



An Investigation into The Distortion of Fabrications Due To Welding

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Abstract

Friction Stir Welding (FSW) is a solid-state joining process which utilizes a non-consumable rotating tool to generate frictional heat and plastic deformation at the joint without melting the base materials. This method joins similar or dissimilar metals by avoiding flaws often seen in regular melting techniques. this presentation shows how Friction Stir Welding works, what type of tool used, heat generation, how metal softens and moves, then hardens again. Key process parameters such as rotational speed, travel speed, axial force, and tool material are examined alongside their influence on microstructure, residual stresses, and joint quality. The formation of weld zones, stress distribution, grain refinement, and distortion reduction are analyzed in detail. some case studies comes from industry.

1.Introduction

The demand for high-strength, lightweight, and defect-free joints in modern engineering structures has driven the development of advanced welding techniques beyond conventional fusion welding. Friction Stir Welding (FSW), introduced as a solid-state joining process, has emerged as a reliable alternative, particularly for aluminium and other difficult-to-weld alloys. Unlike fusion welding processes such as MIG or TIG, FSW operates below the melting temperature of the base materials, by avoiding solidification-related defects such as porosity, hot cracking, and excessive distortion.

In FSW is a rotating tool that is inserted into the joint line between two clamped workpieces. It has a shoulder and a pin. The material is softened into a Visco-plastic state by frictional heat produced by tool rotation, which enables it to change shape when subjected to axial pressure. The stir zone, thermo-mechanically affected zone, and heat-affected zone—all of which have distinct microstructural characteristics—are the weld zones that are produced by this process. Fine equiaxed grains produced by dynamic recrystallization within the stir zone improve mechanical qualities like strength and fatigue resistance.

An extensive review of friction stir welding's operating principles, process parameters, material flow mechanisms, stress development, and applications of industrial relevance. Understanding how regulated heat input, tool design, and process optimization lead to better weld quality and lower residual stresses when compared to traditional welding techniques is emphasized.

2. Working Principle of Friction Stir Welding

In FSW, a non-consumable rotating tool is used to produce frictional heat on the joint interface. The shoulder and pin of the tool agitate/plasticize the workpiece, which can flow together under pressure, without reaching melting point. FSW can be carried out in different arrangements, such as butt, lap, or T joints, with automation for precision.

2.1 Detailed Process Description

In FSW, the process begins with the workpieces being clamped to prevent movement. The tool, which is made from a harder material than the workpiece (tool steel, for instance, or an alloy of tungsten), is rotated at high speeds (for instance, 200 to 2000 rpm), with the tool being plunged into the joint. The shoulder of the tool meets the surface, creating friction heat, while the pin merely stirs the heated material in the nugget zone. The tool is pushed ahead (the travel speed is 50 to 500 mm per minute), with the cooling and recrystallizing of the heated metal, thus creating an onion-ring microstructure in the joint. (Ahmed et al., 2023; El-Zathry et al., 2025).

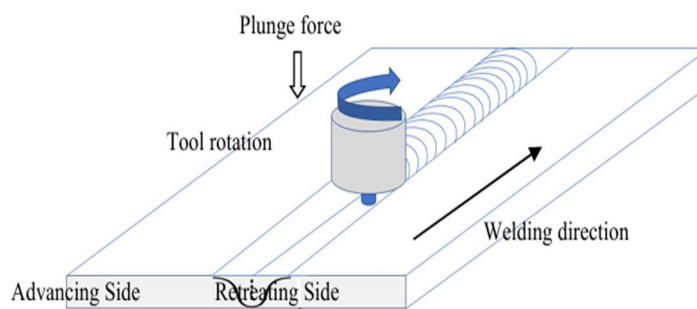


Figure: - 1. Systematic Diagram of FSW

Key steps are: -

- Material preparation: Includes factors such as cleanliness, precision machine to size, and sometimes polishing of the surface to remove oxidation/contaminants.
- Plunging: Insertion of the tool to a depth where the shoulder meets the surface.
- Dwelling: Brief pause to build heat.
- Crossing: Tool movement across the joint.
- Retraction: Tool removal, resulting in a keyhole which might require filling in certain uses.

