Recent Development in Friction Stir Welding Process: A Review

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Abstract

The Friction stir welding (FSW) is recently presented so to join different materials without the melting process as a solid-state joining technique. A widely application for the FSW process is recently developed in automotive industries. To create the welded components by using the FSW, the plunged probe and shoulder as welding tools are used. The Finite Element Method (FEM) can be used so to simulate and analyze material flow during the FSW process. As a result, thermal and mechanical stresses on the workpiece and welding tool can be analyzed and decreased. Effects of the welding process parameters such as tool rotational speed, welding speed, tool tilt angle, depth of the welding tool, and tool shoulder diameter can be analyzed and optimized so to increase the efficiency of the production process. Material characteristics of welded parts such as hardness or grain size can be analyzed so to increase the quality of part production. Residual stress, strain, deformation, and estimations of the temperatures in the welding area can be predicted using the simulation of FSW in the FEM software. Heat generation, thermal, and thermomechanical analyses can also be implemented on the welded parts to analyze the distribution of temperature and strain in the heat-affected zone (HAZ). Moreover, welding operations of dissimilar metals can be analyzed using numerical simulation to increase the capabilities of the welding methodology in different industrial applications. In this article, a review of the FSW process is presented. As a result, the research filed can be moved forward by reviewing and analyzing recent achievements in the published papers.
1. Introduction

The new method of welding operation is presented by The Welding Institute in 1991 [1] as friction stir welding (FSW) to create a solid-state joining methodology. The method is a solid-state joining technique that is by joining the parts at the temperature below the melting point. As a result, some problems related to the melting phase of the materials such as porosity, formation of second phases, embrittlement, and cracking can be presented to create welded parts with lower residual stresses, defect, and distortion [2, 3, 4]. A widely application for the FSW process is recently presented in different industries such as aerospace, railway, and automotive.

A rotating welding tool is pressed against workpiece surfaces so to create a welded part. Then the friction between the welding tool and the materials of the workpiece can create heat that causes the welded material to be softened at a temperature less than its melting point. A schematic of the FSW process is shown in Figure 1.

The FSW process can be widely used in automotive industries as a result of advantages in the produced parts. These include the joining of extruded parts to form “larger extrusions,” the joining of tailor-welded blanks, and the joining of various assembly applications. The FSW in each of these has diverse advantages and resulting cost reductions [5]. To decrease the amount of fuel usage in the produced cars, the total weight of the cars should be decreased. The new trend for the issue in the automotive industries is applying the multi-material concept including a hybrid of light metals. The joining technique can play an important role to join dissimilar materials for lightweight applications in car production systems. It is possible to join the dissimilar materials such as aluminum to steel, aluminum to magnesium, and steel to magnesium alloys, enabling optimum exploitation of the best properties of both materials in the car production industries. The joining method is an effective solution for the weight problem in the car parts because of using the nonconsumable characteristics in the welding operation. Aluminum doors, engine hoods, fuel tank, car seats, and deck lids in the automotive industries can be produced using the FSW process so to increase efficiency in the process of car manufacturing. Also galvanic corrosion can be prevented because of the application of the FSW joining process in the car production industries. The joining process in assembly lines of car industries can be developed using the robotic arms to increase the capabilities of the method in part production. As a result, a robot simulation program can be applied to the system to increase accuracy as well as reachability in the assembly process of car parts. The assembly of aluminum automotive components can be implemented using the FSW process so to provide minimal distortion, higher tensile strength, lower costs, and improved weld capability than other joining processes [6]. The advantages of the FSW in comparison to the resistance spot welding process are now considered in many applications of car production systems so to increase efficiency in the car manufacturing industries.

An advanced analysis system is provided by virtual environments so to analyze and modify the manufacturing

![Figure 1](image_url)
operations. Milling machining operations as a common method of part production are analyzed and modified in virtual environments by Soori et al. [17, 8, 9, 10]. Moreover, the FSW operation can be analyzed so to be modified in virtual environments. Physical couplings between mechanicals and heat transfer, very large deformations and strain rates in the stirring zone around the pin, and material flow during the FSW process can be simulated and analyzed in virtual environments to increase accuracy as well as the efficiency of part production.

A review of the numerical analysis of the FSW process is presented by He et al. [11] that considered the microstructures of friction stir-welded joints and the properties of friction stir-welded structures. Also Nandan et al. [12] presented recent advances in the FSW process that consider weldment structure and properties. Heat generation, heat transfer, and plastic flow during welding and elements of tool design are reviewed in this article so to develop the welding operation. A review in FSW of titanium alloys sheets is presented by Gangwar and Ramulu [13] that considered similar or dissimilar titanium alloys and focused on surface and subsurface properties, such as microstructural, and mechanical properties and texture evolution. Mishra and Ma [14] presented current developments in process modeling, microstructure and properties, material-specific issues, and applications of the FSW process. A review of the tools for FSW and processing is presented by Zhang et al. [15] to develop the FSW tools in the study.

Based on the authors’ findings to date, it was determined that there is no similar review paper in the FSW process, considering the presented topics of the study in this article. It is a new research work review that considered novel issues from effective parameters and challenges with different views of previous review papers in the FSW process [11, 12, 13, 14, 15]. A novel view in reviewing, analyzing, and classifying the recent research works dated from 2000 to 2019 in the FSW process is developed in this article to provide a useful study for researchers in this field of interest. Simulation and analysis of the FSW process and applications in different fields of industries are presented in the study, reviewing and analyzing recent achievements from 115 published papers. As a result, new ideas in the FSW process are introduced to researchers so to push forward this interesting field of research.

In order to categorize and analyze the published papers in the FSW process, the different ideas of research works are classified as follows: Effects of process parameters to the welding operation [16, 17, 18, 19, 20, 21]; Analysis of material flow during the FSW process [22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]; Numerical simulation of FSW for dissimilar metal welding [45, 46, 47, 48]; Material characteristics of welded parts [11, 13, 49, 50, 51, 52]; Heat generation, thermal, and thermomechanical analysis [53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65]; Fatigue behavior of welded parts [66, 67, 68, 69, 70, 71, 72, 73, 74, 75]; Corrosion resistance in the welded parts [76, 77, 78, 79, 80, 81, 82]; Automation in the FSW process [83, 84, 85, 86, 87, 88, 89, 90]; Comparison between the FSW-welded and tungsten inert gas (TIG)-welded parts [91, 92, 93, 94, 95, 96, 97, 98]; Design of the FSW tools [99, 100, 101, 102, 103, 104, 105, 106, 107]; Effect of single and double passes to microstructures and mechanical properties of welded parts [108, 109, 110, 111, 112, 113, 114, 115].

