

Article

Computational Modelling and Comparative Analysis of Friction Stir Welding and Stationary Shoulder Friction Stir Welding on AA6061

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Abstract: This research focuses on the computational modelling and comparative analysis of friction stir welding (FSW) and stationary shoulder friction stir welding (SSFSW) applied to AA6061-T6 aluminium alloy. SSFSW, an FSW variant, employs a stationary shoulder and a rotating pin. This study introduces a numerical model for both processes, using the innovative Smoothed Particle Hydrodynamics (SPH) technique to capture their distinct thermo-mechanical characteristics. The aim is to unravel its mechanics and multi-physics in SSFSW and compare it with conventional FSW. The temperatures predicted by the model exhibited a close agreement between the advancing side (AS) and retreating side (RS). Plastic strain patterns show that regular FSW is different from SSFSW. In SSFSW, the strain is less, and the plastic area is comparatively slightly narrower. The distinct “ironing effect” resulting from the stationary shoulder in SSFSW reduces the heat-affected zone (HAZ). Yet, it maintains efficient plasticisation and material flow within the pin-affected zone (PAZ). This research emphasises the significant impact of temperature, strain, material flow, and thermo-mechanical characteristics on the quality of joints. Future suggestions include exploring process parameters more broadly, examining dissimilar welding techniques and hybrid approaches, and comprehensively investigating the diverse effects of SSFSW under various configurations and joint angles.



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Keywords: friction stir welding; stationary shoulder friction stir welding; numerical modelling; Smoothed Particle Hydrodynamics (SPH); material flow

1. Introduction

Aluminium and its alloys are extensively used in diverse industries as primary construction materials due to their exceptional weldability, formability, strength, and corrosion resistance. However, traditional welding techniques often result in welded joints of aluminium alloys that lack the necessary hardness to withstand wear and abrasion, despite their high strength-to-weight ratio [1]. FSW, a potential solid-state joining method, has gained commercial momentum in several fields, including rail, automotive, marine, and aerospace [2]. The friction-based solid-state processes have significantly contributed to the advancements in Industry 4.0 and advanced manufacturing techniques [3]. The several benefits of FSW are made possible by using aluminium alloys throughout a broad temperature range, from cryogenic to moderately higher temperatures [4]. FSW offers several advantages over traditional welding techniques for joining aluminium alloys. As a solid-state procedure, it avoids problems with fusion welding, including hot cracking and porosity. FSW is a mechanised method requiring little human labour and specialised welding knowledge. It is an affordable and environmentally friendly solution since it does not need filler wire or shielding gas. FSW, which allows gaps of as much as twenty percent

of the plate thickness without affecting the weld quality, may accept poor edge preparation. FSW also prevents fusion, which lowers distortion by reducing thermal contraction [5].

Various approaches and numerical modelling tools were employed for finite element analysis [6]. FSW has been engaged for butt welds in production on a large scale recently, whereas lap welds are becoming more and more common and are being used in more applications. Researchers have shown a growing interest in studying and optimising FSW processes to improve performance. Notable variants of FSW, such as SSFSW [7], Dual Rotation FSW [8], Friction Stir Spot Welding (FSSW), and Refill FSSW [9], have emerged and found extensive applications in various industries. Furthermore, the principle of FSW has been adapted to work on a single plate with different materials, tools, and machine parameters, leading to the development of friction stir processing (FSP) [10,11]. FSP has taken pace in the lightest metal alloys like magnesium [12] and in developing metal matrix mono and hybrid composites [13,14]. These variants and techniques have gained significant attention and recognition for their valuable contributions to the field of FSW.

SSFSW, a process variant of FSW, was introduced by TWI in the late 2004–early 2005 period to join high-temperature and low-thermal-conductive alloys. Unlike traditional FSW, which involves a rotating shoulder that traverses along the weld line, SSFSW employs a fixed or stationary shoulder while the pin tool moves along the joint. This unique approach offers distinct advantages regarding process control, heat generation, and material flow dynamics. The centric welding mechanism consists of a rotating pin that passes through a shoulder component that does not rotate and glides across the material's surface during welding. There has been no or minimal cross-sectional decrease, and the weld surface is smooth and almost polished [7]. It was initially designed for joining high-strength Ti-alloys, but SSFSW has now expanded its application to various other alloys and friction-based processes like FSP. As research and advancements continue, SSFSW is poised to become one of the most important techniques for achieving robust and reliable welds in high-strength lightweight alloy applications [15,16]. It helped obtain a lower welding peak temperature and uniform heat input, resulting in a symmetrical microstructure. SSFSW eliminates root defects and improves material flow. The non-rotational shoulder prevents outflow and enhances surface properties. Also, SSFSW has the great potential advantage of joining plates of different thicknesses and at different joining angles.

The numerical modelling of SSFSW has been relatively unexplored. This is probably due to the complexity of the process challenges due to the limitations of available grid-based meshing techniques. Capturing these multiple physical phenomena, such as heat transfer, material flow, and plastic deformation, accurately in a numerical model requires advanced meshing capabilities that are currently limited. In addition, the lack of extensive research and experimental data on SSFSW further restricts the availability of benchmarking and validation datasets for numerical simulations. Recently, Hosseini et al. [17] developed the numerical model for underwater SSFSW with the coupled Eulerian–Lagrangian (CEL) formulation technique.

In comparison to established grid-based methods such as Eulerian, CEL, Arbitrary Lagrangian–Eulerian (ALE), and Lagrangian incremental methods, SPH offers distinct advantages [18,19]. SPH stands out by providing inherent adaptability to complex geometries [20], dynamic interfaces [21,22], and material deformations [23,24]. Unlike grid-based methods [25], SPH employs a meshless framework that excels at handling free surface flows, fluid–structure interactions, and large deformations without the need for cumbersome re-meshing or rezoning procedures. This unique characteristic makes SPH particularly well-suited for simulations involving intricate or evolving boundaries, contributing to its efficacy in various scientific and engineering applications. Looking at the current study on SSFSW and the earlier work on SPH applied to FSW, we can see that our present study has effectively demonstrated how materials are displaced near the SAZ and PAZ in SSFSW. In addition to possibly strengthening them further and exploring new avenues, this has increased the advantages of numerical techniques currently used in FSW [26]. It is worth mentioning that the prior study conducted by Fraser on SPH for FSW utilized software

that was not commercially available [27,28]. Ansari and Behnagh's study focus solely on SPH modelling of the plunging stage, limiting its scope to this phase of FSW. Consequently, the study lacks any exploration of potential effects from traversing within the SPH framework [29]. The commercial Altair RADIOSS software was used in this study. Our study is a pioneering effort connecting researchers and practitioners, serving as a valuable reference guide for FSW and SSFSW. By combining the insights from our study with previous knowledge, one can better understand the complexities within FSW [30,31] and SSFSW. This opens up new avenues for innovative ideas and perspectives within this field.

SPH, a meshless method, excels in accurately representing large deformations, intricate material flow, and contact behaviour, making it highly suitable for capturing the dynamic and non-linear nature of SSFSW [32]. This mesh-free technique efficiently represents the non-rotational shoulder and its interactions with the stirred material and weld zone, enabling a precise depiction of material flow and deformation throughout the welding process. By integrating SPH meshing into numerical modelling for SSFSW, researchers can achieve enhanced prediction accuracy and gain deeper insights into the process. However, the application of this mesh-free technique for modelling SSFSW has not been previously reported. Thus, the present study focuses on the numerical modelling of SSFSW using the novel SPH technique to unravel the associated mechanics and multi-physics compared with the conventional FSW.

2. Novelty and Application

In the world of welding methods, this study explores new ideas by comparing two essential ways of welding: Friction Stir Welding (FSW) and Stationary Shoulder Friction Stir Welding (SSFSW). In this research, a new method called Smoothed Particle Hydrodynamics (SPH) is used to deeply understand how the physics of these methods are connected and work together. By utilizing SPH, researchers can attain higher accuracy in predicting outcomes and gaining insights into the functioning of friction-based processes, which is a challenging task with conventional meshing techniques. Therefore, these developments aid in improving the welding process as well as make it easier to comprehend all complex engaged dynamics. Even though SPH has been used to understand liquids and structures together, it has not been used before to understand SSFSW. This study is one of the first to try this, looking at how SSFSW works using SPH. This unique approach enables us to observe the motion and operation of things after welding, and we can compare it to the typical method known as FSW. In terms of application, the study's findings have potential implications for industries such as manufacturing and aerospace, offering insights to enhance aluminium alloy welding processes. Adopting SPH in this context also opens doors for its application in broader material processing and welding analyses, expanding its utility in various manufacturing scenarios.

3. Numerical Modelling

The computational modelling and experimental work on FSW was completed by Meyghani [33] previously. The tool geometry, workpiece thickness, and the process parameters like traverse speed, plunge time, and rotational speed were all considered based on the experimental work, as mentioned earlier. This study analyses the interactions between the workpiece material (AA6061-T6 alloy) and the tool material (steel H13) by virtually reproducing the model. H13 tool steel is a commonly used material for the tool, as it is suitable for both soft and hard aluminium and magnesium alloys.

3.1. Geometry

The geometry of the backing plate, workpiece, and tool, including the shoulder and pin, were modelled using CATIA software. Following that, these models were loaded into Radioss 2021.1. For the sake of ease, the measurements are shown in Figure 1. The simulation regarded the backing plate and tool as rigid entities. The intersection of the tool pin, shoulder, and workpiece defines the welding zone along the tool path. Most material

flow and plastic deformation occurs in the weld zone and a small surrounding region. As the material softens and unites due to heat cycles, the weld zone's temperatures are the main focus of this process. Moreover, residual strains result from heat cycles beyond the weld zone. The length of the workpiece in this numerical model is constrained in light of the above-mentioned elements and preliminary observations. This restriction speeds up computations without affecting the level of accuracy. The geometries of the toolset and workpieces in the FSW and SSFSW procedures are identical.

