REVIEW ON FRICTION WELDING OF SIMILAR/DISSIMILAR METALS

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Abstract—The most commonly used technique for welding metals is fusion welding. But, these days friction welding procedures are used widely since welding of metals are made much easier. And, those welds impossible to weld by fusion welding can be produced by the process of friction welding. The industries related to automobile, submarine engineering, aerospace and heavy duty vehicle manufacturers are in huge demand for new applications and in need for new material combinations. In the present study, various research work done in the friction welding field is reviewed.

Keywords—Rotary friction welding, Solid state welding, dissimilar metal welding.

1. INTRODUCTION
Friction welding, a type of joining process that is used to produce high-quality weld joints between two components that are of either similar/dissimilar chemical compositions. Generally, one of the components in friction made stationary and the other is rotated. And, then these components are made to rub against each other under pressure, thus the required heat is generated at the joint. The temperature can be raised to the level where the components subjected to friction maybe welded together. The following is the definition of friction welding according to the American Welding Society (AWS) C6.1-89 standard: “Friction welding is a solid-state joining process that produces coalescence of materials under compressive force contact of workpieces rotating or moving relative to one another to produce heat and plastically displace material from the faying surfaces. Under the normal conditions, the faying area surfaces do not melt. Filler metal, flux, and shielding gas are not required with this process.”

2. TYPES OF FRICTION WELDING
A. Linear friction welding
As the name suggests, the relative movement between the two components across the interface is linear in this form of friction welding process. The components are required to be kept under pressure all the time since, the speeds are much lower in this linear friction welding.

B. Rotary friction welding
Rotary friction welding also known as the spin welding. This is the commonly used process among all the other friction welding types, where one component is rotated against the other which is stationary to generate the required heat for the process.

C. Direct drive friction welding
Also known as the continuous drive, the chuck is continually driven by the drive motor during the heating stages. Then appropriate forge pressure is applied and the weld is achieved.
D. Inertia friction welding

The process is analogous to that of direct drive friction welding, but in addition a flywheel is used additionally in this type of welding. The required kinetic energy is stored by rotating the flywheel to a fixed rotational RPM. The drive is then disconnected and then kinetic energy is shifted into the rotating part. Thus, the required energy to weld the components is provided by the machine’s kinetic energy that is stored in the rotating system.

E. Friction stir welding

The required plasticized state of material is produced in a different manner in friction stir welding. A non-consumable rotating tool, which is of a pin or probe is held under pressure against the components to be welded. A plastically deformed material is generated due to friction between the tool and materials it is in contact with. As the tool moves along the joint line, it mechanically intermixes the two materials and the mechanical pressure applied forges the hot and softened metal.

F. Friction surfacing

It is a technique derived from friction welding for deposition of a layer of coating material onto a workpiece so as to enhance the properties of the underlying metallic surface. A solid consumable rod is rubbed under pressure onto the surface of the underlying material to develop a coating. A plasticised layer is produced at the edge of the consumable rod resulting in deposition of the consumable over the material.

3. WORKING PRINCIPLE

The principle of friction welding is the conversion of mechanical energy into thermal energy at the joint interface. Normally, one of the workpiece is rotated and the other workpiece is kept stationary but can be moved axially. After the required RPM is reached, axial pressure is applied along the X-direction. Due to friction between the workpieces, heat is generated at the joint interface. The rotation is stopped at the point of fusion, where upset pressure is applied axially on the workpiece. Flash is formed during this process and the grain structure is refined at the joint interface because of the hot work. Since heat is generated only at the joint interface,

![Friction welding parameters with respect to time](image)

**Fig. 1: Friction welding parameters with respect to time so there is no melting of the base material takes place during this process.**

In addition, there are various parameters involved in this process (Fig 1). Usually, the workpieces are loaded onto the friction welding equipment, and the welding is carried out in a three step process, which are:
A. **Step 1:**
The workpiece which is turned in a spindle is raised to a foredestined rotatory speed and then a pre-decided axial force is applied on the workpiece which is stationary.

B. **Step 2:**
The above conditions are maintained to a pre-determined time until, the desired material condition and temperature exist. It is at this step, where the two materials are plastically deformed at the interface.

C. **Step 3:**
The rotational speed is stopped at this point and the forge pressure is applied for another pre-determined time. Thus, completing the weld process and this provides grain refinement at the interface.

4. **PURPOSE OF THE REVIEW**
A total of 50 papers are collected between the periods of 1995-2018 of various journals and following are the review objectives:
- To study the work done by different researchers in the area of friction welding.
- To study their findings and the related research issues.
- Optimization of process parameters for the betterment of weld quality

5. **LITERATURE REVIEW**
Gaurav Verma et al., [1] have worked on different combinations of similar/dissimilar friction-welded joints. A horizontal lathe machine was used in this experiment. Friction welded joints between Mild steel-mild steel, Stainless steel-stainless steel, Mild steel-Stainless steel, were studied and their properties were reckoned. The specimens were 10 mm in diameter and 10 cm in length. Six experiments were conducted (two experiments for each combinations) with two varying rotational speeds. The result exhibited that the joints formed at higher RPM have higher strength compared to joints fabricated at a lower RPM.