Section 2 presents a review from research works related to simulation of the FSW process. In Section 3, research works are classified according to the different topics of research on the FSW process.

2. Different Topics of Research Works on FSW

The research works in the field of FSW is recently developed on different topics of effective parameters to increase quality as well as efficiency in the welding operations. Analytical and experimental studies are applied in different research works to develop the previous achievements in FSW joining operation. To analyze and modify the welding operation of the FSW, different related issues of the process are recently considered and presented. The topics are classified in this section so to review the achievements in the research field.

2.1. Effects of Process Parameters on the Welding Operation

There are process parameters in the FSW joining operation such as tool holding time, tool-shoulder geometry, tool tilt angle, tool rotation rate, and tool traverse speed that can increase the quality and efficiency of part manufacturing. Two important parameters are tool rotation rate and tool traverse speed in the joining operation. The effects of the process parameters are analyzed in different research works to increase efficiency in the FSW process.

The principles and recent developments of FSW process is investigated by Gibson et al. [16] to develop the process of part production by using the FSW operations. In this study, the effects of process parameters such as tool-shoulder geometry and rotating speed to the welding operation, methods of evaluating weld quality different applications of FSW, and multiple aspects of robotic FSW are discussed so to present future directions for research works.

To analyze the influence of process parameters such as welding speeds and tool rotating speed on the obtained joints and optimize the overall process for a larger range of tools, process conditions, and materials, a friction model for FSW process simulation using Coulomb’s model is presented by Assidi et al. [17].

Effective parameters of the FSW process such as tool rotating speed and tool holding time are considered by Tozaki et al. [18] to study the static strength of dissimilar parts in friction stir spot-welds between different aluminum alloys.
Gill et al. [19] presented a mathematical modeling of process parameters of friction stir-welded aluminum alloy joints such as tool rotational speed, welding speed, and tool shoulder diameter using a central composite design. The welding parameters such as tool rotational speed, welding speed, and tool shoulder diameter are analyzed in the study to predict mechanical properties of friction stir-welded aluminum alloy joints. As a result, the direct effect of tool rotational speed and tool shoulder diameter on the toughness of the workpiece are analyzed and discussed. The FSW process parameters such as tool rotational speed and feed rate are analyzed and optimized by Lombard et al. [20] to minimize defects and maximize fatigue life in a 5083-H321 aluminum alloy. To analyze the influence of process parameters such as rotational speed, traverse speed, and tool tilt angle to the quality of welded parts, the FSW process is simulated in virtual environments by Subhashini et al. [21]. So accuracy, as well as the quality of produced parts by using FSW, can be increased using the presented methodology in the study. The effects of input and output parameters to develop the FSW process are shown in Figure 2.

To develop the FSW process, the optimization methods can be applied to the effective process parameters by considering accuracy, surface roughness, mechanical properties, and residual stress. As a result, efficiency in the process of the FSW can be increased.

2.2. Analysis of Material Flow as Numerical Simulation and Finite Element Simulation during the FSW Process

The material flow in the FSW process is analyzed in different research works for optimal tool design and to obtain high structural efficiency welds. Advanced FSW tools can be presented as a result of analyzing the rate of material flow to decrease the rate of tool failure in the joining operation. Also the temperature of the joining zone and created forces in the welding process can be analyzed by applying the analysis of the material flow in the FSW operation.

The effects of rotational tool geometry on the numerical simulation of material flow behavior in the FSW process are developed by Ji et al. [22]. To design the geometry of the welding tool shoulder, the finite volume model of FSW is established in the study. Thus, the material flow in the FSW process is modified to decrease the welding tool defects during the FSW process. To describe the material flow around the welding tool, a simple Eulerian thermomechanical modeling of FSW is developed by Jacquin et al. [23].

The failure of the welding tool in the FSW process can be decreased by using the presented analysis of thermal and mechanical stress in the study. Numerical modeling of the FSW process is presented by Neto and Neto [24] to investigate the material flow and heat generation in the welding operation.
Two-dimensional (2D) finite element simulation of material flow in the FSW process is presented by Deng and Xu [25]. In this article, 2D simulation results of the material flow pattern and spatial velocity field around the rotating tool pin during welding and operation and the positions of material particles around the pin after welding operation are investigated.

A simple and robust moving mesh technique for the finite element simulation of the FSW process is studied by Feulvarch et al. [26]. A numerical modeling is developed in the study to model the material flow and heat transfer for an unspecified tool's geometry. A 3D numerical simulation of different phases of FSW is presented by Guerdoux and Fourment [27] so to compute the material flow and the temperature evolution during the three phases of the FSW process.

Zhang and Zhang [28] presented numerical studies on the effect of transverse speed in FSW. In this article, a fully coupled thermomechanical model is developed to analyze the effect of the transverse speed parameter on the FSW process. The power needed for FSW, the material flow patterns, and the ratio of the plastic and frictional contributions to the temperature in the FSW process under different transverse speeds are also studied so to increase the efficiency of the welding operations.

The finite element simulation method based on Lagrangian-Eulerian formulation and adaptive remeshing technique for the FSW process is developed by Zhang et al. [29] to investigate the flow of metal during the welding operation. Simulation and analysis of material flow during the FSW process is presented by Yang et al. [30] by analyzing the distribution of the tracer material Cu in the spot welding operations. As a result, the welding tool pin extrudes the material downwards before the shoulder contacts the upper sheet in the welding process.

Moreover, after the rotating shoulder comes in close contact with the upper sheet, three distinct regions are developed in the welding region. Finite element simulation of material flow in FSW is presented by Xu et al. [31] to analyze possible variations in the material flow pattern due to variations in process parameters.