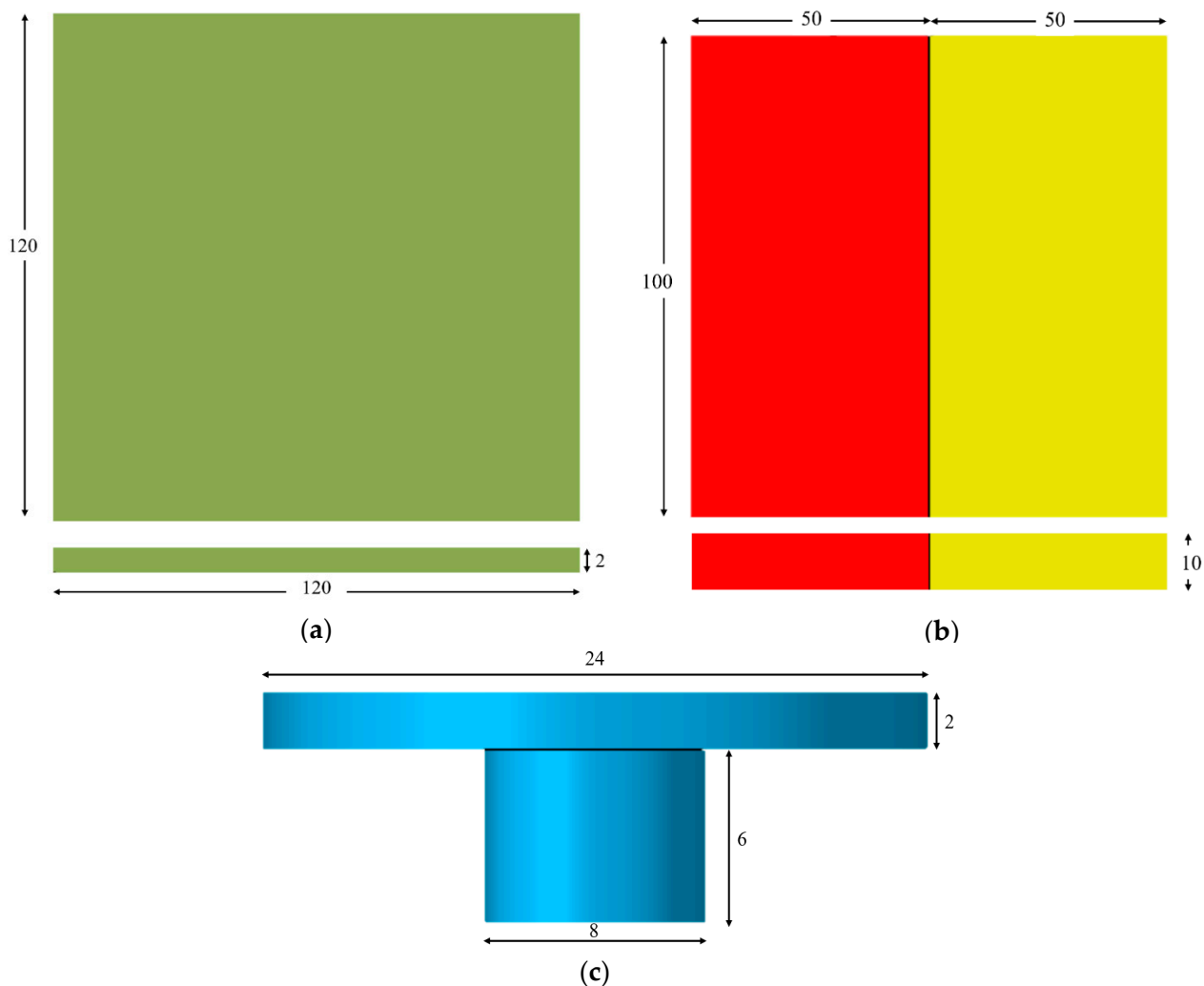


Figure 1. Geometries of modelled parts (a) backing plate, (b) workpiece, and (c) tool.

3.2. Material Model

A proper constitutive equation describing the interplay of flow stress with temperature, strain rate, and plastic strain must be chosen to simulate the material reaction in FSW effectively. Since the Johnson–Cook model can consider the effects of strain, strain rate, and temperature, it has often been used for solid-state joining procedures [34]. The following Equation (1) represents the Johnson–Cook flow stress model and their respective constant values [35]:

$$\sigma = (A + B\epsilon^n) \left[1 + C \ln \left(1 + \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \right] \left(1 - \left[\frac{T - T_{room}}{T_{melt} - T_{room}} \right]^m \right) \quad (1)$$

The parameters take on the following values: A as 324 MPa, B as 114 MPa, C as 0.002, n as 0.42, m as 1.34, and $\dot{\epsilon}_0$ as 1×10^{-6} per second; the material and thermal properties

of AA6061 Al alloy and H13 tool steels used for the numerical simulation are tabulated in Table 1.

Table 1. Properties of AA6061 and H13 steel [36,37].

Property	AA6061-T6	H13
Density (g/cm ³)	2.7	7.7
Young's Modulus (GPa)	69	209
Poisson's Ratio	0.3	0.33
Melting Temperature (K)	925	1700
Specific Heat (J/KgK)	896	461
Thermal Conductivity (w/mK)	166.9	24.4

3.3. Meshing and Contact

As illustrated in Figure 2, the workpiece was modelled with a mesh-free SPH technique with a simple cubic pitch of 1.32 mm with a total of 45,606 nodes for both the left and right workpieces. The tool was meshed using tetrahedral elements with an element size of 2 mm, resulting in 1126 elements. On the other hand, the supporting/backing plate was divided into 576 elements using quad elements with a size of 5 mm. A finer and closer SPH particle system was adopted for the workpiece to improve the temperature and material flow results. The contact state significantly affects the model's output characteristics, including heat generation, stress, forces, strain distribution, and the incidence of defects, due to the significant plastic deformation throughout the process. Therefore, it is essential for the simulation that the H13 steel tool and AA6061 be in the proper contact condition. The principal source of heat is the frictional heat generation between the shoulder of the tool and the specimen. The frictional contact between the tools and the workpieces is controlled in this simulation by Coulomb's law of friction, F_{frict} [38]. It is shown in Equation (2)

$$F_{frict} = \mu F_n \quad (2)$$

In this case, F_{frict} stands for the frictional force, F_n stands for the normal force and μ stands for the friction coefficient. A nodal–surface contact was established between the tool–workpieces and the backing plate–workpieces, respectively. A temperature-dependent Coulomb friction coefficient which varied with interface temperatures and gave a more accurate solution was used in the simulation, as indicated in Table 2.

Table 2. Temperature-dependent friction coefficient between AA6061 and H13 steel [39].

Temperature (°C)	0–12	12–22	22–92	92–112	112–212	212–247	247–257
Coefficient of friction (μ)	0.47	0.35	0.3	0.26	0.08	0.02	0.001

3.4. Simulation Controls and Boundary Conditions

There are several basic steps to the simulation approach, which are briefly outlined below: In FSW, at a plunge time of 8 s and a rotational speed of 1600 rpm, the tool plunge into the workpiece until a depth of 6.15 mm (as the pin length is 6 mm) is highlighted in Figure 3. The tool then transverses for 20 mm at a 100 mm/min speed during the traversing phase, as shown in Figure 4. The process parameters utilized in FSW and SSFSW are identical except that the shoulder has no rotational speed. The main objective was to ascertain whether the process exhibited sensitivity to changes in the shoulder rotational speed and to identify any potential advantages over conventional FSW.

