



**Automation and Process Optimization in Friction Stir Welding for  
Enhanced Manufacturing Efficiency**

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**Abstract**

This paper focuses on Automation and Process Optimization in Friction Stir Welding for Enhanced Manufacturing Efficiency. Friction Stir Welding is an advanced solid-state joining process in which a non-consumable rotating tool generates frictional heat and plastic deformation to join similar or dissimilar materials without melting them. The study highlights that FSW is highly suitable for aluminium, magnesium, copper, titanium, steel, polymers and lightweight engineering materials because it reduces common fusion welding defects such as porosity, cracking, distortion, shrinkage and poor mechanical strength. The paper further explains the importance of automation in FSW through CNC machines, robotic systems, programmable controllers, sensors, real-time monitoring and feedback control mechanisms. Automation improves repeatability, consistency, accuracy, weld quality and productivity by reducing human error and maintaining stable process conditions. Along with automation, process optimization plays a key role in selecting the best welding parameters such as tool rotational speed, welding speed, axial force, plunge depth, tool tilt angle, tool geometry and tool material. Optimization techniques such as Taguchi method, Response Surface Methodology, Analysis of Variance, Grey Relational Analysis, Genetic Algorithm, Artificial Neural Network and machine learning help improve tensile strength, hardness, surface finish, microstructure and defect reduction. The study also discusses how automated FSW enhances manufacturing efficiency by reducing rework, saving material, lowering energy consumption, improving production speed and supporting sustainable manufacturing. However, challenges such as high initial cost, tool wear, fixture design, robotic stiffness, sensor reliability, dissimilar material joining, skilled manpower and maintenance requirements must be addressed. Overall, the paper concludes that the integration of automation and process optimization makes FSW more reliable, intelligent, economical and suitable for modern industrial manufacturing.

**Keywords:** Friction Stir Welding, Automated FSW, Process Optimization, Manufacturing Efficiency, CNC Welding, Robotic Welding, Tool Rotational Speed, Welding Speed, Axial Force

**Introduction**

Automation and process optimization have become essential requirements in modern manufacturing because industries are continuously trying to improve product quality, reduce production time, minimize defects and control overall manufacturing cost. In this context, welding plays a very important role because it is one of the most widely used joining processes in mechanical, automobile, aerospace, railway, marine and structural industries. Traditional welding methods such as arc welding, gas welding, resistance welding and fusion welding have

been used for a long time, but these methods often involve high heat input, melting of base metals, distortion, porosity, residual stresses and defects in the welded joint. To overcome these limitations, friction stir welding has emerged as an advanced solid-state joining technique. It joins materials without melting them, which makes it highly suitable for producing strong, defect-free and reliable joints, especially in aluminium alloys and other lightweight engineering materials.

Friction Stir Welding, commonly known as FSW, was developed as an innovative welding process in which a non-consumable rotating tool is inserted into the joint line of two workpieces. The tool shoulder and pin generate frictional heat and plastic deformation in the material. As the tool moves along the joint line, the softened material is stirred and consolidated behind the tool, forming a strong welded joint. Since the temperature remains below the melting point of the base material, FSW reduces many problems commonly found in fusion welding. It avoids solidification cracking, reduces distortion, improves mechanical properties and provides better microstructural control. Due to these advantages, FSW has become an important technology for joining aluminium, magnesium, copper, titanium, steel and dissimilar material combinations. In the present era of advanced manufacturing, industries are not only concerned with the basic joining of materials, but also with the consistency, repeatability, accuracy and efficiency of the welding process. Manual or semi-automatic welding processes often depend on operator skill, experience and judgment. This may lead to variation in weld quality, process instability, human error and poor productivity. Therefore, automation in friction stir welding has gained significant importance. Automated FSW systems use computer numerical control machines, robotic arms, programmable controllers, sensors, monitoring units and real-time feedback systems to control welding parameters accurately. Automation helps in maintaining uniform tool rotation, welding speed, axial force, plunge depth and tool tilt angle during the welding operation. As a result, the process becomes more reliable, productive and suitable for industrial-scale manufacturing.