P. Venkat Koushik et al., [2] have worked on dissimilar friction welding of H30 aluminium and BS970 mild steel. The specimens were both of 8 mm diameter and 200 mm length. The upset time and the upset pressure were varied, keeping the other process parameters constant. Four welded joints were formed between the specimens, and the observed results exhibited that when the upset time and upset pressure were further increased beyond the optimum level, the strength of the bond decreased and finally failed. The optimum levels were 200 Mpa (upset pressure) and 6 seconds (forging time). This was attributed to the cause that there was no elemental bonding between the two materials because of the high forging pressure. Thus proving a direct relationship of upset pressure and upset time with joints fabricated.

C. Shanjeevi et al., [3] conducted experiments on joining dissimilar materials namely, austenitic stainless steel (AISI 304) and copper. The specimens were 24 mm in diameter and 75 mm in length. The Taguchi Orthogonal array of 27 tests, 4 variables and 3 levels were used in this experiment. The four variables were friction and forging pressure, burn-off length and rotation speed. The combination of higher frictional pressure with low forging pressure tend to increase the soundness of the joints relative to the combination of lower frictional pressure with high forging pressure. And also it was noted that an intermetallic layer was developed at the bonded region due to high friction time. This also decreased the bond strength between the metals. (The optimum conditions were
friction pressure of 33 Mpa, upset pressure of 108 Mpa, rotational speed of 1500 RPM and burn-off length of 1 mm).

R. N. Shubhavardhan et al., [4] analysed the friction-welded joints fabricated between AISI 304 and AA6082 aluminum alloy. The specimen dimensions were of step cut bars of AISI 304, 18 mm outer diameter and extruded part 14 mm in diameter, and step cut bars of AA 6082 aluminum alloy, 17 mm outer diameter and 15 mm inner diameter. The operating parameters namely, rotational speed, upset time, upset pressure were kept constant and friction time, friction pressure were varied during this experiment. The observations made clearly indicated that the outer region was seen well bonded while at the middle, the weld interface was left unbonded. This is because, the temperature was higher at the outer region than the inner region during the friction stage. Thus when the friction time and friction pressure were increased, the strength of the friction-welded joints increased and on additional increase in the values, the strength was noted to be decreasing. The optimum levels were friction pressure of 104M pa, friction time 5 seconds, forging pressure 210 Mpa, forging time 6 seconds and 1400 RPM.

Jeswin Alphy James et al., [5] have worked on joining dissimilar steels such as Stainless steel 304 and AISI 1040. And, also analysed the properties of weld along with/ without inclusion of Nickel interlayer. The parameters such as rotational speed, upset pressure and burn-off were varied in this experiment. The specimens were AISI 1040 cylindrical rods, 75 mm length and diameter 10 mm and SS304 of length 55 mm, diameter 10 mm with holding side of diameter 20 mm. A 50±3 μm thick interlayer was used in this experiment. The maximum strength was obtained when nickel was used as an interlayer which reduced the intermetallic compound being formed at the weld interface. The optimum conditions were rotational speed (2200 RPM), upset pressure (1.570 ton) and burn-off length (8 mm).

B. Jeslin et al., [6] chose Aluminium Alloy 6082 T6 & Copper to fabricate friction welded joints. Both the specimens were 12mm in diameter and nine welded joints were fabricated using the Taguchi design of experiments. Three parameters namely friction pressure, upset pressure and friction time were varied and among these parameters, upset pressure was said to have major impact on the bond strength followed by friction time and friction pressure. The optimal conditions were found out to be friction pressure and upset pressure (43.6 Mpa), friction time (50 seconds) and upset time (2 seconds).

D. Ananthapadmanaban [7] has identified the errors for the case of friction-welded joints fabricated between Low carbon steel-Stainless steel, Aluminium to copper and similar Ti-6Al-4V welds. He concluded that in case of Aluminium-copper welds, lower the rotational speed, higher is the frictional heat generated which could lead to better bonding and higher tensile strength. And in case of weld joints of similar steels high upset and burn-off produced better results and diffusion of chromium at the weld interface was observed.

C. H. Muralimohan [8] have studied the significance of process parameters on the dissimilar welds between AISI 1040 (Medium carbon steel) and AA 6082-T6 aluminium rods (each of 10 mm diameter and 80 mm length). The friction time, upset pressure and friction pressure were varied keeping the others constant. The visual observations indicated flash formation at the interface and the density of the flash increased with an increase in upset pressure. And, thus they concluded that upset pressure is more vital than the friction pressure and the friction time.

