Effect of Rotary Friction Welding Parameters on the Different Alloy's Joint Strength: A Review

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Abstract:- Using economical materials and production techniques is always necessary in today's manufacturing climate. One such technique that is more productive and affordable than other comparable welding methods is rotary friction welding. The manufacturing industry has made extensive use of the friction welding technology. It is a procedure that can combine the majority of engineering materials and is adaptable and tolerant. It is a tried-and-true welding method that can create strong welds between materials that are comparable and dissimilar. Its versatility in using various materials has made it useful in a wide range of applications, including the automotive, aerospace, and other allied industrial industries. This paper reviews about the different types of rotary friction welding, principle and methodology of the rotary friction welding process, the welding parameters, joint strength related to the same. Also discuss about the economic benefits and environmental impact of RFW as compared to Conventional methods.

Keywords:- *Rotary Friction Welding, Welding Parameters, Joint Strength, Friction Time, Forging Time.*

I. INTRODUCTION

A solid-state welding technique called rotary friction welding (RFW) combines two components by applying pressure and heat. Rotating friction welding does not need melting the material, in contrast to conventional fusion welding techniques like arc or gas welding. By exerting pressure and causing friction between the two components' surfaces, it forges a connection. Because of its benefits—which include minimal weld heat input, high production efficiency, ease of manufacture, and environmental friendliness—this solid-state welding method is gaining popularity. It is able to fuse materials that are challenging to fuse with fusion welding methods. The basic idea behind RFW is that one welded part is usually rotated in relation to the other and the forge, where it is compressed by an axial force. Friction work produces the material's heating, which solidifies the bond. In this method, two parts are held motionless while one is rotated quickly and forced against the other. Friction work causes the material to heat up and establish a lasting bond. The materials to be welded in this procedure can be non-metallic, composite, or dissimilar materials. Many times, friction welding techniques are regarded as solid-state techniques. Furthermore, there are a number of noteworthy benefits to rotary friction welding (RFW), such as its environmental friendliness and fast cycle durations for joining both similar and different materials. During World War II, the steady-state frictional process known as RFW was created. It connects components whose surfaces are symmetrical around rotation. At the connection that needs to be welded, frictional welding processes transform mechanical energy into heat. At the joining contact, the components are rubbed together in a unidirectional circular motion while applying axial pressure normal to the flat surfaces. The material in the connecting zone melts as a result of frictional heating. A weld is formed when the molten material hardens under pressure after the circular motion is stopped. Rotary friction welding holds significant importance in the manufacturing industry in producing joints with excellent strength and integrity. The solid-state nature of the process results in welds free from defects such as porosity and solidification cracks, leading to superior mechanical properties. Many materials, such as unusual alloys and different metals, can be joined using this type of welding that may be challenging to combine with traditional fusion welding methods. This versatility allows manufacturers to explore new material combinations and design possibilities for their products. It is a fast process, with welds typically completed in seconds. This rapid production rate contributes to increased manufacturing efficiency and reduced production cycle times, leading to cost savings and improved throughput. Unlike fusion welding methods, rotary friction welding does not require consumable filler materials or shielding gases, reducing material waste and associated costs. Additionally, the precision of the process minimizes the need for post-weld machining, further reducing material waste and machining time. While the initial equipment investment for rotary friction welding machines may be higher compared to traditional welding equipment, the long-term cost savings associated with reduced material waste, faster production rates, and lower labor and energy costs often make it a cost-effective choice for high-volume manufacturing applications. Overall, rotary friction welding's significance in the manufacturing industry lies in its ability to provide high-strength joints, versatility in material compatibility, efficiency in production, environmental sustainability, and cost-effectiveness, making it a valuable asset for various manufacturing processes and application.

A. History and Evolution

A solid-state welding technique called rotary friction welding uses heat produced by friction to fuse two components together. The materials fuse together when the pieces are rotated in relation to one another while under pressure and the required temperature is reached. Since its

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debut, this welding method has seen substantial evolution. The mid-1900s is when rotary friction welding first appeared. It developed as an improvement over previous friction welding methods, which were mostly linear. The plan was to improve the procedure by implementing rotation. The requirement for effective joining techniques for high-strength materials in the aerospace and automotive industries propelled the development of rotary friction welding in the 1950s and 1960s.Because rotary friction welding can combine incompatible materials, such as metals and thermoplastics, and can produce strong, high-quality welds, it became increasingly commonly used in a variety of sectors during the latter part of the 20th century. As technology has progressed, rotary friction welding techniques have been enhanced. Better control systems for managing elements like heat intake, pressure, and rotating speed are among them. Furthermore, the variety of materials that can be successfully welded with this technology has increased due to improvements in materials science. Precision, repeatability, and efficiency have increased in rotary friction welding with the development of automation and robotics technology. With less human involvement, automated devices can complete the welding process, increasing consistency and output. Rotating friction welding has been employed in many different industries, including as manufacturing, aerospace, automotive, and energy. Shafts, pipelines, valves, and other cylindrical or nearly cylindrical items can be joined with it. The need for more complex joining techniques for advanced materials and intricate geometries is driving further advancements in rotary friction welding. The goals of research and development are to increase the effectiveness of the welding process, increase material compatibility, and improve process control.

B. Fundamentals of Rotary Friction Welding

To understand the fundamentals of rotary friction welding, one must be aware of the fundamental concepts and components of the process. The process of rotary friction welding depends on the friction between two parts that needs to be linked to produce heat. While the other is rotating against it, one component is kept immobile. Localized plastic deformation results from heat generated by the contact between the two surfaces. Metals, polymers, and composites can all be joined by rotary friction welding, regardless of how dissimilar the components are. To guarantee a robust weld, the materials being connected must, nevertheless, have mechanical and thermal qualities that are compatible. In order to guarantee close contact between the mating surfaces, pressure and axial force are supplied to the components during the welding process. This pressure aids in the material's flow and the metallurgical bond's development. In rotary friction welding, the rotating component's rotational speed is a crucial factor. It establishes the quantity of heat produced and the pace at which the material softens. The dimensions of the materials being welded, as well as other process factors, affect the ideal rotating speed. Another crucial factor is the amount of time that the welding process takes. It establishes the degree of material consolidation and the heat input. Careful control of the welding duration is necessary to produce a strong, flawless weld. To solidify the connection and stabilize the microstructure, the welded assembly goes through a cooling phase after the welding process is finished. Reduced residual tensions and the creation of undesired phases are two benefits of controlled cooling. To guarantee consistent weld quality, advanced rotary friction welding systems include capabilities for process control and monitoring. To maximize the welding process, variables like displacement, temperature, axial force, pressure, and rotating speed are tracked and changed in real time. To confirm the strength and integrity of the welded junction, post-weld inspection is crucial. To find flaws including porosity, cracks, and incomplete fusion, non-destructive testing methods like visual examination, ultrasonic testing, and radiographic inspection are frequently utilized.

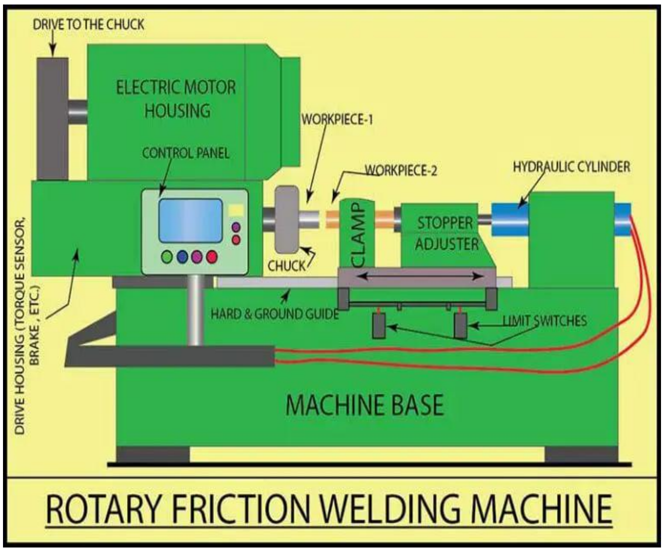

Fig 1 Rotary Friction Welding Machine [18]

A single metal workpiece is rotated at a high-speed while being held in a chuck or collet. The chuck and drive motor can be disconnected using a feature that will be included. The machine is equipped to move the second workpiece metal toward the spinning workpiece while simultaneously applying axial pressure, all while keeping it securely fixed. When the workpieces are first brought into contact and burnished, low contact pressure is used to clean the surfaces. Frictional heat is produced at the interface between the two workpieces as the pressure is raised .The workpiece stops rotating once the heat produced reaches a level suitable for FRW, and the pressure is either kept constant or raised to finish the welding. A portion of the softened metal squeezes out to generate a flash, and a forged joint form at the contact (faying surfaces). Machine-off flashing is possible. In order for friction welding to occur, both workpieces must remain on the same axis. Welding parameters can be changed to lessen flash.

