Friction Welding Processes: A Review

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REVIEW PAPER

Abstract— Friction welding is a sort of solid-state welding process that does not use flux, shielding gases, or filler metal; instead, the heat needed to fuse the materials is produced by the friction between two or more objects moving relative to one another. This kind of welding is an alternative to the traditional fusion and adhesive-based welding procedures. The method is reliable, capable of joining materials that would seem hard to join with traditional welding, and suitable for joining both similar and dissimilar materials including wood, steel, aluminum, copper, masurium, nickel, zinc and carbon steel. Friction welding can be carried out by using several techniques including linear, rotary, friction stir, direct drive and inertia welding. Each of these welding techniques is distinct and are named according to the relative motion involved. Although the process varies slightly subject to the type of motion, the procedure is consistent and the resultant joint is comparable with those obtained through conventional welding technique. This study reviews the distinct friction welding processes and specific techniques involved in the process.

Keywords— Direct drive welding, Friction stir welding, Inertia welding, Linear friction welding, Rotary friction welding.

1 Introduction

Previous studies have established that friction welding is a very creative technique for bonding dissimilar and similar metals or non-metals (Singh *et al*., 2016). Friction welding is gaining attention due to its capacity to overcome attendant difficulties in joining materials that have dissimilar physical properties (Shete and Deokar, 2017). It involves the use of a machine that converts mechanical energy into heat energy through relative movement of the materials (Mallick, 2010). The relative movement raises the temperature at the interface of the material, which then begin to deform plastically (Li and Patel, 2022), and the unwanted interface materials are removed from the edges (Martinsen *et al*., 2015). Friction welding does not require any other external heat or flux (Dawood *et al*., 2017), the friction between the surfaces of the materials is what produces the heat (Kalaiselvan *et al*.., 2021), usually by one component moving in relation to the other or when both components are forcefully pressed against each other by a compressive force. The actual friction welding occurs at the moment the surfaces are rubbed together under pressure (Thomas and Fennn, 2011), such that atoms on the two surfaces attract each other and form bond between the surfaces, which causes the joining/welding (Vural, 2014).

The process is machine controlled and completely repeatable. While one of the materials is moved, the other is held stationary by the welding machine. The material that is moved is brought in contact with the stationary for heat to be generated by rubbing one material against the other, temperature is induced (Fig. 1), The material that is moved is brought in contact with the stationary for heat to be generated by rubbing one material against the other, temperature is induced (Fig. 1), and increases gradually to a point where interface plasticization results from heat generated at the interface (Liu and Hu, 2022; Dixit *et al*., 2020; Fehreenbacher *et al*., 2014), it is important to note that temperature at the bonding zone differs according to materials considered (Geng *et al*., 2019). As long as friction pressure is applied to the materials, the plasticized portions of both materials will be forced out of the interface axially, resulting in a high-integrity, clean interface (Chamanfar *et al*., 2011). The plastic deformation of the heated portion of the materials is dependent on the speed, of the relative motion, axial unit force and temperature conditions. This is so because both the speed and the axial force determine the intensity of heat that allows plastic deformation of the heated workpieces to take place, and when enough heat that can bring the materials to a plastic state is generated and the motion can then be stopped in order to allow an increased axial, compressive force, producing a solid-state joint at the interface, that is the friction welded joint (Meher and Mahapatra, 20022; Leitao *et al*., 2015; Mir *et al*., 2022). At the particular time the motion is stopped, a high force is used to compress the materials then after obtaining the joint, it is allowed to cool.

All of these processes are done in phases. The first stage is called the friction phase, in which one workpiece rotates while the other stays stationary. An axial force is applied after the two workpieces come into contact with a suitable rotational speed. The next stage, known as friction pressure phase involves high-speed rubbing of

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the workpieces and localized heating of the contact, which causes upsetting. Lastly, the forging phase, during which the upsetting is halted (also referred to as the braking phase) and pressure is increased (also referred to as the swelling time) to complete the forging (Fig. 2). The high compressive force is the pressure applied, it is increased uniformly for a few seconds and the workpieces are allowed to cool down (McAndrrew *et al.*, 2017).

