

A Comprehensive Review on Composite Materials, Applications and Future Challenges of Friction Welding



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1 Introduction to Friction Welding (FW)

Since ancient times, it was known fact that metal when heated near to melting point can be easily moulded and fused with another metal component. But as civilization stepped forward towards industrialization, the need was felt to replace the traditional welding techniques to advanced welding processes which can deliver desired mechanical and metallurgical characteristics in weldments [47]. Even during the Bronze age, lap joints were made using tiny circular boxes through pressure welding. Welding is a traditional manufacturing technique in which materials are joined with each other, either metals or non-metals through utilization of force, heat or both. The heat can be generated through electric current, combustion, and chemical reaction of friction. The heat is applied to faces of both materials which are intended to be joined and force is applied (in many instances). As the high temperature reaches near the melting point of weldments, they are fused together which results in a strong joint after cooling [73]. The temperature at the joint is the major factor in all the welding processes but the other factors such as dimensions, impurities, metallurgy and other environmental conditions also influence the quality of the joint. There are various types of welding processes and their subcategories as shown in Fig. 1.

Attempts have been made to develop relationships between process parameters of friction welding and mechanical properties of weldments through numerous experimental, modelling and optimization studies [52]. The hardness, strength, wear behaviour and microstructure of welded joints have been extensively studied by researchers in recent past [27].

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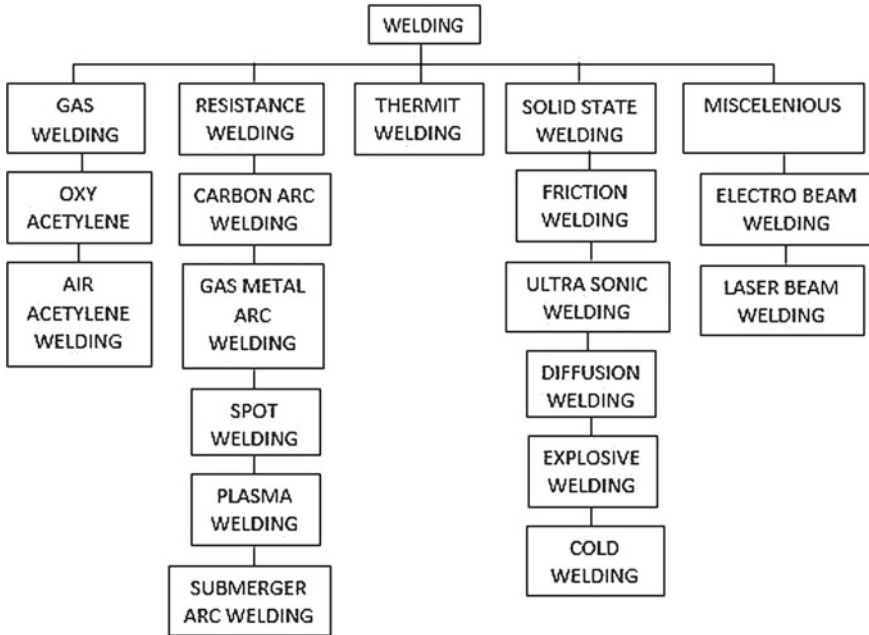


Fig. 1 Welding complete classification and its sub-types

In Solid State Welding, the friction welding as sub category, that is accomplished by the heat generated between two symmetrical and cylindrical parts rotating against each other. In this process the material should be parallel to each other as uniform rotation at an angle is not possible [42, 65]. These metals are pushed against each other by using force which creates friction and finally results in heat generation. Softening of metal occurs due to this friction as intense heat is achieved during the rotary process [45, 71]. The complete setup and schematic of friction welding is described in Fig. 2.

In this process, fusion of materials and plasticization occurs at the friction point also called a weld zone or area [41]. After the whole process is accomplished i.e., relative movement and axial pressure, then the extra materials are removed and a good bond is after solidification of the object.

There are generally three sections (Fig. 3) that are Unaffected Zones (UZ), Partially Deformed Zone (PDZ) and Plasticised Zone (PZ) as described by [14]. The FW is further divided in various types such as Linear Friction Welding (LFW), Inertia Friction Welding (IFW), Spin Welding (SW), Rotary Welding (RW), Friction Stud Welding (FSW), Friction Stir Welding (FSW), Friction Surfacing Welding (FSW) [62]. Basic fundamentals of friction welding are described as motion of material under high pressure which introduces heat between them, reaching plasticised temperature (solid but acts as plastic) without changing its state to liquid, this whole process gives an oxidized free joint and cleans to surface. As soon as it reaches the

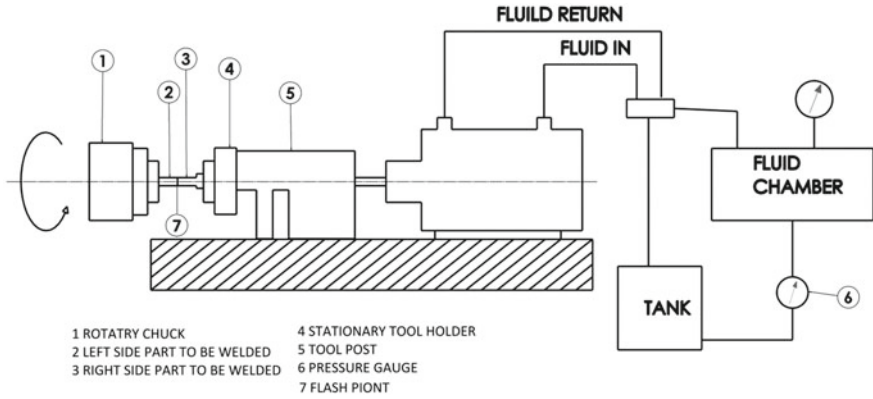


Fig. 2 Description for friction welding system

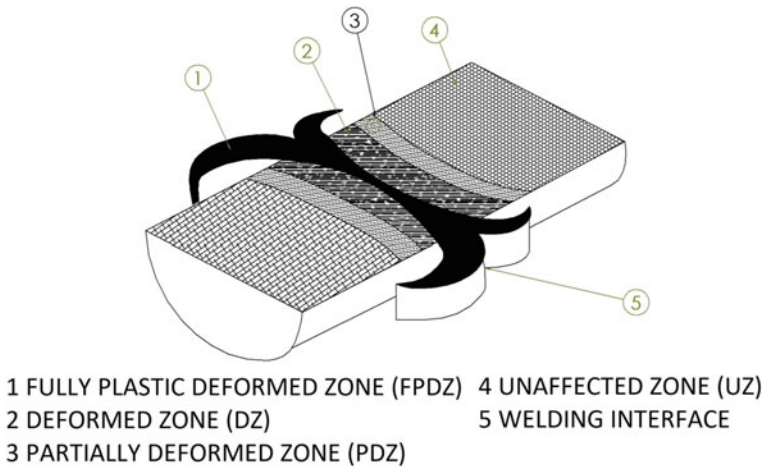


Fig. 3 Position of Unaffected Zone (UZ), Partially Deformed Zone (PDZ) and Plasticised Zone (PZ) on materials

plasticised temperature it becomes soft and then an external load is applied while rotating or linear motion is going on. This process is successful in joining the complex materials and structures that were previously thought to be difficult to join, that’s why the complicated structure is made in parts and after that joined via friction welding i.e., truck differential, turbine shaft and propeller [6]. Table 1 displays the details of different materials, methodologies and key findings during fiction welding studies.