II. LITERATURE SURVEY

Selvaraj R et al. addressed the empirical relationships that were created by combining the friction welding parameters to determine the tensile characteristics of low-alloy steel that had been friction-welded. Tensile parameters, including elongation (EL), yield strength (YS), notch tensile strength (NTS), and notch strength ratio (NSR), were predicted using empirical relationships. The tensile characteristics of the rotary friction-welded low alloy steel (LAS) tubes were ascertained using the test findings.

Mumin Sahin have worked on simulating weld flashes in AISI 1040 (Medium Carbon Steel) welded connections with varying or equal diameters using computer programs. He looked into the possibility that welding components with various diameters and widths would not be able to employ the ideal welding conditions found for parts with identical diameters. Because of this, when welding components with varying diameters and widths, the ideal joint parameters should be routinely chosen through experimentation.

Sahin et al. examined friction welding of steel bars that have undergone plastic deformation. They worked on continuous drive friction welding of the same material bars with different diameters. They achieved that by carburizing steel.

Gailan Ismail Hassan et al. contributed that similar and dissimilar joint of Acrylonitrile butadiene styrene (ABS) and Polyethylene (PE) or poly (methylene)) are studied .The best values of the tensile strength can be obtained at high speed with high friction time in the studied range for PE polymer.

Meshram et al. studied the following dissimilar metal combinations for joining: Cu–Ni, Cu–Ni, Fe–Cu, Cu–Ni, and Cu–Ti. They investigated the effects of interaction duration on the microstructure and tensile properties of friction welding of five distinct metal combinations.

Kamran Shah et al. undertook a study with the primary goal of converting a traditional lathe machine into a friction welding machine while minimizing costs. The study was successful in this goal, and pneumatic system was utilized in place of hydraulic system.

P. Sivaraj et al. conducted an experiment that demonstrates how AISI 1020 steel rods with a 12 mm diameter could be successfully joined to AISI 1018 steel plates that were 15 mm thick in a rod to plate joint configuration using solid-state rotary friction welding. This was done without the need for fusion welding, which would have resulted in defects related to penetration, porosity, and HAZ. This investigation's primary goal is to maximize the tensile strength and weld interface hardness of rod to plate joints made of various grades of low carbon steel by optimizing the rotary friction welding settings. It also analyses the impact of these factors on the joints' TS and WIH.

Chunlin Huang et al. evaluated the oxidation behavior of welded joints, both with and without heat-treatment of HT700 alloy, was examined in saturated water vapor at 700 ◦C in terms of microstructure, oxide layer composition, and oxidation kinetics. The findings demonstrate that there was little difference in the oxide film compositions between the heat-treated and as-welded joints.

Ajay Lohan et al. explains how to measure the forge pressure using a traditional lathe machine. A unique fixture arrangement on the machine's tail stock side is used to assess pressure. The fixture is made up of a pressure gauge-equipped hydraulic jack. The forge pressure used by the operator on the steady task is displayed by that pressure gauge**.**

Hardik D. Vyas et al. investigated the differences in friction welding between grade 304 L stainless steel (SS) and electrolytic tough pitch copper (ETP-Cu) for pipe junction configurations with a 0.06 wall thickness to pipe diameter ratio. The continuous drive friction welding method is used to complete the welding. Visual examination, helium leak detection tests, optical and scanning electron microscopy, energy dispersive x-ray spectroscopy, x-ray diffraction patterns, tensile testing, and hardness measures are all used to assess the welded joint's quality.

Hao Wang et al. discovered that the friction coefficient of interface affects the friction heat production and establishes the correctness of the numerical simulation of the welding process in inertia friction welding (IFW) of Al alloy to steel. A three-dimensional fully linked model was developed to model the IFW process of 304 stainless steels to 2219 Al alloy.

A. Jabbar Hassan et al. contributed to the study of similar and different joints between polyethylene (PE) or poly (methylene) and acrylonitrile butadiene styrene (ABS). ABS and PE polymers cannot be bonded together using rotary friction welding. The results of this study indicate that rotary friction welding is not a viable method for joining PE and ABS polymer.

Seli et al. examined the mechanical properties of mild steel and aluminium welded rods in order to understand the effects of heat. An explicit one-dimensional finite difference method was used to approximate the temperature distribution of heating and cooling at the joint. They discovered that the heat effects of the friction welding decreased the welded materials' hardness in contrast to the parent materials.

Udayakumar et al. have carried out an experimental investigation of the mechanical and metallurgical properties of friction-welded super duplex stainless steel bars. Specimens of super austenitic stainless steel (UNS S32760) measuring 16 mm in diameter and 100 mm in length were employed in the investigations. The four factors, three level central composite designs design (CCD) was used to identify the optimal parameters for the super duplex stainless steel friction welding process.

III. PRINCIPLE OF ROTARY FRICTION WELDING

A strong metallurgical connection is formed by forging two rotating components together under pressure after heat is generated by friction. This is the basis of the rotary friction welding process. Setting up a clean, level mating surface is the first step in preparing two components to be linked.

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Similar or different materials can be used to make these parts. Securing one component in a stationary fixture and attaching the other to a revolving spindle is known as clamping. When two components rotate, they come into contact with each other. One of the components rotates quickly as a result of the revolving spindle applying a regulated rotational force on it**.** Friction is created between their connecting surfaces as the stationary component and revolving component rub against one another. Heat from this contact causes the materials to soften locally and distort plastically. The material softens and a plasticized zone is formed at the interface between the two components as a result of the frictional heat quickly raising the temperature there. The revolving component is stopped when the required temperature is reached, and pressure is then applied axially to forge the components together. Under pressure, the softened material flows, forming close contact and encouraging metallurgical bonding between the mating surfaces. The welded assembly is allowed to cool under carefully monitored circumstances following the completion of the welding process. Cooling preserves the integrity of the weld by stabilizing the microstructure and solidifying the junction. Depending on the application, the welded assembly may undergo additional machining or finishing processes to achieve the desired dimensions and surface characteristics. In rotary friction welding, friction heat generation and plastic deformation are important processes that help the welded components produce a solid metallurgical bond.

➢ *Friction Heat Generation*-

Friction between the rotating and stationary components generates heat at their interface. This heat is localized and intense, raising the temperature of the contacting surfaces. The heat generated during frictional contact softens the material at the interface, making it more ductile and facilitating plastic deformation. The temperature achieved through frictional heat generation is typically below the melting point of the materials involved, ensuring that the process is a solid-state welding technique.

➢ *Plastic Deformation –*

The materials near the interface undergo localized plastic deformation due to the heat produced by friction. Plastic deformation is the permanent, non-fracturing alteration of a material's size or shape. The combination of high temperature and pressure used during the welding process causes plastic deformation. As the material softens, it becomes more malleable and is able to flow under pressure. This flow of material helps to fill gaps, remove surface contaminants, and establish intimate contact between the mating surfaces.

➢ *Steps in Rotary Friction Welding*

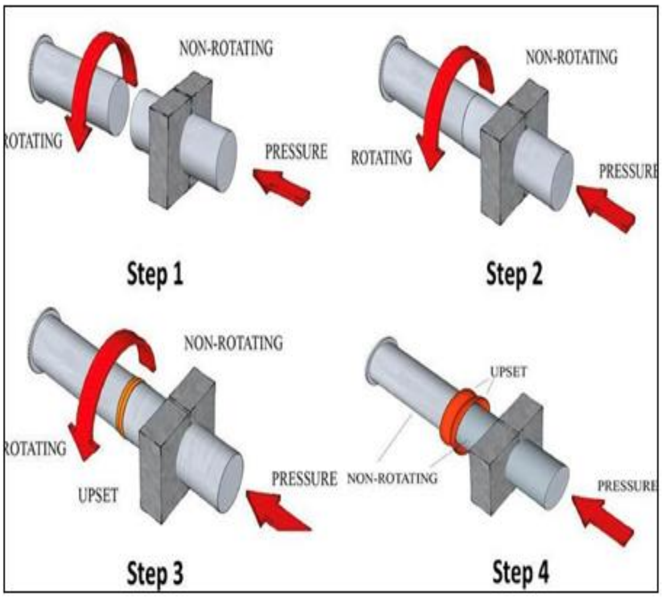

Fig 2 Steps in Rotary Friction Welding [2]

➢ *The Fundamental Steps in Rotary Friction Welding are as Follows:*

- *Preparation:*

In order to prepare the materials for welding, make sure their surfaces are clear of impurities and spotless. Also, the materials in the welding machine need to be securely fastened and oriented correctly.

- *Clamping:*

The welding machine's components are firmly clamped in place. The usual procedure is to rotate one material while keeping the other motionless.

- *Rotation:*

One material is rapidly rotated while the other stays motionless. Friction arises from the rotation between the two surfaces.

- *Heating:*

Localized heating at the interface is caused by friction created between the two surfaces. Heat causes the materials to become malleable and soft.

