7

Material Sustainability During Friction Stir Joining

Raheem Al-Sabur[1]* and M. Serier[2]

[1] *Mechanical Department, Engineering College, University of Basrah, Basrah, Iraq*
[2] *Mechanical Engineering Department, University of Ain Temouchent, Ain Temouchent, Algeria*

Abstract

Sustainable manufacturing aspires to operate available resources with minimum environmental impact by executing eco-friendly strategies. Fusion welding dominates many industrial processes whether simple bonding operations or manufacturing more complex structures. Many manufacturers and environmental protection organizations have been worried about fusion welding problems such as harmful fumes, the high consumption of welding electrode shielded gases, etc. In the last decade, the environmental index granted many gains to the process of friction stir welding (FSW) because of its success in reducing the energy used and solving most fusion welding environmental problems, in addition to its ability to weld asymmetric metals, which made it consider a green technology that gives rise to hope. This chapter deals with the essential aspects of friction stir welding as a sustainable technology, including process history, types, benefits, and limitations compared to other types of welding, as well as recent trends and most frequently used applications.

***Keywords*:** Sustainability, friction stir welding, environmental impact, energy consumption

---

**Corresponding author*: raheem.musawel@uobasrah.edu.iq

S. Thirumalai Kumaran and Tae Jo Ko (eds.) Sustainable Machining and Green Manufacturing, (131–154) © 2023 Scrivener Publishing LLC

7.1 Introduction

Although the term “sustainability” appeared in literature several centuries ago, there is no consensus on a comprehensive definition of it. Sustainability can be defined as finding a balance between ensuring future generation rights and the present need. During the new millennium, many countries considered sustainability an influencing factor in environmental safety. As a result, many factories have faced harsh legislation, forcing many to close [1]. In addition to confronting global warming, legislation to adopt industrial sustainability has become a prerequisite for all new projects and newly established factories. In manufacturing, studies focused on sustainability in the field of welding. They looked at many things, such as the effect on costs, the effect on the environment, reducing resource use, improving joint quality, and maximizing joint quality [2]. Welding is a very influential factor in the industry renaissance, dominating all jointing operations such as bolting or riveting. Welding processes are divided mainly into fusion welding and solid-state welding, in which the welding temperature does not reach the melting point of the welded metals [3]. Fusion welding is widely used and is characterized by its many types that try to cover most industrial uses. Despite these advantages, workers in the welding field are forced to bear difficulties, especially concerning health aspects such as gases and fumes. For example, shielding gases are necessary to solve the problem of hydrogen embrittlement and impurities [4]. In addition, the emission of infrared, ultraviolet, and even visible radiation is common in arc welding, one of the main types of fusion welding. It is also noted that filler metal is required in many types of fusion welding, and the heat-affected zone is relatively large, affecting the welding quality. Martensite welding and the welding of dissimilar metals are complex processes in fusion welding [5]. In the early 1990s, in one of the most famous welding research and technology organizations (TWI), there were several attempts to invent a new type of welding. Wayne Thomas gave the practical principles of friction stir welding (FSW) [6]. FSW was intended to be a revolutionary leap for light metal joining, such as aluminum and magnesium [7, 8].

Q1 correct

Friction stir welding is based on a nonconsumable rotating tool consisting of two connected parts. The upper cylindrical part, called the shoulder, is connected to the welding machine (usually a CNC) and the other end ends in a tapered cylindrical part (usually) called the pin. The pin can be square, triangular, obturator, or cylindrical (not tapered) and can be threaded [9]. In friction stir welding, two plates of similar or dissimilar metals (considering the melting point of each metal) are arranged as a butt

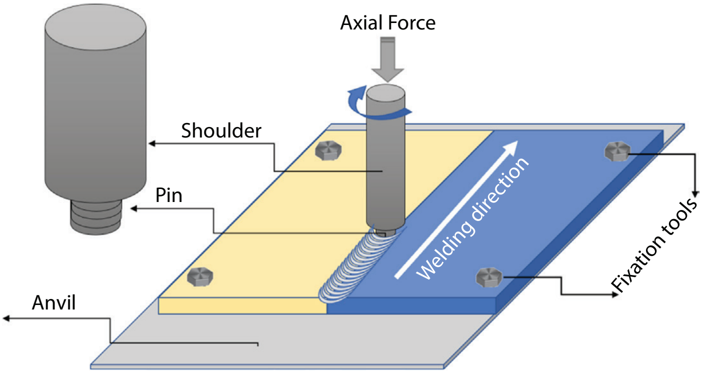

Figure 7.1 Scheme of FSW process and fixation tools.

joint. The two plates are firmly fixed to an anvil to reduce vibration and obtain a homogeneous joint, as shown in Figure 7.1. When the rotational tool reaches the weld seam, the contact area temperature rises, allowing the pin to gradually sink into the two plates until the lower shoulder surface comes into direct contact with the weld seam. In the second stage, the welding tool moves rotationally and linearly toward the weld seam until it reaches the end of the area to be welded. In the third stage, the linear motion stops, and the rotational tool rises, leaving behind welded plates and a hole at the end of the weld [10]. The choice of welding conditions (tool rotation speed, welding speed, and penetration force) depends on the welded materials.

For understanding the metal flow during the process, the spinning tool offers a continuous hot working activity that pushes the material around a pin at temperatures lower than the joining sheets' melting points. This procedure moves metal from the top face of the pin to its trailing edge while plasticizing it in a constrained area. The pin torque delivers the energy to form a viscous texture material, permitting it to flow around the pin as a boundary layer between the pin and the solid parent material driven away or diminished in thickness at the pin's top edge.

The relatively low temperature of friction stir welding has many benefits. In addition to solid-state welding, where there is no melting, the process is considered free from solidification defects such as cracks and porosity [11], and the heat-affected zone becomes better [12]. Moreover, most mechanical properties improve, such as tensile strength [13], fatigue life [14], hardness [15], and fracture toughness [16], which is offset by a decrease in distortion [17] and an ultrafine granular structure [18].

The ability to weld similar and sometimes dissimilar metals and polymers is one of the benefits of friction stir welding [19]. The welding process is automated, and the penetration is high with fewer defects. The welding tool is nonconsumable and does not require post-weld treatment. Safety and health are the essential features of friction stir welding, as there is no spatter, fumes, shielding gases, or arc [20]. On the contrary, there are many limitations that researchers are still striving to overcome, such as the high initial cost of robotic friction stir welding equipment [21], the presence of a keyhole at the end of the welding area [22], and special requirements for the tool materials, especially in welding steel alloys where the tool can be exposed to wear and damage [23]. Also, the sheets must be firmly fixed to the anvil, and the sheets that need to be welded must touch each other.

Sustainability has emerged as an insistent factor, and many restrictions have been placed on factories. On the other hand, countries, especially in Europe, encouraged renewable energies based on sustainability and decarbonization. In production lines, reducing production costs and reducing resource consumption, in addition to preserving the environment and health, are the main factors through which the production line can be considered sustainable.