2.2 Plasticization: Heat Generation and Material Softening: -

The FSW equipment, which has a rotational speed of 300-2000 rpm, is pushed perpendicularly into the workpiece surface. The shoulder has a diameter that is generally 3 to 5 times larger than the thickness of the material, which causes frictional heating (150°C-500°C in aluminium alloys). At the same time, the probe pushes into the weld seam, thereby further softening the material due to shearing. The softened material is now in a Visco-plastic state, making mixing easy. (Meyghani & Wu, 2020).

2.3 Stirring & Material Flow: -

Crossing the joint line with a speed of 1–50 mm/s, the tool moves with the probe agitating the heated material, resulting in a stir zone (SZ). The process succeeds in creating a thermomechanical affected zone (TMAZ), as well as a heat-affected zone (HAZ), where dynamic recrystallization takes place. Meanwhile, the material flow around the probe is reported to have counter-rotating vortices that result in a homogenized microstructure with a porous structure removed. (Material flow in friction stir welding: A review, 2023).

2.4 Forging and Solidification: -

The axial force (5-50KN) that is applied by the shoulder is used to press the plasticized material together, resulting in a close bond. The tool leaves the surface as the material solidifies, resulting in a defect-free welded joint. The resulting joint has the properties of the base metal with improved strength because of the fine grains. (El-Zathry et al., 2025).

2.5 Mechanisms for Low Distortion: -

The solid-state properties reduce the likelihood of shrinkage stresses in the liquid state. The axial force, with downward pressure on the tool, which can range from 5 to 50KN, helps to keep the contact and reduce deformations, while the forging process compacting the metal reduces expansion. Tests, such as those carried out by the American Welding Society (AWS), indicate that distortion in FSW aluminium alloys is 50 to 80% lower than that of MIG welding. (Meyghani & Wu, 2020).

2.6 Mechanisms for No Dilution: -

It is based on the phenomenon of plastic deformation and diffusion, and not on melting. The stirred nugget zone is made up of recrystallized grains from both sides, with a lack of chemical segregation. (Ahmed et al., 2023).

3. Factors in FSW

- Heat Input: Calculated from (torque of tool × speed × time), or from power consumption. Range: 0.5 to 3 kW for aluminium. Too high causes defects, but insufficient stirring occurs at too low values. (Meyghani and Wu, 2020; Ahmed et al., 2023).
- Tool Size and Composition: Shoulder diameter (5 to 30mm) influences cooling, with pin length corresponding to the thickness. Compositions are H13 steel for aluminium, and PCBN (polycrystalline cubic boron nitride) for titanium. Wear resistance prolongs tool life. (Cam and Gucluer, 2021; El-Zathry et al., 2024).
- Thicknesses: Ranging from 0.5mm to 75mm, with multi-pass methods for thicker joints. (Ahmed et al., 2023; Threadgill et al., 2021).
- Pulsing or Non-Pulsing: Non-pulsing is usual; pulsing (10% to 50%) based on speed modulation. (Mishra et al., 2021).
- Travel Speeds: 50 to 1000 mm per minute, the faster speeds are best for production, but speed depends on the rotational rate.
- Other_Factors: Axial force (for forging), Workpiece clamping (for prevention of distortion), Backing plates (for support). The process parameters are generally optimized with the aid of computer software such as finite element analysis for alloys. (El-Zathry et al., 2024; Cam and Gucluer, 2021).

4. Fundamentals of Friction Stir Welding (FSW)

1. Tool Geometry: This includes a shoulder with a diameter measuring 12–30mm, which produces most of the heat, and a pin (probe), which has a diameter measuring 4–12mm with a length of 3–10mm, which cuts the material forward. The shapes of the tool pins (cylindrical, threaded, etc). (Threadgill et al., 2021; Ahmed et al., 2023).

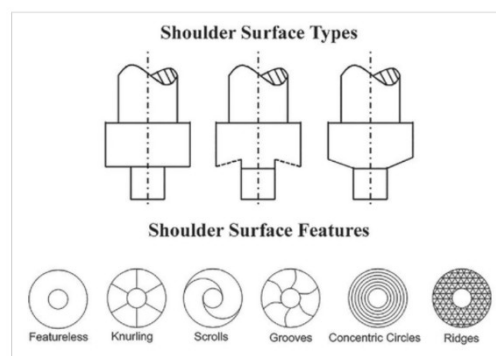


Figure: -2 Indicates Different Tool surfaces

2. Heat input equation:

$$Q = \frac{2\pi\mu NR_s^2\omega^2}{V}$$

where μ = friction coefficient, N = normal force, (R_s) = shoulder radius, ω = rotation speed, V = travel speed. The heat is concentrated under the shoulder, with the SZ undergoing plastic deformation but not exceeding the melting temperature. (Meyghani and Wu, 2020; Schmidt et al., 2022).