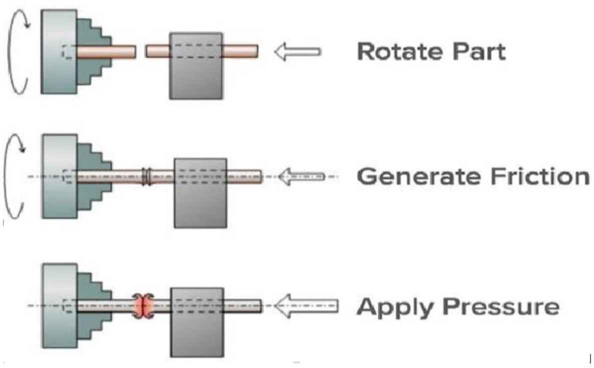

Fig. 1 Friction welding cycle (Spodar, 2018)

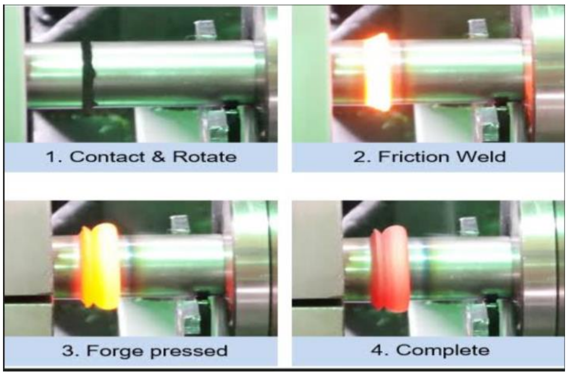

Fig 2 Steps involved in FW process (FW machine, n.d.)

It is important to note that allowing the materials to cool down for some time is necessary as cooling has an advantage on the integrity and interfacial features of the joint and additionally reveal the weakest region of the joint (Peng *et al*., 2019). It is important to predetermine the heating period in order to accurately estimate the amount of energy and temperature condition required for the welding to take place (Yilbas and Sahin, 2014). Fundamentally, friction welding is done on a lathe-like welding apparatus. Two materials are fastened, one to the rotating chuck of the machine and the other to the stationary chuck. Once the material fixed to the stationary chuck and the rotating chuck come into contact, frictional heat and pressure are produced.

2 LITERATURE REVIEW

2.1 TYPES OF FRICTION WELDING AND APPLICATION

2.1.1 STIR FRICTION WELDING

Stir friction welding (SFW) is a welding technique developed to address the difficulty in bonding similar, and dissimilar metals with distinct coefficients of thermal expansion and melting points. Also, the welding technique does not require a consumable tool rather it makes use of a reuseable cylindrical tool with the tool shoulder and a reduced diameter profile pin that extends from the tool shoulder (Patel, *et al.*, 2016). The cylindrical tool and the profile pin that extends from the tool shoulder are wear resistant (Borigoria *et al.*, 2019). Stir friction welding coins its name from the stirring of the cylindrical tool when it comes in contact with workpieces and frictional heat in the form of energy is produced, which fuses the workpieces together (Muhammad and Wu, 2019). The materials are mechanically traversed by the cylindrical rotating tool to produce the joint (figure 3). Stir friction welding is commonly employed for joining thin aluminum plates, extrusions, and sheets. This technique allows for the creation of seam or butt welds without any limitations on the length of the components.

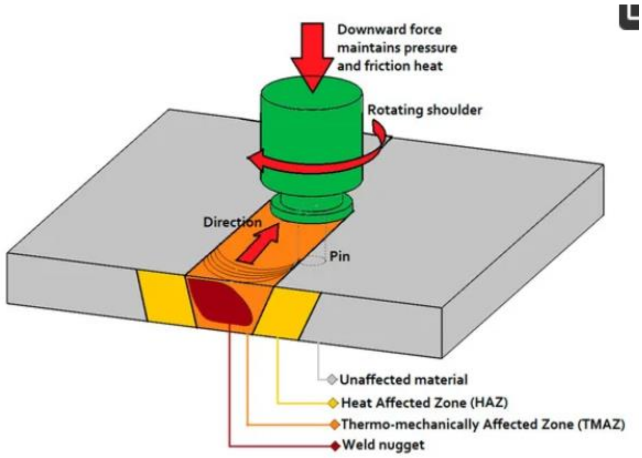

Fig. 3: Schematic of a SFW operation (Taheri et al., 2019)