Tutunchilar et al. [32] presented a simulation of material flow in friction stir processing of a cast Al-Si alloy to predict the material flow pattern, temperature distribution, and effective plastic strain in the weld zone. Lagrangian thermomechanical simulation of FSP by employing the DEFORM-3D as commercial finite element method (FEM) software is used in the study to develop simulation procedures of the welding operation. Lorrain et al. [33] presented the material flow path of the FSW process using unthreaded tools so to analyze the material flow when unthreaded pins are used in the welding operation. In this study, cross sections and longitudinal sections of welds were observed with and without the use of material marker (MM) to investigate the material flow in the FSW operation.

In order to develop the numerical simulations on material flow behaviors, GAO et al. [34] presented different theories such as computational fluid dynamics (CFD) and computation solid mechanics. To simulate the joining process, two-stage methods, plunge stage and steady welding stage, are developed in the study.

To analyze and develop the behavior of material flow in the FSW process of dissimilar parts, Sadeghian et al. [35] developed a simulation of the weldment. Thermal and CFD simulations are developed in the study so to predict the temperature distribution and material flow velocity during the FSW process.

Analysis of the material flow in the FSW process is a challenging process that needs complicated computational models of the joining operation. It can be optimized using the optimization techniques that considered the process parameters as well as welding tool geometries so to increase quality and efficiency in part production.

### 2.3. Stress, Strain, and Deformation Analysis

To analyze the stress and strain of welded parts in the FSW process, the geometrical design of the welding tool can be investigated by applying the static loads against the tool in the joining operation. Also, process parameters such as the rational speed of the cutting tool can affect the stress and strain of the welding tool. The stress and strain of the welded parts will increase when the rotational speed increases.

Li et al. [36] presented residual stresses simulation for friction stir-welded joint by developing the semi-coupled thermomechanical finite element model containing both thermal load and mechanical load. A process model for FSW of age hardening aluminum alloys is developed by Frigaard et al. [37] in order to estimate the mean strain rate within the welding region. Mechanical and thermal modeling of FSW using semi-analytical thermomechanical modeling is presented by Heurtier et al. [38] to obtain the strains, strain rates, and the obtained temperatures and microhardness in the various weld zones.

Experimental defect analysis and force prediction simulation of high weld pitch FSW is developed by Crawford et al. [39] in order to obtain the deflection of the welded parts in the FSW operation. A 3D numerical model is implemented in the study, using the CFD package Fluent to simulate and investigate the parametric relationship of the forces and torques during the FSW process.

In order to obtain the optimized tool speeds on the desired welding temperatures and forces acting on the pin of the welding tool, the simulation and analysis of the FSW process are developed by Ulysse [40]. Simulation and experimental validation in the FSW are presented by Dialami et al. [41] in order to develop mathematical models for the process analysis. A modified Norton's friction law is developed in the study to predict a realistic temperature field, the forces, and torques in the FSW operation. Zhu et al. [42] developed a finite element model to simulate the defect formation during FSW operations.

To predict and analyze the defect formation during FSW based on the coupled Eulerian-Lagrangian method, a 3D
coupled thermomechanical finite element model is developed in the study. As a result, the plasticized zone shape and the presence of a void in the weld quite can be accurately predicted in order to increase the quality of produced parts, using the FSW process. Probing torque, traverse force, and tool durability in FSW of aluminum alloys is developed by Buchibaba et al. [43]. To examine the impact of plate thickness, alloy strength, and processing conditions on the susceptibility of tool failure in FSW, a simulation methodology is developed in the study. Chauhan et al. [44] presented the modeling of defects in FSW by using coupled Eulerian and Lagrangian methods in order to predict the formation of defects during the welding process. To predict defect formation during FSW, a 3D thermomechanical model is proposed in the study to simulate and analyze all the three phases of FSW based on the CEL method.

2.4. Numerical Simulation of FSW for Dissimilar Metal Welding

To increase the capability of the FSW process in different industries such as the automotive industries, joining operations of dissimilar materials can be implemented. The microstructure, hardness, and fatigue properties of the welded part using FSW can be analyzed using numerical simulation so to increase the quality and efficiency of part production.

To obtain the ultimate tensile strength of the welded parts in the FSW process of dissimilar joints, the process is numerically simulated and optimized by Kumar et al. [45]. FSW of dissimilar alloys is studied by DebRoy and Bhadeshia [46] so as to assess the status of FSW of dissimilar alloys. The FSW process for the dissimilar joints Al 6013-T4 to X5CrNi18-10 stainless steel is analyzed by Uzun et al. [47] to study the microstructure, hardness, and fatigue properties of the welded part. To develop the FSW for dissimilar materials between aluminum alloy (AA6061 and AA7075), process parameters such as materials position and welding speed of the welding operation are analyzed and discussed by Guo et al. [48].

FSW welding operations of new composites can be analyzed in order to increase the capability of the method in different industries.

2.5. Material Characteristics of Welded Parts

To increase the quality of welded parts using the FSW process, material characteristics such as texture evolution, hardness and grain size, and structure of the welding zone are analyzed. As a result, the quality of the joining operation can be increased.

Kim et al. [49] presented a numerical simulation of friction stir butt welding process for AA5083-H118 sheets to predict material characteristics of the weld such as hardness, grain size, and possibly for the susceptibility of the weld. Numerical analysis of FSW is presented by He et al. [11] to review the latest developments in the numerical analysis of the FSW process. Microstructures of friction stir-welded joints and the properties of friction stir-welded structures are analyzed in the study to develop the simulation and modification process of the welding method in virtual environments. The recrystallized microstructure of the welded zone in the FSW process of Al alloy using a plane-strain compression test is experimentally tested by Masaki et al. [50] in order to simulate and analyze the recrystallized grain structure of the friction stir welds and the effective strain rate in the welding operation. A continuum-based FEM model for FSW is developed by Buffa et al. [51] to investigate the distribution of temperature and strain in the heat-affected zone (HAZ) and the weld nugget. To develop the FSW process of AA6082-T6 aluminum alloys, applications of the Continuous Dynamic Recrystallization (CDRX) modeling in the FSW operations is investigated by Fratini and Buffa [52]. Gangwar and Ramulu [13] presented a review in FSW of titanium alloys focusing on the surface and subsurface properties, such as microstructural, mechanical properties, and texture evolution. Therefore, the FSW of similar titanium alloys with suggested strategies to tackle emerging problems is discussed in the study in order to increase the quality of produced parts by the FSW.