Table 1 Detailed literature survey of experimental studies using friction welding

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
1	Carbon steel SAE 1020, Aluminium oxide Al ₂ O ₃ , Aluminium 6160/Friction welding [23]	Powder Metallurgy process is used for Aluminium, by cold pressed at 10 MPa and hot pressed to 5 MPa at 500 °C	Rotary speed—2500 rpm, Forging pressure—5 MPa, Friction pressure—10 MPa, Forging time—4 s and time—8 s	Optical microscopy, energy dispersive X-ray spectroscopy (EDAX), Microhardness Profile, Shear Strengths by MFL Universal Test Equipment, Scanning Electron Microscopy (SEM)	Al ₂ O ₃ is homogeneous with small grain size and uniform distribution, Fracture formed due to the metal oxide and Shear strength was inversely proportional to oxide and reinforced particle size
2	St-Al and Al-Cu/Friction welding [78]	Electric motor of 10 kW with 3500 rpm was used, cleaning of sample with acetone to remove any dirt or grease	Rotary speed—[2000, 2500, 2800]. rpm, Applied load—[5–12.74, 6.37–17.83, 7.64–22.93]. kg, Time—[4.7, 10]. s	SEM, Optical microscopy, Microhardness Profile, Tensile Strength, Vickers hardness tester	Steel-Aluminium welds Thick intermetallic layer reduces Tensile value. Oxide film and contaminants reduce the quality of joints. Force, Speed and Time affects the joints and weld properties Aluminium-copper welds Intermetallic layer causes Fracture affecting tensile properties. Speed, load and time have a low impact on the strength of joints

(continued)

Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
3	Copper C44300, Aluminium AA7075-T651/Friction welding [57]	Two cylindrical pipes of same dimension, Half of them threaded and other are not, all threaded have different pitch	Rotary speed—[545, 730, 950, 1320]. rpm, Forging length—[0.25, 0.5, 0.75, 1.00]. mm, Thread pitch—[0, 0.5, 1, 1.5]. mm	Vickers hardness tester, Compression test, Microstructural analysis, SEM IMAGE, Energy-dispersive X-ray	Friction Welding of thread tube to plate, threaded tube gives more compressive strength than unthreaded tube. EDX and SEM analysis has proved the results, 950 rpm gives Optimum joint strength and hardness FW is ten times more efficient than that of traditional butt welding of pipe in terms of electricity and time
4	Virgin PE pipe/Friction welding [19]	A hollow pipe made from Mannesmann process; Intermediate ring used for joining pipes	Rotary speed—500 rpm, Forging forces—420 kN, Time—280 s	Dynamometer, X-ray diffraction (XRD), Optical Microscopy (OM)	The ring is subject to compressive stress and thermochemical effect, microhardness is less at HAZ, Coarser microstructure formed due to FW which may leads to slower cool down, there is increased in micro hardness, FW provides enhanced homogeneous mixture of residual stress
5	API 5L X65 steel/Friction welding [48]	Intermediate ring of same material was used for friction welding the seamless pipe were used from the Mannesmann process	Rotary speed—500 rpm, Forging force—420 kN, Time—280 s	Optical microscopy, Vickers microhardness, X-ray diffractometer	

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Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
6	AA7075-SiC/Friction welding [68]	Alloy is prepared from Ingot AA7075 and Si. It is machined to remove oxidation and get smooth surface	Rotary speed—[1200, 1500, 1800]. rpm, Friction pressure—[50, 75, 100]. MPa, Burn-off length—[1, 2, 3]. mm, Upset pressure—[150, 200, 250]. MPa	Vickers Microhardness, Tensile Test, Genetic Algorithm, Scanning Electron Microscope	Optimized process parameter is Speed = 1491.54 rpm, Upset pressure = 209.26 MPa, Friction pressure = 98.94 MPa, Burn off length = 1.5 mm gives Ultimate tensile strength = 244.2866 MPa and Hardness = 148.2392. Microstructure analysis shows hard material inversely proportional to ductile ability
7	High-speed steel HS 6-5-2-5, Carbon steel for tempering C60/Friction welding [59]	Friction welding with 2400 rpm, Angular velocity 1.2 m/s, Welding time 3–18 s, Friction pressure 70, 80, 90 MPa, Forging pressure 0–120 MPa	Rotary speed—2400 rpm, Friction pressure—[70, 80, 90]. MPa, Angular velocity—1.2 m/s, Forging pressure—[0–210]. MPa, Time—[3–18]. s	Vickers Microhardness, Tensile Test, Scanning Electron Microscope	Forging pressure is suitable between 2.5 and 4 s, hardening of face occurs on HS steel, friction time has not much effect on the width of the joint

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Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
8	Medium carbon steel 1045, 316L stainless steel/Friction welding [28]	Friction welding on lathe with maintaining temperature 780–800 °C	Rotary speed—560 rpm, Angular velocity 1.2 m/s, Time—38 s, Friction pressure 75–155 MPa, Forging time—2 s	K Type thermocouple, microscope and a scanning electron microscopy, hardness and tensile tests, Energy Dispersive X-ray Spectroscopy	Flashing 1045 MCS was more due to Chromium present in SS elevated its hardness and thermal conductivity, increase in hardness at the welded joint, sample 1 gives 513 MPa tensile, 21% elongation and 90% efficiency of joint, forging pressure is proportional to hardness and tensile strength
9	FeAl40 ODS alloy/Friction welding [26]	Continuous drive rotary friction welding machine	Rotary speed—1000 rpm, Friction force—28 kN, Forge force—70 kN, Burn-off length—5 mm	Metallographic technique, transmission electron microscopy, microscope, high resolution electron microscopy	Changes in base alloy was the oxide particle and recrystallization observed along the weld line, big clumps of 0.2–1 mm were also noted
10	UNS S32205 chromium-nickel-molybdenum-nitrogen stainless steel/Friction welding [55]	Pipe of 12.7 mm thick and 10 mm diameter and intermediate ring was used to join due to temperature difference	Displacement—10 mm, Forging force—200 kN, Displacement rate—0.1 mm/s, Forging force rate—7.5 kN/s	Electron Backscatter diffraction (EBSD), type K thermocouple, impact tests, fracture surface analyses, scanning electron microscope (SEM)	Slight change in grain size of both the metals, whereas austenite crystals were completely reformed which has direct effect on toughness simultaneously, flash formation causes cracks which leads to fracture