P. Rombaut et al., [9] gave a clear summary on the friction-welded joints between steel and ceramics. He used Aluminium as an interlayer in this process and so classified his study based on two weld interfaces such as a steel/ aluminium weld interface and an aluminium/ alumina weld interface. The observed results clearly pointed out that the addition of interlayer was essential to reduce the residual stresses and also to increase the strength of the friction-welded joints. And in addition, the intermetallic compound (IMC) is another factor found to be influential on the bond strength. Although, intermetallic compound in small amounts produces sound welds but, thickness exceeding 1 μm is found to deplete the bond strength.
Y. Lekhana et al., [10] analysed the weldability of 316 stainless steel and AA1100 hollow tubes through friction welding process. The friction welding process was done through Finite element analysis. A 3D model of materials, each of 25.4 mm diameter and 100 mm in length was made using the ANSYS workbench. Taguchi design of experiments of L9 was selected for optimization of the process parameters. And, structural analysis was also conceded for bulk deformation, equivalent stress, penetration and sliding (responsible for the flash formation) at the weld interface. Friction and forging pressure tend to have great impact on the penetration levels and friction pressure, friction time tend to affect the sliding at the weld interface. The optimum conditions were friction pressure of 80 Mpa, rotational speed of 2000 RPM, friction time of 5 seconds and forging pressure of 160 Mpa.

Niyazi Özdemýr et al., [11] conducted experiments for optimization of friction parameters on the joints formed between AISI 304L and AISI 1040 steels. The specimens were 12 mm diameter rods each. 27 welded joints in total were fabricated, and the forging pressure is assumed to be twice that of the friction pressure in this study. The visual observation indicated the flash formation at the weld interface which corresponds with increasing the rotational speed, friction time and friction pressure. The combination of higher rotational speed with lower friction time tend to produce an excellent strength of the welded joints which inturn lead to a Fully Plasticized Deformed Zone (FPDZ) at the weld interface. The FPDZ and Deformed Zone width are mainly reliant on the friction time and rotational speed. The optimum conditions were rotational speed of 1700 RPM, friction time of 4 seconds, forging time of 2 seconds, friction pressure of 50 Mpa and forging pressure of 100 Mpa.

M. Azizieh et al., [12] investigated on the joint design on the faying surfaces. They selected ST37 steel and CK60 steel each of 15 mm diameter with two different joint designs namely flat and round heads. The visual observations showed that flash formation was more at the CK60 side, and had a higher temperature difference even higher than the weld interface leading to a higher flash volume. In general, the round head samples showed higher tensile strength, higher burn off and higher welding flash than the flat head samples.

G. Madhusudhan Reddy et al., [13] analysed the use of an interlayer on the friction welds between AISI 4340 and AA6061 (16mm diameter cylindrical rods each). Low burn-off length was initiated in this experiment to lower the heat input which results in less time for the intermetallics formation. A silver interlayer of 20 μm was electroplated on the AISI 4340 side. There was a clear indication that the presence of silver interlayer increased the strength and ductility of joints since the Fe-Al based intermetallics were partially replaced by Al-Ag based intermetallics which are naturally ductile.

Uday M. Basheer et al., [14] studied impact of rotational speeds on the alumina- 6061 aluminium alloy rod joints through continuous drive frictional welding. The specimens were 15 mm diameters each. Varying rotational speeds of 1250 RPM, 1800 RPM and 2500 RPM were used in this experiment with constant friction pressure and friction time. He concluded that the Heat affected zone (HAZ) was very thin, if not non existent in case of 1250 RPM welded joints and furthermore showed cracks and unjoined regions. The joints fabricated at 1800 RPM showed the presence of three different regions and visibly a good joint was achieved. At high speeds of 2500 RPM, the brittleness nature of alumina couldn’t withstand resulting in failure and a broad HAZ was formed due to large amount of specimen being pushed out of the weld zone.

Uday M. Basheer et al., [15] compared the bond strength of Alumina 0.25wt.% YSZ content to 6061 Aluminium alloy (16 mm diameter rods) through friction welding with varying rotational speeds. Since pure alumina lacks the fracture toughness, Zirconia stabilizer has been added to pure alumina to increase the toughness and zirconia also inhibits the alumina grain growth. The soundness of the weld was found through a four - point bend test. They concluded that the bending strength results of alumina-25 wt % YSZ composite joint were greater at lower rotational speeds, while, the results at joints with pure alumina were smaller at higher rotational speeds due to the higher thermal stress during the joining process. The optimum levels were friction pressure (7 Mpa), friction time (60 seconds), forging pressure (10 Mpa) with a forging time (45 seconds) and rotational speed of (630 RPM).
Radosław Winiczenko et al., [16] investigated on the effect of different interlayers on the friction welded joints between ductile iron. A ferritic, pearlitic, and bainitic matrix ductile iron was produced using different parameters of heat treatment. This experiment was carried out using 20 mm diameter and 100 mm length bars. Two different interlayers were used namely stainless steel and armco iron. The observed results were that the ferritic ductile iron's welded with stainless steel as the interlayer showed the lowest tensile strength and the highest was for bainitic structure ductile iron with Armco iron as the interlayer.