2.6. Heat Generation, Thermal, and Thermomechanical Analysis

The generated heat in the FSW process is under the influence of different process parameters such as tool rotation rate, tool traverse speed, and welding tool geometries. To determine the temperature distributions, the effective parameters to the generated heat in the FSW process are investigated in different research works, and the results are also examined. So a developed joining operation can be presented using the simulation and analysis of heat generation in the FSW process.

The plunge stage in the FSW process is experimentally and numerically studied by Mandal et al. [53]. To find the effects of thermomechanical stress in the welding operation, a 3D finite element model and simulation are developed in the study.

The temperature distribution of aluminum alloy (AA)2024-T3 is presented in Figure 3 [53].

Thermomechanical modeling and force analysis of FSW by considering the mechanical effect of the tool using the FEM is presented by Chen and Kovacevic [54]. The longitudinal, vertical, and lateral forces in the welding of AA6061 are obtained in the study in order to obtain the thermal history and stress distribution in the welded zone.

The longitudinal, vertical, and lateral forces in the welding of AA6061 are obtained to study the thermal history and stress distribution in the weld. An analysis on the transient temperature and residual thermal stresses in FSW of AA6061-T6 by using the numerical simulation is presented by Riahi and Nazari [55].
The FSW process of Al6061-T6 is numerically simulated and analyzed so to obtain the distribution model of the residual and thermal stresses in the welded parts. The presented models in the study can correctly predict the nonsymmetric nature of the FSW process, and the relationships between the tool forces and the variation in the process parameters. To develop thermal and thermomechanical analysis, finite element modeling of FSW operation in the butt welding of AA6061-T6 is presented by Chen and Kovacevic [56]. The thermal analysis of the welded zone and the evolution of the longitudinal, lateral, and through-thickness stress in the friction-stirred weld are numerically presented in the study so to develop a dynamic analysis of the FSW.

Numerical simulation of 3D heat transfer and plastic flow during FSW is investigated by Nandan et al. [57]. The equations of conservation of mass, momentum, and energy are solved in three dimensions of moving by using spatially variable thermophysical properties and non-Newtonian viscosity. A thermomechanical model based on the Lagrangian finite element formulation with a nonuniform mesh with adaptive boundary conditions for FSW of Al 6061 is presented by Soundararajan et al. [58]. As a result, stress development in the FSW process can be predicted and decreased by using the presented method in the study.

So to understand residual stress and the variation of transient temperature in FSW of 304L stainless steel, a research work is developed by Zhu and Chao [59]. Experimental and numerical studies based on steady-state heat transfer analysis using FEM techniques in the FSW process is developed by Chao et al. [60] to determine the temperature distributions and generated heat in the workpiece and the welding tool. To analyze the primary conditions under the cavity behind the welding tool, a local model for the thermo-mechanical conditions in FSW is studied by Schmidt and Hattel [61]. To obtain the thermal analysis of the welding operation, the ABAQUS software is used while a fully coupled thermomechanical 3D FE model is developed in the study. A numerical simulation based on the coupled Eulerian/Langrangian computation method for friction stir butt-welding of AA6061 is presented by Zhao et al. [62] in order to analyze the linear motion of the rotating tool in virtual environments. Temperature fields and vector plots are determined by using the finite volume method in order to analyze the effect of the mechanical aspects of the model through temperature-dependent material properties. The FSW process is simulated and analyzed by Zhang [63] in order to contribute to the investigation of heat generation by using numerical studies on the FSW.

To analyze the counterrotating twin-tool system in the FSW process, a simulation study based on the 3D nonlinear thermomechanically coupled transient analysis is developed by Jain et al. [64]. Lower thermal gradients along the transverse and thickness directions are achieved for twin-tool in the FSW operation. FSW is numerically simulated by Paulo et al. [65] to predict and analyze the HAZ using a softening model. As a result, the developed numerical model in the study can simulate the FSW process using a softening model to predict the hardness distribution in the HAZ location with acceptable accuracy.

To decrease residual stress in the welded parts, the generated heats on the welding zone should be analyzed and
decreased. Thus, the performances of the welded parts in actual working conditions can be increased.

### 2.7. Fatigue Behavior of Welded Parts

To predict the performance of the welded parts in actual working conditions, the fatigue behavior of produced parts can be analyzed. Residual stress as well as growth rate of fatigue cracks in the welded parts can be investigated in order to be reduced. As a result, welding performances in actual working conditions can be increased.

The fatigue behavior of FSW and MIG weldments for two aluminum alloys is studied by Moreira et al. [66] so to predict and analyze the macroscopic mechanical behavior of the microstructural feature in actual working conditions. Jata et al. [67] presented a study on the friction-stir welding effects on microstructure and fatigue behavior of AA7050-T7451 so to increase the strength of the welded parts in the fatigue cracks. The role of residual stress and HAZ properties on fatigue crack propagation in friction stir-welded 2024-T351 aluminium joints is studied by Bussu and Irving [68] to analyze and decrease the growth rate of cracks from the weld line. The influence of welding speed on the fatigue of friction stir welds and a comparison between MIG and TIG are investigated by Ericsson and Sandström [69] so to decrease the fatigue cracks in the welded parts. In order to decrease the failure of welded structures and increase welding performances, fatigue properties of friction stir welds in AA5083 is studied by Zhou et al. [70]. Low-cycle fatigue of friction stir-welded Al-Mg alloys is studied by Czechowski [71] to increase performances of welded parts in actual working conditions. In order to increase joint efficiency in the welding process, fatigue properties of friction stir-welded particulate-reinforced aluminum matrix composites is presented by Minak et al. [72]. To improve the weld strength and fatigue life in the welded parts, the effect of shoulder geometry on residual stress and fatigue properties of AA6082 FSW joints is studied by De Giorgi et al. [73]. Moreover, Pao et al. [74] studied the corrosion-fatigue crack growth in friction stir-welded Al 7050 for it to be analyzed and decreased. In the article, the growth rate of the fatigue crack in the welded zone, HAZ, and base metal for both air and 3.5% NaCl solutions are calculated and analyzed. Also, James et al. [75] investigated the weld tool travel speed effects on fatigue life of single-pass friction stir welds in 5083 aluminum in order to decrease the growth rates of cracks and levels of plastic deformation in the welded structures.