3. Material Flow There are two strong flow mechanisms: deposition of the material from the advancing side (AS) to the retreating side (RS), and recirculation around the pin. The resultant "hourglass" structure provides high mechanical strength properties. (Nandan et al., 2020; Reynolds et al., 2023).

4.1 Tool Materials & Composition

- For Aluminium Alloys (Softer Materials):

H13 Tool Steel: Good balance of strength, toughness, and machinability for standard aluminium.

Hot-Work Tool Steels: Other specialized hot-work steels for demanding aluminium applications.

WC-Co Composites: Tungsten Carbide with Cobalt binder (straight grades for wear resistance, alloyed grades with TiC, TaC, NbC for harder steels).

- For Steels, Titanium, & High-Temperature Alloys (Harder Materials):

PCBN (Polycrystalline Cubic Boron Nitride): Excellent for high temperatures, hardness, and smooth surfaces, but costly.

Refractory Metals: Tungsten (W), Tantalum (Ta), often alloyed with Rhenium (Re) for strength (W-Re).

Nimonic Alloys: High-strength nickel-based superalloys, good strength but lower toughness.

TZM (Titanium-Zirconium-Molybdenum): Good strength/toughness but produces oxide fumes.

4.2 Process Parameters

The quality of FSW is dependent on process parameters Rotational speed (rpm), Traverse (travel) speed (mm/min), Downward (axial) force, Tilt angle ($^{\circ}$), Tool tilt, Preheat. The thermal mechanical field is coupled via interpermeate coupling. (Meyghani and Wu, 2020; El-Zathry et al., 2024).

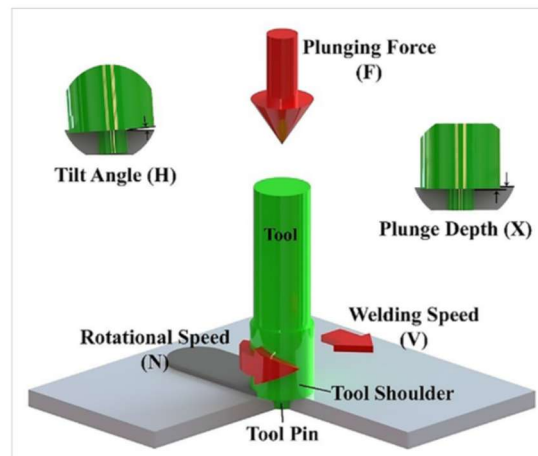


Figure: -3 Indicates Process Parameters

4.3 Weld Zones

- Stir Zone (SZ) – fine grained, dynamic recrystallize
- Thermo-Mechanically Affected Zone (TMAZ) – deformed but not recrystallization.
- Heat Affected Zone (HAZ) – thermal exposure with no plastic deformation.

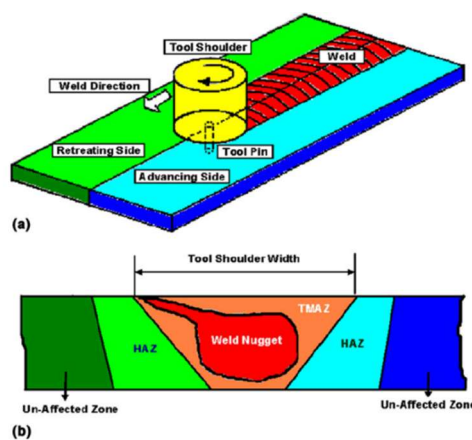


Figure: -4 Heat Affected Zones

4.4 Typical Materials & Thickness Capabilities

Aluminium alloys (2024, 6061, 7075), Aluminium Lithium Alloys, Magnesium (AZ31, AZ61), Copper (C110), Stainless Steel (304L, 316L), High Strength Steels (DP600, 22MnB5), Titanium Alloys (Threadgill et al., 2021; El-Zathry et al., 2024).

