A detailed process design for conventional friction stir welding of aluminum alloys and an overview of related knowledge

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Abstract
Friction stir welding (FSW) has matured considerably since its introduction in 1991. Over the last decades, it has indeed branched and been applied in different fields, such as automotive, aerospace, railway, and shipbuilding. This article aims to survey the basic knowledge related to the conventional FSW of aluminum alloys in order to provide a tool for understanding the friction stir processes. The review covers the five basic process parameters: rotational speed, welding speed, tool geometry, tilt angle, and plunged depth. Furthermore, it presents the related equations and recommended ranges of those parameters to facilitate the process design step for industrial implementation. A sample of 30 published articles was drawn for that purpose. The current article also discusses the main five properties most researchers are interested in, namely, microstructure, microhardness, tensile strength, residual stresses, and distortion.

Key words
aluminum alloys, basic knowledge, friction stir welding, overview, process design, process parameters, weldment properties

1 | INTRODUCTION

Friction stir welding (FSW) is a solid-state welding technique that employs frictional heat to join a wide variety of materials. The process is divided into four stages, namely, plunging, dwelling, welding, and retracting. A rigid rotating tool is plunged into the workpiece and stops once the required plunge depth is reached. The tool is then left to dwell for a prescribed period to build enough heat for joining. After joining is complete, the tool is retracted, leaving a keyhole at the exit.

Heat input to the process is a function of the process input parameters, which are the rotational speed, traverse speed, tool geometry, tilt angle, and plunge depth. These five parameters contribute in different proportions to the amount of heat generated, which affects the material flow patterns and, hence, the final weld properties.

For a given material, a series of experiments are required to determine the best process parameters combination that yields the optimum amount of heat input and, in return, a defect-free weld of high loading capacity. Unfortunately, there
is no general equation for acquiring the best combination other than experimental trials. However, studying the published results can provide an insight into proper process design that can yield satisfying results with minimum trials.

Numerous reviews have been conducted about the process principle, parameters, and properties. However, a small number of studies were dedicated to the process design and selection basis of its parameters. The current review focused on this area and related knowledge. A sample of 30 published articles was drawn to extrapolate the standard process ranges within which the probability of process success increases.

2 | PROCESS PARAMETERS

Figure 1 shows a schematic representation of the FSW process and its parameters. The section herein discusses the roles of the five independent parameters that are essential for the process. They are the rotational speed, welding speed, tool geometry, tilt angle, and plunge depth. There are other auxiliary parameters, which will be covered in future reviews.

2.1 | Rotational and welding speeds

Tool rotational and traverse speeds work in conjunction with each other to create a solid-state joint. The rotational motion is responsible for the material stirring and, hence, breaking the base metals’ (BM)s grains into finer ones. The traverse motion, on the other hand, regulates the rate at which the new material enters the stirring zone. Besides, the two parameters govern the amount of heat input to the process. The faster the tool rotates, the higher the frictional heat gets. The same outcome can be derived by decreasing the welding speed.

Recently, researchers have stopped treating the processing speeds as two separate parameters. Instead, they have reduced them into a single parameter called the Velocity Ratio \((N/V)\), which is the rotational speed \((N)\) divided by the welding speed \((V)\). The new parameter, however, still lacks the comprehensive study of its influence.

2.2 | Tool geometry

The conventional FSW tool consists of two segments known as the shoulder and pin, as illustrated in Figure 2. The tool shoulder is responsible for generating the greatest portion of heat input while the tool speeds govern the rest. Moreover, it prevents the expulsion of plastic material outside the weld pool. The tool pin, on the other hand, is responsible for shearing the material and controlling its flow patterns, depending on the design. The two segments may incorporate extra features to enhance their functions.
2.3  |  Tilt angle and plunge depth

The tool tilt angle \( (H) \) is the inclination angle of the tool’s axis of rotation towards the trailing direction, while the tool plunge depth \( (X) \) represents the magnitude of tool shoulder penetration into the workpiece surface. Both parameters directly affect the plunging force \( (F) \), which is one of the heat input's controlling parameters.\(^5\)\(^7\) They are introduced to the process when extra heat input is required for the same operating speeds and tool geometry.