### 2.8. Corrosion Resistance in the Welded Parts

To increase the quality of welded parts using the FSW process, corrosion properties can be investigated. So the rate of failure in the produced parts due to poor mechanical properties can be decreased.

Corrosion resistance in FSW and MIG welding techniques of A6XXX is studied by Maggiolino and Schmid [76] for it to be analyzed. Thus, the performances of welded parts in actual working conditions can be developed. To decrease the defects resulted from poor mechanical properties of welded parts, Frankel and Xia [77] investigated the localized corrosion and stress corrosion cracking resistance of friction stir-welded AA5454. To increase the safety of welded parts in actual working conditions, pitting and stress corrosion cracking resistance of friction stir welded AA5083 using electrochemical measurements is studied by Zacchi et al. [78].

To evaluate the corrosion properties of an FSW process in 3D 304 stainless steel, Park et al. [79] presented the corrosion properties of these regions using a double-loop electrochemical potentiokinetic reactivation test. Rajakumar et al. [80] developed the predicting tensile strength, hardness, and corrosion rate of friction stir-welded AA6061-T6 aluminum alloy joints so to describe the performances of the welded parts and the tensile strength and hardness of the welded parts.

To evaluate and analyze the corrosion of FSW-welded AA2024 and AA2195, Corral et al. [81] studied the corrosion behavior associated with the FSW of aging aircraft alloy (2024 Al). As a result, mechanical properties of the welded zone as well as corrosion resistance of the welded part are studied in order to be analyzed and modified.

Corrosion behavior of AA6061 joined by FSW and gas tungsten arc welding methods using the optical metallography and scanning electron microscopy together with energy-dispersive spectroscopy (SEM-EDS) is investigated by Fahimpour et al. [82]. So the strength of the welded parts can be increased using the presented methodology in this study.

### 2.9. Automation in the FSW Process

To develop the FSW in the different applications, an automated joining process is presented. Different parameters of the process can be accurately adjusted in order to increase the quality of produced parts. Force control can be applied to the joining operation to decrease the rate of welding tool failure in the welding operation. Also, the surface quality of the welded parts can be increased using torque controlling in the automated welding operation.

Automation and control in the FSW operation is developed by Gibson et al. [16] so to increase weld quality by improving the sensing, control, and joint tracking in the welded parts. Also in order to analyze and develop the accuracy and quality of produced parts using the FSW process, an investigation of force-controlled FSW for manufacturing and automation is presented by Longhurst et al. [83]. An experimental and numerical proof of concept for automation and manufacturing in the FSW of a small-diameter pipe is presented by Lammlein et al. [84] to increase efficiency in the process of part production using FSW process. The automation of FSW through temperature measurement and closed-loop control is presented by Fehrenbacher et al. [85] to improve the controlling systems of the weld quality. An automated
torque control system in the FSW operation, considering the surface conditions of the workpiece, is developed by Longhurst et al. [86] so to increase the surface quality of produced parts using the FSW process. An automation system for the FSW using traverse speed force control is developed by Longhurst et al. [87]. Signals related to the thermal energy in the welding zone with feedback of the axial force is obtained in the study to analyze and control thermomechanical conditions in the welding environment. An automated production system considering the effect of pin length as well as rotation rate on the tensile strength of a friction stir spot-welded Al alloy is developed by Longhurst et al. [88]. Also, in order to join aluminum matrix composites by using optimization procedure, Dinaharan et al. [89] developed the automation of FSW process. Moreover, in order to predict tensile strength, elongation, and wear rate in the optimization process, mathematical models are developed in the study. To control the FSW process temperature with regard to mechanical properties of welded parts, temperature control of robotic FSW using the thermoelectric effect is also investigated by De Backer et al. [90].

2.10. Comparison between the FSW-Welded and TIG-Welded Parts

The TIG welding operation is an effective and powerful technique in the joining operations. To provide a comparison between the performances of produced parts using the FSW and TIG joining processes, different research works are presented. Tensile strength, mechanical properties of the joined parts, and microstructure analysis of welded parts are investigated to select the most suitable joining operation. So the efficiency of part production can be increased as a result of using the most appropriate welding method in the production processes.

A comparison between FSW and TIG welding techniques in AA2024-T3 butt joining is investigated by Squillace et al. [91] to modify the microstructure and pitting corrosion resistance in the welded parts. To analyze and compare the grain sizes in the welded nugget zone of FSW as well as the molten zone of TIG-welded joints, a comparison of FSW and TIG-welded joints in Al-Mg-Mn-Sc-Zr alloy plates is presented by He et al. [92]. Microstructural and mechanical properties of double-sided MIG, TIG, and friction stir-welded AA5083-H321 aluminum alloy is analyzed by Taban et al. [93] to measure hardness, tensile, and bending properties in the welded parts. A comparison of fatigue properties between friction stir and TIG welds is presented by Wang et al. [94]. The obtained results in the study proved that the fatigue properties of FSW welded joints are better than those of TIG-welded joints. Carlone and Palazzo [95] studied the characterization of TIG- and FSW-welded parts in cast ZE41A magnesium alloy so to measure the tensile and hardness properties of the welded parts. The results of the study proved the capabilities of the FSW process as well as some advantages of the TIG process in the mechanical properties of the welded parts. Microstructure and properties of TIG/FSW welded joints of a new Al-Zn-Mg-Sc-Zr alloy is analyzed by Lei et al. [96] so to obtain better mechanical properties of the FSW joint and homogeneous chemical compositions in the welded parts. Also, Munoz et al. [97] presented a comparison of TIG-welded and friction stir-welded Al-4.5 Mg-0.26 Sc alloy. Then the mechanical properties of the welded parts are evaluated using microhardness measurements as well as uniaxial tensile tests. Therefore, the study proved that the TIG welding operation has more effects on the hardening properties in comparison with the FSW process. A comparative study on mechanical and dry sliding wear behavior of Al 7075-T6 welded joints fabricated by FSW, TIG, and MIG is presented by Prasad et al. [98]. Thus, the study proved that FSW joints were better than TIG and MIG joints in comparison to the grain sizes and grain growth of welded parts.