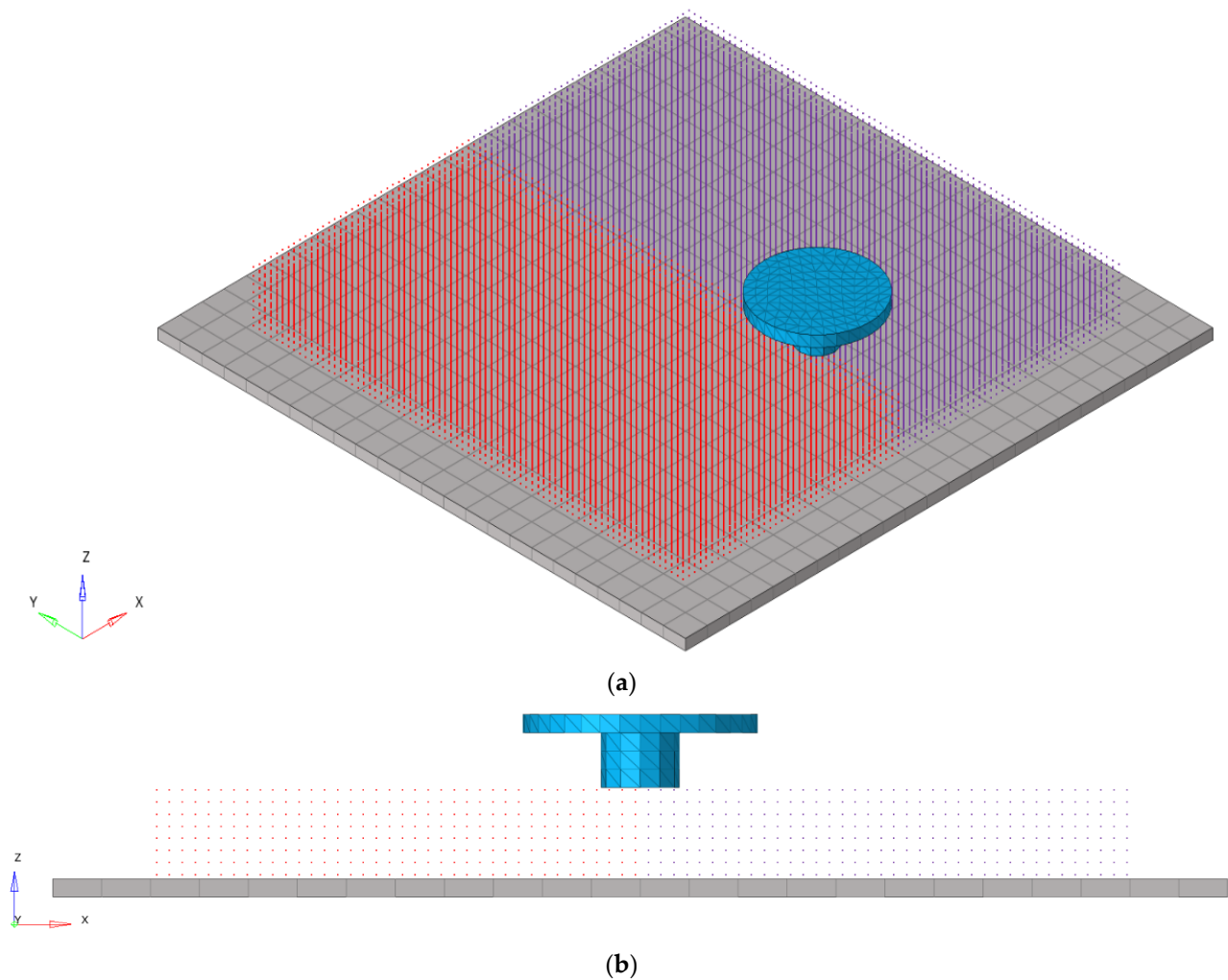


Figure 2. Meshed model of the FSW process: (a) isometric view and (b) side view.

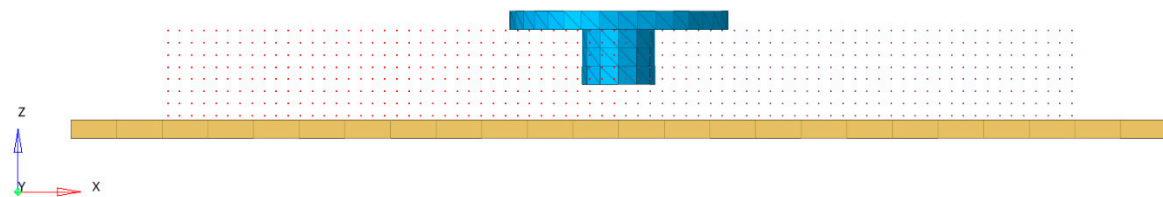


Figure 3. Tool plunged with 6.15 mm.

The boundary conditions applied in this study are as follows: the tool can only move in specific ways, like rotational, plunging, and traversing. This means it cannot freely move in translation in the vertical direction (here, Z-axis) and rotate about the same. It can translate along the Y-axis. All other tool movements are constrained. The backing plate and corners of the workpieces are constrained in all degrees of freedom. Using IMPDISP, users can select nodes/components to move with respect to time. On the other hand, IMPVEL can be used to define linear/rotational velocities with respect to time. These methods are applied in the context of SSFSW, where IMPDISP controls the tool's movement in the Y and Z directions, while IMPVEL defines the rotational speed of the tool along the Z axis. In SSFSW, the shoulder was allowed to move freely in the translational-Y and Z-axis directions to facilitate its movement along with the pin. However, the rotation of the tool shoulder was set to zero, thereby defining the configuration as a stationary shoulder with a rotating pin. The tool shoulder and pin were considered separate rigid components in the SSFSW

model to model this. This separation allowed for defining individual master nodes with distinct translational and rotational motion properties.

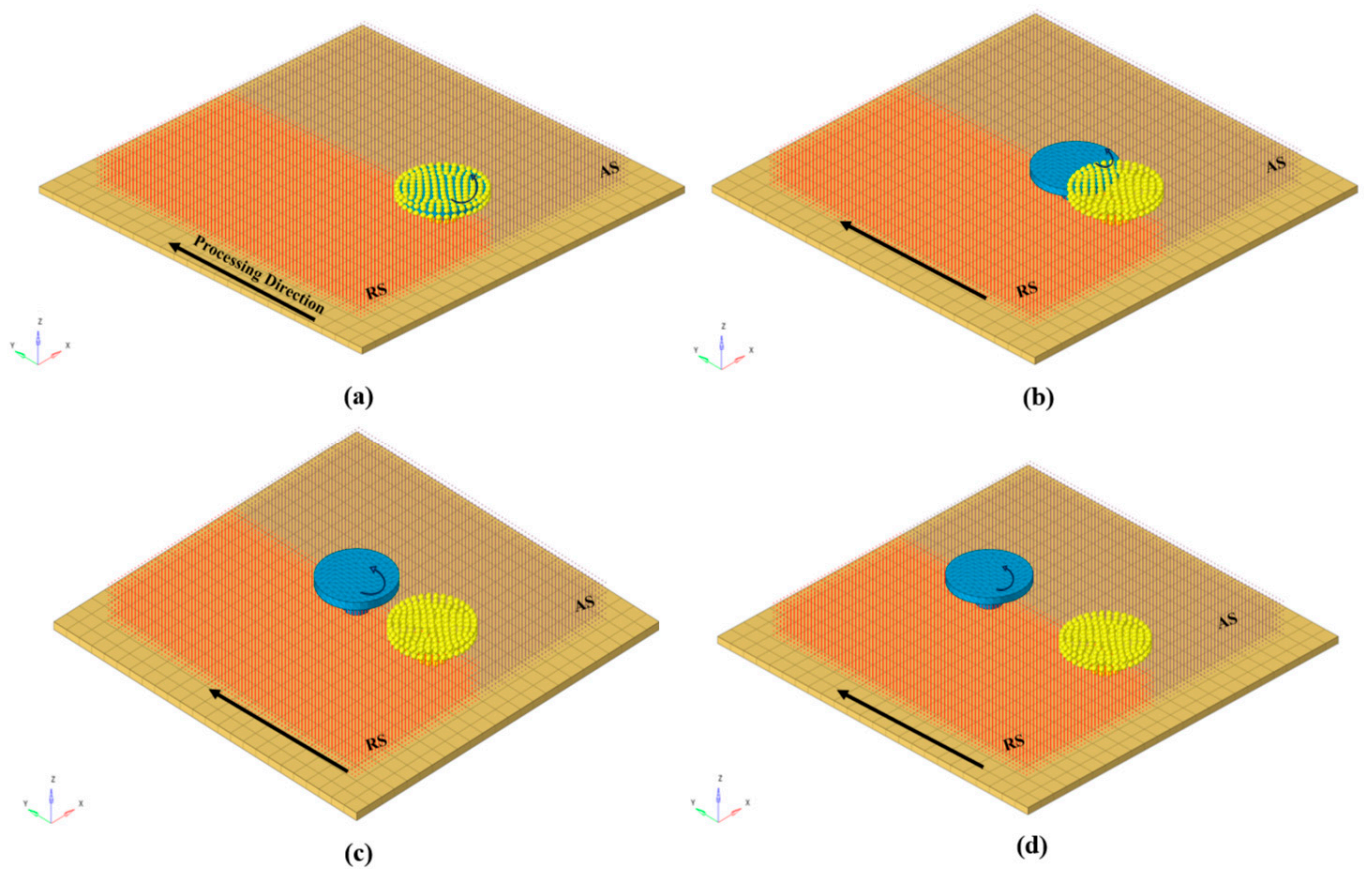


Figure 4. Traversing Phases (a) Beginning of Plunge, (b) 5 mm beyond Plunge, (c) 15 mm beyond Plunge, and (d) End of traversing at 20 mm.

4. Results and Discussion

In the context of FSW, temperature measurements were taken 2 mm away from the shoulder and at a depth of 3 mm after a transverse distance of 20 mm, which was identical to the locations of the thermocouples from the experiment. The temperature difference between the AS and RS is shown in Figure 5. The temperatures recorded through the numerical analysis on both the AS and RS have been confirmed through experimentation conducted by Meyghani [29]. In the context of Friction Stir Welding (FSW), the temperature profile exhibits distinct phases as depicted in the curve. Initially, the temperature rises from room temperature as the process commences, progressing through the plunging phase. This temperature elevation continues until the welding tool reaches the traversing phase. Upon reaching this point, the temperature trend starts to flatten. These findings exhibit a notable agreement between the experimental and numerical temperature results. On the AS, the experimental temperature measured was 581 K, while on the RS, it was 563 K. Simulation results indicated a temperature of 588 K on the advancing side and 576 K on the retreating side, which were both measured at a distance of 20 mm at the transverse end. The percentage error between experimental and simulated temperatures is 1.2% for the AS and 2.3% for the RS. Analysing temperature data, the calculated errors were within an acceptable range, raising belief in our simulation's accuracy using the SPH method. Furthermore, the reliability of this model is strengthened when we observe material movement and plasticisation.