3  |  PROCESS DESIGN

The FSW process is a multiobjective optimization problem that requires a clear definition of its constraints. The process aims for a defect-free weld with high tensile strength and minimum residual stress (RS) and distortion. Friction stir welds’ properties are sensitive to the variations in material flow patterns that are controlled by the amount of heat input to the process, as demonstrated in Figure 3.

From the previous section, it can be concluded that the heat input is highly dependent on the five previously mentioned parameters. Each of these parameters has lower and upper bounds within which the probability of the process success increases. The current section provides an insight based on a sample of 30 published articles that can help define the process boundary conditions accurately. Table 1 summarizes the data extracted from the sample.

3.1  |  Processing speeds

Figure 4 highlights the typical operating range based on the sample drawn. As shown in the figure, the majority of data points fall within a range starting from 250 to 2000 rpm for the rotational speed and from 20 to 200 mm/min for the welding speed. The figure also signifies that little research has been conducted to investigate the effect of high processing speeds. It should be noted that BM properties and machine capabilities are the main determinants of speed selection.
TABLE 1 Process parameters’ values obtained from different studies

| BM   | t  | N  | V       | H  | X  | d   | D   | L   | ST | Mat | Reference |
|------|----|----|---------|----|----|-----|-----|-----|----|-----|-----------|
| 2017 | 5  | 1500 | 25600   | 3  | 0  | 6   | 15  | 4.7 | F  | n/a | 8         |
| 6016 | 1  | 1120 | 1800    | 0.25 | 0  | 3   | 10  | 14  | 0.5 | C F | n/a       |
| 6061 | 5  | 1200 | 75      | 0   | 0  | 6   | 18  | 5.5 | F  | n/a | 10        |
| 2219 | 5  | 250  | 325     | 60  | 0  | 7.89 | 18  | 20  | n/a | F  | n/a       |
| 5083 | 12 | 420  | 500     | 80  | 2  | 0.35 | 8.9 | 18  | 22  | F  | H13       |
| 2014 | 5  | 800  | 100     | 0.3  | 0  | 4.5  | 15  | 4.5 | F  | H13       |
| 2060 | 2  | 750  | 950     | 95  | 2  | 0.5  | 3.5 | 12  | 1.7 | F  | GH4169    |
| 5086 | 6  | 1100 | 22      | 1   | 0  | 5.56 | 18  | 5.7 | F  | HSS       |
| 6061 | 5  | 800  | 1000    | 80  | 0  | 5    | 18  | n/a | F  | H13       |
| 7075 | 4.9| 630  | 32      | 2   | 0.4 | 5.7  | 30  | 4.8 | F  | H13       |
| 6061 | 16 | 500  | 700     | 120 | 2.5 | 0    | 16  | 30  | 15.8| F  | n/a       |
| 2219 | 5  | 400  | 800     | 30  | 2  | 0    | 5   | 15  | n/a | F  | H13       |
| 5086 | 6  | 500  | 800     | 41.5| 0  | 6    | 16  | 5.7 | C  | H13       |
| 7020 | 5  | 900  | 50      | 0  | 0   | 6    | 16  | 3.7 | C  | H13       |
| 7050 | 5  | 600  | 100     | 2.5 | 0.2 | 4.4  | 13.8| 4.85| C  | Die St.   |
| 6061 | 3  | 900  | 1000    | 2.4 | 0.2 | 3.45 | 12  | n/a | C  | H13       |
**TABLE 1** Continued