- *Application of Pressure:*

After the materials have reached the required temperature, axial pressure is applied to forge the materials together after the rotation has ceased. Pressure is kept at that level until the weld cools.

- *Solidification:*
  The ingredients combine to produce a robust junction as the weld cools.

- *Post-Weld Operations:*
  To obtain the required dimensions and surface quality, the weld zone may need to be machined or undergo other finishing procedures after welding. Excess material or flash may also need to be removed.

➢ *Methodology for Rotary Friction Welding under Spray Cooling Technologies*

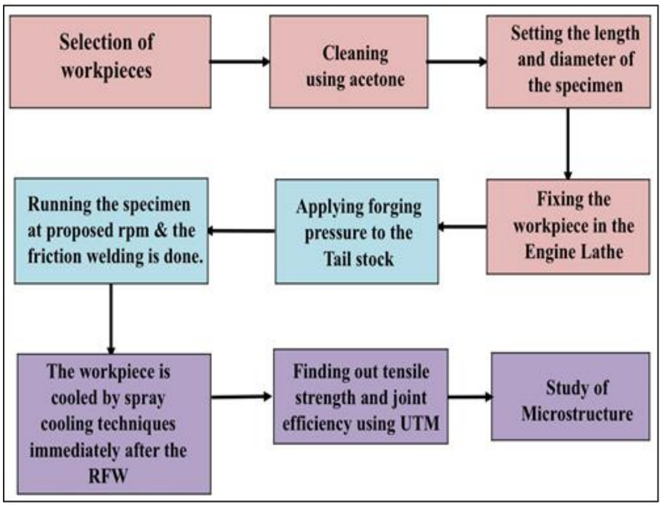

Fig 3 Methodology of RFW

When selecting materials, make sure they are appropriate for rotary friction welding. Usually, this method is applied to combine metals that are similar or different, including titanium, steel, aluminum, and their alloys.

Materials should be prepared by cleaning surfaces to get rid of any impurities, oxides, or coatings that can impede the welding process. To achieve a strong connection, surface pretreatment is essential. The cleaning agent used is acetone which thoroughly clean surfaces to guarantee adequate bonding throughout the welding procedure. Next step is to set the length and diameter of the work piece which is gone to undergo rotary friction welding. Before welding, make sure the materials are securely fastened in a fixture. Accurate alignment and stability are ensured during the procedure by using the right fixturing. Applying axial pressure and spinning one component against the other will initiate the rotary friction welding process. Heat produced by friction at the interface softens the materials and promotes bonding. Throughout the heating process, keep an eye on the temperature to make sure it reaches the appropriate range for welding. Unwanted microstructural changes or material deterioration can result from excessive heat. Once the materials have heated enough, apply more pressure to forge them together. In this process, the joint is strengthened and the materials' metallurgical bonding is encouraged. Stop applying pressure and rotating when the forging process is finished. To avoid deformation or cracking, let the welded junction cool and solidify under regulated conditions. Spray cooling techniques are used for cooling process and the fluids are brine solution, oil or blast air. To obtain the appropriate dimensions and surface finish, carry out finishing procedures like machining or grinding as needed. Ensuring the welded junction satisfies the necessary requirements in terms of strength, integrity, and functionality is known as quality assurance. Now record the welding parameters to determine the tensile strength, and examine the welded workpiece's microstructure.

IV. KEY COMPONENTS OF ROTARY FRICTION WELDING

➢ *The Main Components and their Functions:*

- *Rotating Spindle:*
  The rotating spindle is responsible for holding and rotating one of the components to be welded. It provides the rotational motion necessary to generate frictional heat at the interface between the two components. It prevents movement of the stationary component while allowing the rotating component to apply pressure and rotational motion.

- *Pressure System:*
  The pressure system applies axial force to the components to ensure intimate contact and facilitate material flow during welding. It may consist of hydraulic or pneumatic actuators that exert controlled pressure on the components.

- *Control System:*
  The control system maintains ideal conditions for successful welding by controlling and monitoring a number of welding process parameters. It might have sensors to measure things like displacement, temperature, pressure, and rotational speed. To preserve consistency and weld quality, the control system modifies process parameters in real-time.

- *Cooling System:*
  The cooling system is responsible for dissipating heat from the welded assembly after the welding process is complete. It prevents overheating and helps solidify the weld joint, stabilizing the microstructure and minimizing distortion.

- *Clamping Mechanism:*
  The components are held firmly in position both before and throughout the welding process by the clamping mechanism. It guarantees accurate alignment and stops any movement or misalignment that can lower the weld's quality.

- *Tooling and Fixturing:*
  Tooling and fixturing components are custom-designed to accommodate the specific geometries of the components being welded. They provide support and alignment for the components throughout the welding process.

- *Safety Features:*
  Safety features such as guards, interlocks, and emergency stop mechanisms are essential to protect operators and equipment during welding operations. They help prevent accidents and ensure compliance with safety regulations.

V. TYPES OF ROTARY FRICTION WELDING

There are Several Types of Friction Welding, each with its own Variations and Applications. Some of the Common Types of Friction Welding Include:

- *Friction Stir Welding (FSW):*
  A variation of friction welding that uses a non-consumable rotating tool to generate heat and join materials without melting them. Widely used for joining aluminum and other non-ferrous alloys.

- *High-Frequency Friction Welding:*
  Uses high-frequency vibrations to generate heat. Suitable for small and intricate parts.

- *Rotary Friction Welding:*
  Involves turning one element in opposition to a stationary element. frequently employed to link cylindrical components such as pipes, tubes, and shafts. Axial force presses down on one welded part while it rotates in relation to the other and the forge. Friction work produces the material's heating, which solidifies the bond.

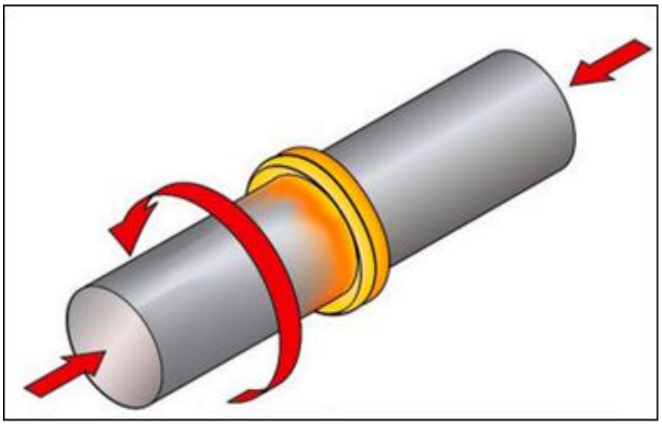

Fig 4 Rotary Friction Welding [4]

- *Inertia Friction Welding:*
  Similar to rotary friction welding but involves using an inertia or flywheel to generate heat. Commonly used for joining dissimilar materials.

- *Continuous Drive Friction Welding:*
  Uses a continuous drive motor to maintain constant rotation during the welding process. Suitable for high volume production.

- *Low Frequency Friction Welding:*
  Uses vibrations at low frequencies to produce heat during the welding process. can be applied to materials that are challenging to fuse together using traditional friction welding techniques.

- *Friction Surfacing:*
  Involves using frictional heating to deposit a layer of material onto a substrate. A plasticized layer forms in the rod at the contact with the substrate when a rod made of the coating material is rotated under pressure. utilized in applications involving surface improvement and repair.

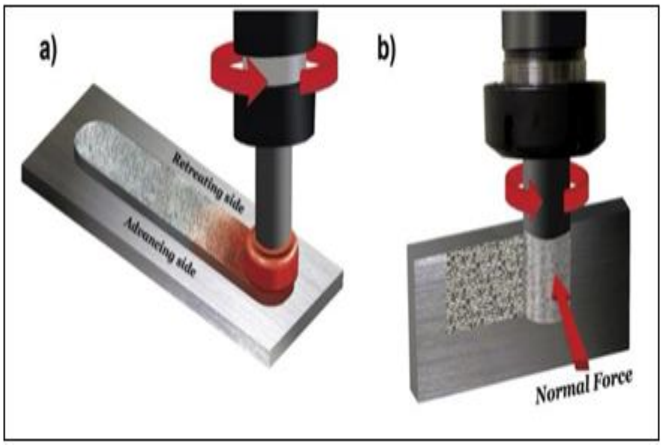

Fig 5 a) Horizontal Frictional Surfacing; b) Vertical Frictional Surfacing [5]

- *Radial Friction Welding:*
  One component must rotate around a fixed axis in order for it to work. often employed for components with intricate geometry. To prevent the pipe ends from turning or moving, they are butted together and firmly secured.