The energy mode is called "friction," and the rotation of the tool is represented by the term "stir." Stir friction welding does not melt workpieces as workpieces welded below their melting temperature does not requires shielding gases nor filler metals (Verma and Misra, 2015). The welding process eliminates welding defects and is environmentally friendly. The process is of low distortion and the resulting joint is of high strength, toughness and fine-grained structure that resists fatigue stress Bharti *et al.*, 2024). At the inception of stir friction welding, it could only weld metals with low melting points such as magnesium, aluminum and copper. However, with recent technological advancement, it can weld high melting point metals such as steels, Ni-based super alloys and Ti alloys. The scope of stir friction welding has even widened to joining dissimilar metals such as steel using titanium, aluminum, magnesium, copper, and other alloys as well as woods with different qualities. This method of welding has low-risk and is cost-effective for many applications (Shinde *et al.*, 2023). Stir friction welding is utilized to join aluminum components used in automotive and aviation industries (Ahmed *et al.*, 2023). It is also used in marine, armory and railway industries. However, as much efficient as it is, more advancement is

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still expected so that a joint with improved integrity can be obtained between high temperature alloys.

2.1.1.1 Factors to be Considered for a Good Weld Quality when Carrying Out Stir Friction Welding (SFW)

To guarantee a successful and effective weld, the traverse and tool rotation speeds are very important. By decreasing the traverse speed or raising the rotation speed, a higher temperature weld with improved quality can be achieved. This is so because the workpiece that surrounds the tool needs to be hot enough to permit a large plastic flow that is necessary and to reduce the stresses that could cause the tool shown in figure 1 to break. However, the heat has to be regulated by controlling the rotation speed between 400 and 1500 rpm, while the transverse speed ranges between 50 and 200 mm/min depending on the materials involved to avoid a bad weld quality eventually (Sushil *et al*., 2017). Similarly, forging speed, tool pin profiles and tool angle influence the tensile strength of the joint and other mechanical properties (Karwande *et al*., 2016; Devaiah *et al*., 2018). The tool rotational speed should be maintained between 15 and 100 mm/min, forging pressure should be regulated between 1 and 10 MPa, while the friction pressure should be between 3 and 9 MPa, while the friction duration should be between 15 and 500 seconds depending on the materials involved.

Using a single-pin tool will result in a good ultimate tensile strength while using a dual-pin tool will lead to a higher ultimate tensile strength, coverage of more area within the same period, induce heat output and subsequently, material flow and microstructure of the joint (Zhou *et al*.., 2018). A phase transition occurs in the microstructure of steel due to the peak temperature and cooling rate, making it a more challenging material compared to aluminum alloys (Sadeesh *et al*., 2014; Liu *et al*., 2018; Muhammad and Wu, 2019). Peak temperature of steel is regulated between 600 and 1200 °C while for aluminum alloy it is regulated between 150 and 700 °C. Irrespective of materials, the base of materials undergoing welding remains unaffected by heat due to its distance from the recrystallized zone (Sadeesh *et al*., 2014; Sushil, *et al*., 2017) and the holding time is also monitored but can last 60 minutes depending on materials involved.

2.1.2 Rotary Friction Welding

The rotary friction welding (RFW) is a weld method that produces coalescence in metals or non-metals by applying a load and creating heat between the surfaces of the two materials by mechanically induced circular rubbing motion (Bhate and Bhatwadekar, 2004). As shown in figure 4, in rotary friction bonding method, one part is fixed while the second is rotated. The rotated part and the fixed part generate interfacial heat that advances to coalescence. The part rotated against the fixed part causes friction generation, and the generated friction leads to friction welding (Murugan *et al*., 2021). The phase where friction is generated and heat is produced at the interface of the materials under consideration is the friction phase and the forging phase is where the frictional heat causes coalescence (figure 5). The most often used form of friction welding is rotational friction welding, which is commonly employed for joining pieces that have at least one component with rotational symmetry, such as tubes or bars.

