstructural characterization Mater. Des. 31 2305-11.
[13] Cheepu M, Muthupandi V, Srinivas B and Sivaprasad K 2018 Development of a friction welded bimetallic joints between titanium and 304 austenitic stainless steel Techno-Societal 2016, International Conference on Advanced Technologies for Societal Applications ICATSA 2016 ed
Pawar P M, Ronge B P, Balasubramaniam R and Seshabhattrar S (Springer, Cham) Chapter 73 709-17. https://doi.org/10.1007/978-3-319-53556-2_73

[14] Katoh K and Tokisue H 1994 Properties of 6061 aluminium alloy friction welded joints Weld. Int. 8 863-68.

[15] Buffa G, Cammalleri M, Campanella D and Fratini L 2015 Shear coefficient determination in linear friction welding of aluminum alloys Mater. Des. 82 238-46.

[16] Cheepu M, Ashfaq M and Muthupandi V 2017 A new approach for using interlayer and analysis of the friction welding of titanium to stainless steel Trans. Indian. Inst. Met. 70 2591-600. https://doi.org/10.1007/s12666-017-1114-x

[17] Muralimohan C H, Ashfaq M, Ashiri R, Muthupandi V and Sivaprasad K 2016 Analysis and characterization of the role of Ni interlayer in the friction welding of titanium and 304 austenitic stainless steel Metall. Mater. Trans. A. 47 347-59.

[18] Kumar SS, Muthukumaran S, Venkateswarlu D, Balaji GK and VinoS 2012 Eco-friendly aspects associated with friction welding of tube-to-tube plate using an external tool process, Int. J. Sustainable. Eng. 5 120-7.

[19] Coskuna T K, Volgyi B and Nagl I S 2015 Investigation of aluminum-steel joint formed by explosion welding J. Phys. Conf. Ser. 602 20126. doi:10.1088/1742-6596/602/1/012026

[20] VenkateswaruluD, Mandal NR, MahapatraMMand HarshaSP 2013 Tool design effects for FSW of AA7039Weld. J. 9241-7.

[21] Kumar A, Mahapatra MM, JhaPK, MandalNR and Devuri V 2014 Influence of tool geometries and process variables on friction stir butt welding of Al-4.5%Cu/TiC in situ metal matrix composites Mater. Des. 59406-14.

[22] Mohanty HK, Venkateswarlu D, Mahapatra MM, Kumar P and Mandal NR Modelling the effects of tool probe geometries and process parameters on friction stirred aluminium welds, J. Mech. Eng. Autom. 2(4) 74-9.

[23] Liu H J, Li J Q and Duan W J 2013 Friction stir welding characteristics of 2219-T6 aluminium alloy assisted by external non-rotational shoulder Int. J. Adv. Manuf. Technol. 64 1685-94.

[24] Ni Z L and Ye F X 2016 Weldability and mechanical properties of ultrasonic joining of aluminum to copper alloy with an interlayer Mater. Lett. 182 19-22.

[25] Cheepu M M, Muthupandi V and Loganathan S 2012 Friction welding of titanium to 304 stainless steel with electroplated nickel interlayer Mater. Sci. Forum. 710 620-25.

[26] Muralimohan C H, Haribabu S, Reddy Y H, Muthupandi V and Sivaprasad K 2014 Evaluation of microstructures and mechanical properties of dissimilar materials by friction welding Procedia Mater. Sci. 5 1107-13.

[27] Muralimohan C H, Muthupandi V and Sivaprasad K 2014 Properties of friction welding titanium-stainless steel joints with a nickel interlayer Procedia. Mater. Sci. 5 1120-29.

[28] Muralimohan C H and Muthupandi V 2013 Friction welding of type 304 stainless steel to CP titanium using nickel interlayer Adv. Mater. Res. 794 351-57.

[29] Deng Y, Sheng G and Xu C 2013 Evaluation of the microstructure and mechanical properties of diffusion bonded joints of titanium to stainless steel with a pure silver interlayer Mater. Des. 46 84-7.