Process optimization is another important aspect of friction stir welding. The quality of an FSW joint depends on several process parameters, including tool rotational speed, welding speed, axial force, plunge depth, tool tilt angle, tool geometry, tool material and workpiece material properties. Even a small variation in these parameters can affect heat generation, material flow, grain structure, hardness, tensile strength, surface finish and defect formation. For example, if the rotational speed is too high, excessive heat may lead to grain coarsening and reduced mechanical strength. If the rotational speed is too low, insufficient heat generation may result in poor material mixing and tunnel defects. Similarly, improper welding speed may cause incomplete bonding, voids, or weak joints. Therefore, selecting the correct combination of parameters is necessary for achieving high-quality welds. The optimization of FSW parameters is generally carried out by using experimental, statistical and computational methods. Techniques such as Taguchi method,

Response Surface Methodology, Analysis of Variance, Grey Relational Analysis, Genetic Algorithm, Artificial Neural Network and machine learning approaches are increasingly used to identify the best process conditions. These optimization techniques help researchers and



industries to understand the relationship between input parameters and output responses such as tensile strength, hardness, elongation, impact strength, surface roughness and defect percentage. By using these methods, it becomes possible to reduce trial-and-error experimentation and improve the efficiency of the welding process. Thus, optimization supports both quality improvement and cost reduction. Automation and optimization are closely connected in friction stir welding. Automation provides accurate control of welding operations, while optimization provides the best parameter settings for achieving desired weld quality. When both are integrated, the FSW process becomes more intelligent, stable and efficient. For example, an automated FSW machine equipped with sensors can continuously monitor temperature, force, torque, vibration and tool position during welding. If any variation occurs, the feedback control system can adjust process parameters in real time. This reduces defects and ensures consistent joint quality. Such smart welding systems are highly useful in industries where safety, reliability and precision are very important, such as aerospace and automotive manufacturing. Despite its advantages, automation and process optimization in FSW also face certain challenges. Automated systems require high initial investment, skilled technical knowledge, proper machine setup and regular maintenance. Tool wear, tool material selection, clamping arrangement, heat management and joining of dissimilar materials are still important technical issues.

### **Overview of Friction Stir Welding**

Friction Stir Welding, commonly known as FSW, is an advanced solid-state welding process used for joining two similar or dissimilar materials without melting them. In this process, a specially designed non-consumable rotating tool is inserted between the adjoining edges of two workpieces. The tool consists of two main parts, the shoulder and the pin. When the rotating tool comes in contact with the material, frictional heat is generated between the tool and the workpiece. This heat softens the material around the joint area, but the temperature remains below the melting point of the base metal. Due to this reason, the material does not melt like in conventional fusion welding. Instead, it becomes plasticized and is stirred mechanically by the rotating pin. As the tool moves along the joint line, the softened material flows from the front side of the tool to the rear side and consolidates to form a strong welded joint. Friction Stir Welding was developed to overcome several limitations of traditional welding processes. In fusion welding methods, the base material melts and then solidifies, which can create problems such as porosity, solidification cracking, distortion, shrinkage and loss of mechanical strength. FSW reduces these problems because it takes place in the solid state. Since there is no melting and solidification, the welded joint generally shows better dimensional stability, improved microstructure, lower residual stresses and fewer welding defects. This makes FSW highly useful for materials that are difficult to weld by conventional methods, especially aluminium alloys. Apart from aluminium, FSW is also used for magnesium alloys, copper alloys, titanium alloys, steels, polymers and dissimilar material combinations. The working principle of FSW is based on the combined action of frictional heating, plastic deformation and mechanical stirring. The rotating tool is first plunged into the joint line until the shoulder touches the surface of the workpiece. The shoulder produces most of the frictional heat and helps in containing the

plasticized material, while the pin performs the stirring action inside the joint. After reaching the required plunge depth, the tool is moved forward along the weld line. During this movement, the material around the pin is softened and transported from the advancing side to the retreating side. The pressure applied by the tool shoulder helps in compacting the stirred material and forming a sound weld behind the tool. The final joint is formed due to plastic flow and metallurgical bonding between the materials.