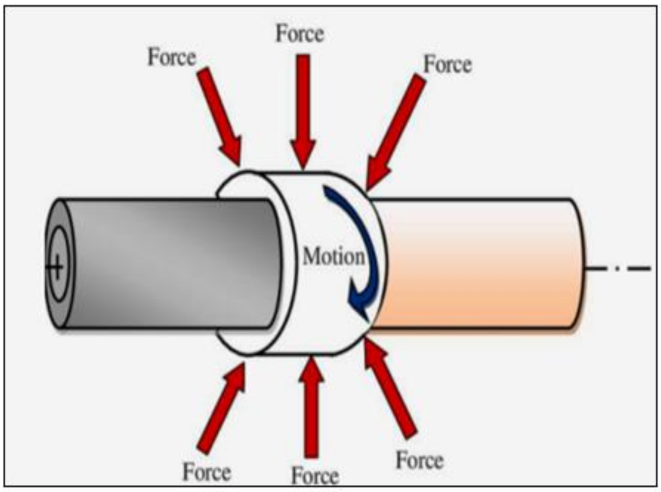

Fig 6 Radial Friction Welding [14]

VI. VARIATIONS OF ROTARY FRICTION WELDING TECHNIQUES

Rotary Friction Welding, a Solid-State Joining Process, has Several Variations, each Tailored to Specific Applications, Materials, or Desired Outcomes. here are some Notable Variations:

- *Friction Welding in Orbital Motion:*
  This technique combines rotational and orbital motion, enhancing material mixing and heat distribution. It's often used for applications requiring uniform heating and joint quality, such as aerospace components.

- *Hybrid Friction Welding:*
  Hybrid friction welding integrates rotary friction welding with another process, such as linear friction welding or friction stir welding. This combination allows for unique joint configurations, improved material compatibility, and enhanced weld properties.

➢ *Friction Welding with Tilted Axis:*

In this variation, the rotational axis is tilted, enabling the welding of non-parallel or angled surfaces. It's useful for joining components with complex geometries or those requiring specific joint orientations.

➢ *Friction Welding with Induction Heating:*

Induction heating is incorporated into the rotary friction welding process to preheat the materials, reducing the energy required for frictional heating. This variation can improve process efficiency and reduce heat-affected zones.

➢ *Innovative Material Combinations:*

Manufacturers are exploring new material combinations and applications for rotary friction welding, such as dissimilar metal welding, thermoplastic welding, and composite material joining. These variations expand the capabilities and potential applications of the process.

VII. TYPES OF MATERIALS SUITABLE FOR ROTARY FRICTION WELDING

The Qualities, Compatibility, and Needs of the Application Determine if a Material is Suitable for Rotary Friction Welding. the Following Materials can be used in Rotary Friction Welding:

➢ *Metals*

- *Ferrous Metals:*

Because of their extreme strength and endurance, ferrous metals like carbon, stainless, and alloy steels are frequently bonded utilizing rotary friction welding.

- *Non-Ferrous Metals:*

These include titanium, copper, aluminum, and their alloys; rotary friction welding can also be used with these. Because of their lightweight nature, these materials are frequently utilized in automotive and aeronautical applications.

➢ *Alloys:*

- *Alloys Based on Nickel:*

Known for their high temperature and resistance to corrosion, alloys based on nickel, such as Inconel and Hastelloy, are appropriate for rotary friction welding, particularly in the chemical processing and aerospace industries.

- *Cobalt-Based Alloys:*

Because of their great strength and resilience to thermal fatigue, these alloys are utilized in high-temperature applications such gas turbine engines and are appropriate for rotary friction welding.

➢ *Composite Substances:*

- *Metal Matrix Composites (MMCs):*

MMCs provide enhanced mechanical qualities including strength and wear resistance by reinforcing a metal matrix with ceramic fibers or particles. These materials can be joined by rotary friction welding, especially for applications that call for strong yet lightweight components.

- *Polymer Matrix Composites (PMCs):*

Although less often, rotary friction welding can be used to join some PMC types, particularly those with thermoplastic matrices. During the welding process, care must be taken to guarantee compatibility and avoid heat deterioration.

➢ *Different Materials:*

In addition, rotary friction welding can be used to fuse together materials that are not the same, like metal and polymer mixtures. To guarantee a solid and dependable connection, however, careful consideration of material compatibility, thermal expansion coefficients, and joint design is required.

VIII. APPLICATIONS OF ROTARY FRICTION WELDING

Because rotary friction welding produces dependable, high-strength welds with little material waste, it is used in a wide range of industries. Among the major sectors that frequently employ rotary friction welding are the following:

➢ *Automobile Sector:*

In the automotive industry, rotary friction welding is used to combine pieces like engine parts, axle shafts, steering columns, and drive shafts. It makes it possible to produce components with great strength and low weight, which enhances vehicle performance and fuel economy.

➢ *Aerospace Sector:*

Rotating friction welding is used in the aerospace industry to combine vital parts such engine shafts, landing gear components, turbine blades, and structural elements. The procedure makes it possible to create materials of aerospace quality that have exceptional mechanical qualities and fatigue resistance, enhancing the dependability and safety of aircraft.

➢ *Gas and Oil Industry:*

Gas and oil industry uses rotary friction welding to create drill pipes, well casings, pipeline parts, and downhole tools. The procedure yields welds that are exceptionally strong and intact, able to survive the high pressure and corrosive conditions found in oil and gas production and exploration.

➢ *Industry of Power Generation:*

Rotating friction welding is used in the power generation industry to fabricate parts for heat exchangers, generators, and turbines .It makes it possible to produce high-performance materials that can survive harsh working temperatures and conditions, enhancing power plants' dependability and efficiency.

➢ *Medical Device Sector:*

In the medical device sector, rotary friction welding is used to combine parts including orthopedic implants, surgical instruments, and medical equipment. The procedure results in precisely controlled joint quality and biocompatible welds, enhancing the functionality and safety of medical equipment utilized in patient care.

➢ *Manufacturing Sector:*

Rotating friction welding is used in general production, outside of specialized industries, to link different parts of machinery, equipment, and infrastructure.

Compared to conventional welding techniques, it has benefits like lower production costs, better product quality, and increased manufacturing flexibility.

IX. RESEARCH AND DEVELOPMENT

The incorporation of modern control systems, encompassing real-time monitoring and feedback mechanisms, has resulted in improved precision and consistency in rotary friction welding procedures. These technologies provide operators the ability to identify flaws early and alter process parameters, which improves weld quality and lowers scrap rates. The goal of research and development has been to increase the variety of materials that can be employed in rotary friction welding. This involves creating new welding processes and tool designs to handle different material combinations, such composite or metal-to-polymer couplings, creating new opportunities for the manufacturing of multi-material components.

New developments in tooling and machine design have made it possible to boost welding rates and rotational speeds, which has shortened cycle times and enhanced throughput. High-volume production settings, like the automobile and aerospace industries, benefit greatly from high-speed rotary friction welding. To maximize the strength, fatigue resistance, and integrity of rotary friction welds, engineers have been experimenting with new joint designs and geometries. Researchers have improved the overall performance of welded components by customizing joint configurations to meet particular application needs, such as load-bearing capacity or thermal performance. Increasing efficiency, reproducibility, and safety in manufacturing processes has resulted from the integration of automation and robots into rotary friction welding systems. Labor expenses can be decreased and process control can be enhanced by robotic welding parameter manipulation and automated workpiece loading and unloading. Reducing heat input and maximizing energy consumption have been the main goals of efforts to make rotary friction welding processes more energy-efficient. To lessen waste heat and improve process sustainability, this includes the development of sophisticated cooling systems, energy-efficient driving mechanisms, and thermal insulation techniques. The prediction and optimization of rotary friction welding processes have been made easier by developments in computer modeling and simulation approaches. With virtual prototyping, engineers can reduce development time and costs by exploring various process scenarios, evaluating design alternatives, and identifying potential faults or performance concerns prior to physical implementation.

X. ADVANTAGES AND DISADVANTAGES OF RFW

➢ *The Main Advantages are Mentioned Below:*

- *High Strength Joints:*

Because of the metallurgical link created between the materials being welded, RFW creates joints with great strength and integrity. As a result, the welded components are strong enough to resist large mechanical loads and strains.

- *Minimal Material Waste:*

Since RFW is a solid-state welding technique, it doesn't generate molten metal or need consumable filler. In contrast to conventional fusion welding procedures, this results in very little material waste.

- *Applicability for Dissimilar Materials:*

RFW is able to combine materials that differ in thickness, composition, and other characteristics. This capacity makes it possible to fabricate components made of many materials that incorporate the best qualities of each element.

- *Large Production Rates:*

RFW is suited for large-volume production situations because it can achieve high welding speeds and throughput rates. Manufacturers are able to shorten lead times and meet production targets as a result.

- *Automation Potential:*

RFW's simple integration with robotics and automated systems enables productive, repeatable manufacturing procedures. Automated RFW systems have the potential to lower labor expenses, increase overall productivity, and improve process uniformity.

- *Minimal Residual Stress and Distortion:*

Since RFW eliminates the need to melt the materials being welded, the welded components have less residual stress and distortion. Better dimensional precision and less post-welding machining are the outcomes of this.