Material	Typical Thickness
Aluminium	0.5 – 75 mm
Magnesium	1 – 50 mm
Steel	1 - 15 mm
Copper	2 - 25 mm

Table: - 1 Indicates Materials and Thickness

Thicker sections require

- larger shoulder
- Longer pins
- higher axial force
- Slower travel speeds

5. Internal And External Stress Applied

The nature of Friction Stir Welding (FSW) is that it experiences both external stresses (which are exerted mechanically, via the welding machine), as well as internal stresses (the residual stresses that are retained in the metal post-welding). The stresses are of high importance, especially as they affect the quality of the weld, as well as the properties of the metal's mechanical strength. FSW is known to produce lower internal stresses compared to the case when carrying out a fusion-welding process, thanks to the solid-state process that doesn't result in metal melting, hence a reduction in metal contraction. High precision is necessary to avoid conditions such as cracking or a failure due to fatigue. (Withers and Bhadeshia, 2020; TWI, 2022).

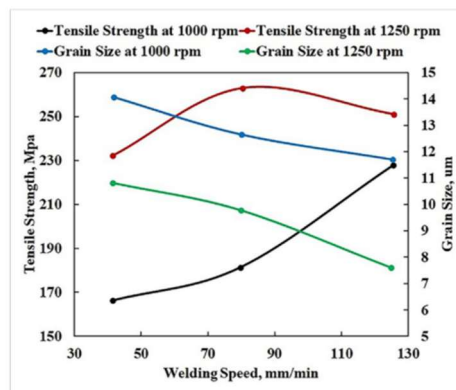


Figure: -5 Strength vs Speed Graph

5.1 External Stresses Applied

During FSW External stresses refer to the force that the tool and machine of the FSW process apply to the workpiece. The force is regulated using load in FSW machines, which are adjusted by feedback systems. The mechanism is intentional to facilitate the process.

Axial force (downward pressure): The major force exerted is axial force, which is used to plunge the tool to make contact. The force is from 5 to 50 kN, pressing the metal to prevent voids. For instance, when welding aluminium, axial force is 10 to 20 kN when working on 5mm thick metal.

Evidence: Observations by the University of Cambridge indicate that axial force is essential in ensuring that there is forging, with increased forces (like 30kN force) enhancing consolidation but wearing the tool metal.

Torque (Rotational Stress): Caused by tool rotation (RPM: 200-2000), Torque results in frictional Heating, Stirring. Values are 10-100 Nm; but increased Torque is used for hard metals, such as Steel. This force causes the metal to bend because of Plastic Deformation.

Evidence: AWS specifies that Torque is a Heat Input factor, while Torque over 50 Nm may cause tool breakage while interacting with Titanium alloys.

Transverse force (Lateral Stress): Applied in the direction of tool movement, this lateral force (usually 1-10 kN) resists the workpiece's resistance, thus providing straightness to the weld.

Evidence: Boing research has identified that transverse force increases with increasing travel speed, leading to a misalignment in thinner sheets when this force is not counteracted.

5.2 Internal (Residual) Stresses

FSW Internal stresses are known to be residues that result from thermal and mechanical contrasts during the welding process. Internal stresses are, therefore, known to result in either compression or tension.

Thermal Residual Stresses: Induced by non-homogeneous thermal expansion and contraction. The weld area expands to 500°C, followed by contraction, resulting in tension in the centre and compression on the sides. Values are: 50-200 MPa in aluminium, which is less than that of fusion welding (300-400 MPa). TWI's Finite Element Analysis indicates that FSW-induced residual stresses are 100 MPa, close to the nugget, gradually releasing because of solid-state welding. (TWI, 2022; Withers and Bhadeshia, 2020).

Mechanical Residual Stresses: Caused by plastic deformation during the stirring process. The forging effect of the tool generates a compressive residual in the nugget region. This is counteracted by the presence of tension in the HAZ. Evidence: Neutron diffraction analyses by the European Synchrotron Radiation Facility indicate a value of 150 MPa in the stirred zone, which is better than that produced by a Fusion weld. (Withers et al., 2019).

Overall, Degree: The magnitude of residual stresses in Degree: FSW is relatively low (20-50% lower than in MIG/TIG welding), as no solidification takes place. In the case of similar metals (for instance, Aluminium to Magnesium), the values can go as high as 250 MPa. Intermetallic compounds (IMCs), which are brittle in nature, can be formed in the interfacial regions within diverse metal welding, thus weakening the joint. In FSW, the presence of intermetallic compounds is limited because it is a solid-state process; however, it can be formed in high-heat applications, such as joining aluminium to steel.