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Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
11	Al–SiC metal and Al–Mg–Si alloys matrix composite/Friction welding [46]	Metals were casted by vertical direct cool billets with extrusion of 800 tons press	Rotary speed—3000 rpm, Friction force—30 MPa, Forge force—[50, 75, 100] kN, Burn-off length—[1, 2, 1, 3, 3, 3, 8, 6, 8] mm	Thermocouple, Hot-torsion testing, optical microscope, electron back scattering pattern (EBSP), Transmission electron microscope (TEM), Vickers hardness test (5 kg load)	Mathematical derived results are in tolerance with the physical experiment. Plasticized region is observed at the outer side of the weld line, variation in Axial values affects flow of material due to force applied while welding. Strain in the metal decreases within the region during welding
12	ABS and Nylon 6/Friction welding [67]	Dissimilar polymer/plastic materials that is reinforcement with Fe and Al separately	Rotary speed—[500, 775, 1200]. rpm, Time—[4, 6, 8] s, Feed rate—[0.045, 0.090, 0.180]. mm/rev	Optical micrograph, Optical micrograph, Minitab software	Hardness value—79.0, from 775 rpm, 0.045 rev/mm and 6 s time Tensile strength—0.5375 kg/mm ² , from 1200 rpm, 0.045 rev/mm and 8 s time, %age porosity—7.16%, from 1200 rpm, 0.090 rev/mm and 4 s time
13	AISI 304 SS/Friction welding [63]	Rods of 16 mm diameter and 130- and 50-mm length with hot extrusion process. emery papers used on Faces to polished, and acetone to clean	Rotary speed—1125 rpm, Friction time—[3, 5, 8] s, Friction pressure—[1.5, 2] MPa, Upsset time—[5, 7, 3] s	Transition Electron Microscope (TEM), Tensile test, Vickers's, Impact test, scanning electron microscope (SEM)	Joint strength inversely proportional friction time and hardness. Ductile Surface was observed without any dimples. Impact strength has no variation in result

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Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
14	Ti-6Al-4 V/Friction welding [16]	Bar of 50 mm diameter is friction welded with hydraulically controlled drive capable of giving 40 kN axial load	Rotary speed—[1500, 3000, 4500]. rpm, Friction pressure—[136, 272]. MPa, Forging pressure—408 MPa, Burn-off length—2 mm	Ultimate tensile strength (UTS), Vickers microhardness	Best tensile results from low pressure and rotating speed, transformation region width depends upon the applied pressure. i.e. 1500 rpm with 136 MPa gives best results whereas 4500 rpm and 272 MPa gives poor results
15	6082-T6 aluminium alloy and pure copper/Friction welding [50]	Cylindrical rod of 120 mm length and 20 mm Diameter is used and flash is removing via lathe machine	Rotary speed—1500 rpm, Friction pressure—110 MPa, Forging pressure—[80–160]. MPa, Forging time—4 S, Friction time—[1–4]. s	Optical metallography technique, X-ray diffraction (XRD), scanning electron microscope (SEM), V-notch impact	Optimized parameters of experiment are forging pressure and time 160 MPa and 4 s respectively. Higher tensile strength is achieved that is 198 MPa with 3.8% elongation. Strain hardening causes increased hardness at weld zones. Structure failure is ductile type with dimples presence

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Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
16	UNS S32205/Friction welding [4, 5]	Sample of 10×10 were cleaned with acetone and electro-etching performed by 10% oxalic acid for 30 s at 9 V	Rotary speed—[1000–2000]. rpm, Friction pressure—[45–125]. MPa, Upset pressure—[140–200]. MPa, Burn off length—[2.5–4.5]. mm	Tensile test, Vickers microhardness test, MATLAB, Mathematical equation	Speed, upset pressure and Friction pressure are directly proportional to hardness and tensile strength, whereas burn off length is inversely proportional. Upset forces and rotary speed have direct impact on tensile strength and hardness
17	AISI 304L and 4340 steel/Friction welding [54]	Rod of 12 mm diameter and after cleaning it is micro polished using $0.3 \mu\text{m Al}_2\text{O}_3$ powder	Rotary speed—[1500–2500]. rpm, Friction pressure—40 MPa, Forging pressure—60 MPa, Forging time—10 s, Friction time—5 s	Scanning electron microscopy (SEM), tensile test, X-ray diffraction (XRD)	Microstructure change in the region deformed zone and fully plasticized zone. To obtain strong tensile strength we need high speed for a short time. quality and strength of weld depends upon fusion process occurred at the weld zone

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Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
18	SAF 2507/Friction stir welding [60]	Sample of 300 × 100 × 2 mm was used and the tool was given 3° angle from normal of plate liquid cooled tool was used to prevent oxidation	Rotary speed—[50–250]. rpm, Force—14 kN, Length—270 mm	X-ray diffraction (XRD), K-type thermocouple, e X-ray spectroscopy (EDS), optical microscopy (OM), scanning electron microscopy (SEM), Vickers hardness	Almost all the speed parameters give a solid joint except 250 mm/min. Tinny equal sided grain were observed that are decreased with the increased rpm and less heat input. Sigma face is absent at interface due to rapid cooling. Weld speed is directly proportional to the hardness and tensile strength
19	AA6092/17.5 SiCp-T6/Friction stir welding [1]	Sample of 150 × 60 × 6 mm is used was used and the tool was given 2° angle	Rotary speed—[1000, 1500, 2000]. rpm, Tool Pin Dia.—6 mm, Force—14 kN, Length—100 mm	Macroscope, scanning electron microscopy (SEM), Vickers microhardness, ultimate tensile strength (UTS), Energy Dispersive Spectroscopy (EDS)	All speed parameters give defect free weld with uniform particle distribution, alignment of grains is vertical at weld zone. But hardness varies along the weld line. Lower rpm gives good results with less destruction. Brittleness occurs at high speed

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Table 1 (continued)

No.	Material/methodologies	Details of experiments	Parameters of experiment	Testing techniques and equipment	Results/findings
20	Al/SiC/Al ₂ O ₃ /Friction welding [2]	Friction welding machine of 20 ton with servo motor of 20 HP was used for experiment	Rotary speed—[2000, 2250, 2500]. rpm, Friction pressure—[40, 50, 60]. MPa, Upset pressure—[100, 120, 145]. MPa, Burn-off length—[1, 2, 3]. s	Tensile strength (TS), Vickers hardness, field emission scanning electron microscope (FESEM), X-ray spectroscopy (EDX), micrograph, macroscopic visual analysis	Strain and plastic deformation at the weld zone increased hardness. Optimum parameters for this experiment are 60 MPa frictional pressure, 120 MPa upset pressure, 1 mm burn off length and 2250 rotatory speed. Equal size flash, aligned matrix and uplifted the characteristics quality and S/N ratio

2 Applications of Friction Welding

Although this technology is new in the industry but many industries rely on this technology for their parts which are discussed in this section.