In the automotive sector, aerospace and electronics manufacturing, this is the friction welding procedure that is most frequently utilized. The method has been applied to the production of engine valves, drive shafts, steering columns, gear box forks, suspension rods, and other parts where the welding of dissimilar valve stem and head materials are necessary (Parmar *et al*., 2022).

Fig. 4 Fixed and rotating Parts of RFW machine (Parmar *et al*., 2022)

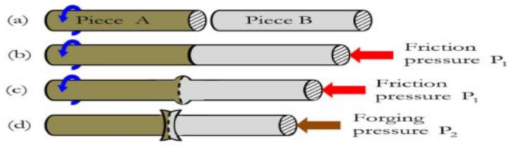

Fig. 5 RFW process (Khalfallah *et al*. 2020)

2.1.2.1 Factors to be Considered for a Good Weld Quality when Carrying Out Rotary Friction Welding

Factors to be considered when using rotary friction welding method to weld materials include friction duration, friction pressure, forging time, rotational speed, and forging pressure. These factors have significant effect of weld quality. Studies have shown that the more the rotation (in revolution per minute) the better the weld, the stronger the joint, however, the rotation speed has to be regulated because excessive rotation speed has damaging effect on the welding area. Excessive rotational speed causes excessive frictional heat that softens a wider area of the materials. The joint that would have been welded excellently at a regulated rotational speed would be affected by excessive rotational speed. Excessive rotational speed reduces tensile strength that would have been realized at a regulated speed (Wang *et al*., 2018).

The rotation speed can be regulated between 400 and 1450 revolution per minute. Optimal control of friction duration is crucial for achieving high-quality welds, as excessively extended friction duration can have adverse effects on weld quality. A layer of oxide shall accumulate on the surface of the component during an extended friction period, impeding the course of diffusion and

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influencing the formation of the intermetallic phase necessary for the strength of the joint (Dahlan *et al*., 2023). Friction duration should be regulated between 1 and several dozen seconds. In the similar vein, forging pressure has to be regulated as an excessive forging pressure will adversely affect tensile strength of the welded joint. At a regulated forging pressure, tensile strength reaches maximum but an excessive forging pressure reduces the tensile strength. Forging pressure in this case ranges between 0.5 and 6 MPa depending on materials involved. However, rotation friction welding method is restricted to circular and tubular cross-sections (Bonte *et al*., 2010). Friction pressure on the other hand has to be sufficient to achieve a good joint. If friction pressure is inadequate the resulting joint will not be strong but if it is excess, the joint will experience significant deformation. In other words, friction pressure has to be regulated between 0.5 and 5 MPa (Selvaraj *et al*., 2023).

2.1.3 Direct Dive Friction Welding

Direct Drive Friction Welding (DDFW) is a bonding technique that joins two distinct metal pieces by simultaneously applying axial pressure and rapidly rotating one of the individual components. The two materials are made to rub against each another causing frictional heat at their point of interface, which melt the interface and forges a strong bond (Liu *et al*., 2020). During a preset period of the welding cycle, the direct motor connection of a welding machine provides the energy needed for direct drive friction welding. While one of the two components is squeezed and revolved slowly, the other is fixed to a motorized apparatus. The workpiece that is powered by the motor (figure 6) rotates at a set, steady speed. After forcing the work pieces that need to rotate for a predetermined time, a friction force is applied (Trancossi and Dumas, 2010). When the front surfaces of the materials known as weld interfaces rub against one another, heat is produced. This keeps going until a certain degree of axial upset occurs, or for a predefined amount of time. The application of a braking force or the weld itself stops the spinning work piece when the rotary driving force is removed (Senthil *et al*., 2020).