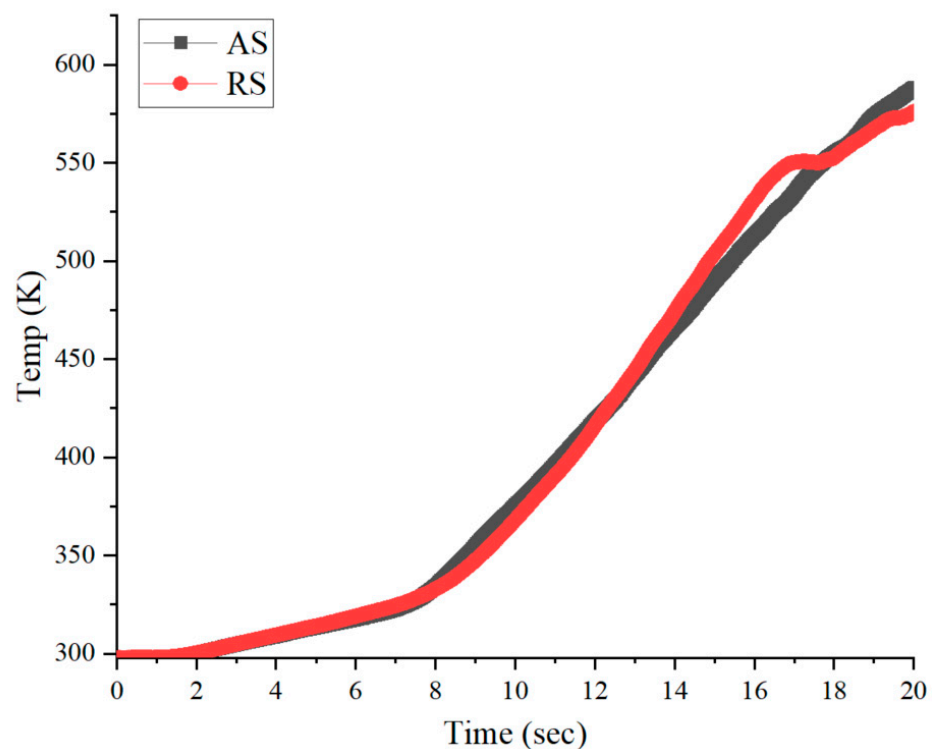


Figure 5. Nodal temperatures in FSW measured 2 mm away from the shoulder with 3 mm depth.

This variation in the temperature is from a complex interaction between several deciding elements. The AS often has higher temperatures because of the enhanced frictional forces that the contact between the spinning tool and workpiece produces. As a result of the increased friction, the conversion of mechanical energy into thermal energy is amplified, which results in increased heat production [31,40]. In parallel, as it aligns with the tool's circular motion, the material on the AS side experiences significant plastic deformation, resulting in increased energy consumption and higher temperatures [41]. Additionally, the substantial material amalgamation produced by the controlled rotation and movement of the tool on the AS aids in a more evenly dispersed dispersion of the created heat. This efficient heat dispersion prevents the development of localised overheating, which significantly boosts heat dissipation. The tool is more prone to greater temperatures on the AS because it holds a more extensive reservoir of residual heat left behind as it travels. The higher temperature on the AS enhances the material's inherent ability to transmit heat, which is another crucial factor in the process. This improvement makes it easier for heat to dissipate by spreading it more evenly throughout the material. In sharp contrast, the RS receives significantly lower temperatures and could have less effective heat conduction and dissipation. Thus, the higher temperatures seen on the cutting edge of FSW result from a synergistic interaction between increased frictional heating, heightened plastic deformation, improved heat dispersion through mixing, increased heat conduction, and increased retention of residual heat. These complex interactions create a dynamic thermal environment, resulting in temperature discrepancies between the AS and RS during welding. Figure 6 shows an axisymmetric pattern about the tool centre for the temperature distribution during the FSW. A sudden temperature increase is seen at the start of the diving phase and lasts for 8.2 s. The temperature then rises gradually inside the weld region, which is followed by a steady fall as the distance from the centre of the weld increases. This pattern is visible in the results depicted in Figure 6c. As the 20 s traversal period ends, a distinct nugget zone behind the shoulder is distinct, as shown in Figure 6b. Throughout the process, the temperature gradually rises from plunging to traversing. Notably, temperature variations affect the material's stirring and softening throughout the FSW operation, since they directly correlate with the quantity of heat produced. The shoulder's perimeter is the

focal point of maximum temperature during FSW, and at the 20 s point, that area achieves a maximum temperature of 769 K. This is equivalent to around 83% of the material's melting point, which is a figure often stated in the literature on friction stir welding [42].

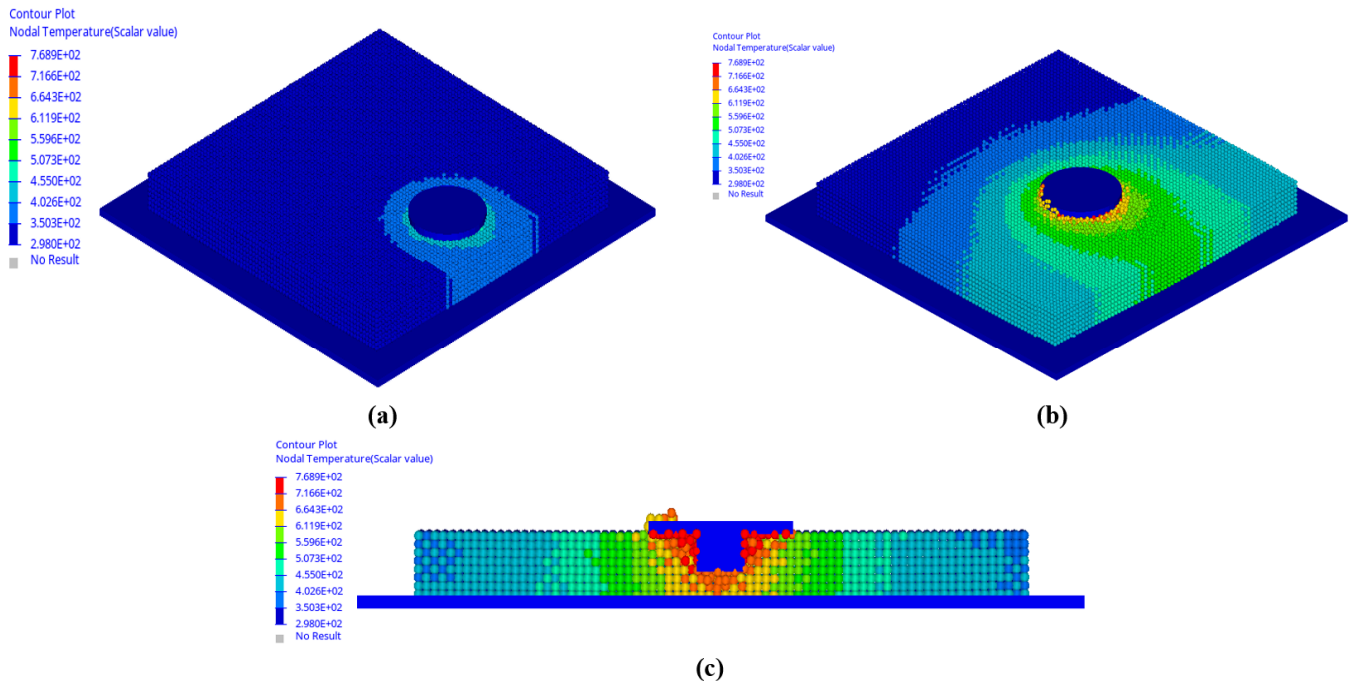


Figure 6. FSW nodal temperatures at (a) plunging, (b) at the end of traversing and (c) cut section at the end of the process.

Alternatively, the temperature fields for SSFSW are depicted in Figures 7 and 8. Due to the stationary shoulder's lack of movement, which slides over the joint line during welding, significantly lower temperatures are observed than those of traditional FSW. The achieved temperatures are primarily concentrated near the pinning zone, serving as the input for plastic deformation and from the frictional interaction between the pin and bottom sides. The temperatures are 733 K, which is approximately 32 K lower than conventional FSW. From Figures 6c and 7c, the region where there is no material movement but only the thermal effect can be identified as HAZ, SSFSW exhibits significantly lower temperatures than the HAZ region seen in conventional FSW. As a result, this leads to reduced and more precisely focused heat generation across the weld thickness. This lower peak welding temperature and uniform heat input throughout the thickness contribute to a thin concentrated symmetrical finer microstructure along the weld line [15]. The narrower and lower temperatures field in SSFSW eliminates root defects commonly observed in conventional FSW.

Moreover, the stationary shoulder acts as a protective seal, preventing the outflow of plasticised material from the weld. Additionally, the stationary shoulder's ironing effect on the plasticised material promotes vigorous material flow exclusively within the weld zone, potentially resulting in a finer equiaxed microstructure. The material's flattening effect, referred to as the "ironing effect" of the stationary shoulder, eradicates the material ruffling caused by the rotational movement of the tool pin [15,43]. As a result, this enhances surface properties and improves the joint's fatigue life. Despite the relatively lower heat generation associated with SSFSW, it is essential to note that the required and adequate amount of heat for softening the SZ material is effectively supplied. The primary cause of this substantial softening is the swift breakdown of hardening precipitates inside the AA6061 alloy substrate, which occurs at elevated temperatures within the SZ. This hotter environment increases the material's shear-ability and mobility while improving its shear-

ability. Furthermore, the strong diffusion bonding between adjacent sheets is strengthened at this high-temperature range.