2.1 *Aerospace Industries*

The requirement for accurate and clean joints for aerospace industries are achieved from friction welding because they produce tough and smooth joints while welding the materials, Aerospace has utilized the solid-state contact-based welding procedures inside the previous decade such as Rotary Friction welding (RFW) which is performed on two types of machines i.e., Continuous Friction Welding (CFW), Inertia Friction Welding (IFW) [56]. A Friction based welding has an ability to self-clean the rough surface of material as it comes in contact because when the load applied, it compresses the plasticised material at the weld zone to outwards in a ring shape, which removes any surface impurities or oxides that existed earlier, making it pointless to utilize protecting gas or any other accessories during welding. Inertial welding is used in aerospace industries more frequently among the past times, particularly in joining titanium alloys, nickel-based super alloys and steel air motor barrel shaped segments, is known for giving parts of clean and high-quality joints, contrasted and the utilization of fusion welding [15]. FSW is preferred to combine titanium alloys and aluminium alloys parts for the aerospace industry due to their sophisticated design that makes it difficult to approach joints that are to be welded. As these processes are so efficient that no defects were found during the microscopic inspection and X-ray scanning [34].

2.2 *Manufacturing Industry*

Butt welds that are made in bars or cylinders can be welded to plates or one another. One of the parts is commonly round in shape, friction welding is also used in joining different shapes but with some limitations like square bar can be welded. There are various sizes that can be used for friction weld from tiny diameter wire that are utilized in the hardware business with length of 150 mm approx., for example in the engine business [51]. Models like drive shafts, axles and valves that have a large combination of heat-opposing heads are to be welded to that of a lesser expensive one. We can weld bar stock to the plate that has to be a delivery dish. Most alloys as well as metals, exceptions like cast iron that cannot be friction welded. Fragile zone doesn't exist in friction welding of Divergent metals, which frequently happens with circular arc welding, for example we can weld steel to aluminium or vice-versa [43].

2.3 Marine Industries

As we know, the sea water is salty and very corrosive in nature. That's why we use a propeller shaft of aluminium 5083, that metal is very effectively and efficiently welded on the shaft with the help of RFW. As it is difficult to make propellers and shafts all together, so they are prepared separately and assembled using RFW, where crystalline structure is less weak at Heat Affected Zone (HAZ) and result in better strength at weld point than any other traditional joining method [13]. Welding in air and welding underwater is a very different process. Underwater welding requires high speed during welding because water decreases temperature quickly during welding and makes welding difficult. This high speed causes reduction in grain sizes and increment in microhardness at the interface. Elongation is twice at interface and tensile is almost near to original metal [30].

3 Comparative Analysis of FW with the Traditional Welding Processes

As we know that traditional methods were not cost effective nor eco-friendly, so nowadays industries are switching to friction welding than that of arc welding, gas welding etc. as we know that they also need some extra accessories like filler metal, gas, and their necessary parts but on the other hand friction welding don't require such additional things, and on top of it the welded joint are much cleaner and stronger than other methods. On top of it metals characteristics are not changed, mixed or affected in this technique [58]. FW is elaborated and distinguished in different parameters is compared in Table 2.

3.1 Arc Welding Versus Friction Welding

Arc Welding is an old method of joining objects generally metals, has many demerits than that of frictional welding such as it requires welding rod that is compatible with the welding material from a wide variety of metals, welded surface is not clean as compared to friction welding, the welded area of metal via arc welding give heterogeneous mixture was observed whereas homogeneous mixer was evaluated in friction welding at a microscopic level. That was authenticated in the results of the tensile test. Friction welding parts can withstand a large amount of pressure at the welded area Materials Research [66]. Friction welding overcomes arc welding by following points discussed:

1. Quality of weld is better than the traditional method.
2. The bending occurs after cooling in arc welding is very less with less power consumption of friction welding.

Table 2 Friction welding comparison with other types of welding [74]

Basic property	Friction welding	Electron beam welding	Electrical resistance welding	Electrical arc welding
Weld type material	Almost any	Metals only	Conductive only	Conductive only
Compatibility cross section to welded joint	Complete	Surface only	Surface only	Surface only
Welding geometry	Limited (mostly circular)	Any	Any	Any
Preparation of parts	Shafts, pipes, propeller etc.	Metal parts	Metal parts	Metal parts
Time taken	Low	Long	Quick	Moderate
Additive of materials	N.A	Powder or wire	N.A	Electrode
Process control	Mechanical rotary or linear motion	Servo motor control via computer	Push pedal by worker	Worker
Running cost	Cheaper	Very costly	Costly	Costly

3. It needs no shielding gas or additional metal, and it doesn't create any gas or fumes.
4. Lifespan of setup of friction welding is longer as it requires less maintenance, with very silent operation.
5. Almost each type of composites, metals and non-metals can be welded except few materials.
6. Strength of the welded area is similar to the base metal [31].

3.2 Tungsten Inert Gas (TIG) Welding Versus Friction Welding

Though, both of the processes are capable of joining the aluminium alloys. TIG is unable to perform without filler material due to the presence of iron impurities in high volume, as these impurities will lead to fracture due to temperature range. Even though there is a large difference in the test results of both, FSW performs better in terms of tensile strength, hardness at either base, HAZ, TMAZ etc. FSW produces greater ductility and strength, on the other hand TIG WELDING produces high levels of hardness in the HAZ and literally depends upon the variation of current applied to the work piece [24]. FSW process gives crystal growth like tree shape at microscopic level due to recrystallization process occurring. Although TIG has no such shape because rapid cooling by air occurs after the welding process. The observation of the welded material at a microscopic level showed the presence of

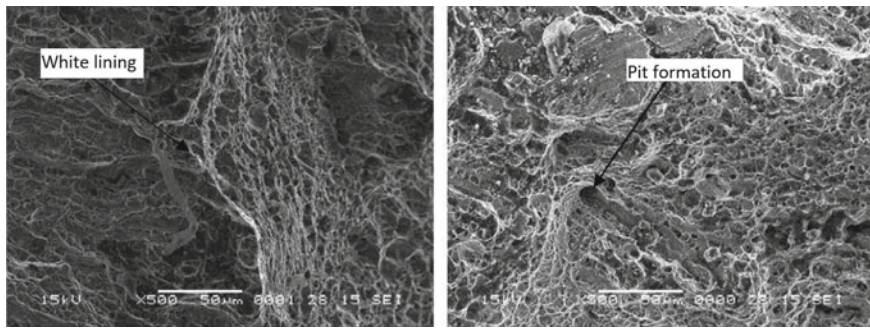


Fig. 4 Fracture on metal surface via scanning electron microscope (SEM) of AISI 304

micro fractured gain by tensile test as shown in Fig. 4. There can be clearly visible divergence in structure, proportion of spots than other [69].