| BM     | $t$  | $N$  | $V$  | $H$  | $X$  | $d$  | $D$  | $L$  | ST   | Mat  | Reference |
|--------|------|------|------|------|------|------|------|------|------|-------|-----------|
| 6061   | 2.5  | 920  | 60   | 0.2  | 0.1  | 3.6  | 10   | 2.2  | F    | n/a   | 23       |
|        |      | 1000 | 100  |      |      |      |      |      |      |       |           |
| 7075   | 6    | 508  | 25   | 1.5  | 0    | 6    | 25   | 4    | C    | D2    | 24       |
|        |      | 720  |      |      |      |      |      |      |      |       |           |
|        |      |      |      |      |      |      |      |      |      |       |           |
| 6061   | 4.76 | 900  |      | 3    | 0.2  | 6.1  | 15   | 4.7  | C    | H13   | 25       |
|        |      | 1100 |      |      |      |      |      |      |      |       |           |
|        |      | 1300 |      |      |      |      |      |      |      |       |           |
|        |      | 1500 |      |      |      |      |      |      |      |       |           |
|        |      | 1700 |      |      |      |      |      |      |      |       |           |
|        |      | 1900 |      |      |      |      |      |      |      |       |           |
| 5059   | 4    | 600  |      | 2.5  | 0    | 3.5  | 12   | 3.7  | F    | HSS   | 26       |
|        |      | 742  |      |      |      |      |      |      |      |       |           |
|        |      | 950  |      |      |      |      |      |      |      |       |           |
|        |      | 1158 |      |      |      |      |      |      |      |       |           |
|        |      | 1300 |      |      |      |      |      |      |      |       |           |
| 5083   | 6    | 280  |      | 140  | 0    | 8.10 | 24   | 5.8  | V    | HS6-5-2| 27       |
| 7075   |      | 355  |      |      |      |      |      |      |      |       |           |
|        |      | 450  |      |      |      |      |      |      |      |       |           |
|        |      | 560  |      |      |      |      |      |      |      |       |           |
| 6063   | 4.75 | 900  | 50   | 1.5  | 0    | 7.3  | 20   | 4.5  | F    | H13   | 28       |
| 5083   | 6    | 400  | 50   | 0    | 0.2  | 6.355| 25   | 5.7  | F    | K720  | 29       |
|        |      | 100  |      |      |      |      |      |      |      |       |           |
|        |      | 160  |      |      |      |      |      |      |      |       |           |
| 2024   | 5    | 800  | 20   | 0    | 2.5  | 0    | 5    | 16   | 4.8  | F    | n/a      | 30       |
| 6082   | 6    | 800  | 40   | 1    | 0    | 4.5  | 18   | 5.5  | F    | H13   | 31       |
| 2024   | 3.2  | 750  | 50   | 0    | 0.2  | 2.4  | 15.8 | 2.7  | F    | n/a    | 32       |
| 2198   |      | 1000 |      |      |      |      |      |      |      |       |           |
| 6061   | 6    | 900  | 75   | 0    | 3    | 0.1  | 4.5  | 18   | n/a  | F    | H13     | 33       |
| 7075   | 6.5  | 765  | 20   | 3    | 0.1  | 6.35 | 18.2 | 6.3  | C    | H13   | 34       |
|        |      | 1070 |      |      |      |      |      |      |      |       |           |
|        |      | 1500 |      |      |      |      |      |      |      |       |           |
| 5083   | 4    | 900  | 240  | 3    | 0.15 | 4    | 12   | 3.8  | C    | SKD61 | 35       |
| 6061   | 0.8  | 2000 |      | 0    | 0    | 2.5  | 6    | 0.62 | F    | n/a   | 36       |
|        |      | 8000 |      |      |      |      |      |      |      |       |           |
|        |      | 1500 |      |      |      |      |      |      |      |       |           |

Abbreviations: BM, base metal; ST, shoulder type.
3.2 | Tool design

3.2.1 | Tool material

Severe plastic deformations at high loading rates and temperatures are part of the FSW process. The FSW tool is the one responsible for inducing these deformations. Therefore, its material has to be carefully picked based on specific criteria suitable for the function. The criteria are as follows Reference 37:

- High strength and hardness.
- High wear resistance.
- High machinability.
- Low chemical reactivity.
- Low cost.