➢ *Limitations of RFW are:*

- *Equipment Cost:*

Compared to certain other welding techniques, the initial capital investment for RFW equipment may be somewhat more. This could make it more difficult for small-scale or low-volume producers to get started.

- *Limited Joint Configurations:*

Because RFW rotates, it works well to join components that are cylindrical or nearly cylindrical. RFW welding of complex joint geometries may be difficult and require specific tools and fixturing.

- *Surface Preparation Requirements:*

Cleanliness and alignment of the mating surfaces are essential components of a successful RFW. The quality and integrity of the weld can be severely impacted by any impurities or misalignment.

- *Limitations on Material Selection:*

RFW is capable of joining a large variety of materials, however successful welding of some material combinations may be more difficult. Careful consideration must be given to elements including thermal conductivity, melting temperatures, and material compatibility.

- *Process regulate Complexity:*

In order to achieve the best possible process parameters and weld quality in RFW, it may be necessary to carefully regulate factors such rotational speed, axial pressure, and heat input in addition to having a solid understanding of the process basics.

- *Environmental Considerations:*

RFW produces heat and noise while welding, hence proper ventilation and noise abatement techniques may be required in the workplace. In evaluating the sustainability of RFW processes, energy consumption and environmental impact should also be considered.

XI. SPRAY COOLING TECHNIQUES IN RFW

➢ *Water Spray Cooling:*

This technique includes misting or spraying a fine mist of water onto the weld joint. Water has a large heat capacity and thermal conductivity, which makes this technique ideal for attaining quick cooling rates. To accurately manage the cooling rate, the flow rate and pressure of the water spray cooling system can be modified.

➢ *Air Mist Cooling:*

This technique uses a fine mist of air to cool the welded junction. Air mist cooling is frequently utilized when water cooling is impractical because of corrosion or contamination issues, even though it is less efficient than water spray cooling in terms of cooling rate.

➢ *Localized Cooling:*

To obtain desired microstructures or qualities, spray cooling may occasionally be administered just to particular regions of the welded joint. Using precise nozzles or other tools, the spray can be directed into the desired places to do this.

➢ *Gas Spray Cooling:*

This method of controlled cooling involves spraying inert gases, like nitrogen or argon, onto the welded junction. In instances where water or coolant spray cooling is not appropriate, gas spray cooling can be useful for reducing oxidation of the welded joint and providing uniform cooling rates.

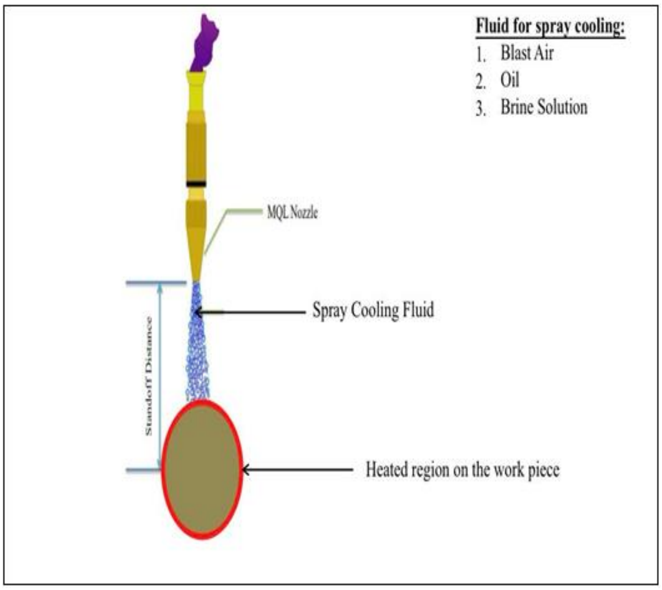

Fig 7 Spray Cooling Techniques

➢ *Coolant Spray Cooling:*

This method of controlled cooling entails spraying specialized coolant fluids, including oils or emulsions, over the welded joint. When it comes to specific materials or applications, coolant spray cooling may be favored over water spray cooling due to its potential benefits, including a lower risk of corrosion.

➢ *Combination Cooling:*

To maximize cooling rates and accomplish required qualities, certain RFW systems may make use of a mix of several cooling methods. As an illustration, water spray cooling can be utilized first for quick cooling and then air mist or gas spray cooling for more regulated cooling as well as to avoid deformation or cracking.

➢ *Fluids for Spray Cooling Techniques*

- *Blast Air:*

It is a technique where a high-velocity jet of compressed air is directed onto the welded joint right after the welding process. In order to attain particular mechanical and microstructural qualities, this method seeks to quickly cool the welded connection. Blast air cooling quickly can also aid in preventing excessive grain growth in the welded joint, which may have an impact on the weld's mechanical qualities. The welded junction may go through post-weld inspections after blast air cooling to make sure it satisfies the necessary quality standards. Visual examination, non-destructive testing, and mechanical testing of the weld may all be part of this.

- *Oil:*

The temperature of the welding process can be more efficiently regulated by spraying oil onto the weld interface or onto the fixtures and tools. By acting as a coolant, the oil lowers the component temperatures and keeps them from overheating. The materials being welded may deform or warp as a result of excessive heat. By maintaining temperatures within an ideal range and lowering the possibility of thermal tensions that result in deformation, oil spray cooling aids to limit this distortion. During the welding process, oil can also serve as a barrier to prevent oxidation. Oil spray cooling can stop oxides from accumulating on the metal surfaces, which could damage the weld joint, by creating a protective layer over them. The fixtures and equipment used in rotary friction welding may have their lifespans increased with the use of oil spray cooling. Oil cooling can reduce wear and increase the equipment's operational lifespan by lowering the amount of heat accumulation on the tool surface. Depending on the particular welding parameters, materials, and environmental circumstances, oil spray cooling can be modified and optimized. Optimizing the cooling procedure guarantees dependable and constant weld quality.

- *Brine Solution:*

Applying a solution of water and salt (usually sodium chloride) to the welded joint speeds up the cooling process when using a brine solution as a cooling strategy in rotary friction welding (RFW). When it comes to controlling the cooling process, brine solution cooling is superior than ambient air cooling or natural cooling. One can customize the cooling rate to match certain welding requirements by varying the flow rate or the concentration of salt in the solution. Brine solutions' quick cooling can reduce residual strains and deformation in the welded joint. Components with intricate geometries or tight dimensional tolerances will especially benefit from this.

XII. METHODS TO ASSESS THE QUALITY OF RFW WELDS

To guarantee the integrity and dependability of welded components, rotary friction weld quality assessment is essential. A number of techniques are frequently employed to assess the quality of rotary friction welds:

➢ *Visual Inspection:*

The simplest technique for determining the quality of a weld is visual inspection. In order to detect surface defects like fractures, porosity, flash, or inadequate bonding, operators visually inspect the weld region. Although visual examination offers preliminary input, it could miss internal flaws or inconsistent behavior.

➢ *Testing without Harm (NDT)*

High-frequency sound waves are used in ultrasonic testing (UT) to find intrinsic flaws in the welded connection, such as cavities, cracks, or a lack of fusion. It preserves the component's integrity while offering comprehensive information on the internal structure of the weld. Radiographic testing is the process of creating an image on a film or digital detector by transmitting X-rays or gamma rays through the welded joint. It works well for identifying interior flaws including porosity, partial penetration, or a lack of fusion. In order to find surface and near-surface flaws in conductive materials, Eddy Current Testing uses electromagnetic induction. It is very helpful in locating surface discontinuities, laps, or cracks in the weld zone.

➢ *Testing without Damage (DT):*

- *Tensile Testing:*

Welded specimens are pushed apart to assess the strength and ductility of the joint. It provides details about the weld's yield strength, elongation, ultimate tensile strength, and fracture behavior.

- *Microstructural Analysis:*

This method involves examining cross-sections of welded specimens under a microscope in order to evaluate the grain structure, weld penetration, intermetallic development, and any faults in the weld zone. Optical microscopy, metallography, and scanning electron microscopy (SEM) are among the techniques commonly used for this.

➢ *Testing Mechanically:*

- *Hardness Testing:*

This technique assesses how resistant the weld material is to deformation when a load is applied. It offers data on the distribution of hardness throughout the weld zone, which may reveal differences in the material's characteristics and any flaws.

- *Impact Testing:*

By applying abrupt loads to specimens, impact testing assesses the weld's resilience and resistance to fracture. It aids in determining how well the weld can tolerate impact events and dynamic loads.

➢ *Leak Testing:*

To guarantee the integrity of the weld, leak testing is done on welded components meant for applications requiring the containment of gases or fluids. Leaks or discontinuities in the weld zone can be found using methods like dye penetrant testing, pressure testing, or helium leak testing.

➢ *In-Situ Monitoring:*

Real-time monitoring of welding process factors such as vibration, temperature, axial force, and rotation speed can provide valuable insights into the weld quality and process stability. Modern sensors and monitoring systems are able to recognize changes from the intended settings and instantly notify operators of any potential flaws or anomalies.