TIG process applied without the filler material will produce cracks on aluminium alloy due to the presence of iron in aluminium, FSW joints are proven to give better results in terms of strength and ductility than TIG welding joints [64]. Medium speed is preferred for good results as higher will increase the hardness and lower will not give optimum joining due to less heat generated [36].

3.3 Friction Welding Versus Metal Inert Gas Welding (MIG)

MIG is a very popular type of welding since the 90s and dominated arc welding due to its convenient structure but not superior than friction welding in welding circular shaft, hollow pipe and welding of composites. As it requires filler wire and shielding gas (Argon) which increases cost whereas no such requirement in friction welding due to its simplicity. As, aluminium weld by MIG causes hardness due to rapid cooling and chances of fatigue of aluminium is much more frequent than that of friction welding. As we can see after weld images in Fig. 5 the friction welded area is dense whereas porous in TIG and MIG [49, 70].

4 Friction Welding Materials and Methods

In the universe, there is a wide range of metals and non-metals exist, they are welded to each other or similar as per need of manufacturing, but not all processes or techniques are there that can weld all the metals, so friction welding is preferred over the traditional welding method because it has the capability to weld almost all the materials that are used in industries. Intermediate layers of metal are used during

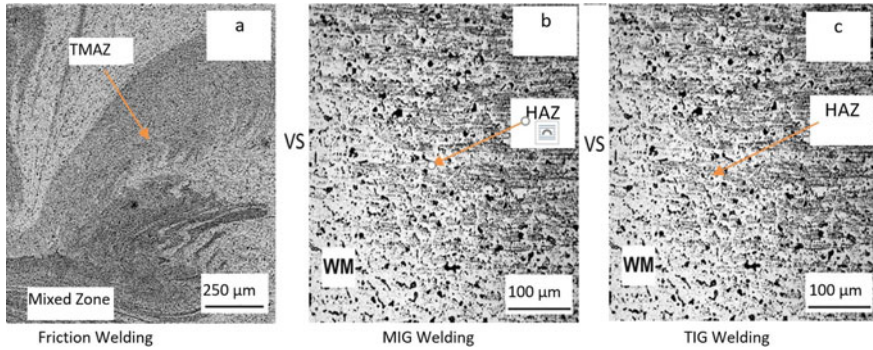


Fig. 5 Experimental image after friction welding of 5086-H32 aluminium alloy, MIG welding and TIG welding at welded zone

friction welding on those metals with high melting temperature difference between them [7].

4.1 Steel and Its Alloys Welding

Friction welding is a better and more cost-efficient method in terms of joining Stainless Steel with steel or its alloys than that of any other welding process. As, it produces less hardness and more toughness to bear stress and strain during working. Burn off length also has an effect on the toughness and hardness at the weld zone, as we increase the burn-off length it will increase hardness and decrease toughness and will help in removal of oxidized layers on faces of each other. But excessive burning of length produces brittle fracture due to increased hardness and develops intermetallic compounds and carbides near weld zones [11]. Though different composites of steel have different optimized parameter value, such as 105 MPa Friction Pressure, 180 MPa Upsetting Pressure, 2000 rpm Rotary Speed, 3.9 mm burn-off length are the optimized values for FW of UNS S32205, which gives 827.17 MPa and 325.61 Hv as Hardness and Tensile strength respectively observed from the result [4].

4.2 Copper and Copper Alloys

Friction welding between copper and low carbon steel (LCS) at 30 MPa friction pressure, 2.4 s friction time gives low fracture joint and 40% efficient joint, but 80% can be achieved by using 180 MPa forging pressure.

Friction time is directly proportional to the efficiency of the joint [29]. In FSW 1250 rpm with 61 mm/min parameters gives no defect at interface, but reduction in grain size at the weld zone. Softening region developed at the interface, and reduction

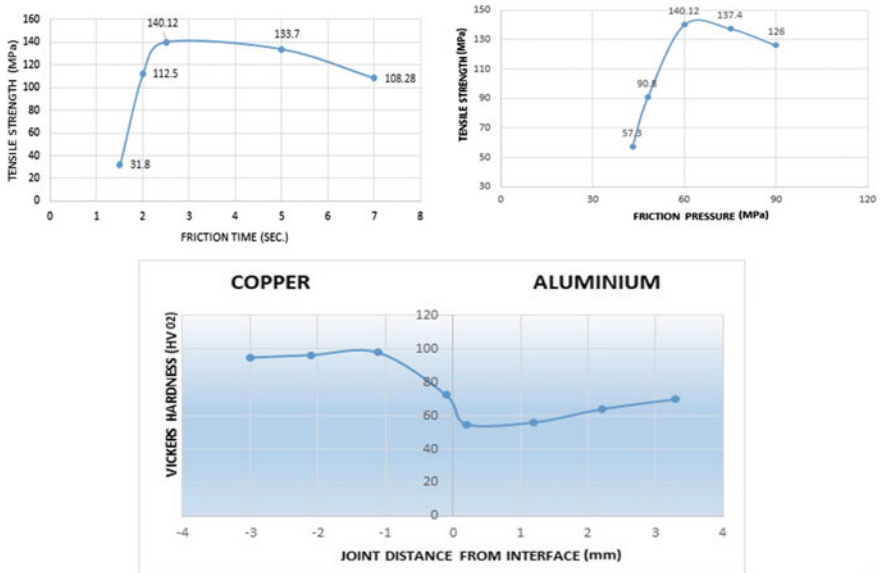


Fig. 6 Al–Cu friction welding graphical representation of friction pressure to tensile strength, tensile strength to friction time and hardness to distance from interface

in size of grain as compared with original metal. Hardness was larger at the centre and gradually reduced the hardness of the base material. Comparing base material, the tensile strength reduced to 87% [35].

Intermetallic layer formed at the interface due to the brittle nature of copper and 6061 aluminium alloy, that's why we use an intermediate layer of material to join them successfully with 136–760 HV of hardness from base to interface [61] as shown in Fig. 6. The temperature of welding reached to 580 °C that greater than Al–Cu alloys [53].