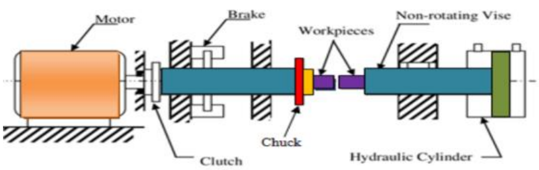

Fig. 6 Illustrative diagram of a direct drive friction welding (Senthil *et al*., 2020)

After rotation stops, the friction force, also known as the forging force, is sustained or increased for a predefined duration (Trancossi *et al*., 2010). The usage of direct drive friction welding in production is growing due to its ability to create a strong bond between various materials and alloys, including heterogeneous components that are arduous to combine by means of conventional joining techniques (Titouche *et al*., 2019). Both ferrous and non-ferrous metals, including brass, titanium, aluminum, steel, and stainless steel, can be bonded by direct drive friction welding (Vyas *et al*., 2021). It finds use across several sectors, including industrial tools like drill bits, consumer goods like kitchenware, aerospace engineering for components like engine blades, automotive manufacturing for brakes and suspension systems, medical devices for implants, and defense applications for weapons components. More strength and dependability, quicker production cycles, lower costs, better material properties, and more accurate control over heat input are just a few of the benefits this approach offers over other welding techniques. Minimal post-weld cleaning or machining is also necessary for direct drive friction welding (Totouche *et al*., 2019).

2.1.3.1 Factors to be Considered for a Good Weld Quality when Carrying Out Direct Drive Friction Welding

The most crucial factors influencing the quality of welded joint done by direct drive friction welding are rotation speed, friction period, and friction pressure. Rotation speed determines the cooling and deformation rates. Unregulated rotation speed will have an adverse effect on the microstructure of the joint because rotation speed determines the amount of inherent temperature involved. However, rotation speed in DDFW is usually lower than rotation speed in RFW. High friction pressure results in a refined grain and good bond of high hardness value but it is otherwise for a low friction pressure. Similarly, not having a predetermined friction time will cause inadequate or excess temperature (Vyas *et al*., 2021; Belkahla *et al*., 2021; Hassan *et al*., 2019; Azizieh *et al*., 2016; Liu et al., 2020)[49-53]. Friction can be regulated between 50 and 300 MPa with respect to material and size. If friction time increases without control, the temperature will also increase and lead to deformation of workpieces. The friction time is between 5 and 15 seconds with respect to size of parts involved and it can be more. A regulated increase in forging pressure will produce a good bond but if unregulated, it will lead to heat affected zone formation and consequently, intermetallic formation that will weaken the bond (Jeong-Won *et al*., 2022).

2.1.4 Linear Friction Welding

Another method of welding is linear friction welding (LFW). where one material is maintained static while the other rapidly slides against it in a straight line. A high

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contact load exists as one component is held stable while another is oscillating linearly against it. Both materials fuse together due to friction that is produced when they heat up (figure 7). The clamped components are pushed together by a slight compressive force, also referred to as friction force. After a predetermined amount of time, the parts are pulled together under a minor force, and one of the oscillations of the part is increased and stabilized (Sadallah, 2020). When the friction force reaches a particular point, heat is generated at the boundary. The component at the border becomes plasticized due to the contact load and erupts out of the joint as flash due to the shaving action between both components and the applied tension. This burn-off, or loss of weld material, causes the pieces to get shorter. For good alignment, the amplitude typically decreases to zero over a certain period of time once a predetermined loss of length, or burn off distance, is attained. The joint is then consolidated by quickly applying and maintaining a forging force for a predetermined period of time. The most common case is for the friction force to be equal to or larger than the forging force. The welded parts are removed from the machine after being released from the clamps. Metals, polymers, and ceramics can all be joined together using the friction welding technique, and been used successfully in connecting compressor discs and blades in an aero engine. Linear friction welding prevents the parent material from melting by creating small heat-affected zones, high integrity joints, and forge quality (Parmar *et al*., 2022). Unlike the similar technique of rotational friction welding, which requires the pieces to be cylindrical, this process has the advantage of allowing the parts to be of any form. Linear friction welding is employed in applications such as jet engine components and near-net forms, where the restriction on the parts is solely determined by the mass of the moving part rather than the geometry of the interface.