### **Automation in Friction Stir Welding**

Automation in Friction Stir Welding refers to the use of machines, computer-controlled systems, sensors, robotic mechanisms and feedback control techniques to perform the welding process with minimum human intervention. Friction Stir Welding is a process in which accuracy, force control, tool movement, rotational speed, welding speed and plunge depth play a very important role. If these parameters are not controlled properly, the weld joint may develop defects such as voids, cracks, tunnel defects, poor bonding, excessive flash and weak mechanical strength. Therefore, automation becomes highly important in FSW because it helps in maintaining proper control over the entire welding operation. In automated FSW, the machine controls the movement of the rotating tool along the joint line and ensures that the required process parameters remain stable throughout the welding cycle. The basic purpose of automation in FSW is to improve repeatability, consistency, productivity and weld quality. In manual or semi-automatic welding, the quality of the joint depends greatly on the skill and experience of the operator. Different operators may apply different levels of force, speed, or positioning accuracy, which can produce variation in weld quality. Automated systems reduce this dependency on human skill by using programmable machines and control systems. CNC-based FSW machines and robotic welding systems can follow a predefined welding path with high accuracy. They can maintain constant tool rotation, travel speed, tool tilt angle and axial force. As a result, automated FSW produces uniform welds and is suitable for industrial production where large numbers of components need to be joined with the same quality standard. In automated Friction Stir Welding, several components work together to control the welding process. These include a rigid machine structure, rotating spindle, tool holder, clamping system, programmable controller, servo motors, sensors and monitoring devices. The machine structure provides stiffness and stability during welding because FSW requires high axial force. The spindle rotates the welding tool at the required speed, while the feed mechanism moves the tool along the joint line. The clamping system holds the workpieces firmly to prevent movement or separation during welding. The programmable controller stores and executes the welding program. Sensors measure important process variables such as temperature, force, torque, vibration and tool position. These measured values help in monitoring the process and maintaining welding stability.

One of the major features of automation in FSW is real-time monitoring. During welding, process conditions may change due to tool wear, material thickness variation, fixture instability, or changes in heat generation. If these variations are not detected, they may affect the quality of the weld.



Real-time monitoring systems continuously observe the welding process and provide information about the actual condition of the joint formation. Temperature sensors or infrared cameras can be used to monitor heat generation. Force sensors measure axial force and lateral force during tool movement. Torque sensors help in understanding material resistance and tool loading. Vibration sensors can indicate tool instability or defect formation. By collecting such data, automated systems can identify abnormal conditions and support quality control. Feedback control is another important part of automated FSW. In a simple automated system, the machine follows fixed parameter values throughout the welding operation. However, in advanced systems, feedback control allows the machine to adjust parameters automatically according to process conditions. For example, if the temperature becomes too high, the system may reduce tool rotational speed or increase welding speed.

### **Process Optimization in FSW**

Process optimization in Friction Stir Welding is an important technique used to obtain the best welding conditions for producing strong, defect-free and reliable joints. In FSW, the quality of the welded joint depends on several process parameters such as tool rotational speed, welding speed, axial force, plunge depth, tool tilt angle, tool geometry and tool material. These parameters control heat generation, material flow, plastic deformation, grain refinement and final weld strength. If the parameters are not selected properly, the weld may develop defects such as tunnel defects, voids, cracks, excessive flash, incomplete bonding, or poor surface finish. Therefore, process optimization is required to identify the most suitable combination of parameters that can improve weld quality and manufacturing efficiency. The main objective of process optimization in FSW is to achieve maximum mechanical performance with minimum defects and minimum production cost. Mechanical performance includes properties such as tensile strength, hardness, impact strength, fatigue strength, elongation and joint efficiency. In addition to mechanical properties, optimization also focuses on surface quality, microstructure, dimensional accuracy, energy consumption and production time. Since FSW is widely used in industries such as aerospace, automotive, railway, marine and defense manufacturing, the welded joints must meet high quality and safety standards. Optimized welding conditions help industries produce consistent joints with better strength and reliability.