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XIII. STANDARDS AND GUIDELINES RELEVANT TO ROTARY FRICTION WELDING QUALITY ASSURANCE

A solid-state welding technique called rotary friction welding (RFW) is used to fuse together metals that are comparable and dissimilar. Respecting different norms and rules related to welding procedures and material joining is necessary to ensure quality assurance in RFW.

➢ *The Following are some Pertinent Rules and Regulations:*

- *ISO 15620:2001 - Friction in Welding Metallic Material Welding:*

  The specifications for the friction welding of metallic materials are laid out in this international standard. Terminology, qualifications for welding procedures, and quality standards are covered.

- *AWS D17.2/D17.2M:2018 - Specification for Resistance Welding for Aerospace Applications:*

  Although primarily focused on resistance welding, this specification includes requirements and guidelines for friction welding in aerospace applications. It provides detailed guidelines for welding procedure qualification, inspection, and acceptance criteria.

- *AWS QC7-93 - Standard for AWS Certified Welders:*

  This standard outlines the requirements for qualification and certification of welding personnel. It includes specific provisions for friction welding and other welding processes.

- *ASTM E2428/E2428M - Standard Test Method for Evaluation of Friction Stir Welding of Aluminium Alloys by Radiography:*

  While primarily focused on friction stir welding, this ASTM standard provides guidance on evaluating welded joints through radiographic testing, which may be applicable to RFW as well.

- *ISO 3834 series - Quality Requirements for Welding:*

  ISO 3834 standards provide comprehensive quality requirements for welding, including processes like RFW. They cover aspects such as quality management, welding procedure specification, personnel competence, and inspection.

- *ASME Boiler and Pressure Vessel Code (BPVC):*

  Section IX of the BPVC provides guidelines for qualification and certification of welding procedures and personnel. While not specifically tailored to friction welding, it offers valuable insights into welding quality assurance.

- *NADCAP (National Aerospace and Defence Contractors Accreditation Program):*

  NADCAP provides industry-managed approaches to conformity assessment of special processes and products, including welding. NADCAP accreditation ensures compliance with rigorous standards and guidelines specific to aerospace and defence applications.

- *Customer Specifications:*

  In addition to industry standards, manufacturers often need to adhere to specific customer requirements and specifications for RFW. These specifications may include additional quality criteria, inspection methods, and documentation requirements.

XIV. WELDING PARAMETRS IN RFW

A solid-state welding technique called rotary friction welding rotates one cylindrical component against the other while exerting axial pressure to fuse the two together. A strong, metallurgical bond might form because of the material's softening properties caused by the heat in rotary friction welding, the following are the crucial welding parameters:

➢ *Rotation Speed (RPM):*

One important factor is the components' rate of rotation. It has an impact on the heat produced during the procedure. Although there is an ideal speed for every material and application, higher rotational speeds often result in more heat generation and faster welding.

➢ *Axial Pressure (Force):*

Achieving the right deformation and bonding during welding requires the application of axial pressure, also known as force, to the components. In order to provide the required surface contact for successful welding, it must be managed.

➢ *Friction Time:*

The amount of time that the parts are in contact and spinning against one another is known as the friction time. It is a critical factor that establishes the quantity of heat produced and the amount of time available for bonding and softening the material.

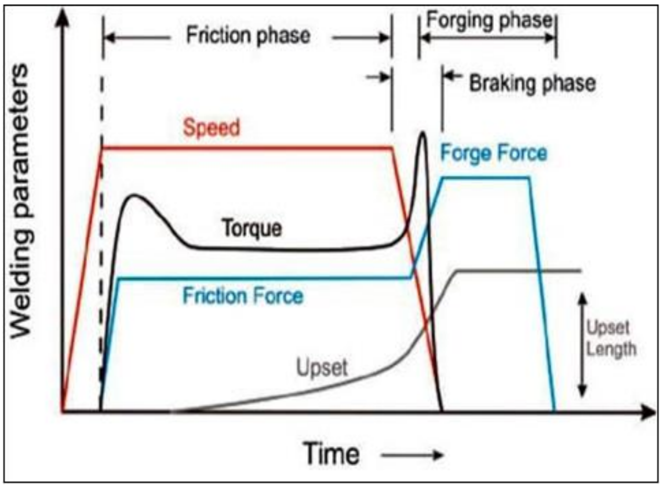

Fig 8 Parameters and Phases of Continuous Drive Friction Welding [9]

➢ *Forge or Upset Pressure:*

To create the bond and forge the softened material, more axial pressure is applied after the friction phase. This pressure is essential to the formation of a robust metallurgical bond.

➢ *Welding Power:*

In some rotary friction welding setups, external heating elements may be used to preheat the materials before the friction welding process. The power supplied for preheating, combined with the heat generated through friction, contributes to the overall welding process.

➢ *Material Properties:*

Different materials have varying responses to friction welding. Factors such as the thermal conductivity, melting point, and metallurgical properties of the materials being joined influence the welding parameters.

➢ *Cooling Time:*

After the welding process, a controlled cooling time may be necessary to prevent the formation of unwanted microstructures and ensure the desired mechanical properties.

➢ *Part Geometry and Size:*

The size and geometry of the parts being welded can impact the welding parameters. Larger or more complex parts may require adjustments to the rotational speed, axial pressure, and other parameters.

It's crucial to remember that the ideal welding parameters can change depending on the particular materials being welded, how big they are, and the qualities the finished joint is supposed to have. To ascertain the optimal characteristics for a particular application, testing and experimentation are frequently required.

➢ *Friction Phase:*

In the initial stage of rotary friction welding, referred to as the friction phase, heat is generated when two components are coming together due to friction. This phase is essential because it softens the materials and prepares them for bonding. Frictional forces are produced at their interface as the rotating component comes into contact with the stationary component. There is a localized temperature rise at the interface as a result of these frictional forces converting mechanical energy into heat. The materials near the contact get softer due to the frictional heat, which raises their temperature to the point where they become pliable and ductile. Usually, during the friction phase, a temperature is reached that is high enough to cause plastic deformation but yet below the melting point of the materials.

➢ *Forging Phase:*

The softened materials are solidified and fused together to form a strong junction during the forging phase of rotary friction welding, which follows the friction phase. The friction phase of the welding process, which generates heat and softens the materials, is followed by the forging phase. In order to prepare for the forging process, the welding parameters, such as axial pressure and rotational speed, must now be changed. To compress and forge the softened materials together, more axial pressure is given to the rotating component during the forging process. To guarantee even consolidation of the materials along the joint contact, uniform pressure is applied.

➢ *Braking Phase:*

In order to safely stop the spinning of the welded components, the braking phase of rotary friction welding takes place after the forging phase. Axial pressure is used throughout the forging process to fuse the softened elements into a robust junction. The forging phase is finished when the pressure is released, signifying the achievement of the intended forging parameters. Following the forging stage, the parts must be safely and effectively stopped from rotating. This is required to guarantee uniform weld quality, avoid undue wear on the machinery, and make it easier to remove the welded assembly from the welding machine.

➢ *Speed:*

The quantity of heat produced during the welding process is directly influenced by the rotational speed. More frictional heat generation usually occurs at the contact between the two materials being welded at higher rotational speeds. Especially when it comes to metals, increased rotating speed may cause the materials being welded to soften more. For the two materials to form a metallurgical bond, this softening is necessary. The strength and integrity of the weld are impacted by the rotational speed. The selection of optimal rotational speeds is necessary to guarantee that the weld attains the intended strength qualities. Rotational rates that are too high or too low may result in poor bonding or even material degradation.

➢ *Torque:*

The weld joint's shape is impacted by torque. Achieving the appropriate weld size and reducing flaws like flash or excessive material expulsion are made easier with torque control. Inadequate torque settings may result in flaws including partial bonding, voids, or material expulsion, which could jeopardize the weld joint's integrity. The welding process's stability is influenced by torque as well. For consistent heat generation and dependable weld quality, torque application must be consistent.

➢ *Upset:*

"Upset" refers to the forging process that occurs during rotary friction welding, in which the heat generated by the friction causes the material at the contact to soften and allow the joining of the two components. In rotary friction welding, upset can have a big impact on the welding parameter. During the welding process, upset has an impact on the amount of heat produced. Higher upsets typically result in larger frictional forces and heat generation, which might affect the weld zone's metallurgical characteristics. In rotary friction welding applications, maintaining the integrity of the welded components, maximizing process efficiency, and attaining consistent weld quality all depend on regulating upset as a welding parameter.