2.11. Design of the FSW Tools

The most influential parameter in the joining process development is the suitable designing of the welding tool. Welding tool failure, material flow in the welding operation, generated heat, surface roughness, microstructure properties, created forces, and deflection of welded parts are under the influence of the FSW tool designing. The shoulder and pin of the welding tool can be analyzed so to obtain the optimized design technique.

A heating tool design for FSW of thermoplastics is developed by Banjare et al. [99] to provide a better surface roughness and lower chip formation and material loss during the FSW process. The influences of welding tool parameters to mechanical properties of friction stir weldments of AA 2014-T6, the FSW tool design using TRIZ, and parameter optimization process using gray relational analysis are presented by Gadakh and Kumar [100]. Shoulder design developments for FSW lap joints of dissimilar polymers using different materials and geometries are investigated by Esfami et al. [101] to analyze the quality of the welds and appearance.

To obtain the best mechanical and metallurgical properties in the welded parts, Mehta and Badheka [102] developed the influence of tool pin design on the properties of dissimilar copper-aluminum FSW process. To study the microstructural properties and worn surfaces of welded parts in the FSW process, Amirafshar and Pouraliakbar [103] investigated the effect of tool pin design on the microstructural evolutions and tribological characteristics of friction stir-processed structural steel. Azdast et al. [104] presented the effective parameters on the strength of polymeric nanocomposites welded parts in order to enhance the quality of produced parts using the FSW process. The effect of tool parameters as pin and shoulder diameter and pin height on mechanical properties, temperature, and force generation during the FSW process is investigated by Akbari et al. [105] to obtain the optimum values for shoulder diameter, pin height, and pin diameter of the welding tool. Experimental study for the effect of tool design on the mechanical properties of bobbin-tool friction stir-welded AA6061-T6 aluminum alloy is presented by Amin et al. [106] to select the right design of the bobbin welding tools, which have superior mechanical properties in the welded zone.
The influence of friction stir processing a tool design on microstructure and superplastic behavior of Al-Mg alloys is studied by Garcia-Bernal et al. [107] to obtain the best mechanical properties in the welded parts using the optimized parameters of the welding tool.

Advanced welding tools can be presented using the optimization techniques, considering the tool wear, tool geometry, and selection of tool material. As a result, the FSW processes in different industry applications can be developed using the advanced welding tool.

2.12. Effect of Single and Double Passes to Microstructures and Mechanical Properties of Welded Parts

The effects of the number of welding passes to the microstructures and hardness of welded parts can be analyzed to increase the quality of produced parts. Part thickness is studied in different research works to obtain the microstructure, mechanical properties, and residual stress of the welded area. So the produced parts using the FSW process can be developed by applying the most appropriate number of welding passes due to different working conditions.

In order to study the influence of the number of welding passes to microstructures and hardness of welded parts, a microstructural evaluation of a single and double pass of the FSW process for a 9% nickel steel alloy is studied by Casanova et al. [108]. Also, Sahu and Pal [109] presented the mechanical properties of dissimilar thickness aluminum alloy welded parts by considering the single/double pass of the FSW process in order to study the challenges of FSW welding operations in dissimilar thickness plates. An investigation of single-pass/double-pass techniques on FSW of aluminum is presented by Sathari et al. [110] to study and modify the microstructure of the welded area in the welding operation. To improve the flow rate of material and finer grains in the stir zone of welded parts, Garg and Bhattacharya [111] studied the influence of Cu powder on strength, failure, and metallurgical characterization of single- and double-pass friction stir-welded AA6061-AA7075 joints. To evaluate the microstructure and mechanical properties of the welded area using an optical microscope, tensile test and Vickers hardness test, and mechanical and microstructural characterization of single and double pass Aluminum AA6061 friction stir welded joints are investigated by Othman et al. [112]. Single- and sequential double-sided FSW process in RQT-701 steel is presented by Barnes et al. [113] in order to analyze and develop residual strains and microstructure conditions using energy-dispersive synchrotron X-ray diffraction. In order to analyze the metallurgical structure and joint strength in the welded parts, the effects of single- and double-pass FSW lap joining of AA5456 sheets with different thicknesses is studied by Behmand et al. [114]. Moreover, Kumar et al. [115] presented a comparative study of the mechanical properties in single- and double-sided friction stir-welded aluminum alloy joints so to investigate the mechanical properties like surface hardness and tensile strength of the welded parts.

Recent developments of the FSW simulation are presented in Table 1.