In this chapter, the concept of sustainability in friction stir welding will be highlighted by reducing three aspects: cost, environmental impact, and energy consumed to maximize the efficiency of the resulting weld joints. It will also refer to the factors affecting FSW as “solid-state welding” and the technical improvements that accompanied the development of FSW tools. In addition, several industrial applications and projects will be mentioned in the context of industrial sustainability.

7.2 FSW Parameters

7.2.1 Rotation Tool Speed and Traverse Velocity

During FSW, speeds are the essential parameters, as there are two types of speed [24]. The first type is the tool rotational speed, which represents the speed at which the pin penetrates the metal, and the shoulder presses the sheet contact region. The second is the velocity of tool travel (traverse) along the required welding line. It can be considered a linear velocity associated with the rotational speed of the tool.

It is difficult to determine the optimal values for both types of speed, as they vary according to the joined metals and other parameters. The force acting on the tool can be on multiple axes, the longitudinal force, the vertical force, and the lateral force for the X, Y, and Z axes. The longitudinal force performs parallel to the tool movement and is positive in the x-direction. Since this force emerges due to the material's resistance to the tool motion, these forces will likely decrease as the material's temperature increases. The vertical or downward force is crucial to keep the tool positioned at or below the material surface. Some FSW equipment works under load control, but the tool's vertical position is often preset so that the load will alter during FSW. As torque is applied to rotate the tool, it depends on the downforce, friction coefficient, and material flow. The downforce, or lateral force, operates perpendicular to the traverse direction of the tool and is described as positive toward the FSW advancing side. When added to the effect of thermal impact, these forces can cause the fixture and the sheets being processed to deform and affect the tool's wear. These effects will make it harder to figure out how residual stresses will form in the welding and how long tools will last.

It is worth noting that controlling the traverse velocity and the rotational speed contributes significantly to sustainability. Reduced speed reduces energy consumption and production costs, significantly contributing to environmental improvement. In general, the forces generated in FSW processes are affected by the amount of rotational speed and travel velocity. The speed increase can help increase the force on the shoulder, correct Q3 but it may be off the pin. Table 7.1 shows the relationship between the rotational speed, the traverse velocity, and the effect of force components.

Table 7.1 Effect of tool rotational speed and travel velocity on force components.

Tool part	Force component	Tool rotational speed*	Tool traverse velocity
Pin	Longitudinal	↓	↑
	Vertical	↑	—
	Lateral	↑	—
Shoulder	Longitudinal	↓	↑
	Vertical	↑	↓
	Lateral	↑	—

*Symbols ↑ (increase), ↓(decrease), and—(no effect).

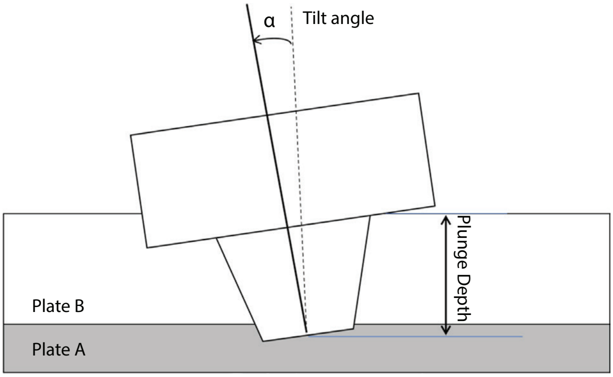

Figure 7.2 Tilted tool and plunge depth of FSW tool (cross-sectional view).

7.2.2 Plunge Depth and Tilt Angle

The plunge depth, a crucial factor in maintaining weld quality, is described as the distance between the shoulder lowest point and the plate surface. The pressure below the tool is increased by lowering the shoulder below the sheet surface, ensuring proper forging of the material at the tool's back. If the plunge depth is too great, the pin could rub against the surface of the backing plate, or there could be a big difference between the weld depth and the base material.

During the FSW, the plunge depth adjustment is necessary to ensure suitable downward pressure and complete penetration of the tool into the welded plate. The tilting of the FSW tool by α = 2–4 degrees is necessary to overcome the incredible tool deflects and reset the plunge depth to the standard setting, as shown in Figure 7.2 [25].

7.3 FSW Sustainability Review

The term sustainability has appeared in many studies of the FSW in recent years. The section reviews only the previous articles in which sustainability appeared in their titles. Bevilacqua *et al.* [26] used life cycle assessment software to analyze the results of AA5754 sheet joining by friction stir welding. They found that it is more sustainable than other welding methods, as it reduces energy consumption and resource depletion. They also indicated a noticeable sustainability in the environmental impact commensurate with the speed of rotation of the tool. Sued *et al.* [27] concluded that the total power used for friction stir welding was at most 130 kW when joining AA3000 aluminum plates. The total energy used is very little

Q4 correct

compared to fusion welding. They used a travel speed of 155 mm/min, a dwell time of 15 sec, and three rotational speeds of 700, 800, and 900 rpm. Sethi *et al.* [28] reviewed several studies in the FSW of similar and dissimilar metals regarding welding process parameters and their impact on the interlayer, microscopic structure, and the resulting mechanical properties. The researchers did not address cost calculations, energy consumption, or the environmental and health impacts, which are the most studied topics in the subject of sustainability in manufacturing. The same matter also happened in many articles, such as [29–31], where sustainability studies should have been discussed. The study presented by Majeed *et al.* [32] is considered one of the best published in the sustainability studies of FSW, as it included a clear explanation and helpful schematic diagrams about the potential aspects of sustainability in FSW, in addition to a comparison of economic feasibility with other types. The researchers discussed the environmental friendliness criterion and did not overlook the limitations of FSW processes. Al-Wajidi [33] studied the effect of using lubrication on FSW sustainability for joining 6061-T651 and 5052-H32 plates. The study focused on four aspects, cost, energy consumption, environmental impacts, and waste management, and showed that adding lubrication can reduce the required welding forces in addition to improving the mechanical properties and microstructure. Suresh *et al.* [34] suggested an algorithm to predict the best eco-friendly FSW parameters when welding AA6061-T6 alloys. In the study, nanoparticles of Al_2O_3 were put in the keyhole; the tool's rotation speed was 1,387 rpm, and its traverse speed was 7 mm/min. Azeez and Akinlabi [35] conducted an in-depth study on the relationship between the tensile strength and generated heat of FSW joints and the sustainability criteria through economic, environmental, and health aspects. The emissivity, welding energy, and life cycle assessment (LCA) were analyzed. It was found that the lower FSW temperature led to a higher Weibull modulus, which is considered a criterion for better sustainability. To improve sustainability, Sharma *et al.* [36] used the LCA methodology to study the environmental effects associated with friction stir processing (FSP) of alloyed alloys. The study addressed the method of manufacturing the FSP tool and suggested developing it through "zinc-coated cutting wires," which makes it more suitable for environmental considerations.

7.4 FSW Sustainability Aspects

The system is supposed to be unsustainable when resources are consumed, and waste is created faster than nature's ability to cope [37]. Friction stir

correct Q5

Figure 7.3 FSW sustainability aspects.

welding is considered a successful and sustainable alternative to fusion welding. In addition to its high efficiency, the energy used in it is much less than that in similar types of welding. This section discusses the FSW as a sustainable tool according to six sections, as indicated in Figure 7.3; minimize cost, maximize process efficiency, minimize environmental impact, and minimize energy consumption.