[30] Balasundaram R, Patel VK, Bhole SD and Chen DL 2014 Effect of zinc interlayer on ultrasonic spot welded aluminum-to-copper joints Mater. Sci. Eng. A. 607 277-86.

[31] Nandan R, Debroy T and Bhadeshia HKDH 2008 Recent advances in friction-stir welding-process, weldment structure and properties Prog. Mater. Sci. 53980-1023.

[32] Elangovan K and Balasubramanian V 2008 Influences of tool pinprofile and welding speed on the formation of friction stir processingzone in AA2219 aluminium alloy J. Mater. Process. Tech. 200 163-75.
[33] Davies PS, Wynne B P, Rainforth WM, Thomas MJ and Threadgill PL 2011 Development of microstructure and crystallographic texture during stationary shoulder friction stir welding of Ti-6Al-4V Mater. Trans. A. 42 2278-89.

[34] Buffa G, Fratini L, Arregi B and Penalva M 2010 A new friction stir welding based technique for corner fillet joints: experimental and numerical study Int. J. Mater. Form. 3 1039-42.

[35] Arora KS, Pandey S, Schaper M and Kumar R 2010 Effect of process parameters on friction stir welding of aluminum alloy 2219-T87 Int. J. Adv. Manuf. Technol. 50 941-52.

[36] Zhao S, Bi Q, Wang Y, Shi J 2017 Empirical modeling for the effects of welding factor on tensile properties of bobbin tool friction stir-welded 2219-T87 aluminum alloy Int. J. Adv. Manuf. Technol. 90 1105-18.

[37] Elangovan K and Balasubramanian V 2008 Effect of pin profile and rotational speed of the tool on the formation of friction stir processing zone in AA6061 aluminium alloy J. Mater. Manuf. Process. 23(3) 251-260.

[38] Zhang Z and Zhang H W 2009 Numerical studies on controlling of process parameters in friction stir welding J. Mater. Process. Technol. 209 241-70.

[39] Xu W, Liu J, Zhu H, Fu L 2013 Influence of welding parameters and tool pin profile on microstructure and mechanical properties along the thickness in a friction stir welded aluminum alloy Mater. Des. 47 599-606.

[40] Babu K K, Panneerselvam K, Sathiyaraj P, Haq A N, Sundarraj S, Mastanaiah P and Murthy C V S 2017 Experimental investigation on friction stir welding of cryorolled AA2219 aluminum alloy joints Surf. Rev. Lett. 24 1750001. doi:10.1142/S0218625X17500019

[41] Cheepu M, Muthupandi V and Che W S 2018 Improving mechanical properties of dissimilar material friction welds Appl. Mech. Mater. 877, 157-62. doi:10.4028/www.scientific.net/AMM.877.157

[42] Venkateswarulu D, Cheepu M, Krishnaja D and Muthukumaran S 2018 Influence of water cooling and post-weld ageing on mechanical and microstructural properties of the friction-stir welded 6061 aluminium alloy joints Appl. Mech. Mater. 877, 163-76. doi:10.4028/www.scientific.net/AMM.877.163

[43] Cheepu M, Haribabu S, Ramachandraiah T, Srinivas B, Venkateswarulu D, Karna S, Alapati S, and Che W S 2018 Fabrication and analysis of accumulative roll bonding process between magnesium and aluminum multi-layers Appl. Mech. Mater. 877, 183-89. doi:10.4028/www.scientific.net/AMM.877.183

[44] Devireddy K, Devuri V, Cheepu M and Kumar B K 2018 Analysis of the influence of friction stir processing on gas tungsten arc welding of 2024 aluminum alloy weld zone Int. J. Mech. Prod. Eng. Res. Dev. 8(1) 243-52. DOI: 10.24247/ijmprfeb201828

[45] Cheepu M, Venkateswarlu D, Mahapatra M M and Che W S 2017 Influence of heat treatment conditions of Al-Cu aluminum alloy on mechanical properties of the friction stir welded joints, Korean Welding and Joining Society, 11, 264-264.

http://www.dbpia.co.kr/Journal/ArticleDetail/NODE07278590