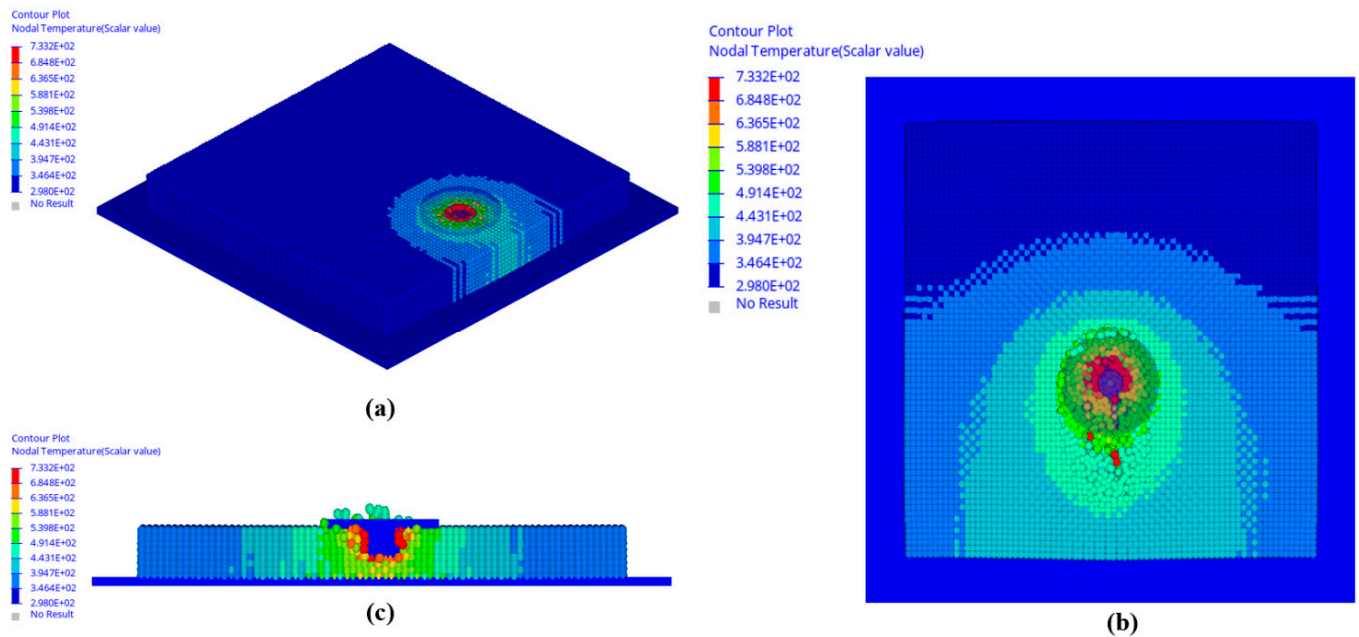


Figure 7. SSFSW nodal temperatures at (a) plunging, (b) at the end of traversing, and (c) cut section at the end of the process.

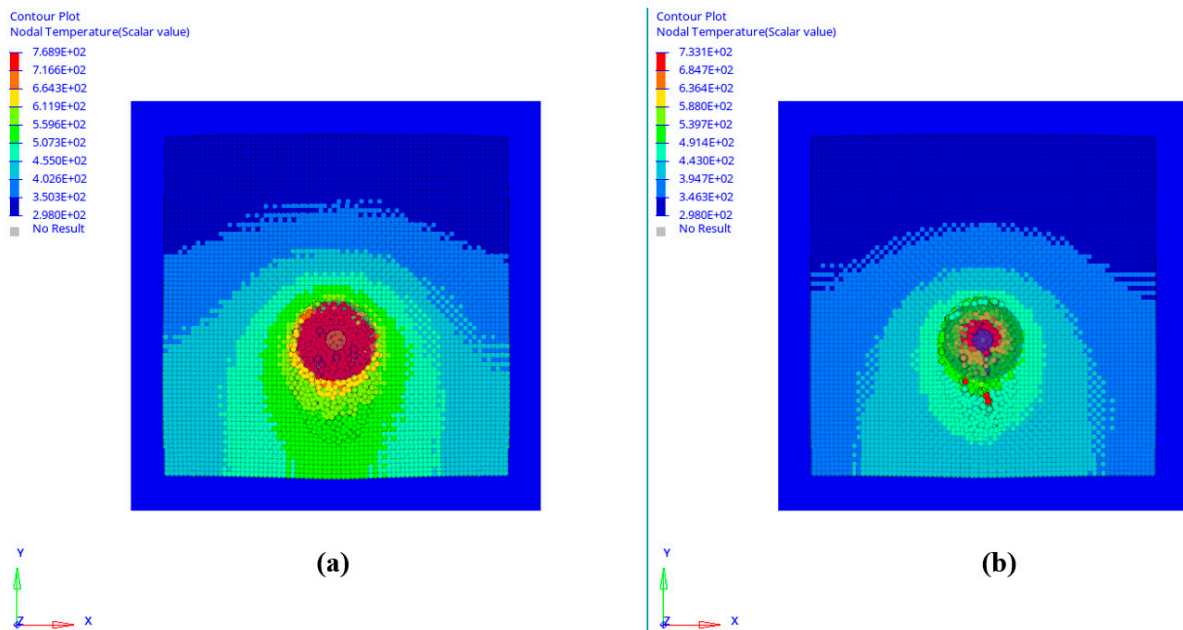


Figure 8. Comparative temperature field at the end of (a) FSW and (b) SSFSW.

The outcome of FSW greatly hinges on temperature, strain, and strain rate, as these factors significantly influence the eventual microstructure and grain size. While characteristic zones can often be identified through a micrograph analysis of experimental data, quantifying the specific plastic strain experienced by the material, leading to developing a particular microstructure, remains challenging through experiments. However, simulation results make it feasible to ascertain the localised plastic strain the material undergoes during the FSW process. This is evident in the plastic strain distribution presented in Figure 9a–d, showcasing the evolving plastic strain at various stages of conventional FSW and SSFSW,

respectively. As discussed earlier, the HAZ typically indicates the region influenced by temperature without incurring plastic strain. This distinction becomes evident by analysing both variations' plastic strain contours and temperature distributions. Adjacent to the nugget zone, a narrow region characterised by moderate plastic strains exists and is known as the TMAZ. This area experiences moderate temperatures and mechanical material movement. In SSFSW, the TMAZ appears as a narrow strip immediately beside the pin, whereas in FSW, it extends wider. In the context of FSW, the nugget zone experiences intensified plastic strains to a little wider extent due to the added heat and deformation arising from both the shoulder and pin, as depicted in Figure 9a. The “pin-affected zone” (PAZ) is the area around a pin during a welding or joining process. This area experiences changes in material properties due to the heat and mechanical forces caused by the pin's actions. The pin's effects, specifically, lead to these alterations. Conversely, in the SSFSW scenario, the strain values, as shown in Figure 9c, exhibit lower magnitudes than those observed in FSW. In SSFSW, these strains are predominantly concentrated in the PAZ, with a narrower moderate/lower plastic strain (TMAZ) in the shoulder-affected zone (SAZ).

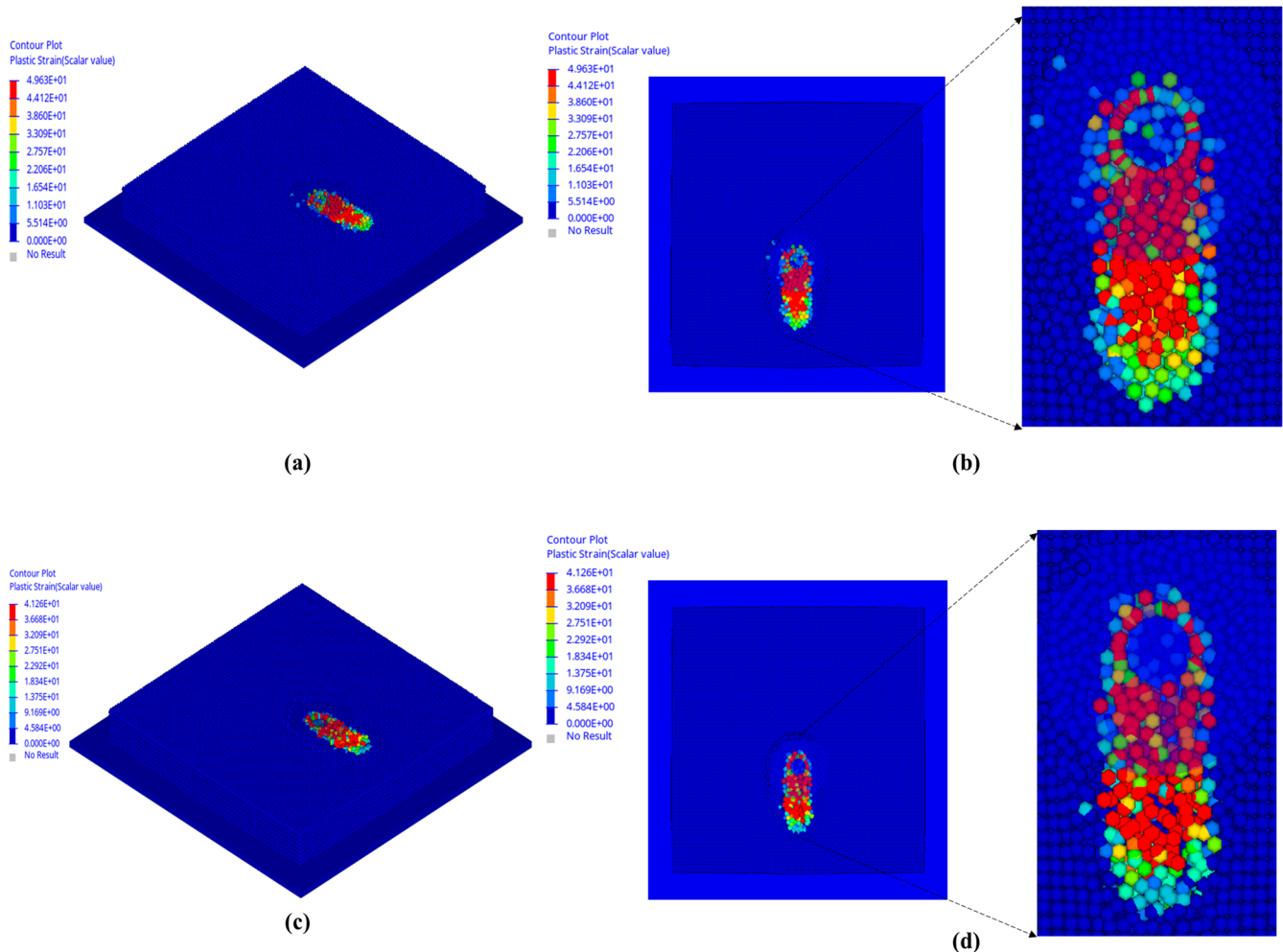


Figure 9. Plastic strain contours with magnified weld zone for (a,b) FSW and (c,d) SSFSW.