There are plenty of materials that fit the previous criteria, such as AISI-H13, which is the most frequently used tool material in friction welding of aluminum alloys, as highlighted by the sample. The tool material may require heat treatment to enhance its properties for longer service life.

3.2.2 | Tool dimensions

Tool torque and axial force are functions of the tool dimensions, namely, the shoulder and pin diameters. There are no available relations that give deterministic diameter values owing to the variety of welding techniques and configurations. Zhang et al., however, developed two empirical equations to determine the dimensions in terms of workpiece thickness. The equations were built based on a sample of 53 published articles. The authors herein adopted a similar approach but with a different set of data.

Figure 5 portrays the relationship between tool dimensions and workpiece thickness. It can be observed that tool diameters increase linearly with the thickness, which is in good agreement with Zhang’s equations. The two equations developed herein imply that with increasing the thickness, more heat input is required and, hence, larger diameters are necessary to generate the required amount.

3.2.3 | Tool features

Tool shoulder and pin may incorporate additional features to enhance heat generation and material flow. Figure 6 illustrates the most common tool shoulder features. As demonstrated, the shoulder surface can be flat, convex, or concave.
Based on the sample, the flat shoulder is the most common type, followed by the concave shoulder. The flat shoulder is simple and easy to machine but inefficient in maintaining the plasticized material beneath its surface. Hence, flash is most likely to appear on the surface. The convex shoulder is suitable for welding sheets of different thicknesses, but, like flat shoulder, it tends to produce flash. The concave shoulder does not have the limitation that flat and convex shoulders have. It acts as a reservoir for the plastic material. As the tool traverses, new material enters the reservoir, pushing the entrapped material behind the pin. At high welding speeds, the entrapped material does not have much time to exit the cavity. Consequently, the reservoir ends up holding more than its capacity causing the tool to be pushed upwards. The tool is tilted by 1° to 3° towards the trailing direction in order to maintain the reservoir and avoid tool lift.

Some features help overcome the limitations associated with each shoulder surface type. The scroll type is the most common among the others (see Figure 6). Scrolls serve as passages that direct the plasticized material towards the pin. When added to either flat or convex shoulders, scrolls help reduce the amount of flash, which reduces the possibility of local thinning. In the case of the concave shoulder, scrolls eliminate the tool lift problem in addition to the need for tool tilting.

Tool pin features are versatile owing to the numerous material flow studies. For ultrathin sheets, a pinless tool is preferable to reduce the possibility of defect formation and local thinning. For thicker workpieces, a tool with a cylindrical or tapered pin may be used to consolidate material flow through the thickness. For very thick plates (up to 60 mm), more sophisticated designs are used, such as Whorl and MX-Triflute tools. They are characterized by having a high swept rate
and achieving sound joints at a very high welding speed. Figure 7 summarizes pin features with respect to workpiece thickness.

### 3.3 Tilt angle and plunge depth

Tool tilt angle varies from 0° to 4° according to the sample. Tools with flat shoulders and scrolled concave shoulders do not require a tilt angle. Tools with smooth concave shoulders do require a tilt angle from 1° to 3° to avoid the tool lift issue. On the other hand, researchers tend to set plunge depth at some arbitrary value within the pin clearance. There is no recommended value or range found in the literature as a little to no significant work has been done to investigate the effect of varying plunge depth.

### 4 PROPERTIES

The following section briefly explores how process responses respond to the variations in the input parameters. Five responses were selected due to their significance in the industrial field. They are microstructure, microhardness, tensile strength, RS, and residual distortion.

#### 4.1 Microstructure

The key to understanding weldment’s physical and mechanical properties is studying its microstructure. Weldment’s microstructure gives information about grain size, grain orientation, welding defects, and so on. This information is then used to justify the weldment performance and optimize the process for future trials.