4.3 Aluminium and Aluminium Alloys

Friction welding is the best procedure for welding dissimilar metals i.e., aluminium & aluminium alloys etc. We obtained good Tensile strength and micro hardness from aluminium and its composites. Though the ductility of material was reduced but it was reasonable, whereas, chemical properties of composites have compromised the properties of weld if we use Fe as alloy of aluminium [12]. There are various parameters values in friction of different materials to get desired values of strength, hardness etc. that certainly affect the joint strength of the structure. The perspective of aluminium with iron welding process will give rise to intermetallic phases due to melting temperature variation between metals that leads to brittle weld joints [9].

4.4 Tungsten and Titanium Welding

As we know that tungsten is harder than titanium that's the major effect of heat or we can say plasticised temp of titanium melts faster than tungsten and the heat affected zone is majorly on titanium side. Generally, 750 rpm is used to obtain defect free joints rather than 1500 rpm because of large variation in melting temperature of both metals, so the weld joints are brittle and prone to breakage on drop. Interlayer metal i.e., copper is used to eliminate micro cracks formed during welding process [8]. The predicted heat distribution in the simulating model is similar to the experimental model performed physically i.e., length shortening value predicted was 2.8 mm and in actual it was 2.5 mm. Similarly, in terms of temperature it was 1340 °C in both the results. Variation in friction coefficient of model due to high temperature during welding which results in change in thermal field [37].

4.5 Titanium and Iron Welding

As there is a huge melting temperature difference between iron and titanium, as titanium is used for cutting iron or steel, it is inapplicable task of welding them due to the appearance of intermetallic phases after welding. Due to these intermetallic phases, there is no guarantee that complete welding across the cross-sectional area is successful, as these phases generate higher value of hardness among the metal and cracks in the weld zone are produced [40]. We can get good tensile value at high friction pressure and upsetting pressure but with poor bending test and fracture at the weld zone, due to intermetallic layer and titanium a brittle substrate. Surface roughness is inversely proportional tensile strength and directly proportional to residual strain obtained during welding process. To obtain good results low temperature around 550 °C but strictly not above 700 °C is required with short holding time [18].

4.6 Nylon 6 and ABS Reinforced Fe

Researchers used 40% of iron powder as additives in ABS and PA6 polymer matrix, so as to perform the friction welding process and get good bond strength between them, as reinforcing Fe brings their melting point closer to each other that helps in bonding. In their pure state polymers are impossible to yield good results as a very little tensile force can break the bond easily. This feed rate plays an important role. For better joint strength, we need slow feed rate, high rpm and adequate time [33].

5 Process Parameters of Friction Welding

As we know the parameters are very crucial part of any experiment, same is in friction welding it consists of various parameters i.e., speed, applied force, friction time etc. as in Fig. 7.

Friction Welding Experiments performed with some parameters taken in aspect are speed, feed with range of 700–1350 rpm, 75–115 mm/min. We get different values with different steps as written in Table 3 as described by Yilbas et al. [77]. The outcomes describe that hardness and tensile strength increases when speed is 1350 rpm with feed 115 mm/min as found by Hussain and Pasha [25].

5.1 Speed

Speed is the most important and phenomenal factor in the friction welding and its categories such as tensile strength and hardness i.e., Strength and hardness increases gradually with rise in speed as shown in Fig. 8. So, the speed has an impact on all the

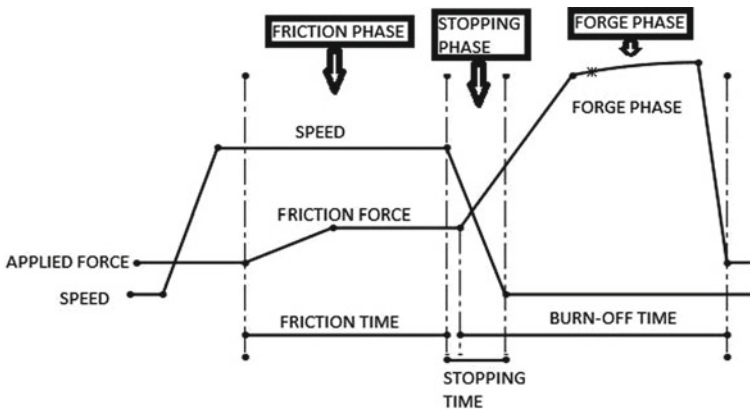


Fig. 7 Stages of friction

Table 3 Hardness and tensile strength measurements at conditions

No.	Speed (rpm)	Feed (mm/min)	Tensile strength (MPa)	Vickers hardness (HV)
1	700	75	160	85
2	900	90	166	88.5
3	1150	108	171	88.9
4	1350	115	172	90.2
Parent metal values			250	93.5

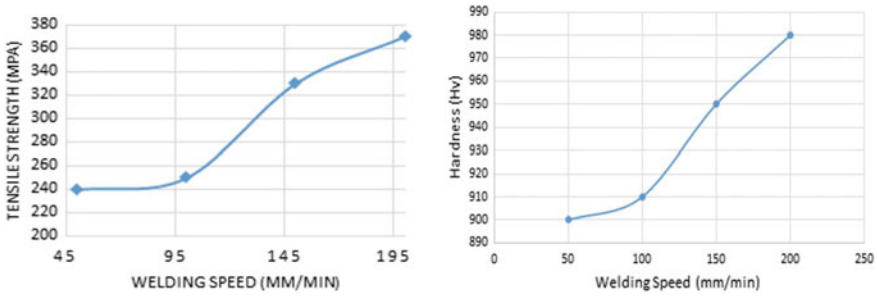


Fig. 8 Graphical relation of welding speed of SAF 2205 with respect to **a** hardness and **b** tensile strength

factor on the welded material, but it is inversely proportional to speed because there is elevation in temperature at the contact point which leads to plasticization of metal and the strength will tend to decrease at that area, even at the microscopic level the impact of speed is visible [39].

Aluminium alloy showed different results at different speeds at the Stir Zone (SZ) i.e., as speed increases it decreases the grain size and width of material as shown in Fig. 9 as found by Kumar and Kailas [32]. Residual stress is symmetrical in Bobbin Tool Friction Stir Welding (BTFSW) and it is maximum at centre and decreased to normal as we move to base metal. Similarly, Hardness is symmetrical at the weld zone and lowest at Heat Affected Zone (HAZ). 70% efficiency of the joint is observed at the test results [76]. Welding Aluminium with Aluminium Ytria Stabilized Zirconia (YSZ) composite gives strong joints at 630 rpm, on the other hand in pure aluminium bending strength is better at 2500 rpm, however, and results may vary after joining the metal due to internal flaws induced by thermal stresses. Though fracture may occur due to high temperature caused by high-speed rotation [72].