After the traversing, strain growth occurs at the back side of the pin and shoulder for SSFSW and FSW. This is because the material flowing from the AS to the RS was wiped out to fill the cavity at the end of the tool. Consequently, the non-rotating pressing shoulder in SSFSW has a moderated impact compared to the rotating shoulder and pin in FSW. This reduction in strain distribution thus leads to a compact processed zone with narrower TMAZ, thus encompassing several of the inherent advantages of SSFSW. SSFSW

and FSW exhibit obvious refined equiaxed recrystallised grains resulting from dynamic recrystallization. This process predominantly occurs in the vicinity of the pin zone for SSFSW, while in FSW, it occurs and PAZ and extends into the SAZ [44,45].

The quality of the weld joint is highly dependent on the material flow during the SSFSW and FSW processes. As indicated in the numerical modelling section, Radioss 2021.1 encompasses both processes, facilitating the observation of particle displacement and its movement deviation from their original state. At every time increment and node in the study, temperature-displacement computations are entirely linked. Tracer displacement caused by material flow may be understood better by examining the micron-sized tracer particles displayed in various colours. Displacement values range from a maximum to 15.22 mm in FSW and 9.46 mm in SSFSW vectors illustrated in Figure 10a,b. The precise changes in displacement between these two FSW variants may be affected by several variables, including the tool's geometry, the rotating speed of the shoulder and pin, the traverse speed along the joint line, and more. However, with SSFWS, these variables are restricted to the pin alone, leading to less deformation, less plastic strain, and displacement, as well as better material flow, all of which improve the microstructure and characteristics of the material. These elements interact intricately, affecting how the material flows and deforms overall and eventually affecting how the displacement is determined.

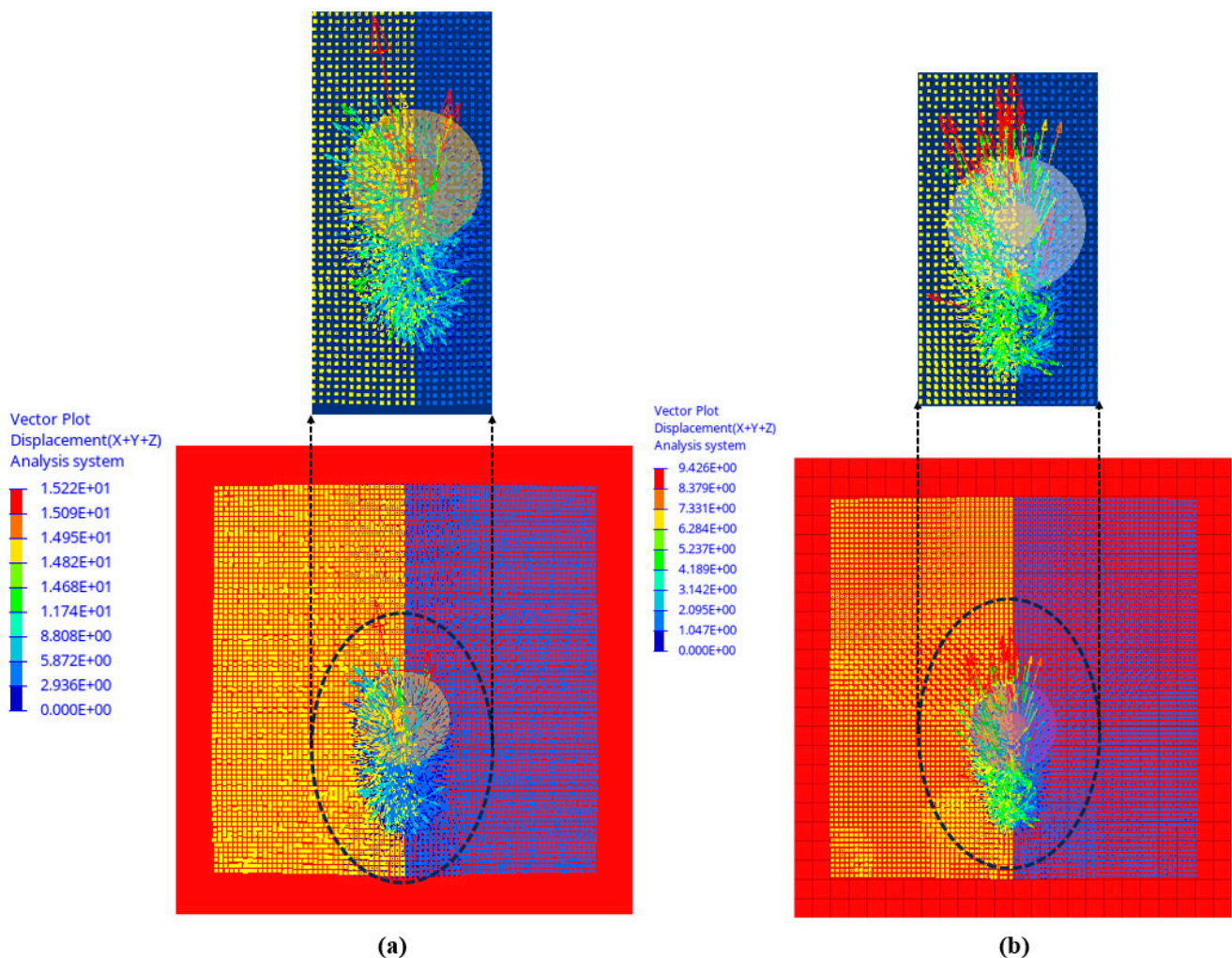


Figure 10. SPH particles displacement for (a) FSW and (b) SSFSW.

Differences in displacements in both processes can be attributed to how heat and material flow are distributed during the process. SSFWS's primary heat source and plasticisation originate from the rotating cylindrical pin. The material predominantly flows

around the pin, contributing to the welding of a narrower welded track. However, heat and material flow distribution differ in typical FSW because the shoulder and the pin move. The size of the processed or nugget zone and the amount of material displacement during the plunge-to-traverse phase are both influenced by the geometry of the tool, especially the pin and shoulder diameters. Heat production, material displacement, mixing, and compression by the tool are determined by rotational speed, traversal speed, and plunge depth and are further controlled by the tool's tilt angle and axial pressure. Maintaining a specific minimum welding temperature, and assuring sound welds within a predetermined temperature range is necessary to achieve optimum material mixing at the weld line for both the FSW and SSFSW processes, which both use the AA6061 alloy. The visual depiction of particle behaviour indicating the material flow in both the right and left plates is shown in Figures 11 and 12. Although there is no adequate particle mixing before the diving or plunging phase, there is operative mixing throughout the traversing phases because of the process's softening phenomena.