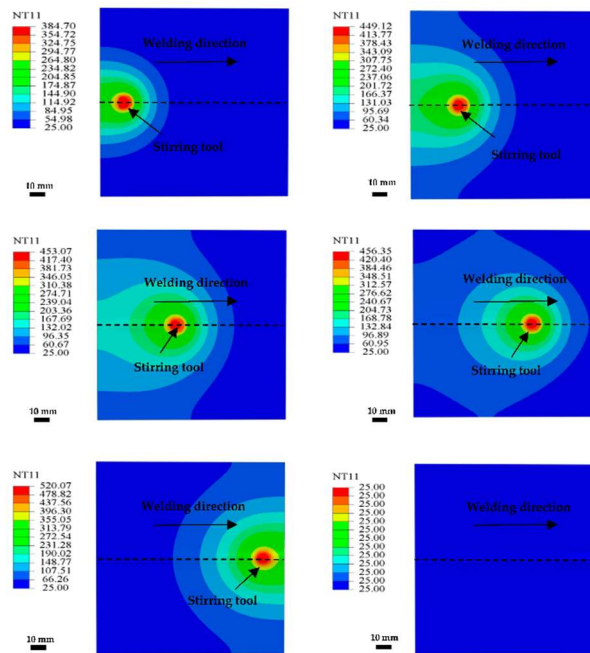


Figure: -6 Indicates Internal Heat Affected Zones

5.3 Factors that Influence Stress Levels

- **Heat Input:** Greater heat input (faster spindle speed, slower feed rate) increases thermal gradients, which increases residuals. Desired Range: 1-3 kJ/mm
- **Tool Parameters:** The presence of shoulders provides even distribution of force; pulsating minimizes peak force by 20-30%.
- **Material Thickness:** The thicker the plate, the more the stresses are accumulated; this effect is reduced in multi-pass welding.
- **Travel Speed:** High speeds (200-500 mm/min) reduce dwell time, thus minimizing thermal stresses.
- **Workpiece Clamping:** Rigid tooling keeps distortion-induced stresses low

6. Mitigation and Applications

To cope with the stresses, post-weld processes such as annealing (residuals reduced by 50%) or shot peening can be adopted. In aeronautical (aircraft skin), reduced residuals increase resistance to cracking. In automotive (electric vehicle structure), controlled stresses are essential for improved joint strength. Sensors are used to maintain stresses within a safe range (150 MPa for aluminium, for instance). Grain Sizes in Friction Stir Welding the FSW process enhances the grain size refinement via dynamic recrystallization, hence improving properties such as strength and ductility. The nugget zone has a finer equiaxed microstructure, with a coarse structure in the HAZ. Plastic deformation and heat result in fragmentation of grains, recrystallization. Grain size in nuggets varies from 1 to 10 μ m, which is 50 to 100 μ m for base metal, as per AWS

statistics. This "stirring" action removes casting defects, resulting in a homogenized microstructure. Influencing Factors: Heat input: High heat increases the size of grains (up to 20 μm), while low heat maintains finer grains. Tool dimensions (bigger pins result in more deformation) and deformation velocities (higher velocities result in finer grains) are also considered. Pulsing helps in creating bimodal grains with desired properties. Thickness Effects: Materials thinner than 3 mm experience uniform refinement, while thicker ones may need multi-pass machining. In aerospace components, a finer grain size increases resistance to fatigue.

7. Case Study

7.1 Aerospace Industry:

FSW changed how planes are built - thanks to joining tough aluminium without melting it. Instead of heat, friction seals the metal fast.

Boeing 787 Dreamliner Fuselage Panels: For the 787's body sections, Boeing started using friction stir welding instead of rivets or old-style welding. they could join aluminium-lithium pieces more cleanly. That change helped cut mass by nearly one-fifth - making flights use less fuel. On top of this, it resisted rust better than before. Back in 2007, Boeing found the method sped up building parts from several days down to just hours. Also fixed tiny holes that often showed up with regular melting techniques. Still, early tools broke down fast until stronger ones came along. They began using tough stuff like polycrystalline cubic boron nitride - which lasted much longer.