All friction stir welded parts share the same microscopic feature, which is having four distinct zones. The four zones are the nugget zone (NZ), the thermomechanically affected zone (TMAZ), the heat-affected zone (HAZ), and the BM. Each zone has its characteristics. Figure 8 illustrates the four weld zones and their characteristics. First, NZ is located at the weld center. The NZ experiences a thermal cycle and severe plastic deformation due to direct contact with the tool. During the welding process, the original grains disintegrate and dynamically recrystallize, producing finer grains. If the thermal gradient is high enough, grain coarsening is most likely to happen. Second, TMAZ is located right next to NZ. It also experiences a thermal cycle and some plastic deformation for being in the vicinity of the NZ. However, the plastic strain is not large enough to induce dynamic recrystallization. Third, the HAZ is located beyond the TMAZ. It only experiences a thermal cycle without any plastic deformation. The heat input is sufficient to alter the zone’s properties. Fracture is most likely to happen in this zone. Fourth, BM is the only zone whose properties remain the same after the welding process. Hence, some researchers call it the “Unaffected” zone.
Weldment’s microstructure may contain some discontinuities as a result of poor process design. These discontinuities are referred to as “imperfections” or “defects.” The most common defects are kissing bonds, lack of penetration (LOP), and voids. Kissing bonds appear within the NZ as dark zigzag lines of aluminum oxide particles extending from the weld root. Kissing bonds are noticeable in weldments produced at high welding speeds (ie, cold welds). Poor heat input associated with high welding speeds can lead to poor material stirring, which leads to a partial breaking of the oxide layer in return. Broken oxide particles hinder material flow resulting in the zigzag shape. To avoid this kind of defect, researchers recommend welding at sensible speeds to disperse the oxide particles evenly across the NZ or, better yet, removing the oxide layer by machining before welding.

Similarly, LOP appears within the NZ as a crack extending from the weld root. LOP, as the name implies, arises when the tool probe is too short or when the plunge depth is too shallow. Increasing probe length amplifies material flow, ensuring better mixing near weld root. Finally, voids appear as empty regions within NZ. Some researchers refer to them as “tunnels.” Voids, or tunnels, are associated with cold welds. Rapid heat dissipation causes the plasticized material to freeze before filling the voids formed during the process. As a solution, Rasti suggested increasing the downward force and the rotational speed to enhance void closure. Moreover, he recommended decreasing the welding speed for any combination of downward force and rotational speed. Figure 9 schematically illustrates the shapes of the three defect types and the typical locations where they may appear.

4.2 Microhardness

There are two groups of aluminum alloys: heat-treatable alloys and nonheat-treatable alloys. The two groups differ in the hardening mechanism. First, heat-treatable alloys’ hardness depends on the second phase particles distribution across the microstructure. Sato and Kokawa showed this in their work using AA6063-T5. They divided the hardness profile into four zones, namely, BM, LOW, MIN, and SOF. The hardness value of each zone varied under different heat treatment conditions. Figure 10 shows the hardness profiles for the different conditions included in their study. It also shows the microstructure of the four zones for the “as-welded” condition.

For the “as-welded” condition, the highest hardness value was in the BM zone because it consisted of a high density of needle-shaped particles and a low density of rod-shaped particles just like the BM. On the other hand, the lowest hardness value was in the MIN zone, where needle-shaped particles wholly disappeared, and rod-shaped particles existed
in a lower concentration. A complete dissolution of both particle types took place in the SOF zone. It had a slightly higher hardness value than the MIN zone. Sato and Kokawa justified this observation with grain size. The SOF zone had very fine grains, which was the reason behind the higher hardness in the absence of strengthening particles. For the rest of the heat treatment conditions, the hardness profile was more homogeneous. This observation was attributed to the even distribution of the second phase particles across the weld.

Second, nonheat-treatable alloys' hardness depends on the grain size. According to Jamalian et al, two factors are affecting the microhardness. They are the annealing effect of heat input and the stirring action of the tool probe. High heat input results in soft welds due to grain growth. On the other hand, intense stirring action results in more dynamic recrystallization.