Accepted Q6

7.4.1 Minimizing the FSW Costs

Reducing the cost of production while ensuring high performance is the main goal in consideration of economic feasibility. Cost reduction is the key to achieving sustainability. Estimating the total cost of production is critical when deciding on welding types. Several studies have tried to estimate and compare the production costs of many welds, including FSW [38]. Boeing showed that the use of FSW reduced the welding cost to about 60% in Delta IV and Delta II, and the welding period was also reduced by 74%, which is a very encouraging factor if the FSW is compared to other types of welding [39]. Boeing reports were an essential and decisive factor in favoring FSW over others. Despite the strict safety requirements in airplanes, the increasing use of this type of welding in the aviation sector indicates that FSW has taken the lead in the welding industry. Regarding FSW cost estimation, the cost of machinery, power, tools, and fixtures, in addition to the labor cost, are the main elements for calculating the total cost, where the machinery and labor costs constitute 95%, while the total costs of tools and power are 5%, as shown in Figure 7.4 [40].

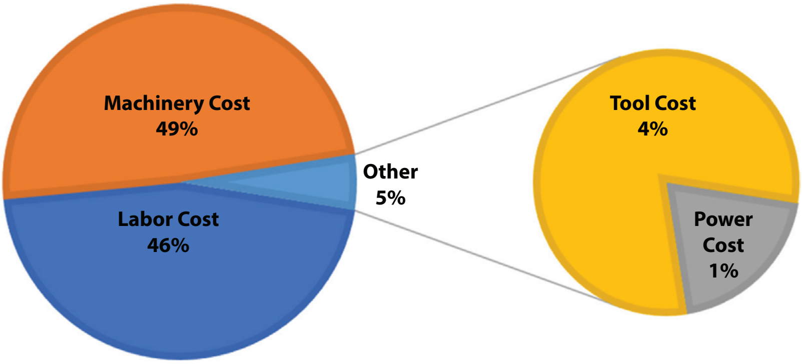

Figure 7.4 Cost distribution in the FSW process.

The machinery cost (Cm) and labor cost (C_{lc}) are calculated for FSW from the following equations [40]:

$$C_{mc} = \frac{C_M \times [(W_T \times \mathrm{n}) + T_s + T_{ch}]}{MR \times 60} \tag{7.1}$$

$$C_{lc} = \left(\frac{W_T \times \mathrm{n}}{OF} + T_W \right) \times \frac{C_L}{60} \tag{7.2}$$

where C_M is machine rate ($/hr), W_T is time to weld (min), n is number of passes, T_S is setup time (min), T_{Ch} is tool change-over time (min), MR is machine reliability (assuming 95%), T_W is weld preparation time (min), C_L = Labor rate ($/hr), and OF = Operating factor. The remaining costs (tools, fixtures, and power) are restricted to 5% of the total cost [33].

Several studies tried to compare the cost of FSW with other processes. When comparing the labor costs of the MIG welding process vs. the FSW, it was discovered to be roughly double, at 78% for MIG vs. 46% for FSW [40]. When comparing FSW with submerged arc welding (SAW), it was found that the direct machine cost is 47% in SAW vs. 95% for FSW while the personal and overhead cost was 30% in SAW vs. only 3% in FSW [41]. In the test evaluation, the FSW production time was 82% of the corresponding MIG [42].

accepted Q7

7.4.2 Minimizing the FSW Energy Consumption

FSW is solid-state welding, meaning that the process takes place at temperatures lower than the melting point, and this has contributed to a

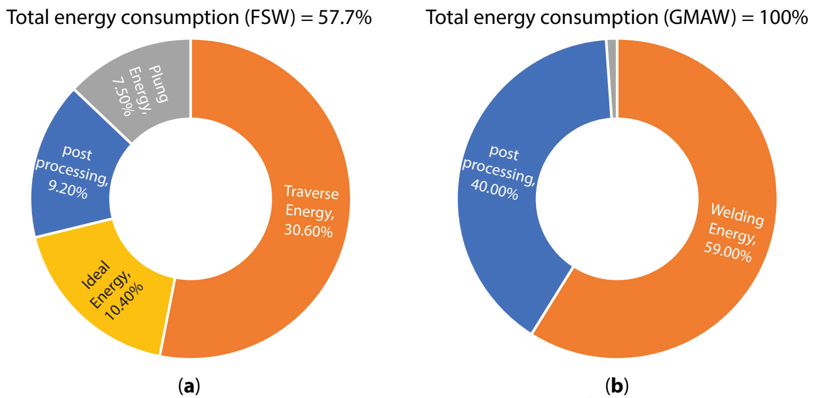

Figure 7.5 Comparison between the total energy consumption of (a) FSW and (b) GMAW.

decrease in the energy consumption used in welding. In addition, the FSW process does not require a post-weld, which is another positive factor in reducing energy consumption. A low energy consumption in FSW is an attractive factor for manufacturers and investors because it supports government requirements toward sustainability and reducing global warming.

Majeed *et al.* [32] summarized a set of comparisons between energy consumption in FSW and other welding processes, especially GMAW. They concluded that the energy consumption is much lower than that of all arc welding processes. When comparing FSW with GMAW, FSW consumes about 42% of the energy consumed in GMAW [43]. Moreover, Dawood *et al.* [44] confirmed that the energy consumed in FSW consumes a quarter of what is consumed by GMAW. It is also comparable to other types of welding; when compared to laser welding, FSW is superior by less than 2.5% energy consumption [45]. The FSW energy consumption consists of postprocessing (cutting), traverse, plunge, and idle energies, while in the GMAW, it consists of postprocessing (grooving), weld energy, and standby energy. Figure 7.5 compares FSW and GMAW energy consumption using subdividing ratios [46]. The welding energy was reduced from 59% in GMAW to only 7.5% in FSW, which is a clear indication of the sustainability achieved by switching to FSW.

Q8
Gas Metal Arc Welding

accepted Q9

7.4.3 Maximizing the FSW Process Efficiency

The efficiency of a joint, or how much load it can withstand under service conditions before failing, is used to determine its quality [47]. The ratio of the joint tensile strength to the base metal is called joint efficiency [48]. Concerning the welding of similar metals in FSW, the results of joint efficiency in aluminum alloys were surprising and very encouraging. For the AA1100 joints, the ultimate joint efficiency was 114%; for AA6061-T651, it was 69% [48].

Many studies in the field of FSW of dissimilar metals have focused on the joint's efficiency for aluminum and magnesium. A joint efficiency of 61% was achieved for the FSW of AZ31B magnesium alloy with A5052-H aluminum [49]. Masoudian *et al.* [50] noticed that a brittle-mode fracture occurred when the joint efficiency reached 76% for the FSW of AA6061 Al and AZ31 Mg alloys. Malarvizhi and Balasubramanian [51] found that for the same alloys, the joint efficiency could be increased by up to 89% if the shoulder diameter was made to be about 3.5 times the sheet thickness. Mahamud *et al.* [52] studied improving joint efficiency using ER5356 filler to enhance intermetallic compounds for the FSW of AZ31B magnesium and A6061 aluminum alloys. The use of the filler increased joint efficiency by 9%, from 67% to 76%. The post-weld heat treatment can improve the overall joint efficiency and promote irregular grain growth through different characteristics and softening behaviors formed in the resulting joints [53, 54].