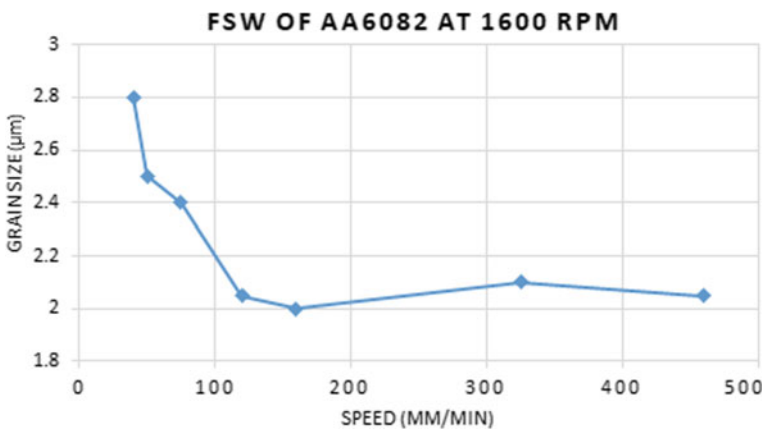


Fig. 9 Graphical relation of speed impact on grain size of AA6082 [32]

5.2 Friction Force

It is the force applied during the rotary process which makes friction more effective but hardness. Joint strength relies on particle bond quality at the weld zone, pure metal will have good bond as compared to composites, as impurity percentage mixing also has an impact on the strength of bond, as it basically depends upon the lattice size of both the materials. This helps in fabricating the metal matrix composites as per material [79]. Friction pressure is directly proportional to tensile strength, but excessive pressure than certain limit will also decline the strength i.e., welding between SS410 and INCONEL 718 at 190 MPa of friction pressure that is optimum value for tensile strength. Fracture observed on interfaces was a mixture of dimple and quasi-cleavage fracture. Dynamic recrystallization at the interface causes increased hardness value [10, 75].

5.3 Axial Pressure or Torque

Welded joint's bond strength majorly depends upon the axial pressure exerted during the experiment. As there is any change in axial pressure, it will reflect in the properties i.e., 135 MPa of axial pressure gives the highest tensile strength of 432 MPa because fusion of alloys with steel, but excessive pressure will cause ductile failure as shown in Fig. 10, but torsional strength will increase because it will transfer extra mass due to heavy axial pressure. Bond strength has direct relation with temperature, that is directly proportional element diffusion [21].

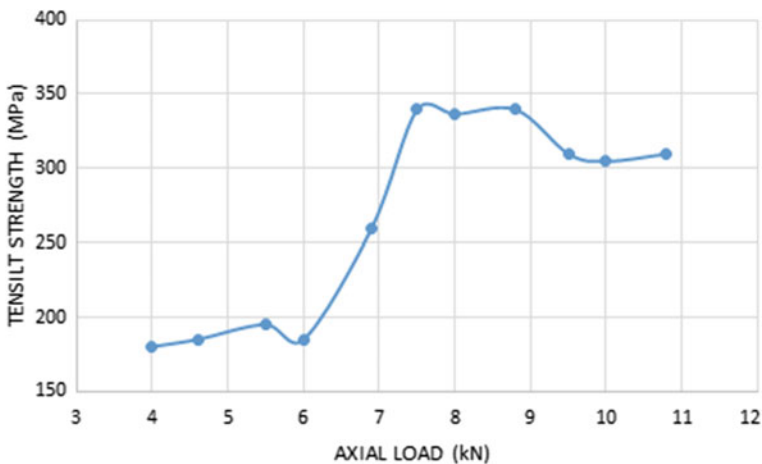


Fig. 10 Graphical relation of axial load and tensile strength with fracture point

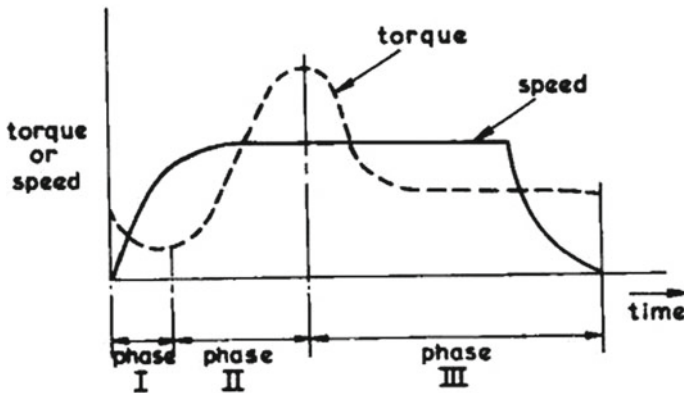


Fig. 11 Constant axial load with respect to time

As each parameter has their own impact on the outcome result, similarly change or variation in axial pressure is reflected on friction welds. 120 MPa axial pressure gives the optimum tensile strength and impact toughness, but due to brittleness the sample doesn't pass the basic requirements [32]. But, unfortunately the hardness of the specimen reached maximum value due to high temperature caused by high axial pressure. It has three faces with respect to time as shown in Fig. 11, torque firstly decreases [3] and then becomes constant before reaching peak during experiment [22].

5.4 Welding Time

Weld time is an important factor in friction welding as the welding time had major impact on hardness and burn off length, but tensile strength and bending strength are not affected during welding. If tempered or quenched material is used with friction timing of 14 and 15 s gives lower toughness value. Whereas more time is needed for such material to get reliable value, but excessive time duration will cause overheating of microstructure grains which will affect toughness values [17]. In experiment with parameters from 0.5 to 4 s time for welding, 3 s gives best results that are very fine material structure that is near to base metal, same as in case of HAZ regarding tempered hardening of metal. Time is directly proportional to length shortening [38].

Generally, Low fatigue strength of joints develops due to high speed, less force and less time duration. Friction time is inversely proportional to fatigue limits and tensile strength [20]. In the experiment it was observed that if at a certain speed we obtain tensile strength and fatigue limit values, these values can be increased just by giving more time with the same parameters. So, speed, time, pressure and force are the main parameters for better joint strength results as shown in Fig. 12 that shows relation of load with time in AISI 304 and AISI 1021 welding process [44].