G. Subhash Chander et al., [17] investigated on the joints between AISI 304-AISI 4140 through continuous drive friction welding with different rotational speeds keeping the friction force, upset force and burn off constant. The visual observations sighted the flash formation at the joint line and density of flash was larger on the AISI 4140 steel side. And, it was also observed that the deformation rate in the friction stage decreases with increase in values of rotational speed. And in forging stage, deformation rate increases with increase in values of rotational speed. Thus, the rotational speed had to be in optimum level so as to obtain better results and thus have a direct relationship with the deformation rate of the friction-welded joints.

Mumin Sahin [18] studied the effect of different diameter ratios on the plastically deformed austenitic stainless steels (AISI 304) through continuous drive friction welding. A prior plastic deformation was done on AISI 304, and parts of different or equal diameters were friction welded. Friction time and friction pressure were varied, keeping the other parameters constant. The optimum conditions were friction pressure of 60 Mpa, friction time of 9 seconds, upset time 20 seconds and upset pressure of 110 Mpa. It clearly indicated that the prior plastic deformation doesn’t have any influence on the process variables or on the weld strength. And, the strength of the friction-welded joints decreased as the diameter ratio were increased in the plastically deformed parts.

N. Ozdemir [19] chose AISI 304L and AISI 4340 steels, each of 12mm diameter to study the bond strength of the friction-welded joints. Five weld joints were fabricated with varying rotational speed and all other parameters to be considered constant. The microstructural studies for AISI 304L/ AISI 4340 friction welded joints revealed that there were four different regions at the interface and the width of these regions change as a function of rotational speeds. The tensile strength tend to be greater in the samples which were welded at higher rotational speeds. And so, higher values of rotational speed, friction pressure and upset pressure, along with low values of friction time should be applied to obtain sufficient strength of the joints. The optimum levels were rotational speed of 2500 RPM, friction pressure of 40 Mpa, forging pressure of 60 Mpa, friction time of 5 seconds, forging time of 10 seconds with axial shortening of 4.8 mm.

Amit Handa et al., [20] conducted experiments on the friction-welded joints of plastically deformed AISI 304 steels (20 mm diameter and 100mm length). Five weld samples with different axial pressure were considered, keeping the other weld parameters constant. The samples that were weld at lower axial pressure tend to fail at the interface while the samples weld at higher axial pressure also tend to fail at the weld interface but showed necking behavior before getting failed at the interface.

Radosław Winiczenko et al., [21] investigated on the different metal matrix of ductile iron friction welded with stainless steel as the interlayer. Both Ferritic Ductile Iron (FDI) and Bainitic Ductile Iron (BDI) were produced using different parameters of heat treatment method. The specimens were 20mm in diameter and 100 mm in length. The visual observations clearly indicated the flash formation and the density of flash increased with increase in friction time for the BDI joints and viceversa for the FDI joints. It clearly indicated that the strength of the BDI joints were more compared to FDI joints fabricated. There was diffusion of Cr and Ni atoms from stainless steel to ductile iron and Carbon from ductile iron to stainless steel. And, the range of diffusion of Ni and Cr atoms in the ductile iron doesn’t exceed 50 μm.

K. Koundinya et al., [22] analysed on the specimen geometries namely square joint, vee-joint and plain joint on the dissimilar friction-welds between 405 ferritic stainless steel and 705 Zr alloy with an interface material between them. A 3D model of materials, 25 mm in diameter and 100 mm length, and a pure aluminium sheet was used as an interface material. Taguchi design of
experiments, L9 was preferred and finite element analysis was employed for this experimentation. It clearly indicated that the introduction of an interface material enhanced the strength of the welded joint and the vee-joint is said to impart good weld strength due to mechanical interlocking.

G. Madhusudhan Reddy et al., [23] investigated on using nickel (Ni) as an interlayer between the friction-welded joints of maraging steel and low alloy steel. Six friction-welded joints were made by combining various conditions of post weld heat treatments (PWHT), presence of interlayer and under the As-Welded conditions. The specimens were of 18 mm in diameter and 65 mm in length with a 5mm length of an interlayer. It was observed that nickel was squeezed out of the tri-metal joint as flash. The result showed that weld samples with nickel as the interlayer exhibited higher tensile strength compared to those samples welded without nickel interlayer and, the post-weld heat treatment in further reduced the toughness in case, without interlayer. Thus, nickel when used as an interlayer acts as an effective barrier for diffusion of carbon and manganese so as to overcome the problem of carbon migration.