3. Conclusion and Future Research Works

In this article, recent developments in the FSW process are reviewed. The effects of process parameters such as plunge depth, dwell time, traverse speed, toll rotation, and tool retraction to the welding operation [16, 17, 18, 19, 20, 21] are studied in order to increase the efficiency in the process of part production. Analysis of material flow during the FSW process [22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35] is presented to analyze the velocity field around the rotating tool pin during welding and the positions of material particles around the pin after the welding operation. Stress, strain, and deformation analyses [36, 37, 38, 39, 40, 41, 42, 43, 44] are studied to analyze the effects of welding tool forces acting on the pin of the welding tool as well as the workpiece. As a result, the damage in the welding tool and workpiece can be decreased. Numerical simulation of FSW for dissimilar metal welding [45, 46, 47, 48] is presented to increase the application of the welding operation in the part production process. So availabilities and challenges of dissimilar welding operation using the FSW are studied. To determine the material characters welded parts after welding operation, material characteristics of welded parts are analyzed and presented [11, 13, 49, 50, 51, 52]. Hardness as well as microstructure behavior modeling of the FSW such as grain size changing in the welded part are analyzed to increase the quality of produced parts using FSW. Heat generation, thermal, and thermomechanical analyses [53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65] are studied to predict and analyze the HAZ during the welding operation. The presented research works prove that FSW is an effective method to create welded parts without the melting process. Fatigue behavior of welded parts is studied [66, 67, 68, 69, 70, 71, 72, 73, 74, 75] to improve performances of welded structures in the actual working conditions. To increase the quality of the produced part using the FSW process, corrosion resistance in the welded part is investigated [76, 77, 78, 79, 80, 81, 82] by improving corrosion cracking resistance parameters. So to increase weld quality by improving the sensing, control, and joint tracking in the welded parts, automation, and robotics in the FSW process are developed [83, 84, 85, 86, 87, 88, 89, 90]. A comparison between the FSW-welded and TIG-welded parts are presented in different papers [91, 92, 93, 94, 95, 96, 97, 98] to compare and obtain better mechanical properties in the produced parts. To increase efficiency in the FSW process and improve the mechanical properties of the welded part, the welding tool is designed and modified [99, 100, 101, 102, 103, 104, 105, 106, 107]. The effect of single and double passes to microstructures and mechanical properties
| Topic of research work                                      | Papers | Process parameter                                                                 | Model description (tool and workpiece)               | Workpiece materials                          | Findings/discoveries                                                                                                                                 |
|------------------------------------------------------------|--------|-----------------------------------------------------------------------------------|------------------------------------------------------|-----------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| **Effects of process parameters to the welding operation** | [18]   | Tool rotational speed and tool holding time                                       | Developed by the authors                             | 2017-T6 and 5052 aluminum alloys             | Tensile shear strength increased with decreasing tool rotational speed and increasing tool holding time, while cross tension strength decreased with increasing both parameters. |
|                                                            | [21]   | Rotational speed, traverse speed, and tool tilt angle                            | Developed by the authors                             | AA2014 aluminum alloy                        | 1. Quality welds could be produced with the tool rotational speeds of 1000-1200 rpm.  
2. As the tool rotational speed increased, the tensile properties marginally increased | |
|                                                            | [22]   | Shoulder geometry and pin geometry                                                | Finite volume model                                   | AA2014 aluminum alloy                        | The decrease in width of the screw groove and the decrease of the cone angle of the pin can make the material flow velocity increase. |
|                                                            | [23]   | Rotational speed                                                                  | Eulerian thermomechanical model                       | AA2024 aluminum alloy                        | The sliding ratio increases with the tool rotational velocity and decreases with the temperature in the vicinity of the tool. |
|                                                            | [28]   | Transverse speed                                                                  | Coupled thermomechanical method                       | AA2095                                       | 1. The variation of the transverse speed does not significantly affect the power needed for FSW.  
2. When the transverse speed is higher, the stirring effect of the welding tool becomes weaker, which is the reason for the occurrence of a weld flaw. |
|                                                            | [31]   | Rotation rate, traverse speed                                                     | Two finite element models (the slipping interface model and the frictional contact model)             | AA6061-T6 alloy                              | The interface between the pin and the surrounding material is mostly a slipping interface. Also, there is very little sticking between the rotating pin surface and the surrounding material. |
|                                                            | [36]   | Rotational speed of the tool, welding traverse speed                              | Semi-coupled thermomechanical finite element model   | 2024-T4 Al alloy                             | The pressure from the tool shoulder led to a reduction in the longitudinal residual stresses in the weld zone. |
|                                                            | [43]   | Welding speed, tool rotational speed                                              | The numerical model-based finite element model       | AA7075 and AA7039 Al plates                  | 1. An increase in both welding speed and plate thickness resulted in lower peak temperature, and higher torque, traverse force, and resultant maximum shear stress on the tool.  
2. An increase in workpiece alloy strength led to higher traverse force and resultant maximum shear stress, and lower tool durability. |
|                                                            | [44]   | Tilt angle, tool pin height, tool rotational speed                                | Coupled thermomechanical, nonlinear transient model based on CEL method                              | AA6061-T6 aluminum alloy                     | To decrease the residual stress, a pin height of 2.5 mm is found as the optimum pin height of the welding tool. |
|                                                            | [45]   | Rotational speed, welding speed                                                   | Mathematical model is developed by the author        | AA6061 and AA2024 aluminum alloys            | At the optimum level of process parameters, using the Taguchi method with 1700 rpm of rotational speed, 60 mm/min of welding speed, and 2 kN axial force, ultimate tensile strength is successfully increased. |
|                                                            | [48]   | Rotational speed, welding traverse speed                                           | Developed by the authors                             | AA6061 and AA7075 aluminum alloys            | 1. The tensile strength of the dissimilar joints increases with decreasing heat input.  
2. The highest joint strength was obtained when welding was conducted with the highest welding speed and AA6061 Al plates were fixed on the advancing side. |
| Topic of research work | Papers | Process parameter | Model description (tool and workpiece) | Workpiece materials | Findings/discoveries |
|------------------------|--------|-------------------|----------------------------------------|---------------------|---------------------|
| Material characteristics of welded parts | [49] | Rotational speed, linear translation speed of tool relative to the workpieces | Thermomechanical modeling method | AA5083-H18 sheets | Based on the finite volume method simulation, thermal and deformation histories of material elements are calculated, to predict material characteristics of the weld such as hardness or grain size, and possibly for the susceptibility of the weld to abnormal grain growth (AGG) after post-weld heat treatment. |
| | [52] | Tool feed rate, tool pin rotational speed | Developed by the authors | AA6082-T6 aluminum alloys | The local effects of strain, strain rate, and temperature; an inverse identification approach, based on a linear regression procedure, is developed in order to obtain the proper material characterization. |
| | [54] | Tool rotational and longitudinal speeds | 3D model based on a FEM | AA6061 aluminum alloy | The longitudinal force is strongly influenced by the welding parameters. It decreases with an increase in the tool rotational speed and increases with increasing traverse speed. The vertical force decreases with an increase in the rotational speed and increases slightly with an increase in the traverse speed. |
| | [63] | Rotating speed, tool geometry | Thermomechanical analysis using FEM | AA6061-T6 plates | The classical Coulomb friction model can be accurate enough for the simulation of FSW in a lower angular velocity. But in higher angular velocity, the classical Coulomb friction model fails to work due to the increase of the dynamic effect of the welding tool. |
| | [65] | Tool pin rotational speed | Numerical model developed by the authors | AA2024-T3 plates | An acceptable prediction of the material softening in the HAZ is developed to predict the temperature history and the hardness distribution on a welded plate. |
| Fatigue behavior of welded parts | [67] | Tool rotational and longitudinal speed | Thermomechanical modeling method | AA7050-T7451 | 1. The fatigue-crack propagation in the weld-nugget region is inferior, while it is superior in the HAZ region. 2. To increase the fatigue crack growth resistance in the HAZ region, residual stresses are more dominant than the microstructure improving. |
| | [68] | Rotational speed, welding traverse speed | Eulerian thermomechanical model | AA2024-T351 aluminum | Crack growth behavior in the FSW joints was generally dominated by the weld residual stress. Also, microstructure and hardness changes in FSW joints had a minor influence. |
| | [73] | Tool pin and tool rotational speed | Developed by the authors | AA6082 aluminum alloy | The influence of three shoulder geometries on the FSW joint performance by evaluating, in particular, residual stresses and fatigue life of welded parts, is analyzed. |
| Topic of research work | Papers | Process parameter | Model description (tool and workpiece) | Workpiece materials | Findings/discoveries |
|------------------------|--------|-------------------|---------------------------------------|---------------------|----------------------|
|                        |        |                   |                                       |                     |                      |
| Corrosion resistance in the welded parts | [76]   | The tool-shoulder geometry | Thermomechanical modeling method | AA6XXX aluminum alloy | The joint welded via FSW is more corrosion resistant than that welded via Metal Inert Gas technique. |
|                        | [80]   | Tool rotational speed | Thermomechanical model | AA6061-T6 aluminum alloy | A tool rotational speed between 1155 and 1157 rpm is an optimum input to obtain an excellent welded component produced from AA6061-T6 aluminum alloy. |
| Automation in FSW process | [83]   | Effect of force control via traverse speed | Developed by the authors | Aluminum alloy | Force control via traverse speed and rotational speed are more stable. It can effectively maintain a constant force when there is a minimum amount of workpiece variation present. |
|                        | [89]   | Optimized rotational speed and welding traverse speed | Developed by the authors | Aluminum matrix composites | The optimized process parameters as the total rotational speed of 1132 rpm, welding speed 51 mm/min, and axial force 5.8 KN can be used to obtain desirable joint properties. |
| Comparison between the FSW welded and TIG welded parts | [92]   | Welding traverse speed and tool pin | Thermomechanical analysis using FEM | Al-Mg-Mn-Sc-Zr alloy plates | The tensile strength, elongation, and welding coefficient of FSW-welded joint parts are higher than the TIG-welded joint parts. |
|                        | [95]   | Tool pin and tool rotational speed | Thermomechanical modeling method with X-ray analysis | ZE41A magnesium alloy | Higher yield strength and lower ductility are exhibited by FSW joints with respect to TIG joints, while similar ultimate tensile strength is provided by both welds. |
|                        | [97]   | The tool-shoulder geometry and tool rotational speed | Finite element model | Al-4.5 Mg-0.26 Sc alloy | The FSW joints exhibit higher mechanical properties than those obtained by A-TIG. |
| Design of the FSW tools | [99]   | The tool-shoulder geometry | X-ray analysis and thermomechanical modeling method | AA2014-T6 aluminum alloy | An assisted heating tool design can provide a better weld surface finish, lower chip formation, and material loss and improve the tensile strength during FSW of thermoplastics. |
|                        | [106]  | The tool-shoulder geometry | X-ray analysis and finite element model | AA6061-T6 aluminum alloy | 1. The dimensions of the bobbin tool (shoulders and pin) have a significant effect on the welding quality. 2. For the best bobbin tool design, the internal diameter of the pin is nearly similar to the substrate thickness, and the shoulder diameter should be three times the pin diameter. |
| Effect of single and double passes in the welded parts | [111]  | Tool rotational speed and depth of welding | Thermomechanical model | AA6061-AA7075 aluminum alloy | Grain size distributions in the stir zone were observed to be relatively finer in double-pass FSW joints compared to the grain size in single-pass joints. |
|                        | [114]  | Tool-shoulder geometry, tool rotational speed | Thermomechanical modeling method | AA5456 sheets of aluminum alloy | The best results for metallurgical structure and joint strength were achieved by a tilt angle of 58° for a single pass, and the tilt angle, rotational speed, and traverse speed of 58°, 250 rev/min, and 50 mm/min, respectively, for double pass. |
of welded parts are investigated [108, 109, 110, 111, 112, 113, 114, 115] to increase the quality of produced parts using FSW. The FSW process is an effective method in the joining process by providing good properties in strength, ductility, fatigue, and fracture toughness of the welded parts. Dissimilar materials can be welded using the FSW process for lightweight applications in automotive industries. Problems of welded parts related to the melting phase of the materials such as porosity, formation of second phases, embrittlement, and cracking can be prevented as a result of the joining operation at the temperature of parts below the melting point. So the joining method can be considered for the manufacturing process of advanced parts with a high level of accuracy as well as efficiency in part production.