Consequently, finer grains appear within the weld. The two factors are present in every process, but one of them becomes dominant under certain conditions. In their study on Al-5086-H34, the stirring action was more dominant at high rotational speeds. They also stated that grain size decreased further with increasing the welding speed at high rotational speeds due to the lower heat input.

4.3 Tensile strength

It is a common practice to evaluate a weldment utilizing a tensile test. A typical tensile specimen is cut perpendicular to the weld line and tested until fracture on a universal testing machine. Fracture type, fracture location, tensile strength, and ductility are the main interests of many researchers. This subsection mainly focuses on weldment's tensile strength.

Weldment's tensile strength is sensitive to variations in process parameters. El-Sayed et al studied the effect of operating speeds and tool probe features on Al-5083-O tensile strength. They set the rotational speed at 400 and 630 rpm and the welding speed at 100 and 160 mm/min. Moreover, they used two different tools, which were a threaded cylindrical tool and a smooth tapered tool. Figure 11 summarizes the results of their study. Four observations can be made from the figure. First, weldments obtained by the threaded tool had higher strength than those obtained by the tapered tool except for the case of 630 rpm and 160 mm/min. Second, the strength of weldments obtained by the threaded tool decreased with increasing the welding speed for either rotational speeds, and so did the strength of weldments obtained by the tapered tool at 400 rpm. Third, the strength decreased with increasing the rotational speed for the same welding speed except for weldments obtained by the tapered tool at 160 mm/min. Fourth, the optimum strength was obtained by the threaded tool.
at 400 rpm and 100 mm/min. Upon investigating the macrostructure, El-Sayed et al stated that all weldments obtained by the tapered tool had a tunnel defect within their weld nugget.

Moreover, tunnel defects appeared in weldments obtained by the threaded tool at 630 rpm only. At 400 rpm, the threaded tool produced defect-free weldments. They concluded that the tunnel defect had an inferior effect on the strength of Al-5083-O, which was the reason behind low strength values obtained by both tools.

Similarly, Jamalian et al19 studied the effect of rotational speed and welding speed on Al-5086-H34 tensile strength. They studied all combinations of five rotational speeds of 500, 800, 1000, 1250, and 1600 rpm and three welding speeds of 41.5, 80, and 125 mm/min. The microstructural analysis showed that weldments obtained at 500, 800, and 1600 rpm contained tunnels. Therefore, no further analysis was conducted for these weldments. On the other hand, weldments obtained at 1000 and 1250 rpm were defect-free. In the case of 1000 rpm, grain size decreased with increasing the welding speed, which resulted in higher strength values, as shown in Figure 12. At 1250 rpm, strength increased to a specific value with increasing the welding speed to 80 mm/min as a result of grain refinement. Further increase in welding speed caused a decrease in strength. Jamalian et al stated that inadequate heat input due to high welding speed caused a poor material flow pattern, which was the main reason behind that phenomenon.

For Al-2219-T87, Arora et al11 studied the effect of operating speeds and tool dimensions on the tensile strength. Results showed that weldment’s tensile strength decreased as rotational speed, and shoulder diameter increased. Since Al-2219-T87 is a heat-treatable aluminum alloy, its strength is highly dependent on second phase particles distribution
within the matrix. Large heat input associated with high rotational speed and large shoulder diameter caused dissolution and overaging of the second phase particles. Consequently, the alloy drastically lost its strength.

On the other hand, the heat input decreased as they increased the welding speed. So, strength increased with increasing the welding speed. Arora et al concluded that the most significant parameters affecting the tensile strength were welding speed, shoulder diameter, and rotational speed, in order. Probe diameter was found insignificant because it did not contribute to the heat input by the same amount as the other parameters. Figure 13 illustrates the tensile strength’s dependence on the process parameters considered in their study.