The FSW process, on the other hand, improved thermal efficiency, which is the percentage of heat flow into the weldment compared to total heat generated [55, 56]. The excited thermal efficiency of Al 7075 T6 for FSW was 88% [57], 79% for 7039 alloy [58], and it was around 85%–88% for the AA6061 alloy [59, 60]. It was optimized up to 95% for AA2195 aluminum alloy using the M2 steel tool [61]. The thermal efficiency in the magnesium AM60B alloy was achieved at 91% using a hardened steel tool [55]. For steel alloys, the thermal efficiency was 50% for 304L stainless steel [62], while it was 75% for the AISI 1018 steel alloy when using the molybdenum- and tungsten-based FSW tool [63].

In summary, FSW contributes to the improvement of the performance of weld joints, as the ultimate tensile strength and yield strength are increased. Not only that, but the hardness also improved significantly, and the defects were reduced or absent in many cases. Welding has become more uniform in the surface layer and has better penetration into other metal layers. All of these improvements are factors affecting the Industrial Sustainability Index.

accepted Q10

7.4.4 Minimizing the Environmental Impact

Environmental impacts are short- or long-term changes that affect the inhabitants of the ecosystem system in the natural or built environment

[64]. Regarding welding, the processes are excessively affecting the health of its workers and the environment by generating fumes, dust, greenhouse gas emissions, and process wastes, in addition to the impact on energy and resource consumption [65]. The LCA can be utilized to expect the environmental impact of discrete metal-forming processes [66]. LCA provides a more accurate, comprehensive view of the actual environmental impact of a process over its entire life cycle [67]. In FSW, the environmental impact studies focused on analyzing the influence of FSW parameters using LCA methodology, such as the effect of rotational and welding speeds on pin tool wear.

Bevilacqua *et al.* [65] used the LCA method to compare FSW, gas tungsten arc welding (GTAW), and laser beam welding using the same functional unit. The study proved that FSW had greater environmental sustainability than the GTAW process and little environmental benefits over laser beam welding. For AA5754-H114 aluminum alloys, the rotational speed influences the environmental impact less than the welding velocity. The variation in the welding velocity clearly affects reducing the energy absorbed during the friction stir welding processes of aluminum alloys [26, 65]. For aluminum alloys, the absorbed energy is inversely proportional to the increase in welding speed for all rotational speed ranges, as shown in Figure 7.6.

In summary, the combination of cost reduction and resource consumption with improved weld joint performance points to the fact that the FSW is an influential contributor to environmental impact. This contribution, aided by a significant amount of applied research, was also aided by the rapid adoption of stir welding in many industrial applications because it

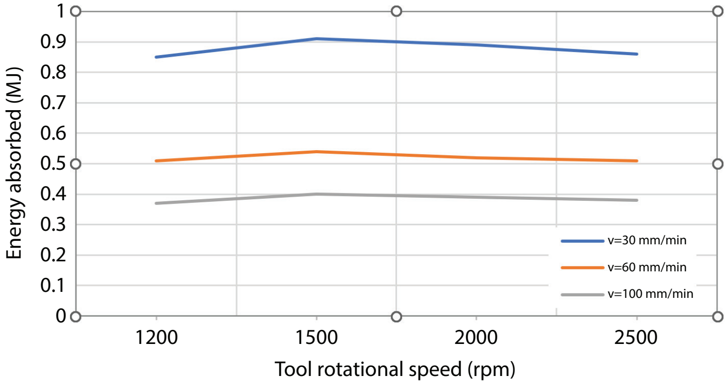

Figure 7.6 Energy absorption of Al alloys during FSW.

is considered an environmentally friendly welding method. Therefore, expectations indicate that environmental safety determinants and global warming requirements will increase the use of environmentally friendly welds such as FSW.

7.5 Recent Modifications in FSW Processes

The continuous development of FSW equipment is evidence that this industry is influential and moving in the right direction. Recently, there have been many developments on the research side as well as on the applied side. In the research aspect, the follower can note the massive articles on FSW that are published annually. Many companies have devoted a special section to the friction welding industry in the industrial field, and the matter has developed further so that we have many companies worldwide specialized in providing friction stir welding services or selling their equipment. This part reviews some research developments in FSW tools.

accepted Q11

7.5.1 Double-Sided FSW Tool

In order to obtain more symmetrical welds and reduce the reactive torque and input heat, TWI researchers developed an FSW tool using two opposing tools on both sides of the joined sheets, as shown in Figure 7.7. This technique is known as the double-sided FSW tool [68]. The pins need not connect but should be arranged adequately close together so that the softened material around the two pins overlaps near the pin ends to forge a good FSW process.

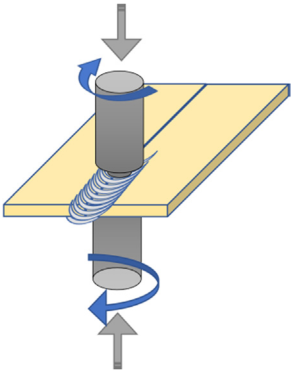

Figure 7.7 Scheme of the double-sided FSW process.

The double-sided tool was later used in many studies, such as studying the influence of tool size on the tensile strength of the Al alloys [69] and using convex and concave double-sided tools to study the plastic deformation and heat generation of the magnesium alloys [70]. It is also extended to investigate the effects of adding nanoparticles to the nugget zone [71] and double-sided friction stir spot welding of aluminum and steel alloy sheets [72]. In conclusion, even though double-sided FSW is being used increasingly, its industrial applications still need to be more ambitious and may require more in-depth scientific research.

7.5.2 Twin-Tool FSW Process

In some cases, the entire FSW process requires more than one pass; additional passes are needed to improve the welding quality and the mechanical properties obtained. However, using more than one pass is not desirable in solid-state welding processes, which initially depend on sustainability, maximizing resources, and minimizing consumption. Therefore, the twin-tool FSW concept was born to overcome the requirements of using more than one pass in the welding process. TWI first developed the idea in 1999 [73] using parallel twin tools, and it was later developed using tandem twin tools [74]. In both types of twin-tool FSW, the welding time will be significantly reduced, the rotating speed of the tools can be reduced, and the travel speed can be increased while maintaining the heat generated by friction. These improvements can be considered positive steps toward achieving sustainability and reducing resource use. In order to distinguish between the two types, in parallel twin-tool FSW, the arrangement of the two tools is according to the welding direction: side by side and transverse, while in tandem twin-tool FSW, they are arranged in line with the welding direction, as shown in Figure 7.8.

The tandem strategy will improve the weld's quality by breaking up any leftover oxide layers in the first weld area. Without losing mechanical properties, a second weld is produced over the previous one in the opposite direction. Similarly, because tool orientation dictates that one tool follows the other, the second tool passes through softened material.