New ideas for future study in the FSW process can be obtained by using the reviewing and analyzing previous research works. Simulations of assembly processes using FSW can be considered in future research works to predict the stress and deformation of produced components using the welding operation. Moreover, the method can be combined with the other welding operation in order to present hybrid joining processes. So more advantages in the new method can be obtained to increase the application of the welding operation. To develop the FSW process capabilities, joining of the dissimilar materials can be considered as a future research work to be simulated and analyzed using numerical methods. Plastic flow in the tool pin during the welding operation can be accurately simulated and analyzed to decrease the defect size and create the defect-free weldment. The CFD, CP-FEM, and numerical analysis can be applied to the FSW process to analyze the material flow, the effect of grain boundaries, and particle-reinforced metallic alloys. To simulate the behavior of cracks under actual working conditions, CFD simulations with XFEM and GTN models can be combined together to share the advantages of the methods. Non Destructive Test methods such as the ultrasonic testing method can be applied to the produced part using FSW in order to determine the size and locations of defects of the parts and increase the safety of the produced parts. To provide a better stir of the welded material in the joining operation, the welding tool pin can be developed by applying the additional ultrasonic vibration. To increase analysis abilities in virtual environments, other numerical methods such as the finite difference method, particle method, and fluid mechanics method can also be applied to the FSW processes. The virtual simulation of the FSW process can be developed using advanced programming languages to optimize the process parameters. So more added value in the production method using the FSW can be achieved. Automated welding operations can be applied to the complex structures so as to increase the mechanical properties of the welded parts such as hardness and joint strength. These are some ideas for future research works so to develop the production process using FSW. Wear of the welding tool can be analyzed so to develop its use in new superalloys. As a result, more strengths and capabilities in welding operations can be achieved. The application of the FSW process to new metallic materials such as copper, titanium, steel, magnesium, and composites can be studied in future research works so to increase the capabilities of the welding technique in the different industries.

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