A. Chennakesava Reddy [24] analysed on the joint design on the friction joints between Austenitic stainless steel and Mild steel. Three different joint designs namely, square joint, plain joint and vee-joint were taken into consideration. The specimens were of length 300 mm and diameter 25 mm. The joints were welded at rotational speed of 4000 RPM, friction time 10 seconds, friction pressure 10 ton, upset pressure 20 ton and upset time of 30 seconds. The observed results showed, the vee-joint was found to have a higher tensile strength compared to the other two joint designs. Eventhough, square joints has a greater surface area compared to the other two designs, the distribution of forging pressure was not uniform throughout the friction welding process resulting in poor joint strength. In case of vee-joint, the pressure distribution was even, resulting in better weld quality.

V. Srija et al., [25] analysed the optimum friction parameters on joints between UNS C23000 Brass and 2024Al alloy. Finite element analysis was performed to model the friction welding process. A 3D model of the specimens each of 100 mm in length and 25.4 mm in diameter was made using the ANSYS workbench software. Taguchi design of experiments, L9 was preferred for this experimentation and contact analysis was also conceded to find out sliding of materials and the penetration depth. And, so the optimal conditions obtained were frictional pressure (40 Mpa), rotational speed (1500 RPM), frictional time (4 seconds) and upset pressure (37.5 Mpa). In these particular welded joints, the forging pressure was lesser or almost equal to frictional pressure, since the generated heat during the friction stage was high enough for the materials to weld. The penetration and sliding of materials was good at these optimal levels.

Sachin Kumar et al., [26] conducted experiments on Aluminium and AISI 304 (12 mm diameter and 70 mm length) by friction welding. The joints were fabricated on a vertical milling machine because of its stability and less vibration in relative to the lathe machine. Eight joints were fabricated by varying parameters like the weld time, revolutions per minute and burn off length. The highest strength was witnessed in the specimen welded with a higher rotational speed due to the carbon migration from stainless steel to weld zone. The optimum conditions were rotational speed of 1800 RPM, burn-off length 1.5 mm and weld time 20 seconds.

Sangathoti Haribabu et al., [27] conducted experiments on the joints formed between dissimilar steels, AISI 304 and AISI D3 tool steel (16mm diameter and 100mm of length). A new combination of frictional pressure to upset pressure, upset pressure to frictional time and frictional pressure to frictional time were used for optimizing the parameters and also to achieve high quality joints. And the combination of frictional pressure to frictional time achieved higher efficiency than the other combinations.

Amit Handa et al., [28] conducted experiments on the friction-welded joints between similar steels AISI 1021. Twelve bars of 20 mm diameter and 100 mm length were used for the first set of readings and similarly for the next two sets were prepared for this experiment. An existing lathe machine was modified to suit the requirements of the friction welding process and the friction joints were prepared under varying rotational speeds and axial pressure keeping the other parameters constant. The results established that the highest strength was conceded at a higher rotational speed.
And, thus the rotational speed and the axial pressure were primarily a determinant factor in the tensile strength of the joints between AISI 1021.

Sandeep Kumar et al., [29] fabricated friction welded joints between aluminium alloy and mild steel each of 12 mm in diameter and 75 mm in length. A vertical milling machine was used for this experimentation and eight joints in total were fabricated by altering the rotation speed, burn-off length and friction time. The maximum strength was achieved in the specimen where all the parameters were at a higher value. Burn off length and friction time were found to be more responsible for variation in bond strength than the rotational speed, which was found to have very little impact on the tensile strength values. The optimum conditions were rotational speed of 1800 RPM, burn-off length of 2.5 mm and weld time of 30 seconds.

Amit Handa et al., [30] evaluated friction-welded joints between AISI 304 and AISI 1021 steels by varying the forging pressure. The visual observations of the five joints fabricated between the dissimilar steels revealed that the flash was seen greater towards the AISI 1021 steel for all the cases. And, the flash density tend to increase with rise in forging pressure values. This was attributed to the presence of Cr in AISI 304 steels, and also due to greater hardness at higher temperatures as compared to the AISI 1021 steels. And the strength of the friction-welded joints tend to increase with rise in forging pressure levels.

P. Shiva Shankar [31] conducted experiments on the copper alloy (Cu Zn30) to investigate on the optimum welding parameters and also for less upset. The specimens were of 19 mm in diameter and 90-100 mm in length. The Taguchi design of experiment were used in this experimentation. They concluded that the joint strength tend to increase with increase in upset pressure and at moderate levels of rotational speeds. The optimum levels for higher tensile strength were rotational speed (1500 RPM), friction time (5 seconds), friction pressure (10 bar) and forging pressure (20 bar). For less upset, rotational speed (1400 RPM), friction time (4 seconds), friction pressure (10 bar) and forging pressure (20 bar).