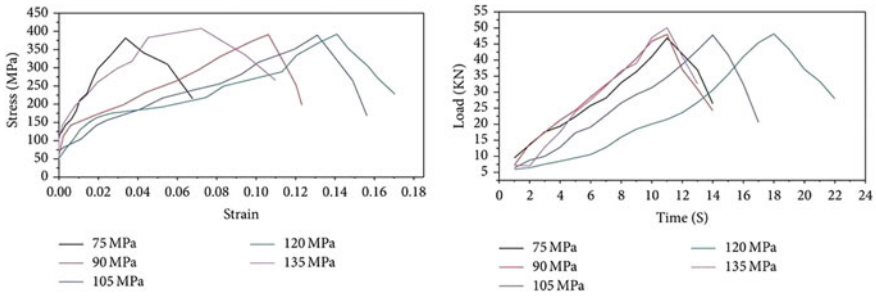


Fig. 12 Relation of load and time, stress and strain of AISI 304 and AISI 1021 steels

The data has been collected for the Clarivate Analytics portal which indicate that total 3453 articles have been published in refereed journals. It can be noticed from Fig. 13 that the research in friction welding has been increasing since 2011. Moreover, China leads in the world while reporting the research based on friction welding followed by India and Iran.

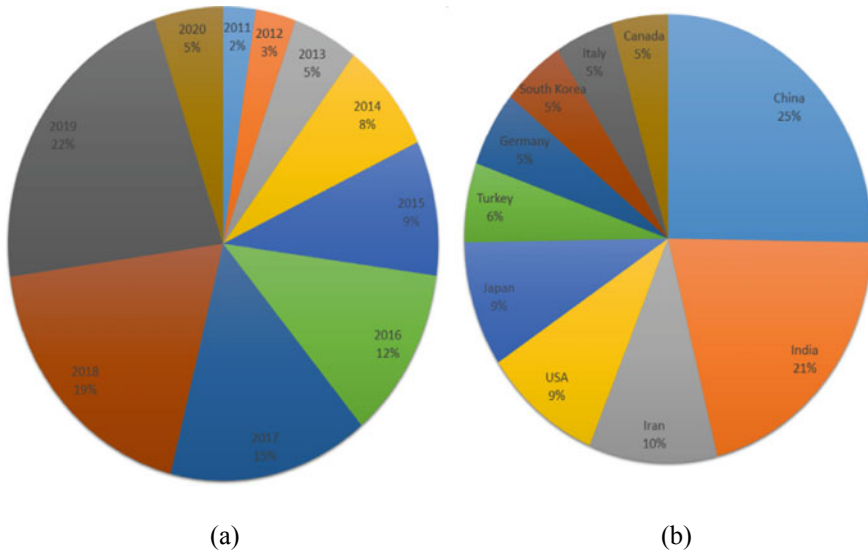


Fig. 13 Statistical data of published articles since last ten years **a** year wise **b** country wise

6 Conclusions

From critical literature review the following conclusions can be drawn:

From literature review it was observed that FW is generally performed at the speed range of 1000–4500 rpm and pressure at 40–60 MPa for metallic materials on the other hand this range was found to be 500–1200 rpm for plastic components. This technique can be performed on almost all metals and composites.

- During friction welding of Carbon steel SAE 1020, Aluminium oxide and Aluminium 6160 it was observed that fracture occurred due to the metal oxide and shear strength was inversely proportional to oxide as well as reinforced particle size.
- Friction welding of thread tube to plate, threaded tube gives more compressive strength than unthreaded tube.
- FW is ten times more efficient than that of traditional butt welding of pipe in terms of electrical power consumption and time. Utilizing this technique there was enhanced homogeneous mixture of residual stress reported. Further friction time has not much effect on the width of the other hand forging pressure is proportional to hardness and tensile strength.
- Variation of grain size has directly affected the toughness and flash formation hence further causes cracks and consequently leads to fracture.
- During friction welding of AISI 304 S.S component examined by using Transition Electron Microscope (TEM), Tensile test, Vickers's, Impact test and scanning electron microscope (SEM) resulted that the Joint strength was inversely proportional friction time and hardness.
- Friction welding of titanium alloy of 50 mm diameter with hydraulically controlled drive capable of giving 40 kN axial load resulted in the best tensile results were observed at low pressure and rotating speed, in addition to this transformation region width depends upon the applied pressure. During experimentation best results were observed that 1500 rpm and 136 MPa
- FW of Aluminium alloy and pure copper having 20 mm diameter and 120 mm length work piece examined by optical metallography technique, X-ray diffraction (XRD), scanning electron microscope (SEM) and V-notch impact revealed that optimum forging pressure and time was observed at 160 MPa and 4 s. Strain hardening was the main cause of increased hardness at weld zones. Further Structure failure was of ductile type having dimples in addition to this it was found that intermetallic joints failure occurs where the tensile strength was less.
- Performance analysis of UNS S32205 Friction Welding revealed that Speed, upset pressure and Friction pressure are directly proportional to hardness and tensile strength, whereas burn off length is inversely proportional, furthermore Upset forces and rotary speed has direct impact on tensile strength and hardness.
- Fusion process affects the quality and strength of weld within weld zone and for obtaining strong tensile strength there is a requirement of high speed within a short time interval.

- This type of welding can be performed along with traditional welding processes having several benefits over conventional types in context with environment, economical and performance aspects. FW has wide applications in industries like aerospace, marine, fabrication of shaft, rod, pipes, in addition to this square bar can also be welded using this technique. As far as material point is concerned this welding technique can be applied to Steel and its Alloys, Copper and Copper Alloys, Aluminium and Aluminium Alloys, Tungsten and Titanium, Titanium and iron welding as well as non-metallic materials like Nylon 6 and ABS Reinforced Fe.
- The process parameters that affect the performance of FW are speed, friction pressure or axial force, welding time etc. The bond strength directly depends upon the axial force applied; welding time has major influence on hardness and burn off length without altering the tensile strength and bending strength. Further friction time relates inversely proportional to the fatigue limits and tensile strength.
- A Friction based welding has an ability to self-clean the rough surface of material as it comes in contact because when the load applied, it compresses the plasticized material at the weld zone to outwards in a ring shape, which removes any surface impurities or oxides that existed earlier, making it pointless to utilize protecting gas or any other accessories during welding.
- Inertial welding is used in aerospace industries more frequently among the past times, particularly in joining titanium alloys, nickel-based super alloys and steel air motor barrel shaped segments, is known for giving parts of clean and high-quality joints, contrasted and the utilization of fusion welding.

7 Future Challenges

- The studies have been performed to optimize various input parameters to achieve desired results during the friction welding process. Since, there are conflicting solutions when the number of response parameters are more than one, there is a need for multi-objective optimization studies.
- Thus, hybrid welding processes can be developed where FW can be combined with other processes which increase the possibility of achieving better output characteristics.
- Simulation and modelling of FW process parameters for different materials, alloys and composites is yet to be studied. This would help to predict and achieve the desired response in terms of mechanical strength and microstructure before initiating actual process.
- The process capability, environmental degradation of FW process, economical aspects and possibility of joining of materials with variable melting point is yet to be explored.

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