Many studies have tried to shed light on using the twin-tool FSW. A comparative study between a twin tool and a single tool for welding aluminum alloys showed that plastic deformation occurred more when using the twin tool. The increase in deformation is due to the steady rise in heat generated along the joint seam [75]. In addition to obtaining a defect-free joint, an increase in hardness was observed.

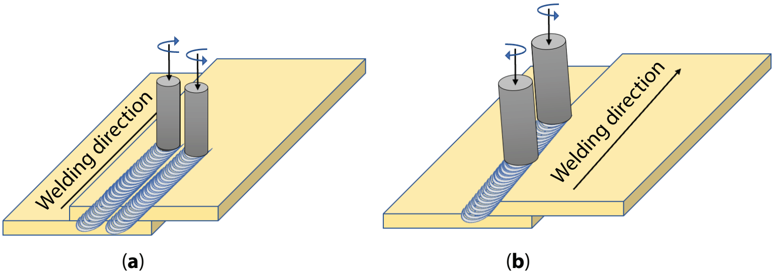

Figure 7.8 Scheme of (a) parallel-twin tool FSW, (b) tandem twin-tool FSW.

7.5.3 Dual-Rotation FSW Process

In traditional FSW, the shoulder and the pin rotate at the same speed, which is often constant throughout the welding process. This is also unaffected by recent advancements such as twin-tool FSW and double-sided FSW. The other interesting point in traditional FSW is that the relative speed starts at zero in the center of the pin and gradually increases until it reaches the maximum in the outer diameter of the shoulder. In the case of dual-rotation FSW, the FSW tool is made of two separate parts, the pin is centered on the shoulder, and both rotate in the same direction, as shown in Figure 7.9.

The developed technology provides many advantages, such as the ability to control the relative speed and rotate the shoulder at a speed different from the speed of the pin. Furthermore, this development allows the shoulder and the pin to rotate in opposite directions. The sheets overheating and uncontrolled material flow rate at high temperatures are determinants of

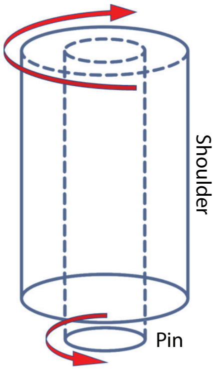

Figure 7.9 Dual-rotation FSW of the shoulder and pin arrangement.

FSW, so dual-rotation FSW can be considered one of the reliable solutions for that. A relatively low rotational speed is often used for the shoulder while keeping the pin rotating at a high speed, which reduces excessive heating and controls the material flow rates within acceptable limits.

As with other improvements in the FSW method, dual-rotation FSW has been used in several studies. One of the essential references for studying this technique on aluminum alloys was made by Liu *et al.* [76], where 5A06 aluminum alloy was used. The study showed that good joint efficiency was obtained using a low rotational speed, not exceeding 200 rpm for the shoulder and 400 rpm for the pin. On the other hand, conventional FSW was compared with dual-rotation FSW, and it was found that the joint results were defect-free when using dual-rotation FSW. Also, the welding process was more stable due to the remarkable improvement in the metal flow rate [77].

7.5.4 Friction Stir Spot Welding

FSSW is a special issue of traditional FSW, including all of its benefits, especially sustainability concerns [78]. The primary distinction between traditional FSW and FSSW is that there is no travel speed or movement in the FSSW, as shown in Figure 7.10, which concentrates the entire process in one point, so this type is classified as spot welding. From a manufacturing sustainability perspective, FSSW is superior to corresponding joining methods such as riveting, resistance, and laser spot welding. FSSW consumes less energy and does not require melting the weld region. It also does not need a professional worker, and no consumer rods need to be replaced periodically. About 90% of the consumed energy can be minimized by replacing resistance spot welding (RSW) with FSSW, and the cost can be reduced to 40% [79].

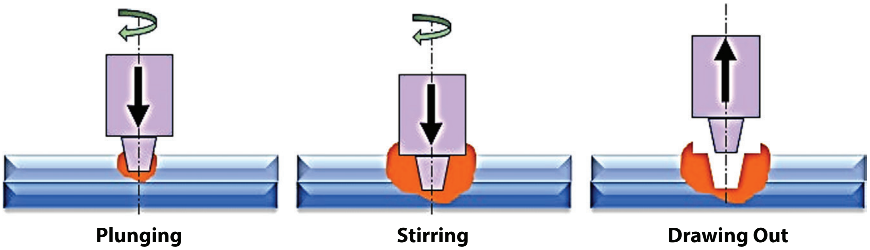

Figure 7.10 Scheme of FSSW stages.

There are several forms of FSSW used in literature for many applications. Traditional FSSW [80], which is widely used, refill FSSW to overcome the keyhole [81], pinless FSSW with only one shoulder [82], and swing FSSW with swinging movement over the surface of the weld or coating surfaces [83].

7.6 Recent Applications of FSW

Friction stir welding has progressed from the realm of research and limited application to active participation in various countries worldwide in the last 10 years. The increasing demand for friction stir welding as a sustainable tool has led to many companies specializing in manufacturing equipment for this type of welding or providing unique services ever Q12 are moving toward. FSW can be automated, which improves precision and speeds up production compared to other types of welding. Because of the weight and cost savings, FSW was embraced for bonding fuel tanks on satellite vehicles, commercial aircraft manufacture, alloy rims, engine blocks, and battery boxes. FSW was used in the Eclipse 500 business jet, the Boeing 747 freighter, the Legacy 500 aircraft, and the Embraer aircraft [84]. Several cooperative projects in the field of FSW have recently been completed, including the 6.8-million-euro European Industrialization of Friction Stir Welding (EuroStir®), the 88.0-million-euro Technology Application for the Near-Term Business Goals of the Aerospace Industry (TANGO), and the 5.1-million-euro Welding of Airframes by Friction Stir (WAFS). Furthermore, FSW was used in several rail applications, such as the Commuter EMU Series 20000 and Express EMU Series 885 built by Hitachi and the 700 Series Shinkansen managed on the Tokaido and Sanyo Lines in Japan [85].

No any
Problem

7.7 Conclusions

This chapter attempted to shed light on the concept of sustainability and its applications to friction stir welding through four essential aspects: reducing the environmental impact, reducing the energy and resources consumed, reducing the cost of production and labor, and maximizing the welding process efficiency.

The chapter showed that by reviewing several novel studies, friction stir welding succeeded effectively in all four aspects compared to other welding processes. This remarkable success has led to the growing role of this type of welding in the industry in recent years. Moreover, it has become an integral part of many industries, especially transportation, such as planes, trains, and cars, due to its significant contribution to reducing weight and cost. It has also been assigned many recent applications, such as manufacturing batteries. In conclusion, friction stir welding will contribute to the global vision of industrial sustainability in the coming years, and its areas of use will increase steadily.