To summarize, there are numerous studies about the effect of process parameters on weldment’s tensile strength. Each study recommends a certain combination of process parameters, which is only valid within the selected experimental domain. The authors of the current overview chose the previous three studies for the sole purpose of illustrating the strength’s dependence on process parameters. Two conclusions can be drawn from these studies. First, macroscopic defects act as stress concentrators that drastically weaken the weldment’s strength. Second, grain size and second phase particles distribution profoundly affect the strength depending on the operating speeds. Most researchers forget an important factor affecting the resulting strength that is the RS. The following subsection reviews RS in the FSW process.

4.4 Residual stresses

FSW process involves mechanical and thermal loading cycles. At the end of those cycles, the workpiece remains stressed even after removing clamps and cooling to room temperature. The remaining stress is referred to as "RS." RS significantly affects the welded part’s mechanical properties positively (if RS is compressive) or negatively (if RS is tensile). Given that, it is vital to determine the magnitude of RS before putting the welded part into service. There are several techniques to measure RS, such as acoustic emission, hole-drilling, neutron diffraction, ultrasonic, and X-ray diffraction. Besides, finite element simulation offers an easier and cheaper way to predict RS, which can help optimize the welding process.

Measurement of RS takes place in two directions, namely, longitudinal and transverse directions. Upon investigating the measured values in either direction, RS appears to be tensile within weld nugget boundaries and compressive in nearby regions (ie, nondeformed regions) to counter the tensile stress. Figure 14 presents a typical RS distribution along the transverse direction. Tensile stress reflects the state weld nugget experiences, which is stretching. Nondeformed regions act as rigid constraints that prohibit weld nugget shrinkage during the cooling stage. In other words, they stretch the weld nugget from the position where it was supposed to shrink freely to the position where it does not shrink due to the interaction among different zones. Typically, researchers are interested in the distribution of longitudinal stress along the transverse direction and ignore the distribution of transverse stress due to its insignificance.

RS is highly dependent on the parameters that directly control the heat input to the process, namely, rotational speed and welding speed. He et al studied the effect of rotational speed on RS in Al-6061-T6 16 mm thick sheets. Results showed that the peak tensile value increased by increasing the rotational speed. However, the peak value’s location was fixed in all cases, which was at the edge of the tool shoulder on the advancing side. The distribution of the measured
values was asymmetric, M-shaped, as shown in Figure 15. It is worth mentioning that they measured RS employing the Hole-drilling technique. For the same alloy, Farajkhah and Liu\textsuperscript{51} studied the effect of clamping area and welding speed on RS in 6 mm thick sheets. They used finite element simulation to predict and visualize RS distribution in each case. In all cases, RS distribution was symmetric, M-shaped with peak tensile value at the edge of the tool shoulder on both sides.

A remarkable decrease in the peak value was observed as the clamping area increased. Moreover, the effect of welding speed was more notable in models of large clamping area. In those models, the peak value increased with increasing the welding speed. Besides, RS distributed over a narrower region than that in models of low welding speed. Bachmann et al\textsuperscript{52} reported the same observation regarding the effect of welding speed on RS in Al-2024-T3 sheets. In a different study, Tutum and Hattel\textsuperscript{53} stated that increasing welding speed resulted in a slightly higher tensile stress while holding rotational speed at a constant value. Their statement was in excellent agreement with References 51,52. On the other hand, increasing rotational speed for a fixed welding speed resulted in a lower peak tensile value and a wider tensile region, as shown in Figure 16. It was the opposite of what He et al reported in their article.

In conclusion, RS is inevitable due to the nature of the welding process. It develops as a result of weld nugget expansion and contraction over the thermal cycle. The measured RS values follow M-shaped distribution with tensile values in the middle and compressive values on the sides. Tensile RS affects the welded part’s performance in an inferior way. So, the lower the peak tensile value gets, the better the performance becomes. In order to generate a better RS distribution, researchers suggest lowering the welding speed for a fixed rotational speed and increasing the clamping area. If
RS is overlooked during the process design stage, distortion may occur, resulting in welded part rejection. The following subsection discusses the distortion problem and how to cure it in FSW parts.