XV. JOINT STRENGTH OF DIFFERENT ALLOYS

"Joint strength" describes the welded joint's structural soundness and mechanical integrity as a result of the process. A solid-state welding technique called rotary friction welding can be used to fuse two materials together by applying pressure and the frictional heat generated by at least one revolving component. The material's tensile strength multiplied by the boss's cross-sectional area yields an estimate of the joint strength. The equation for joint efficiency is given below:

$$\text{Joint Efficiency} = \frac{\text{Strength of welded part}}{\text{Strength of base material}}$$

Table 1 Showing Ultimate Tensile Strength, Yield Strength and Elongation of Different Alloys

Metal or Alloy	TS (MPa)	Ys (MPa)	δ- ψ (%)
Steels	1725	205	65-2
Iron	185-285	40-200	60-3
Aluminum	90	35	45
Aluminum Alloys	90-600	35-550	45-4
Copper	220	70	45
Copper Alloys	140-1310	76-1100	65-3
Nickel	320	58	30
Nickel Alloys	345-1450	105-1200	60-5
Titanium	275-690	140-550	30-17
Titanium Alloys	415-1450	344-1380	25-7
Molybdenum Alloys	90-2340	80-2070	40-30
Magnesium	160-195	90-105	15-3
Magnesium Alloys	240-380	130-305	21-5

In Table 1 'Ts" denote for tensile strength , "Ys" denotes Yield Strength and "δ" denote for elongation .For the welded components to function and be reliable, the strength of the joint created by rotary friction welding is essential, especially in applications where load-bearing requirements or mechanical stress are important. Various mechanical tests, such as tensile, shear, or fatigue testing, are commonly used to measure joint strength. These tests examine the joint's capacity to endure applied forces without failing. The qualities of the material, welding parameters (such as rotation speed, pressure, and duration), weld geometry, and post-welding treatments are some of the factors that affect joint strength in rotary friction welding. Optimization of these parameters is essential to achieving the necessary level of joint strength and ensuring that the welded components meet the requirements of their intended application.

Table 2 shows the outcomes of tensile testing welded specimens made with rotary friction welding of both ABS and PE polymers. PE stands for polyethylene, and ABS stands for Acrylonitrile Butadiene Styrene. In addition, the elongation, time before breakage, peak stress, and peak load are shown in the table. Given the weak welded interface between the two polymers and the failure of four specimen pairs, it was found that the fracture happened at the weld site.

Table 2 Experimental Tensile Test Results of ABS and PE [17]

Test number	Type of polymer	Friction Speed rpm	Friction time sec.	Peak stress MPa	Peak load KN	Joint efficiency %	Average burn-off length mm
1	ABS	560	60	24.5	0.695	0,863	10.8
2	ABS	600	75	20.5	0.55	0.723	11.1
3	ABS	650	90	16.3	0.46	0,574	11.4
4	PE	650	90	14.175	0.4	0,474	2.56
5	PE	650	63	9.6	0.268	0,321	6.9
6'	ABS+PE	560	105				4.76
7	PE	1030	80	17.5	0.49	0,585	3.86
8'	ABS	1030	60				4.98
9	PE	950	62	1.9	0.096	0,063	7.5
10'	ABS+PE	950	90				4.58
11'	ABS+PE	1030	74				4.48
12'	ABS	1030	93				3.24

For thermoplastic, there is a critical sliding speed for each type of polymer. This speed generates a localized flash temperature at the interface that can be reached, which results in surface melting and thermal softening at the contact surfaces. This flash temperature is caused by adhesive friction at the instantaneous contact surface. Relative rotational speed is the key rotary friction metric, although it has the inherent disadvantage of not working with components with non-circular cross sections. Experimentally, it has no appreciable effect on the quality of the welding connection, even if it varies across a wide range. Tests 8 and 12 for the ABS type of polymer failed because the rotating speed was higher than the critical parameters. Furthermore, the failure of tests 6, 10, and 11 involving the rotational friction welding of ABS and PE suggests that this technique is not practical for uniting the two materials.

XVI. ALLOYS PREFERED FOR ROTARY FRICTION WELDING

The alloys used for rotary friction welding process is a combination of Copper Nickel alloy and Stainless Steel.

Copper-nickel alloys, sometimes referred to as cupronickel alloys, are frequently employed in rotary friction welding applications, especially in the manufacturing, aerospace, and automotive sectors. By applying heat created by the friction between two metal components, rotary friction welding is a solid-state welding technique that unites them.

➢ *Rotating Friction Welding is Preferred for Copper-Nickel Alloys for a Number of Reasons.*

- *Excellent Weldability*: Copper-nickel alloys can be bonded using rotary friction welding successfully and without the need for additional filler material because of their good weldability.

- *Excellent Corrosion Resistance* is exhibited by copper-nickel alloys, which makes them appropriate for applications requiring resistance to corrosive environments such as seawater, moisture, and other conditions. This is especially crucial for offshore and marine applications.
- *Thermal Conductivity*: The high thermal conductivity of copper-nickel alloys aids in the uniform distribution of heat during the rotary friction welding process. Welds that are reliable and of good quality may come from this.
- *Ductility*: Materials made of copper-nickel alloys are ductile, which means they can bend without breaking. This characteristic lessens the possibility of cracking during welding and permits more design freedom for welded components.
- *Compatibility with other Materials*: Stainless steel, titanium, and aluminum are just a few of the materials that copper-nickel alloys can be welded to. These materials are frequently utilized in technical applications. They are appropriate for a variety of welding applications due to their adaptability.

Stainless steel has many advantageous qualities, including strength, corrosion resistance, and weldability, which make it a popular material for rotary friction welding. Stainless steel is frequently utilized in rotary friction welding for the following reasons:

- Stainless steel is renowned for having exceptional **resistance to corrosion**, which makes it appropriate for uses in which the welded junction may come into contact with corrosive materials or severe environments.
- *Strength*: Good mechanical qualities, such as high tensile strength and toughness, are characteristic of stainless-steel alloys and are crucial for guaranteeing the integrity and functionality of the welded junction.
- *Weldability***:** The majority of individuals concur that stainless steel is easily welded using a variety of welding methods, including rotary friction welding. The material's low heat conductivity and metallurgical properties make it an excellent choice for solid-state welding methods like friction welding.
- *Compatibility with other Materials*: When rotary friction welding, stainless steel is frequently combined with other materials like carbon steel, titanium, or aluminum. Because of its versatility, it can be used to create hybrid constructions with specific characteristics.
- *Cost-Effectiveness*: Although stainless steel may cost more than certain other materials, in some applications, especially those needing resistance to corrosion or high temperatures, it may be a more cost-effective option due to its long-term durability and low maintenance requirements.

XVII. ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

A solid-state joining technique called rotary friction welding involves rotating two components against each other while exerting pressure. The friction creates heat, and when the materials get to a plastic state, a weld is formed. Several elements are taken into account while analyzing the economic and environmental aspects of rotary friction welding. These include:

A. Environmental Considerations

- *Energy Consumption Benefits:*

Because rotary friction welding doesn't require external heating sources like gas or electricity, it can be more energy-efficient than traditional welding techniques like arc welding. Energy is still used in the process, mostly in the form of mechanical power to rotate the components. Energy waste can be reduced by designing and using machines efficiently.

- *Material Effectiveness:*

Because the technique concentrates on attaching the pieces by friction-induced plastic deformation, it frequently results in minimal material waste. The qualities of the material determine its efficiency, and certain materials may produce more waste than others. The materials' potential for recycling should also be taken into account.

- *Pollution& Emissions:*

Compared to conventional welding techniques that involve gas or electrical heating, rotary friction welding usually results in lower emissions. The materials and machinery used may still produce emissions. It could be necessary to install adequate exhaust and ventilation systems to lessen any possible environmental impact.

B. Economic Factors

- *First Outlay of Capital:*

Although the initial expenses of rotary friction welding machines may be higher, the long-term financial benefits sometimes surpass the initial outlay. A company's consideration should be to balance the equipment's initial expenditures with possible long-term material and energy savings.

- *Costs of Operations:*

Because rotary friction welding uses less energy and requires fewer consumables than other welding techniques, it might have lower operating expenses. The need for qualified workers and routine maintenance could raise overall operating expenses.

- *Efficiency of Production:*

Because rotational friction welding has shorter cycle durations and requires fewer post-welding procedures, it can result in improved production efficiency Depending on the particular application and the materials being welded, the efficiency improvements could differ.

- *Costs of Materials:*

The total economic viability of rotational friction welding may be affected by the cost of the materials utilized. High-performance materials might come with a price.

➢ *Reliability and Quality:*

Because the technique is solid-state, it frequently produces high-quality welds with fewer flaws. Testing and quality control investments could be required, affecting overall prices.

XVIII. ENVIRONMENTAL IMPACT OF ROTARY FRICTION WELDING TECHNIQUES AS COMPARED TO OTHER TRADITIONAL TECHNIQUES

When assessing the environmental impact of rotary friction welding in comparison to conventional welding methods, a number of elements must be taken into account, including waste production, energy consumption, emissions, and material utilization. We may talk about some broad issues, but it's important to remember that the precise environmental impact can change depending on the situation and particular procedures used.

➢ *Energy Consumption:*

- *Rotary Friction Welding (RFW):*

Because RFW produces the weld using friction and rotational motion rather than external heat input, it is generally thought to be more energy-efficient than traditional welding techniques.