P. Kannan et al., [32] introduced silver interlayers on dissimilar friction welding process with the aim of reducing the percentage of particle fracture. It was also compared with the dissimilar friction welded joints between MMC/AISI 304 stainless steel produced without interlayer. The experiment was conducted with 15 mm bars of 6061-T6 base consisting of 10 vol% of reinforcing Al2O3 particles. The nickel strike layer was first coated over the stainless steel substrate, over which the silver interlayer was electrodeposited. The percentage of reinforcing particles in the friction-welded joints without interlayer were considerably higher than the percentage of reinforcing particles in the welds with silver interlayer. Thus, there is a decrease in particle fracture when compared to the normal friction welding process.

K. Reddi Prasad et al., [33] successfully applied continuous drive friction welding to weld aluminium alloy (AA6061) pipes at T6 condition. Taguchi’s design of experiments of L25 experimental design was used to weld the specimen dimensions of 19.5 mm outer diameter, 150 mm length and pipe thickness 3 mm. The results revealed that most of the joints failed at away from the weld region. And, so the important process parameter was burn off length followed by upset time followed by speed followed by upset force followed by friction force. The optimum levels to weld aluminium pipes were rotation speed of 2200 RPM, friction force 0.6 ton, burn-off 3.5 mm,upset force and upset time of 2.1 ton and 0.5 seconds.

A. Fuji et al., [34] conducted experiments on the friction-welded joints between MMC/AISI 304 stainless steel. The specimens were of 19mm diameter rods each. Notched tensile testing was used in this experimentation, since the conventional tensile testing can produce results that may not show the actual mechanical properties which exist at the joint line, and instead show the properties of material immediately next to the weld interface (bondline). And, so the results showed that joints fabricated with low frictional pressure, rotational speed and friction time values contained microcracks located at the joint interface. And those welded joints fabricated with high frictional pressure had the highest strength showing an extremely thin transition layer at the weld interface. And, so frictional pressure and rotation speed have major impact on the joint strength properties.
Uday M. Basheer et al., [35] experimented on the effect of different specimen geometries on microstructural development. In this experiment, pin, taper pin and flat faces of ceramics were welded with flat metal face of 6061-aluminium alloy. Due to the different specimen geometries of the ceramic faces, the diameter of the ceramic faces varies and the length of both the material were 50 mm. Forging time, rotational speed and forging pressure were kept constant throughout the experiment. Better results were seen in the taper pin 60º specimen geometry. And, so the specimen geometry also have significant effect on the weld strength.

Koen Faes et al., [36] developed a new technique for joining pipelines as long as 18 m. A rotatable intermediate ring (filler material) was used to generate the necessary heat, since it is impossible for the pipelines as long as 18m to be brought into rotation. The welding ring was inserted between the pipes which is to be welded, and rotating the ring subjected to an axial pressure induced by the pipes, brings out the necessary heat. Pipes of 88.9 mm outer diameter and 7.6 and 10 mm of wall thickness were discussed in this paper. The material used was the pipeline steel API-5L X42. Two steels were considered for the welding ring material namely, a quenched and tempered steel and the other one was a fine-grained normalised steel. And so, the fine-grained normalised steel was found more suitable as welding ring material for welding pipes, since hardness is low and the impact toughness is higher compared.

C. Maldonado et al., [37] evaluated the strength of friction-welded dissimilar materials Al 6061-T6 and AISI 304 with or without the silver interlayer. The Nickel strike layer was first coated over the stainless steel substrate, which was then electroplated with the Silver interlayers. The nickel strike served as a base for subsequent silver coating. The experiment was conducted with varying friction pressure and other parameters to be considered constant. The highest tensile strength were obtained in the friction welds where silver was employed as an interlayer and the strength tend to increase with rise in friction pressure values.

U. Caligulu et al., [38] investigated on the joints fabricated between AISI 4340 and AISI 2205 duplex stainless steels each of 12mm diameter. Six friction-welded joints were fabricated with altering the rotational speed and friction time, and the other parameters was kept constant. The maximum strength was observed in the specimen welded with the higher rotation speed and lower frictional time. And, aslo the friction welding process showed three distinct zones across the weld interface. The optimum levels were rotational speed of (2200 RPM), friction pressure (40 Mpa), forging pressure (80 Mpa), friction time (6 seconds) and forging time (3 seconds).

Anantkirtay Ishwarbhai Patel [39] studied the friction-welded joints between Taper Inconel 718 and Stainless steel 304. The specimen dimensions were 100 mm in length and 12 mm in diameter. The experiment were conducted with three different taper angles (30º, 45º, 60º) of the Inconel 718 material and the frictional factor or parameter that plays the vital role in the friction-welded joint was studied in this paper. The results revealed that, for a taper angle of 30º, speed is the main factor affecting the burn-off length. For the 45º taper angle, time plays the maximum contribution on the welded joint. As time is increased, burn-off is also increased. For the 60º taper angle, frictional pressure is the main factor affecting the burn-off length.