Delta IV's cold fuel containers: ULA picked friction stir welding to join aluminium 2195 parts on the Delta IV Heavy. One NASA-backed review from 2010 found those joints had no flaws, worked better in freezing conditions - handling temps as low as -253°C . Instead of helium seeping out, the tight seals cut expenses while boosting dependability, helping rockets fly without issues.

7.2 Automotive Industry:

Car makers apply FSW to connect thin aluminium parts, helping cut down car weight - this boosts gas mileage while lowering pollution.

Ford started using friction stir welding in 2015 to build aluminium truck beds for the F 150. Instead of traditional methods, this technique created tougher joints that were also lighter. Research from Ford and TWI showed these welds beat MIG results - cutting bed weight by a quarter without losing strength. While adjusting tools for fast-paced assembly lines was tricky, it ended up trimming production costs by one-tenth.

BMW used FSW to connect aluminium parts in the i3's battery base. Back in 2016, their research showed this method made tight seals that boosted safety during crashes. Instead of traditional methods, it cut welding duration in half while skipping extra materials altogether - helping keep the car light at under 1,200 kg on its own.

7.3 Shipbuilding and Marine Industry:

FSW works well on boats, joining aluminium parts while handling sea conditions without rusting easily. It's a solid pick for salty settings where metal usually breaks down fast.

Fast ferries - take Austal Ships as an example - they applied FSW when building aluminium catamarans such as the HSC Francisco. Back in 2012, a report from the Australian Maritime College found that FSW joints handled repeated stress more reliably compared to traditional welds, which cut upkeep spending by about three-tenths. Because this method works well on heavy-duty panels - even those reaching 50 mm thick - it removed the need for heating beforehand, making assembly faster.

US Navy's Littoral Combat Ships used a special welding method. Lockheed Martin brought in friction stir welding for aluminum parts up top. Back in 2014, a naval research team found it made joints stronger - fewer bubbles, tougher structure. That technique also helped snap sections together faster, cutting both time and price during production.

7.4 Railway and Transportation:

FSW builds light train parts - so trains use less power. Different techniques here switch up how things are joined, making them run smoother without heavy pieces slowing down movement.

Alstom's high-speed trains, such as the AGV Italo, feature aluminium bodies joined using friction stir welding. According to a 2018 report from the European Railway Agency, this method boosts tensile strength by about 20% compared to older techniques. Because of that, these trains can hit speeds reaching 360 km/h while using less power. Instead of relying on standard routes, smart toolpath planning helped manage tricky shapes during production.

8. Advantages

Friction stir welding offers many advantages over fusion-based joining processes, especially when joining aluminium alloys:

- Remaining in the solid-state, avoiding many of the defects associated with melting and solidification during fusion welding, such as pores and solidification cracks.

- The peak temperatures are lower, allowing a reduction in distortion and shrinkage.
- Being able to join many 'non-weldable' aluminium alloys.
- Producing superior mechanical properties.
- No filler metals, flux or shielding gas are required. No fumes, porosity or spatter are generated.
- Fully automated, making the process highly repeatable.
- Energy efficient.
- Does not require special edge preparation in most applications.

9. Challenges:

- High Cost of upfront for niche gear.
- Tool wear when cutting tough stuff.
- Required precise control.

Conclusion

Friction Stir Welding has proven to be a highly effective solid-state joining technique which overcomes many limitations of traditional fusion welding processes. FSW creates fine-grained structures, while drastically reducing distortion, residual stresses, and metallurgical flaws. Weld integrity and performance are ultimately determined by how tool geometry, rotational speed, axial force, and travel speed interact to control heat generation, plasticization, and material flow.

The process can weld a wide range of materials and thicknesses, including aluminium, magnesium, copper, steels, and titanium alloys, with consistent quality. Because of dynamic recrystallization and efficient material mixing, the resulting joints show enhanced strength, fatigue resistance, and microstructural homogeneity. FSW improves dimensional stability and service life because residual stresses are significantly lower than those in fusion welding.

Industrial applications across aerospace, automotive, marine, railway, and transportation sectors demonstrate the versatility and economic advantages of FSW, including weight reduction, energy efficiency, reduced production time, and improved reliability. Despite challenges such as high initial equipment costs and tool wear for hard materials, the overall benefits make friction stir welding a key enabling technology for modern manufacturing.

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