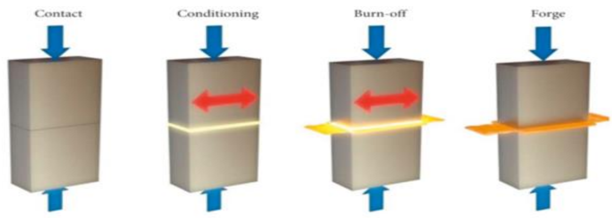

Fig. 7 Linear friction welding process (Sadallah, 2020)

2.1.4.1 Factors to be Considered for a Good Weld Quality when Carrying Out Linear Friction Welding

LFW process factors like oscillation frequency, friction pressure, forging pressure, and forging time improve the quality of the joint quality. The thermo-mechanically impacted zone and the weld width are both significantly influenced by forging pressure. Tensile strength of the joint increases as forging pressure increases, but if forging pressure is increased arbitrarily, the joint loses strength (Mukundhan *et al*., 2023). The forging pressure ranges between 0.5 and 15 MPa with respect to the material involved and the friction pressure ranges between 5 and 30 MPa. The duration of friction affects how flash and upset joints look. The duration of friction rises linearly with upset length but stronger joints come from controlled friction time; and uncontrolled friction time weakens the joint. Friction duration could be as low as 30 seconds and could dozens of seconds in some other cases. At higher oscillating frequency, temperature at the interface is increase quickly, and shortening in the axial direction occurs faster. Low friction pressure will result in inadequate upset of interface and produce a joint of low tensile strength. Oscillation frequency should range between 20 and 70 Hz (Akram *et al*., 2023).

2.1.5 Inertia Friction Welding

Inertia friction welding (IFW) is a joining process where kinetic energy withy applied force are used to bond components together. One workpiece is held motionless in a clamp while the other is rotated in a chuck, which uses a flywheel to generate rotational momentum and store kinetic energy as the workpiece is rotated against the stationary one (figure 8), initiating a forging force and producing enough heat at the weld interface, which soften the workpieces (Iracheta *et al*., 2015). The softened surfaces are extruded as flash and the workpieces coalesce. The speed of the chuck and flywheel are regulated as it provides the required energy that will weld the workpieces. The weld is finished when the rotation ceases but the forging force is kept constant briefly, enabling the welded junction to solidify. The total amount of time it takes to perform a weld depends on the power input given to the two components (Mortensen *et al*., 2001). IFW has application in aerospace industry.

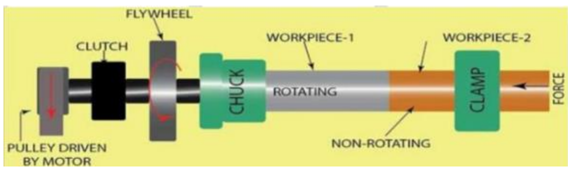

Fig. 8 Process of inertia friction welding (Iracheta *et al*., 2015)

2.1.5.1 Factors to be Considered for a Good Weld Quality when Carrying Out Inertia Friction Welding (IFW)

In inertial friction welding (IFW), inertial mass, forging pressure, welding energy, rotation speed and flywheel inertia are the main factors to be considered. The spindle speed is increased to a predetermined value as the materials are brought into contact with the spindle, but at the moment the contact is achieved, the power input and flywheel spindle speed decreases gradually until the welding is achieved (Attallah and Preuss, 2012; Turner *et al*., 2016).

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3 CONCLUSION

The fundamentals of friction welding techniques have been covered in this study. While the procedure may differ significantly based on the type of friction welding, it is uniform and appropriate for joining materials that are comparable to one another and those that are not. Each of the distinct welding technique can produce joints with high integrity. Friction welding is worth exploring because it can be used for mass production of automobile, locomotive and aeronautic parts and saves time compared to fusion welding. This study has reviewed the steps involved in carrying out friction welding and also described the parameters that are of significance and how to control them. However, most of the welding machines used for friction welding are expensive, noisy, and have peculiar kind of joint each can produce. To improve friction welding process, factors such as pressure and rotational speed, and how the materials are made ready need to be adjusted and sensors should be incorporated into existing welding machines to monitor and control vibration, temperature and pressure. In addition, friction welding process can be automated and new dissimilar and composite materials' coalescence should be investigated.

Conflict of interest

The authors hereby confirm that no conflict-of-interest interests to declare that are relevant to the content of this article.

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