References

1. McGrath, J.E., Hickner, M.A., Höfer, R., Introduction: Polymers for a sustainable environment and green energy, in: *Polymer Science: A Comprehensive Reference 10*, 2012. p 1-3
Q13 2. Jamal, J., Darras, B., Kishawy, H., A study on sustainability assessment of welding processes. *Proc. Inst. Mech. Eng. B J. Eng. Manuf.*, 234, 3, 2020. p 501-512
3. Akca, E. and Gürsel, A., Solid state welding and application in aeronautical industry. *Period. Eng. Nat. Sci. (PEN)*, 4, 1, 2016. p 1-8
4. Mohan, D.G. and Wu, C.S., A review on friction stir welding of steels. *Chin. J. Mech. Eng. (English Edition)*, 34, 1, 2021.
Q14 5. Liu, L., Introduction to the welding and joining of magnesium, in: *Welding and Joining of Magnesium Alloys*, L. Liu, (Ed.), pp. 3–8, Woodhead Publishing, 2010. location: Cambridge
6. Al-Sabur, R., Jassim, A.K., Messele, E., Real-time monitoring applied to optimize friction stir spot welding joint for AA1230 Al-alloys. *Mater. Today Proc.*, 42, 2018–2024, 2021.
7. Xu, W.F., Wu, X.K., Ma, J., Lu, H.J., Luo, Y.X., Abnormal fracture of 7085 high strength aluminum alloy thick plate joint via friction stir welding. *J. Mater. Res. Technol.*, 8, 6, 2019. p 6029-6040
8. Ma, Z.Y., Feng, A.H., Chen, D.L., Shen, J., Recent advances in friction stir welding/processing of aluminum alloys: Microstructural evolution and mechanical properties. *Crit. Rev. Solid State Mater. Sci.*, 43, 4, 2018. p 269-333
9. Bahedh, A.S., Mishra, A., Al-Sabur, R., Jassim, A.K., Machine learning algorithms for prediction of penetration depth and geometrical analysis of weld in friction stir spot welding process. *Metall. Res. Technol.*, 119, 3, 2022. p 305
10. Asmare, A., Al-Sabur, R., Messele, E., Experimental investigation of friction stir welding on 6061-t6 aluminum alloy using Taguchi-based GRA. *Metals*, 10, 11, 2020. p 1480
11. Jacquin, D. and Guillemot, G., A review of microstructural changes occurring during FSW in aluminium alloys and their modelling. *J. Mater. Process. Technol.*, 288, 2021. p 116706

12. Khalaf, H., II, Al-sabur, R., Abdullah, M.E., Kubit, A., Derazkola, H.A., Effects of underwater friction stir welding heat generation on residual stress of AA6068-t6 aluminum alloy. *Materials*, 15, 6, 2022. p 2223
13. Al-Sabur, R., Tensile strength prediction of aluminium alloys welded by FSW using response surface methodology-comparative review. *Mater. Today Proc.*, 45, 2021. p 4504-4510
14. Silva, A.C.F., Braga, D.F.O., de Figueiredo, M.A.V., Moreira, P.M.G.P., Ultimate tensile strength optimization of different FSW aluminium alloy joints. *Int. J. Adv. Manuf. Technol.*, 79, 5–8, 2015. p 805–814
15. Güleryüz, G., Relationship between FSW parameters and hardness of the ferritic steel joints: Modeling and optimization. *Vacuum*, 178, 2020. p 109449
16. Nishida, H., Ogura, T., Hatano, R., Kurashima, H., Fujimoto, M., Hirose, A., Fracture toughness and fatigue crack behaviour of A3003/SUS304 lap friction stir welded joints. *Weld. Int.*, 31, 4, 2017. p 3901
17. Q15 He, W., Li, M., Song, Q., Liu, J., Hu, W., Efficacy of external stationary shoulder for controlling residual stress and distortion in friction stir welding. *Trans. Indian Inst. Met.*, 2019.vol 72, p 1349–1359
18. Morishige, T., Tsujikawa, M., Oki, S., Kamita, M., Chung, S.W., Higashi, K., Friction stir processing of cast Mg-Y-Zn alloy. *Adv. Mater. Res.*, 15–17, 2007. p 369-374
19. Al-Sabur, R., Khalaf, H., II, Świerczyńska, A., Rogalski, G., Derazkola, H.A., Effects of noncontact shoulder tool velocities on friction stir joining of polyamide 6 (PA6). *Materials*, 15, 12, 2022. p 4214
20. Rangel Pacheco, M., Paul Kabche, J., Thesi, I., Nunes Diesel, F., Temperature distribution analysis in plates joined by friction stir welding. *ASME 2009 International Mechanical Engineering Congress and Exposition, Proc*, vol. 11, 2010. p 163-169
21. Smith, C.B., Robotic friction stir welding using a standard industrial robot. *2nd Friction Stir Welding International Symposium*, 2000.
22. Mehta, K.P. and Patel, R., On FSW keyhole removal to improve volume defect using pin less tool. *Key Eng. Mater.*, 821, 2019. p 215-221
23. Fernandez, G.J. and Murr, L.E., Characterization of tool wear and weld optimization in the friction-stir welding of cast aluminum 359+20% SiC metal-matrix composite. *Mater. Charact.*, 52, 1, 2004. p 65-75
24. Buchibabu, V., Reddy, G.M., Kulkarni, D., De, A., Friction stir welding of a thick Al-Zn-Mg alloy plate. *J. Mater. Eng. Perform.*, 25, 3, 2016. p 1163–1171
25. Yoon, J., Kim, C., Rhee, S., Performance of plunge depth control methods during friction stir welding. *Metals*, 9, 3, 2019. p 283
26. Bevilacqua, M., Ciarapica, F.E., D'Orazio, A., Forcellese, A., Simoncini, M., Sustainability analysis of friction stir welding of AA5754 sheets. *Proc. CIRP*, 62, 2017. p 529-534
27. Sued, M.K., Samsuri, S.S.M., Kassim, M.K.A.M., Nasir, S.N.N.M., Sustainability of welding process through bobbin friction stir welding. *IOP Conf. Ser. Mater. Sci. Eng.*, 318, 1, 2018. p 012068