Tool rotational speed is one of the most important parameters in FSW optimization. It controls the amount of frictional heat generated between the tool and the workpiece. When the rotational speed is too low, insufficient heat is produced, which causes poor material softening and improper stirring. This may result in defects such as voids, tunnel defects and weak bonding. On the other hand, if the rotational speed is too high, excessive heat is generated, which may cause grain coarsening, excessive flash, softening of the material and reduction in mechanical strength. Therefore, an optimum rotational speed is necessary to maintain proper heat input and material flow. Welding speed is another important factor that affects the quality of the FSW joint. Welding speed refers to the forward movement of the tool along the joint line. It controls the time available for heat generation and material mixing. At very high welding speed, the tool moves too quickly and the material may not get enough time to soften and flow properly. This can produce incomplete bonding and internal defects. At very low welding speed,

excessive heat may accumulate in the weld zone, leading to wider heat affected zones and reduction in strength. Therefore, welding speed must be optimized along with rotational speed to maintain a balance between heat generation and material movement. Axial force and plunge depth also play a significant role in FSW optimization. Axial force is the downward force applied by the tool on the workpiece during welding. It ensures proper contact between the tool shoulder and the material surface. If the axial force is insufficient, the tool may not generate enough heat or forging pressure, resulting in poor consolidation of the welded material. If the axial force is too high, it may cause excessive thinning, tool wear, or damage to the workpiece. Similarly, plunge depth determines how deeply the tool penetrates into the material. Proper plunge depth is necessary for complete stirring through the thickness of the joint. Incorrect plunge depth may cause root defects or excessive flash formation. Tool tilt angle is also considered during process optimization. A slight tilt of the tool helps in forging the plasticized material behind the tool and improving joint consolidation.

### **Manufacturing Efficiency through Automated FSW**

Manufacturing efficiency through automated Friction Stir Welding refers to the improvement of production quality, speed, consistency, cost-effectiveness and resource utilization by using automatic control systems in the FSW process. In modern manufacturing industries, efficiency is not limited only to producing more components in less time. It also includes producing highquality products with minimum defects, minimum material wastage, low energy consumption, reduced human error and better repeatability. Automated FSW supports all these objectives because it uses computer-controlled machines, robotic systems, sensors and feedback mechanisms to control welding parameters accurately. As a result, the process becomes more stable, predictable and suitable for large-scale industrial production. One of the main ways automated FSW improves manufacturing efficiency is by producing consistent weld quality. In manual or semi-automatic welding, the quality of the welded joint often depends on the skill, attention and experience of the operator. Human error may cause variation in tool position, travel speed, pressure, or weld path. These variations can lead to defects such as voids, tunnel defects, poor bonding, excessive flash and weak joints. Automated FSW reduces such variation because the machine follows pre-set parameters with high accuracy. Tool rotational speed, welding speed, axial force, plunge depth and tool tilt angle can be maintained throughout the welding operation. This consistency improves product reliability and reduces the need for repeated inspection and correction.

Automated FSW also increases productivity by reducing production time. Since the welding path, tool movement and process parameters are programmed in advance, the machine can perform the operation continuously and accurately. This is especially useful in mass production where similar parts need to be welded repeatedly. Automated systems can complete long welds and repeated weld cycles with less interruption compared to manual methods. In industries such as aerospace, automobile, railway, shipbuilding and electric vehicle manufacturing, automated FSW helps in producing lightweight and strong components at a faster rate. This improvement in production speed directly contributes to overall manufacturing efficiency. Another important benefit of automated FSW is the reduction of defects and rework. Defective



welds increase production cost because they require inspection, repair, rejection, or replacement. In critical industries, even a small defect can affect safety and performance. Automated FSW reduces the chances of defect formation by maintaining proper heat input, tool movement and forging pressure. Sensors can monitor temperature, force, torque, vibration and tool position during the process. If any abnormal condition occurs, the system can detect it and help in correcting the process. This reduces rejection rates and improves first-time-right production, which is a key indicator of manufacturing efficiency. Material saving is another major contribution of automated FSW. Conventional fusion welding often requires filler material, shielding gas, flux and post-weld cleaning. In many cases, FSW does not require these additional materials because it is a solid-state joining process. Automated control further reduces wastage by ensuring accurate tool movement and proper joining conditions. Less scrap generation means better use of raw material and lower production cost. This is particularly important when expensive materials such as aluminium alloys, magnesium alloys, titanium alloys, or special lightweight materials are used in advanced manufacturing.