4.5 Residual distortion

Despite having lower heat input than fusion welding processes, the FSW process is also associated with significant RS that arise due to mechanical and thermal loading cycles. When these stresses surpass the yield strength of the BM, the welded part plastically deforms once the clamps are removed. Distortion of a welded part refers to the lack of geometric acceptance, that is, the part is out of dimensional tolerance. Small, welded specimens in earlier studies did not display any mode of distortion, so researchers used to believe that FSW was a nondistortion welding technique; recent studies on large-scale sheets showed the opposite. Shi et al.\textsuperscript{54} investigated the effect of welding parameters on friction stir welded Al-6013 sheets distortion. Results showed that distortion increased with the increase of both panel length and rotational speed. Welding speed had no apparent effect on the degree of distortion. All panels exhibited a reversed saddle-shaped distortion, as shown in Figure 17. Yan et al.\textsuperscript{55} also reported a reversed saddle-shaped distortion in Al-6056-T6 sheets. They justified the convex shape by longitudinal RS distribution. Beyond approximately 100 mm from the weld center, the stress changed from compressive to tensile and kept increasing as moving towards sheet edges. They stated that adding stiffeners in longitudinal direction reduced the distortion in the same direction significantly, but not much in the transverse direction.

Price et al.\textsuperscript{56} managed to eliminate distortion in Al-2024-T351 sheets by manipulating RSs pattern through mechanical tensioning. Similarly, Altenkirch et al.\textsuperscript{57} and Wen et al.\textsuperscript{58} stated that post-weld direct rolling (PWDR) was an effective technique to reduce Al-2xxx sheets distortion. PWDR aims to induce compressive stresses into the weld through squeezing the sheet under a roller moving along the weld line. In FSW of Al-2024-T3, Larose et al.\textsuperscript{59} reported that needle peening successfully removed 37% of traversal distortion and 82% of longitudinal distortion, which established a foundation for needle peening as a distortion control technique.

The major limitation of the previous techniques is the added cost of special equipment. To avoid the additional expense, stationary shoulder friction stir welding is a promising distortion-control technique, according to recent studies.\textsuperscript{60,61}

5 CONCLUSIONS

The current article reviewed the conventional FSW process and its parameters, namely, the processing speeds, tool geometry, tilt angle, and plunge depth. Furthermore, it briefly scrutinized some of the primary process responses, which were the microstructure, microhardness, tensile strength, RS, and residual distortion.

Detailed process design was provided to facilitate parameter selection for novel researchers in the FSW field.

Finally, the following research gaps were revealed:

- The velocity ratio influence on weld properties requires a comprehensive study.
- The effect of pinless tool geometry on weld properties needs to be considered in future research.
- The total number of distortion-related studies is limited, signifying the need for further exploration.
PEER REVIEW INFORMATION

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

AUTHOR CONTRIBUTIONS

Mohamed El-Moayed: contributed to the data curation; formal analysis; investigation; methodology; resources; validation; visualization; writing-original draft; writing-review and editing. Ahmed Shash: contributed to the conceptualization; formal analysis; investigation; methodology; resources; supervision; validation; visualization; writing-original draft; writing-review and editing. Mahmoud Abd Rabou: contributed to the formal analysis; methodology; supervision; validation. Mahmoud El-Sherbiny: contributed to the formal analysis; investigation; methodology; supervision; validation; visualization.

NOMENCLATURE

Symbol  Term
BM  base metal
\( t \)  workpiece thickness, mm
\( N \)  rotational speed, rpm
\( V \)  welding/traverse speed, mm/min
\( H \)  tool tilt angle, degree
\( X \)  tool plunge depth, mm
\( d \)  tool pin diameter, mm
\( D \)  tool shoulder diameter, mm
\( L \)  tool pin length, mm
ST  shoulder type
TM  tool material

END NOTES

1 Also known as the “probe.”
2 See “Process Design” section.

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