M. Deepak Kumar et al., [40] investigated on the friction welds between AISI 304 and aluminium alloy 6082-T6. The length of aluminium alloy (6082-T6) and AISI 304 were 79 mm and 76 mm, each of 12 mm in diameter respectively. The impact of various process parameters were studied in this experiment. It was noted that the strength initially increased as the friction time and forging pressure increased and upon additional increase, the strength decreased. This is due to the conversion of coarser to fine structure of grains. And in combination of friction pressure with forging time, the strength decreased as the parameter values were increased and upon additional increase, the strength increased. This was due to transformation of finer to coarser grain structure. The optimum condition was found to be friction pressure of 95.46 Pa, forging pressure 78.15 Pa, friction time 4 seconds and forging time 2 seconds.
K. Boonseng et al., [41] investigated on the consequence of frictional parameters such as rotational speed and burn-off length. The material chosen for this experiment was SSM356 aluminium alloys and the dimensions of this specimen were 50 mm in length and 12 mm in diameter. A lathe computer numerical control machine was specifically designed and modified for this experiment since the conventional lathe machine lacked stability and precise compared to it. Six joints were fabricated with varying rotational speeds and burn-off length, keeping the other parameters constant. It clearly indicated that the increase in burn-off length values increased the strength of joints. This is because higher the burn-off, higher is the density of the weld. Similarly, increase in rotational speed values also tend to increase the tensile strength. This is due to high heat generated at the time of welding can soften the specimens easily. However, further more increase in rotation speeds tends to decrease in strength of the friction-welded joints since the materials is pushed into the flash.

Sirajuddin Elyas Khany et al., [42] investigated on the effect of frictional parameters on the friction welded joints between SS 316 and EN-8. The stainless steel of length 200 mm and medium carbon steel of length 100 mm, each of 16mm in diameter were used for analysis. The taguchi orthogonal array design was preffered for this experiment and the parameters condidered were upset pressure, rotational speed and cooling method. It was witnessed that the maximum strength was obtained for higher values of upset pressure, rotational speed and water as the cooling method. So, the control factors having the major impact on the friction-welded joint was upset pressure followed by rotational speed and finally cooling method.

T. Santhosh Kumar et al., [43] analysed the joints fabricated between AISI 1021 steel and 2024Al Alloy through finite element analysis. A 3D model of the specimen each of 100 mm in length and 25.4 mm in diameter was made using the ANSYS workbench. Taguchi design of experiments, L9 was preferred. It was noted that the 2024Al Alloy material turned down into flash because of high thermal conductivity and soft nature of the material. The optimal conditions were frictional pressure (35 Mpa), rotational speed (1500 RPM), frictional time (3 seconds) and forging pressure (37.5 Mpa). There was good mechanical bonding at these optimal conditions.

C. H. Muralimohan et al., [44] investigated on the friction-welded joints between stainless steel and pure titanium with nickel as the interlayer. The specimens were of 16mm in diameter and 100mm in length. In addition, the nickel interlayers of varying thickness (20 μm, 40 μm, 60 μm and 80μm) were electroplated over the surface of the stainless steel specimens. The parameters such as frictional pressure, forging pressure were varied and the rotational speed, friction time, forging time were kept constant. The maximum strength of 310 Mpa was observed in the joint produced with 60 μm thick Interlayer. Thus, the decrease in strength of the friction-welded joints with increase in thickness of more than 60 μm is attributed to the accumulation of massive intermetallic compounds at the joint line.

Murali Mohan Cheepu et al., [45] also studied the friction-welded joints between 304 austenitic stainless steel and pure titanium with nickel as the interlayer. The specimens were of 16mm diameter rods each. 30 μm and 50 μm thick nickel interlayers were electroplated over the surface of AISI 304 specimens. The highest strength of the friction-welded joints obtained was 308 Mpa and the strength increased with increase in thickness of the Nickel interlayer. Because the Fe-Ti phase formation which is considered to be the harmful phase during welding, cannot be avoided if the Nickel interlayer is 30 μm thick and hence more thickness of the Nickel interlayer is required.

P. Anitha et al., [46] investigated on the friction welded joints fabricated between SS410 and IN 718. The specimens were 12 mm in diameter and 75 mm in length. Six joints were fabricated by keeping the forging pressure and friction time as constants, by varying the friction pressure and rotational speed. The visual observations confirmed flash formation at joint line and density of flash increased with increase in friction pressure and rotational speed. The maximum strength was obtained at high levels of friction pressure and moderate levels of rotational speed. The optimum conditions were rotational speed (1500 RPM), friction pressure (189 Mpa), forging pressure (189 Mpa) and friction time (10 seconds).
C. H. Muralimohan et al., [47] studied the effect of friction-welded parameters on 6082-T6 aluminium alloy and commercially pure copper. The cylindrical rods of 120 mm in length and 20 mm in diameter were used in this experiment. This study was conducted by varying the frictional time and forging pressure, and by keeping the frictional pressure, forging time and rotational speed constant. The visual observations confirmed the flash formation was more on the aluminium alloy than the copper side due to the low strength of aluminium. And tensile strength is directly associated with high forging pressure and longer friction time. The optimum conditions were rotational speed of 1500 RPM, friction pressure of 110 Mpa, forging pressure of 160 Mpa, friction time of 4 seconds and forging time of 6 seconds.