Energy efficiency is also improved through automated FSW. Since FSW joins materials below their melting point, it generally requires lower heat input compared to many fusion welding processes. Automated systems make the energy use more controlled and efficient because unnecessary overheating, repeated welding and excessive processing time can be avoided. Proper optimization of rotational speed, welding speed and axial force ensures that only the required amount of energy is used to produce a sound weld. Lower energy consumption reduces production cost and also supports environmentally sustainable manufacturing. Automated FSW improves labor efficiency by reducing dependence on manual operation. Skilled welders are important in manufacturing, but manual welding can be physically demanding and may involve risks such as fumes, heat, radiation and fatigue. In automated FSW, the operator mainly supervises the machine, sets process parameters and monitors the welding cycle. This reduces physical strain and improves workplace safety. It also allows industries to use human resources for higher-level tasks such as programming, inspection, process planning and quality management. Thus, automation does not simply replace labor, but improves the productive use of skilled manpower. Another way automated FSW enhances efficiency is through better process monitoring and quality control. Automated machines can collect real-time data during welding, such as temperature profile, tool force, torque, spindle speed and weld path accuracy. This data can be stored and analyzed for quality assurance. If a defect appears in a welded component, the recorded process data can help identify the cause. This improves traceability and supports continuous improvement in manufacturing. In industries that require strict quality standards, such as aerospace and defense, such process records are very valuable.

Automated FSW is also useful for joining complex and large components. Robotic FSW systems can weld curved surfaces, three-dimensional parts and complex joint paths. CNC-based systems can produce long and straight welds with high accuracy. This flexibility improves manufacturing efficiency because different product designs can be handled with less change in tooling and setup. In modern production systems, flexibility is important because industries often need to produce different models or customized components. Automated FSW

helps manufacturers respond to such requirements more effectively. The integration of automated FSW with process optimization further strengthens manufacturing efficiency. Optimized parameters ensure that the welding conditions are scientifically selected, while automation ensures that these conditions are accurately applied during production. When both are combined, the result is improved weld strength, better surface finish, reduced defects and lower production cost. For example, an optimized combination of rotational speed and welding speed can produce proper heat generation and smooth material flow. Automated control can maintain this combination throughout the process, ensuring consistent results in every weld. Automated FSW also supports sustainable manufacturing. It reduces material wastage, lowers energy consumption, minimizes harmful emissions and improves product life. Since the process produces fewer fumes and does not usually require filler material or shielding gas, it is cleaner than many conventional welding processes. Better weld quality also means longer component life and fewer failures during service.

### **Challenges in Automated FSW**

Automated Friction Stir Welding provides many advantages in modern manufacturing, but its successful implementation also involves several technical, economic and operational challenges. Since FSW is a solid-state joining process, it requires accurate control of tool rotation, welding speed, axial force, plunge depth, tool tilt angle and material flow. In an automated system, even a small error in parameter control can affect heat generation and plastic deformation. If the heat input is too low, the material may not soften properly, which can cause tunnel defects, voids, or incomplete bonding. If the heat input is too high, excessive flash, grain coarsening, material thinning, or reduction in mechanical strength may occur. Therefore, maintaining the correct balance of process parameters is one of the major challenges in automated FSW. One of the most important challenges is the high initial cost of automated FSW systems. Automated machines require rigid machine structures, powerful spindles, CNC controllers, robotic arms, servo motors, sensors, fixtures, data acquisition systems and feedback control units. These components make the setup expensive compared to conventional welding systems. Small and medium-scale industries may find it difficult to invest in such advanced equipment. Apart from installation cost, maintenance, calibration, software updates and skilled manpower also increase the overall cost. Therefore, although automated FSW can reduce long-term production cost, its initial investment remains a major barrier. Tool wear and tool failure are also serious challenges in automated FSW. The welding tool is exposed to high friction, high temperature, axial force and severe mechanical loading during the process. If the tool wears out, its geometry changes and this affects heat generation and material flow. A worn tool may produce poor surface finish, weak joints, voids, or irregular weld profiles. Tool failure can stop production and damage the workpiece or machine. This problem becomes more serious when welding hard materials such as steel, titanium, or dissimilar materials. Therefore, proper tool material selection, tool design, cooling methods and regular inspection are necessary for reliable automated FSW. Another challenge is the complexity of parameter selection. Automated FSW depends on many interrelated parameters and each parameter affects the weld quality differently. Tool rotational speed, welding speed, axial force, plunge depth, tilt angle,



shoulder diameter, pin profile and material thickness must be selected carefully. A parameter combination suitable for one material may not work for another material. Similarly, different joint designs and thicknesses require different welding conditions. Because of this, industries often need experimental trials, statistical optimization, or machine learning-based prediction models to identify suitable parameters. This increases the time and effort required before actual production.