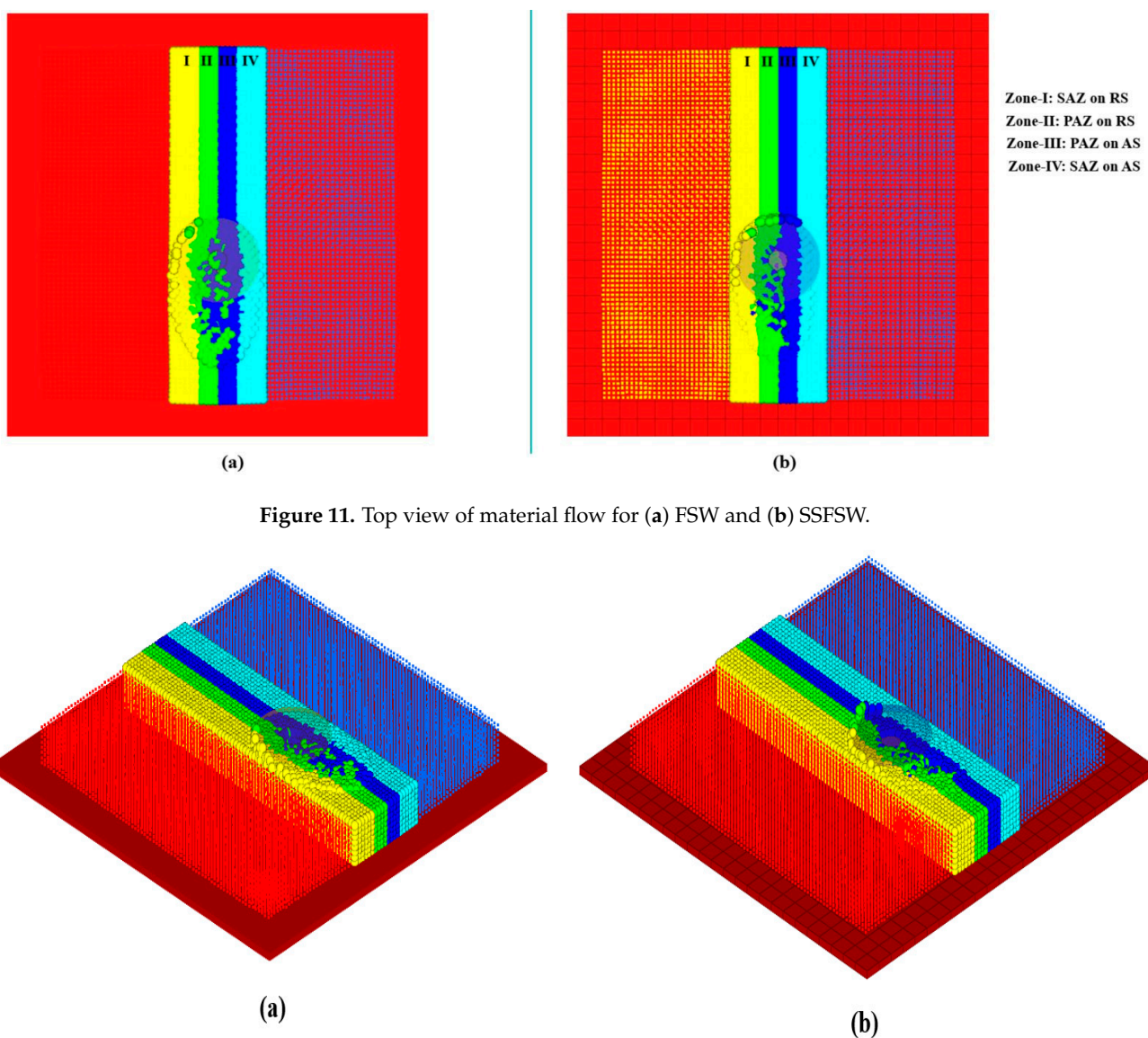


Figure 11. Top view of material flow for (a) FSW and (b) SSFSW.

Figure 12. Iso-view of material flow for (a) FSW and (b) SSFSW.

In discussing the effectiveness of different numerical methods, even though SPH demonstrates superiority over ALE, the CEL approach emerges as most suitable for describing the stirring action during FSW [46]. The challenge of tracing material flow using

alternative modelling techniques cannot be understated, highlighting the importance of comprehending the precise achievement of optimal particle mixing from both workpieces, as referenced in [47,48]. Examining the distinct characteristics of SAZ within SPH nodes during FSW, which indicates turbulence in flow dynamics, is pivotal in material flow analysis. Conversely, when examining FSW scenarios involving a stationary shoulder, the material flow is mainly concentrated in PAZ, with a notable absence of movement in SAZ. In SSFSW, the reduction in PAZ effects significantly enhances material flow across the weld zone. Remarkably, this improvement is achieved without much alteration in the joint thickness—a phenomenon frequently encountered in FSW studies. This progression toward improved material flow, while retaining the fundamental joint attributes, highlights the potential benefits of SSFSW over conventional FSW techniques.

In the context of FSW, distinct flow patterns become visible beneath each element under the shoulder and pin. Conversely, in SSFSW, these components exhibit a scattered arrangement near the pin. The SPH nodes, representing material displacement, tend to accumulate predominantly near the shoulder edge on the RS, specifically within Zone I, as depicted in Figure 11a. However, due to the non-rotating shoulder, the material flow at the shoulder's edge reveals a lower intensity of SPH nodes along that region. This distinction is clearly noticeable in Figure 11b, where the boundary of Zone I's SAZ on the same RS in SSFSW is seen. Furthermore, the flattening effect aids in maintaining material within the PAZ, indirectly curbing material movement away from this area. Notably, the bulging action was observed, which was indicated by the strip lines of Zone II and Zone III appearing more pronounced in FSW due to the combined rotating motion of the shoulder and pin compared to SSFSW. These phenomena of flattening, reduced material flow, and constrained movement are also influenced by differences in the nugget and other zones that can be clearly viewed from isometric perspective illustrated in the Figure 12. With increasing distance, movement becomes negligible. In FSW or SSFSW, components situated beyond the shoulder and pin remain fixed, preserving their original positions. The zones substantiate this observation with no movement, illustrated by the SPH nodes on the outer left of Zone I and the far right of Zone IV, where particles are distanced from the SZ.

5. Conclusions and Future Recommendations

- The current study explored the critical aspects of FSW and SSFSW, revealing complex interactions that involve temperature distribution, plastic strain, material flow, processed zone width, and the unique “ironing effect” exclusive to SSFSW.
- Temperature measurements from the model are in close agreement with experimental values, validating the model. The error percentages are minimal and acceptable, 1.2% and 2.31% in the AS and RS, respectively.
- Differences between conventional FSW and SSFSW were notable in plastic strain distributions. SSFSW exhibited lower strain magnitudes concentrated in the PAZ, while conventional FSW displayed an increased magnitude of plastic strains in PAZ and extended a little wider into the SAZ.
- The distinct “ironing effect” induced by the non-rotating shoulder had a pronounced impact on SSFSW. This effect reduced the processed zone, improved material flow, and enhanced joint attributes, particularly around the pin.
- The SPH technique gave a deeper understanding of the material flow in PAZ and SAZ in both FSW and SSFSW.

Expanding the scope to encompass a broader range of rotational and traversal speeds and diverse tool geometries could lead to a more focused exploration of optimizing process parameters, particularly for SSFSW. Furthermore, hybrid strategies that combine FSW or SSFSW with additional statistical techniques to investigate process stability, dependability, and repeatability through statistical analysis must be explored. Investigation into the impact of SSFSW on dissimilar welding, in comparison with conventional FSW, is another area to explore. Additionally, the effects of SSFSW aligned with friction stir processing should be studied along with exploring further advantages by analysing the influence

of the sole pin on microstructure and surface characteristics. Moreover, an extension of this research could involve the future implementation of Variable Shoulder–Pin Rotational FSW (VSPR-FSW) to assess the specific effects of the shoulder and pin on temperature and material flow, utilizing SPH for enhanced analysis.

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References

1. Rahsepar, M.; Jarahimoghadam, H. The Influence of Multipass Friction Stir Processing on the Corrosion Behavior and Mechanical Properties of Zircon-Reinforced Al Metal Matrix Composites. *Mater. Sci. Eng. A* **2016**, *671*, 214–220. [CrossRef]
2. Thomas, W.M.; Nicholas, E.D.; Needham, J.C.; Murch, M.G.; Temple-Smith, P.; Dawes, C.J. Friction-Stir Butt Welding. International Patent Application No. PCT/GB92/02203; GB Patent Application No. 9125978.8; U.S. Patent Application No. 5,460,317, 6 December 1991.
3. Hassan, A.; Pedapati, S.R.; Awang, M.; Soomro, I.A. A Comprehensive Review of Friction Stir Additive Manufacturing (FSAM) of Non-Ferrous Alloys. *Materials* **2023**, *16*, 2723. [CrossRef] [PubMed]
4. Threadgill, P.L.; Leonard, A.J.; Shercliff, H.R.; Withers, P.J. Friction Stir Welding of Aluminium Alloys. *Int. Mater. Rev.* **2009**, *54*, 49–93. [CrossRef]
5. Price, D.A.; Williams, S.W.; Wescott, A.; Harrison, C.J.C.; Rezai, A.; Steuwer, A.; Peel, M.; Staron, P.; Koçak, M. Distortion Control in Welding by Mechanical Tensioning. *Sci. Technol. Weld. Join.* **2007**, *12*, 620–633. [CrossRef]
6. Meyghani, B.; Wu, C. Progress in Thermomechanical Analysis of Friction Stir Welding. *Chin. J. Mech. Eng. (Eng. Ed.)* **2020**, *33*, 12. [CrossRef]
7. Martin, J.P. Stationary Shoulder Friction Stir Welding. In Proceedings of the 1st International Joint Symposium on Joining and Welding, Osaka, Japan, 6–8 November 2013; pp. 477–482.
8. The Welding Institute Dual-Rotation Friction Stir Welding—TWI. Available online: <https://www.twi-global.com/media-and-events/insights/dual-rotation-friction-stir-welding> (accessed on 15 June 2023).
9. Iwashita, T. Method and Apparatus for Joining. Patent No: US6601751B2, 5 August 2003.
10. Mishra, R.S.; Ma, Z.Y. Friction Stir Welding and Processing. *Mater. Sci. Eng. R Rep.* **2005**, *50*, 1–78. [CrossRef]
11. Mishra, R.S.; Mahoney, M.W.; McFadden, S.X.; Mara, N.A.; Mukherjee, A.K. High Strain Rate Superplasticity in a Friction Stir Processed 7075 Al Alloy. *Scr. Mater.* **1999**, *42*, 163–168. [CrossRef]
12. Marode, R.V.; Pedapati, S.R.; Lemma, T.A.; Somi, V.; Janga, R. Thermo-Mechanical Modelling of Friction Stir Processing of AZ91 Alloy: Using Smoothed-Particle Hydrodynamics. *Lubricants* **2022**, *10*, 355. [CrossRef]
13. Sunil, B.R.; Reddy, G.P.K.; Patle, H.; Dumpala, R. Magnesium Based Surface Metal Matrix Composites by Friction Stir Processing. *J. Magnes. Alloy.* **2016**, *4*, 52–61. [CrossRef]
14. Marode, R.V.; Pedapati, S.R.; Lemma, T.A.; Loyte, A.; Devarajan, Y.; Thandavamoorthy, R. Influence of Silicon Carbide on Microhardness and Corrosion Behavior of AZ91/SiC Surface Composites Processed through Friction Stir Processing: Multi-Response Optimization Using Taguchi-Grey Relational Analysis. *Silicon* **2023**, 1–23. [CrossRef]
15. 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.* **2022**, *47*, 865–914. [CrossRef]
16. Patel, V.; Li, W.; Andersson, J.; Li, N. Enhancing Grain Refinement and Corrosion Behavior in AZ31B Magnesium Alloy via Stationary Shoulder Friction Stir Processing. *J. Mater. Res. Technol.* **2022**, *17*, 3150–3156. [CrossRef]
17. Hosseini, A.; Fallahi Arezoudar, A. Determining the Mechanism of Defect Formation and Material Flow Characteristics in Underwater Stationary Shoulder Friction Stir Welding Using Coupled Eulerian-Lagrangian Simulation. *Int. J. Adv. Manuf. Technol.* **2023**, *127*, 1755–1778. [CrossRef]
18. Gingold, R.A.; Monaghan, J.J. Smoothed Particle Hydrodynamics: Theory and Application to Non-Spherical Stars. *Mon. Not. R. Astron. Soc.* **1977**, *181*, 375–389. [CrossRef]