Emel Taban et al., [48] investigated on the friction-welded joint between 6061-T6 aluminium alloy and AISI 1018 steel. Inertia friction welding was used to create the joint between these two materials. Rods nominally 12.5 mm in diameter were used in these experiments and bars were cut accordingly to the lengths suitable for inertia friction welding. Only the forging pressure was varied throughout these experiments and the maximum strength of 250 Mpa was obtained for a higher value of forging pressure and so, suggest that a higher forging pressure are advantageous for improved joint strengths. The optimum conditions were 4200 RPM, 23 Mpa of friction pressure, 1 second of friction time, 5 seconds of forging time and 60 Mpa of forging pressure.

Ihsan Kirik [49] worked on the effect of nickel interlayer on the friction welded joints of Ti6Al4V to AISI 2205. The specimens were 12 mm in diameter each. In addition, a 10 mm diameter and 3 mm depth was processed on the surface of the stainless steel specimen and the nickel interlayer was then inserted on the processed specimens with a press. This was done to keep the nickel interlayer at the interface and thus avoid the slip of the interlayer used. The experiment was conducted with varying rotational speeds and friction pressures, and with constant friction time, forging time and forging pressure. The visual observation of the welded joint showed the flash formation was much larger on the Ti alloy than on the stainless steel. Moreover, the friction welding made between the two materials in the absence of the interlayer were not attained due to brittle phase reaction. The highest strength was obtained in the sample welded with an interlayer and the strength was seen to increase with increase in friction pressure and rotation speed. The optimum conditions were rotational speed (1800 RPM), friction pressure (125 Mpa), friction time (6 seconds), forging pressure (200 Mpa) and forging time (4 seconds).

M. C. Zulu et al., [50] investigated on the effect of friction-welded joints formed between similar 25.4 mm diameter Ti6Al4V alloy rods. Since the metal is immensely reactive to the surrounding environment at higher temperatures, so the experiment was conducted under argon gas shielding. The visual observation after the tensile test showed, for higher rotational speeds, the failure points were within the zone that was welded. And for lower rotational speeds, the failure points were outside the weld zone. And, thus the tensile strength of the specimens welded at higher rotational speeds were weaker in relative to those welded at lower rotational speeds. This was due to the minimal coefficient of friction acting at higher rotational speeds. And, on the other hand, weld strength was poor for those welded with low axial pressure. This was due to lack of bonding at the weld interface. Thus, he concluded that tensile strength were higher with low rotational speeds or higher axial pressure. And in addition, the width of the weld was directly related to the rotational speed and inversely with the axial pressure.

6. CONCLUSION

The following are the research observations studied from the literature review:

- Friction pressure,
- Friction time,
- Rotational speed,
- Forging pressure,
- Forging time,
- Burn-off length.
Optimization of the above process parameters has always been important in the friction welding processes. For instance, during the process if the rotational speed is too low and if the applied force is too high, then the fusion zone at the interface will be narrow. And the fusion zone will be thick, if the rotational speed is too high and the applied force is too low. By optimization of the above friction welding parameters, the weld quality of the materials can be improved. The optimization of the above weld parameters is highly material specific. And in addition, interlayer between the joints [5], interlayer thickness [44], change of the geometric shape [35], different diameter ratio’s [18], varying taper angles [39], cooling method [42] and the pre/post weld heat treatments [23] also attribute to the betterment in terms of weld quality of the joints.

From the observations made, it can be summarized that the Rotational speeds is the major factor affecting the tensile strength among the variants of Stainless steel materials (i.e. higher tensile strength is obtained with increase in rotational speeds). In case of the Aluminium variants, Burn-off contributes to be the major factor affecting the weld strength. Friction and forging pressures are also to be applied at optimum levels to avoid welding defect possibilities, to avoid fewer sections of the interface to get in contact with and also prolongs the welding time. This parameter dominates in the dissimilar material welds of Aluminium-Stainless steel variants. The addition of interlayers also lead to betterment of the weld joint, as in case of welds between similar Steels (with Nickel as the interlayer), Steel-Ceramics (Aluminium as the interlayer), Stainless steel-Aluminium (Silver as the interlayer). Interlayer thickness also plays a major role as in the case of welds between Stainless steel- Titanium (Nickel as the interlayer) which inhibits the formation of harmful phases (intermetallic compounds) at the joint line. The change in geometric shapes of the specimens such as round headed tips, pin or taper pin types and change in diameter ratios of the specimens to be welded also determine the weld strength of the materials. The optimum process parameters obtained from specimens of equal diameters could not be used in friction welding of specimens of different diameters.

7. References

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