- *Conventional Welding Methods:*

Higher energy inputs may be needed for processes like arc welding, particularly when producing heat using gas or electricity.

➢ *Emissions:*

- *RFW:*

Compared to some conventional welding methods, RFW frequently uses less external heat, which could lead to a decrease in greenhouse gas and air pollution emissions.

- *Conventional Welding Methods:*

Additional pollutants may be created during techniques like shielded metal arc welding (SMAW) or gas metal arc welding (GMAW) since gases are burnt during these processes.

➢ *Material Utilization:*

- *RFW:*

Because RFW doesn't require consumable electrodes or filler materials, it often produces less material waste.

- *Conventional Welding Methods:*

Certain conventional welding techniques may make use of consumable electrodes or filler materials, which could result in waste production and increased material consumption.

➢ *Generation of Waste:*

- *RFW:*

Since the process frequently gets rid of the need for consumable resources, it might produce less waste on its own.

- *Conventional Welding Methods:*

Arc welding, for example, might produce more waste in the form of used electrodes, slag, and extra consumables.

➢ *Safety and Health:*

- *RFW:*

RFW often generates fewer airborne particles and fumes, which could make the workplace safer.

- *Conventional Welding Methods:*

If not adequately managed, many conventional welding techniques may produce higher levels of fumes and particulate matter, endangering the health of the workers.

➢ *Life Cycle Evaluation:*

To take into account the entire environmental impact, a thorough life cycle study would be required. This would include the extraction and processing of raw materials, manufacturing, transportation, and end-of-life concerns for consumables and equipment.

XIX. ECONOMIC BENEFITS AND COST EFFECTIVENESS OF ADOPTING RFW IN MANUFACTURING OPERATIONS

A solid-state welding technique called rotary friction welding involves rotating one component while the other stays fixed, creating heat and friction. The parts are forced together to form a welded junction once the required temperature is reached. This method is cost-effective and provides a number of economic advantages for manufacturing operations:

➢ *Savings in Materials:*

By combining dissimilar materials with rotary friction welding, it is possible to save material by employing more affordable materials for non-critical sections and particular materials for crucial areas. Because the process uses a precision welding technique, it is very effective at reducing material waste.

➢ *Lower Production and Material Costs:*

Lower material costs can be achieved by joining materials without the need for extra consumables like fluxes or filler metals. Lower energy usage as comparison to conventional welding techniques, like arc welding, lowers production costs.

➢ *Enhanced Output:*
Because rotary friction welding is a quick process, cycle times are shortened and overall productivity is raised. Rapid production of high-quality welds is particularly advantageous in high-volume manufacturing settings.

➢ *Energy Effectiveness:*
Rotating friction welding uses less energy than fusion welding, which reduces operating expenses. Fusion welding procedures demand a large amount of energy. Energy efficiency is achieved through the process's localized and controlled nature, which limits heat-affected zones.

➢ *Minimal Procedures*
After Welding: Extensive post-welding procedures are generally unnecessary since rotary friction welding frequently yields welds with few flaws and great precision. This reduces the need for extra labour and tools, which raises the overall cost-effectiveness.

➢ *Improved Caliber and Reliability:*
The procedure results in superior welds with outstanding mechanical qualities, extending the overall dependability and durability of the created parts. The rotary friction welding technique produces fewer faults due to its uniformity and repeatability, which lowers the possibility of rework and its related expenses.

➢ *Versatility and Adaptability:*
Rotary friction welding can be applied to a wide range of materials and shapes, providing versatility in manufacturing operations. The adaptability of the process to different materials and component geometries makes it suitable for diverse applications, leading to cost-effective solutions for various industries.

XX. CONCLUSION

In summary, adopting rotary friction welding in manufacturing operations can lead to economic benefits and cost-effectiveness by reducing material and production costs, increasing productivity, improving energy efficiency, minimizing post-welding processes, and enhancing overall product quality. The specific advantages will depend on the type of components, materials, and production volumes involved. In conclusion, rotary friction welding may be more environmentally friendly than conventional welding methods in terms of waste production, emissions, energy efficiency, and material utilization. Nevertheless, the precise effect is dependent on variables such as the materials being combined, the manufacturing process' size, and the energy sources employed. A more realistic assessment of the welding processes' environmental impact would come from a thorough examination that takes into account their complete life cycle.

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REFERENCES

[1]. A.B. Dawood, S.I. Butt, G. Hussain, M.A. Siddiqui, A. Maqsood, F. Zhang, "Thermal model of rotary friction welding for similar and dissimilar metals", Metals (Basel) 7 (2017) 1–14.
[2]. S.T. Selvamani, K. Palanikumar, K. Umanath, D. Jayaperumal, "Analysis of friction welding parameters on the mechanical metallurgical and chemical properties of AISI 1035 steel joints", Mater. Des. 65 (2015) 652–666.
[3]. M. Sahin, "Joining of stainless–steel and aluminum materials by friction welding", Int. J. Adv. Manuf. Technol. 41 (2009) 487–497.
[4]. T. Dhamothara, Kannan, P. Sivaraj, V. Balasubramanian S. Malarvizhi, Tushar Sonar, Mikhail Ivanov, S. Sathiya, "Joining Different Grades of Low Carbon Steel to Develop Unsymmetrical Rod to Pate Joints using Rotary Friction Welding for Automotive Applications", Forces in Mechanics 10(2023) 100153.
[5]. G. Vairamani, T. Senthil Kumar, S. Malarvizhi, V. Balasubramanian, "Predicting tensile strength and interface hardness of friction welded dissimilar joints of austenitic stainless steel and aluminum alloy by empirical relationships", The. Ind.Ins. Wel. 46 (2) (2013) 67–75.
[6]. Ebrahim Seidi, Scott F .Miller, "Lateral Friction Surfacing: experimental and metallurgical analysis of different aluminum alloy depositions", Journal of Materials Research and Technology (2021);15:5948-5967
[7]. E.P. Alves, F.P. Neto, C.Y. "An Welding of AA1050 aluminum with AISI 304 stainless steel by rotary friction welding process", J. Aero. Technol. Manag. 2 (2010) 301–306.
[8]. Ade Sunardi, Mariyana Mariyana, Adhes Gamayel, "Design & development of friction welding machine based on lathe machine", The 3rd International Conference on Engineering and Applied Sciences (2021) 070002-070009.

[9]. Chunlin Huanga, Jintao Lua, Ming Zhub, Yaxin Xuc, Boshuai Li, Yongli Zhoua, Jinyang Huanga, "Oxidation behaviors of the rotary friction welded joints of HT700 superalloy in saturated water steam at 700 ◦C", Corrosion Communications 6 (2022) 40–4.

[10]. Selvaraj R , Shanmugam K , Selvaraj P , Prasanna Nagasai B , Balasubramanian V, "Optimization of process parameters of rotary friction welding of low alloy steel tubes using response surface methodology", Forces in Mechanics 10 ((2023) 100175.

[11]. Gourav Sardana and Ajay Lohan, "Friction Welding on Lathe Machine with special Fixture", International Journal of Innovations in Engineering and Technology (2) 258-261.

[12]. Zhongsheng Li, Zhengtao Liu, Dajun Chen,Fei Mo, Yangfan Fu, Ye Dai, Xia Wu, Dalong Cong, "Study of Microstructure and Properties of Aluminum/Steel Inertia Radial Friction Welding", Metals 12 (2022) 1 - 13.

[13]. S.Pandia Rajan, S. Senthil Kumaran, L.A. Kumaraswamidhas, "An investigation of metal flow during friction welding of SA 213 tube to SA 387 tube plate with backing block," Alexandria Engineering Journal (2016) 55, 1187–1199.

[14]. Hardik D. Vyas, Kush P.Mehta, Vishvesh Badheka, Bharat Dosh, "Friction welding of dissimilar joints copper-stainless steel pipe consist of 0.06 wall thickness to pipe diameter ratio", Journal of Manufacturing Processes 68 (2021) 1176–1190.

[15]. R. Ramesh Kumar, J.M. Babu, Bahaa Saleh, H. Fayaz, A. Chandrashekar, Tanya Gera, Kottakkaran Sooppy Nisar, C Ahamed Saleel, "Experimental and analytical investigation on friction welding dissimilar joints for aerospace applications", Ain Shams Engineering Journal 14 (2023) 101853

[16]. Uday Mowafak Basheer, "Friction Welding of 6061 Aluminum Alloy with YSZ- Alumina Composite for Improved Mechanical and Thermal Properties", Research Gate (2013).

[17]. Gailan Ismail Hassan1 ,Younis Khalid Khdir , "Effect of Rotary Friction Welding Parameters on the Mechanical Behavior ABS/PE Polymers", Academic Journal of Nawroz University (2018).

[18]. TWI Global website, Stir weld website, American Friction Welding. Friction Welding: Thermal and Metallurgical Characteristics, Book by Ahmet Z. Sahin and Bekir Sami Yilbas.