28. Sethi, S.R., Das, A., Baruah, M., A review on friction stir welding: A sustainable way of manufacturing. *Mater. Today Proc.*, 44, 2021. p 2685-2688
29. Ramesha, K., Sudersanan, P.D., Santosh, N., Jangam, S., Sustainable processing of dissimilar aluminium alloy joints by friction stir welding. *IOP Conf. Ser. Mater. Sci. Eng.*, 1132, 1, 2021. p 012029
30. Azeez, S., Mashinini, M., Akinlabi, E., Sustainability of friction stir welded AA6082 plates through post-weld solution heat treatment. *Proc. Manuf.*, 33, 27–34, 2019.
31. Mimouni, O., Badji, R., Hadji, M., Kouadri-Henni, A., Finite volume modeling of laser assisted friction stir welding of 2017A-T451 aluminum alloy for enhanced sustainability of welded joints. *AIP Conference Proc*, vol. 1769, 2016. p 100014
32. Majeed, T., Wahid, M.A., Alam, M.N., Mehta, Y., Siddiquee, A.N., Friction stir welding: A sustainable manufacturing process. *Mater. Today Proc.*, 46, 2020. p 6558-6563
33. Al-Wajidi, W., *Analysis of Friction Stir Welding Process: Sustainability and Optimization*, PhD Thesis University of Guelph, 2019. Guelph, ON N1G 2W1, Canada
34. Suresh, S., Elango, N., Venkatesan, K., Lim, W.H., Palanikumar, K., Rajesh, S., Sustainable friction stir spot welding of 6061-T6 aluminium alloy using improved non-dominated sorting teaching learning algorithm. *J. Mater. Res. Technol.*, 9, 5, 2020. p 11650-11674
35. Azeez, S. and Akinlabi, E., Sustainability of manufacturing technology: Friction stir welding in focus. *Prog. Ind. Ecol.*, 12, 4, 2018. p 419-438
36. Sharma, R.K., Sodhi, G.P., Bhakar, V., Kaur, R., Pallakonda, S., Sarkar, P., Singh, H., Sustainability in manufacturing processes: Finding the environmental impacts of friction stir processing of pure magnesium. *CIRP J. Manuf. Sci. Technol.*, 30, 25–35, 2020.
37. Hart, S.L. and Dowell, G., A natural-resource-based view of the firm: Fifteen years after. *J. Manage.*, 37, 5, 2011. p 1464-1479
38. di Lorenzo, R. and Fratini, L., A cost model for the friction stir welding process. *ESAFORM 2005*, pp. 1073–1076, 2005.
39. Boitsov, A.G., Kuritsyn, D.N., Siluyanova, M.V., Kuritsyna, V.V., Friction stir welding in the aerospace industry. *Russ. Eng. Res.*, 38, 12, 2018. p 1029-1033
40. Tipaji, P.K., *E-Design Tools for Friction Stir Welding: Cost Estimation Tool*, MSc Thesis University of Missouri-Rolla, 2007. Rolla, MO 65409, United States
41. Toumpis, A., Galloway, A., Cater, S., Molter, L., A techno-economic evaluation of friction stir welding of DH36 steel. *10th International Friction Stir Welding Symposium*, 2014.
42. Mononen, J. and Hänninen, M., H., Cost comparison of FSW and MIG welded aluminium panels. *Weld. World*, 47, 11–12, 2003.
43. Shrivastava, A., Krones, M., Pfefferkorn, F.E., Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum. *CIRP J. Manuf. Sci. Technol.*, 9, 2015. p 159-168

44. Dawood, H., II, Mohammed, K.S., Rajab, M.Y., Advantages of the green solid state FSW over the conventional GMAW process. *Adv. Mater. Sci. Eng.*, 2014, 2014. p 105713
45. Hossfeld, M. and Roos, E., A new approach to modelling friction stir welding using the CEL method. *International Conference on Advanced Manufacturing Engineering and Technologies NEWTECH (Stockholm)*, 2013.
46. Mofeed Alam, M., Jha, A.K., Mukherjee, S., Panda, S., Chakraborty, S.S., A review on friction stir welding—A green manufacturing technology, in: *Lecture Notes in Mechanical Engineering*, vol. 46, 2021.
47. Sejani, D., Li, W., Patel, V., Stationary shoulder friction stir welding–low heat input joining technique: A review in comparison with conventional FSW and bobbin tool FSW. *Crit. Rev. Solid State Mater. Sci.*, 2021. vol 47:6, p 865-914
48. Sharma, C., Upadhyay, V., Verma, V., Tripathi, A., Sharma, S., Tensile behaviour of friction stir welded joints of different aluminium alloys. *J. Eng. Res.*, 9, 2021. p 1-15
49. Morishige, T., Kawaguchi, A., Tsujikawa, M., Hino, M., Hirata, T., Higashi, K., Dissimilar welding of Al and Mg alloys by FSW. *Mater. Trans.*, 49, 5, 2008. p 1129-1131
50. Masoudian, A., Tahaei, A., Shakiba, A., Sharifianjazi, F., Mohandesi, J.A., Microstructure and mechanical properties of friction stir weld of dissimilar AZ31-O magnesium alloy to 6061-T6 aluminum alloy. *Trans. Nonferrous Met. Soc. China (English Edition)*, 24, 5, 2014. p 1317-1322
51. Malarvizhi, S. and Balasubramanian, V., Influences of tool shoulder diameter to plate thickness ratio (D/T) on stir zone formation and tensile properties of friction stir welded dissimilar joints of AA6061 aluminum-AZ31B magnesium alloys. *Mater. Des.*, 40, 2012. p 453-460
52. Mahamud, M., II, Ishak, I., Halil, A.M., Study of dissimilar welding AA6061 aluminium alloy and AZ31b magnesium alloy with ER5356 filler using friction stir welding. *IOP Conf. Ser. Mater. Sci. Eng.*, 238, 1, 2017. p 012002
53. Baghdadi, A.H., Sajuri, Z., Keshtgar, A., Sharif, N.M., Rajabi, A., Mechanical property improvement in dissimilar friction stir welded Al5083/Al6061 joints: Effects of post-weld heat treatment and abnormal grain growth. *Materials*, 15, 1, 2022. p 288
54. Prabhu, S., Sri, M.N.S., Anusha, P., Saravanan, G., Kannan, K., Manickam, S., Improvement of mechanical behavior of FSW dissimilar aluminum alloys by postweld heat treatments. *Adv. Mater. Sci. Eng.*, 2022, 1–8, 2022.
55. Dickerson, T., Shi, Q., Shercliff, H.R., Heat flow into friction stir welding tools. *4th International Symposium on Friction Stir Welding*, USA, 2003.
56. Li, H., Gao, J., Li, Q., Galloway, A., Toumpis, A., Effect of friction stir welding tool design on welding thermal efficiency. *Sci. Technol. Weld. Join.*, 24, 2, 2019. p 156-162
57. Hattel, J.H., Schmidt, H.N.B., Tutum, C., Thermomechanical modelling of friction stir welding. *ASM Proceedings of the International Conference: Trends in Welding Research*, 2009.