Fixture design and workpiece clamping are also major issues in automated FSW. During welding, high axial and lateral forces act on the workpieces. If the plates are not clamped properly, they may separate, bend, vibrate, or move from their original position. Poor clamping can lead to misalignment, root defects, lack of penetration and poor surface quality. In automated production lines, fixture systems must be strong, accurate, repeatable and suitable for different component shapes. Designing such fixtures can be difficult and costly, especially for large, curved, or complex components. Robotic FSW faces additional challenges related to stiffness and force control. Robots are flexible and useful for complex welding paths, but they may not have the same rigidity as heavy CNC-based FSW machines. Since FSW requires high axial force and stable tool positioning, lack of stiffness may cause tool deflection, vibration, inaccurate plunge depth and poor weld quality. To overcome this, robotic FSW needs advanced force control systems, path correction methods and strong robotic structures. These requirements make robotic FSW more complex than simple automated welding operations. Real-time monitoring and feedback control also present technical challenges. Sensors used in automated FSW must measure temperature, force, torque, vibration, tool position and material response accurately. However, welding conditions are harsh and sensors may be affected by heat, vibration, dust, or mechanical loading. Data collected from sensors must be processed quickly and correctly to make real-time adjustments. If the feedback system is slow or inaccurate, it may not prevent defect formation. Therefore, reliable sensor integration, data processing and control algorithms are essential for effective automated FSW.

### **Conclusion**

Automation and process optimization in Friction Stir Welding play a significant role in improving modern manufacturing efficiency. Friction Stir Welding is different from conventional fusion welding because it joins materials in the solid state without melting the base metal. Due to this feature, it reduces defects such as porosity, solidification cracking, distortion, shrinkage and weak bonding. It also provides better mechanical strength, improved microstructure, low residual stress and high joint reliability. These qualities make FSW an effective welding technique for industries such as aerospace, automotive, railway, marine, defense and electric vehicle manufacturing. The study shows that automation improves the performance of FSW by providing accurate control over important welding parameters. Automated systems such as CNC machines, robotic arms, programmable controllers, sensors and feedback control units help maintain uniform tool rotation, welding speed, axial force, plunge depth and tool tilt angle. This reduces human error and improves repeatability, consistency and production quality. Real-time monitoring of temperature, force, torque, vibration and tool position further supports defect detection and quality control during welding.

Process optimization is equally important because the final weld quality depends on the proper selection of parameters. Tool rotational speed, welding speed, axial force, plunge depth, tool geometry and tool material directly affect heat generation, material flow, grain structure, tensile strength, hardness and surface finish. If these parameters are not optimized, defects such as voids, tunnel defects, incomplete bonding, excessive flash and weak joints may occur. Optimization methods such as Taguchi method, Response Surface Methodology, ANOVA, Grey Relational Analysis, Genetic Algorithm, Artificial Neural Network and machine learning help identify the best parameter combinations for stronger and more reliable welds. Automated and optimized FSW contributes to manufacturing efficiency by improving weld quality, reducing rework, minimizing material wastage, lowering energy consumption and increasing production speed. It also supports sustainable manufacturing because it usually does not require filler material, shielding gas, or flux. The process produces fewer fumes and supports the joining of lightweight materials, which is important for fuel-efficient and energy-efficient industrial products. However, the successful implementation of automated FSW requires proper planning and technical expertise. High setup cost, tool wear, tool failure, complex parameter selection, fixture design, robotic stiffness, sensor accuracy, dissimilar material joining, defect inspection and skilled manpower are major challenges. These limitations can be reduced through improved machine design, advanced tool materials, reliable monitoring systems, artificial intelligence, machine learning, preventive maintenance and proper operator training.

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