19. Tartakovsky, A.; Grant, G.; Sun, X.; Khaleel, M. *Modeling of Friction Stir Welding (FSW) Process with Smooth Particle Hydrodynamics (SPH)*; SAE Technical Papers; SAE International: Warrendale, PA, USA, 2006.
20. Marode, R.V.; Pedapati, S.R.; Lemma, T.A.; Awang, M. A Review on Numerical Modelling Techniques in Friction Stir Processing: Current and Future Perspective. *Arch. Civ. Mech. Eng.* **2023**, *23*, 154. [\[CrossRef\]](#)
21. Hamilton, R.; Mackenzie, D.; Li, H. Multi-Physics Simulation of Friction Stir Welding Process. *Eng. Comput.* **2010**, *27*, 967–985. [\[CrossRef\]](#)
22. Dialami, N.; Cervera, M.; Chiumenti, M.; de Saracibar, C.A. Local–Global Strategy for the Prediction of Residual Stresses in FSW Processes. *Int. J. Adv. Manuf. Technol.* **2017**, *88*, 3099–3111. [\[CrossRef\]](#)
23. Monaghan, J.J.; Kajtar, J.B. SPH Particle Boundary Forces for Arbitrary Boundaries. *Comput. Phys. Commun.* **2009**, *180*, 1811–1820. [\[CrossRef\]](#)
24. Lof, J. Elasto-Viscoplastic FEM Simulations of the Aluminium Flow in the Bearing Area for Extrusion of Thin-Walled Sections. *J. Mater. Process. Technol.* **2001**, *114*, 174–183. [\[CrossRef\]](#)
25. Khan, U.; Pao, W.; Sallih, N. Numerical Gas–Liquid Two-Phase Flow Regime Identification in a Horizontal Pipe Using Dynamic Pressure Data. *Appl. Sci.* **2023**, *13*, 1225. [\[CrossRef\]](#)
26. He, X.; Gu, F.; Ball, A. A Review of Numerical Analysis of Friction Stir Welding. *Prog. Mater. Sci.* **2014**, *65*, 1–66. [\[CrossRef\]](#)
27. Fraser, K.; St-Georges, L.; Kiss, L.I. Meshfree Simulation of the Entire FSW Process on the GPU. In Proceedings of the 11th International Friction Stir Welding Symposium, Cambridge, UK, 17–19 May 2016; p. 15.
28. Fraser, K.; Kiss, L.I.; St-Georges, L.; Drolet, D. Optimization of Friction Stir Weld Joint Quality Using a Meshfree Fully-Coupled Thermo-Mechanics Approach. *Metals* **2018**, *8*, 101. [\[CrossRef\]](#)
29. Ansari, M.A.; Behnagh, R.A. Numerical Study of Friction Stir Welding Plunging Phase Using Smoothed Particle Hydrodynamics. *Model. Simul. Mater. Sci. Eng.* **2019**, *27*, 055006. [\[CrossRef\]](#)
30. Meyghani, B. A Modified Friction Model and Its Application in Finite-Element Analysis of Friction Stir Welding Process. *J. Manuf. Process.* **2021**, *72*, 29–47. [\[CrossRef\]](#)
31. Wu, T.; Luo, H.; Guo, H.; Fu, J.; Liu, G. Numerical Simulation of Temperature Field and Material Flow in Friction Stir Welding. In Proceedings of the 2019 International Conference on Modeling, Analysis, Simulation Technologies and Applications (MASTA 2019), Beijing, China, 24–25 March 2019; Atlantis Press: Amsterdam, The Netherlands, 2019; pp. 333–338.
32. Altair Radioss Smooth Particle Hydrodynamics. Available online: https://2021.help.altair.com/2021/hwsolvers/rad/topics/solvers/rad/theory_sph_c.htm (accessed on 22 September 2022).
33. Meyghani, B. *Thermomechanical Analysis of Friction Stir Welding (FSW) on Curved Plates by Adapting Calculated Temperature Dependent Properties*; Universiti Teknologi PETRONAS: Perak, Malaysia, 2018.
34. Janga, V.S.R.; Awang, M. Influence of Plunge Depth on Temperatures and Material Flow Behavior in Refill Friction Stir Spot Welding of Thin AA7075-T6 Sheets: A Numerical Study. *Metals* **2022**, *12*, 927. [\[CrossRef\]](#)
35. Banerjee, B. *MPM Validation: Sphere-Cylinder Impact Tests: Energy Balance*; Report No. C-SAFE-CD-IR-04-001; The University of Utah: Salt Lake City, UT, USA, 2004.
36. Ferreira, G.V.; Neto, F.L.; Miéle, N.; Pestana, M. ANALYSIS OF THE MECHANICAL BEHAVIOR OF A COMPOSITE BLADE USED IN HYDROKINETIC TURBINES. In Proceedings of the 23rd ABCM International Congress of Mechanical Engineering, Rio de Janeiro, Brazil, 6–11 December 2015; ABCM Brazilian Society of Mechanical Sciences and Engineering: Rio de Janeiro, Brazil, 2015.
37. Agha Amini Fashami, H.; Bani Mostafa Arab, N.; Hoseinpour Gollo, M.; Nami, B. Numerical and Experimental Investigation of Defects Formation during Friction Stir Processing on AZ91. *SN Appl. Sci.* **2021**, *3*, 108. [\[CrossRef\]](#)
38. Mishra, R.S.; De, P.S.; Kumar, N. *Friction Stir Welding and Processing: Science and Engineering*; Springer: Berlin/Heidelberg, Germany, 2014; ISBN 9783319070438.
39. Awang, M. Simulation of Friction Stir Spot Welding (FSSW) Process: Study of Friction Phenomena. Ph.D. Thesis, West Virginia University, Morgantown, WV, USA, 2007.
40. Salloomi, K.N.; Hussein, F.I.; Al-Sumaidae, S.N.M. Temperature and Stress Evaluation during Three Different Phases of Friction Stir Welding of AA 7075-T651 Alloy. *Model. Simul. Eng.* **2020**, *2020*, 3197813. [\[CrossRef\]](#)
41. Buffa, G.; Hua, J.; Shivpuri, R.; Fratini, L. A Continuum Based Fem Model for Friction Stir Welding—Model Development. *Mater. Sci. Eng. A* **2006**, *419*, 389–396. [\[CrossRef\]](#)
42. Emamian, S.; Awang, M.; Hussai, P.; Meyghani, B.; Zafar, A. Influences of Tool Pin Profile on the Friction Stir Welding of AA6061. *ARPN J. Eng. Appl. Sci.* **2016**, *11*, 12258–12261.
43. Russell, M.J.; Threadgill, P.L.; Thomas, M.J.; Wynne, B.P. Static Shoulder Friction Stir Welding of Ti-6Al-4V; Process and Evaluation. Presented at the 11th World Conference on Titanium (Ti-2007), (JIMIC-5), Kyoto, Japan, 3–7 June 2007.
44. Pan, W.; Li, D.; Tartakovsky, A.M.; Ahzi, S.; Khraisheh, M.; Khaleel, M. A New Smoothed Particle Hydrodynamics Non-Newtonian Model for Friction Stir Welding: Process Modeling and Simulation of Microstructure Evolution in a Magnesium Alloy. *Int. J. Plast.* **2013**, *48*, 189–204. [\[CrossRef\]](#)
45. Patel, V.; Li, W.; Xu, Y. Stationary Shoulder Tool in Friction Stir Processing: A Novel Low Heat Input Tooling System for Magnesium Alloy. *Mater. Manuf. Process.* **2019**, *34*, 177–182. [\[CrossRef\]](#)
46. Tongne, A.; Desrayaud, C.; Jahazi, M.; Feulvarch, E. On Material Flow in Friction Stir Welded Al Alloys. *J. Mater. Process. Technol.* **2017**, *239*, 284–296. [\[CrossRef\]](#)

47. Aval, H.J. Smoothed-Particle Hydrodynamics (SPH) Simulation of AA6061-AA5086 Dissimilar Friction Stir Welding. *Metals* **2023**, *13*, 906. [[CrossRef](#)]
48. Bagheri, B.; Abbasi, M.; Abdolazadeh, A.; Kokabi, A.H. Numerical Analysis of Cooling and Joining Speed Effects on Friction Stir Welding by Smoothed Particle Hydrodynamics (SPH). *Arch. Appl. Mech.* **2020**, *90*, 2275–2296. [[CrossRef](#)]

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