58. Sharma, C., Upadhyay, V., Narwariya, B.S., Tensile properties of dissimilar friction stir weld joints of Al-2024 and Al-7039 alloys. *Mater. Res. Express*, 6, 2, 2019. p 026524
59. Feng, T. and Zhang, X., Three dimensional model for heat transfer and plastic flow of friction stir welding. *Hanjie Xuebao/Trans. China Weld. Inst.*, 34, 7, 2013. p 105
60. Khandkar, M.Z.H., Khan, J.A., Reynolds, A.P., Prediction of temperature distribution and thermal history during friction stir welding: Input torque based model. *Sci. Technol. Weld. Join.*, 8, 3, 2003. p 165-174
61. Chao, Y.J., Qi, X., Tang, W., Heat transfer in friction stir welding-experimental and numerical studies. *J. Manuf. Sci. Eng.*, 125, 1, 2003.
62. Zhu, X.K. and Chao, Y.J., Numerical simulation of transient temperature and residual stresses in friction stir welding of 304L stainless steel. *J. Mater. Process. Technol.*, 146, 2, 2004. p 263-272
63. Lienert, T.J., Stellwag, W.L., Grimmett, B.B., Warke, R.W., Friction stir welding studies on mild steel. *Weld. J.*, 82, 1, 2003. p 1s–9s
Q16 64. Abdallah, T., *Sustainable Mass Transit*, 2017. Imprint: Elsevier , Oxford, UK
65. Bevilacqua, M., Ciarapica, F.E., Forcellese, A., Simoncini, M., Comparison among the environmental impact of solid state and fusion welding processes in joining an aluminium alloy. *Proc. Inst. Mech. Eng. B J. Eng. Manuf.*, 234, 1–2, 2020. p 140-156
66. Seuring, S., A review of modeling approaches for sustainable supply chain management. *Decis. Support Syst.*, 54, 4, 2013. p 1513-1520
67. Zhao, F., Bernstein, W.Z., Naik, G., Cheng, G.J., Environmental assessment of laser assisted manufacturing: Case studies on laser shock peening and laser assisted turning. *J. Clean. Prod.*, 18, 13, 2010. p 1311-1319
68. W.M.W. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith, C.J. Dawes, Friction stir welding process developments and variant techniques. Google Patents, 1991.
69. Garg, A. and Bhattacharya, A., Effect of tool size on AA6061-T6 double-sided friction stir welds. *Mater. Des. Process. Commun.*, 3, 5, 2021. p 1-8
70. Chen, J., Ueji, R., Fujii, H., Double-sided friction-stir welding of magnesium alloy with concave-convex tools for texture control. *Mater. Des.*, 76, 2015. p 181-189
71. Rahmatian, B., Dehghani, K., Mirsalehi, S.E., Effect of adding SiC nanoparticles to nugget zone of thick AA5083 aluminium alloy joined by using double-sided friction stir welding. *J. Manuf. Process.*, 52, 2020. p 152-164
72. Lyu, X., Li, M., Li, X., Chen, J., Double-sided friction stir spot welding of steel and aluminum alloy sheets. *Int. J. Adv. Manuf. Technol.*, 96, 5-8, 2018. p 2875–2884
73. Thomas, W.M., Threadgill, P.L., Nicholas, E.D., Feasibility of friction stir welding steel. *Sci. Technol. Weld. Join.*, 4, 6, 1999. p 365-372
74. Thomas, W.M., Staines, D.J., Watts, E.R., Norris, I.M., The simultaneous use of two or more friction stir welding tools. *Int. J. Join. Mater.*, 17, 1, 2005. p 52
75. Kumari, K., Pal, S.K., Singh, S.B., Friction stir welding by using counter-rotating twin tool. *J. Mater. Process. Technol.*, 215, 1, 2015. p 132-141

76. Liu, X.M., Zhang, X.M., Yao, J.S., Yin, Y.H., Xia, P.Y., Optimization of rotation speed ratio in dual-rotation friction stir welding by finite element method. *Int. J. Adv. Manuf. Technol.*, 91, 5-8, 2017. p 2869–2874
77. Wang, F.F., Li, W.Y., Shen, J., Wen, Q., dos Santos, J.F., Improving weld formability by a novel dual-rotation bobbin tool friction stir welding. *J. Mater. Sci. Technol.*, 34, 1, 2018. p 135-139
78. Wahid, M.A., Sharma, N., Shandley, R., Friction stir welding process effects on human health and mechanical properties. *IJFEM*, 1, 1, 2020. p 42
79. Choi, D.H., Ahn, B.W., Lee, C.Y., Yeon, Y.M., Song, K., Jung, S.B., Formation of intermetallic compounds in Al and Mg alloy interface during friction stir spot welding. *Intermetallics (Barking)*, 19, 2, 2011. p 125-130
80. Bakavos, D. and Prangnell, P.B., Effect of reduced or zero pin length and anvil insulation on friction stir spot welding thin gauge 6111 automotive sheet. *Sci. Technol. Weld. Join.*, 14, 5, 2009. p 443-456
81. Ikuta, A., North, T.H., Uematsu, Y., Characteristics of keyhole refill process using friction stir spot welding. *Weld. Int.*, 32, 6, 2018. p 417-426
82. Cox, C.D., Gibson, B.T., Strauss, A.M., Cook, G.E., Effect of pin length and rotation rate on the tensile strength of a friction stir spot-welded al alloy: A contribution to automated production. *Mater. Manuf. Process.*, 27, 4, 2012. p 472-478
83. Wu, S., Sun, T., Shen, Y., Yan, Y., Ni, R., Liu, W., Conventional and swing friction stir spot welding of aluminum alloy to magnesium alloy. *Int. J. Adv. Manuf. Technol.*, 116, 7–8, 2021. p 2401–2412

Q17 84. TWI, Friction stir welding of airframe structures, 2022. https://www.twi-global.com/who-we-are/who-we-work-with/industry-sectors/aerospace/joining-of-airframe-structures/friction-stir-welding-of-airframe-structures. see below
85. TWI, Creating a stir in the rail industry, 2001. https://www.twi-global.com/technical-knowledge/published-papers/creating-a-stir-in-the-rail-industry-november-2001. see below

Both 84 and 85 are web sites pages (not journals)The websites
belonged to TWI, one of the world's famous welding establishments.

Answer all Queries (Q) in the margin of the text. When requested, provide missing intext reference citation as well as intext reference for figure/table. Please annotate the PDF and read the whole chapter again carefully. Careful proofing is key to optimal output.

Author Queries

Q1 Please check if changing severe to several is correct. Correct

Q2 Shortened book title was provided. Kindly check if OK. If not, please provide short title with a maximum of 45 characters (including spaces) per Scrivener guideline. accepted

Q3 The citation Table 3 was changed to Table 7.1. Please check. accepted

Q4 Citation was changed according to reference list data. Please check. accepted

Q5 "Please note that this was "Figure 7.2" thus changed to "Figure 7.3" to avoid number duplication and the succeeding figures and citations was renumbered. Edit OK?" accepted

Q6 Please confirm that the change from 'FSW Cost Minimize' to 'Minimizing the FSW Costs' retains your intended meaning. accepted

Q7 Please confirm that the change from 'FSW Energy Consumption Minimize' to 'Minimizing the FSW Energy Consumption' retains your intended meaning. accepted

Q8 Provide the expanded form of "GMAW". Gas Metal Arc Welding

Q9 Please confirm that the change from 'FSW Process Efficiency Maximize' to 'Maximizing the FSW Process Efficiency' retains your intended meaning. accepted

Q10 Please confirm that the change from 'Minimize Environmental Impact' to 'Minimizing the Environmental Impact' retains your intended meaning. accepted

Q11 Please confirm that the change from 'Double Side FSW Tool' to 'Double-Sided FSW Tool' retains your intended meaning. accepted

Q12 There may be excess/missing data here. Please check.

Q13 Please provide page number of references 2, 7, 9, 10, 11, 12, 13, 14, 15, 16, 18, 19, 22, 24, 26, 28, 32, 34, 35, 37, 39, 42, 43, 44, 48, 50, 51, 52, 53, 58, 59, 60, 63, 65, 67, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 82. All required pages add added, please check reference list

Q14 Please provide publisher location of references 5, 33, 40. already added

Q15 Please provide volume and page number of references 17, 47. already added

Q16 Please provide publisher name and location of reference 64. already added

Q17 Please provide journal title, volume and page number of references 84, 85. Both 84 and 85 are web sites pages (not journals)The websites belonged to TWI, one of the world's famous welding establishments.