ENHANCING FRICTION STIR WELDING PERFORMANCE: FINITE ELEMENT SIMULATION STUDY USING FILLER MATERIAL

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ABSTRACT

Friction Stir Welding (FSW) is a groundbreaking method that revolutionizes welding by utilizing friction-induced heat to join metals without melting them. In this study, we conducted a comprehensive investigation into the FSW process using the numerical software Simufact Forming, focusing on the critical aspect of introducing filler material during the welding operation. Our work involved meticulous simulations to analyze the impact of filler material on the quality and integrity of the weld joint. Through detailed modelling and parameter optimization, we successfully demonstrated the significance of the refill stage in achieving superior welding outcomes. Our main results reveal a substantial enhancement in the weld joint's mechanical and metallurgical properties when filler material is strategically introduced. The simulations provided valuable insights into the optimal conditions for the refill stage, including tool movement, material feeding rates, and key process parameters. These findings contribute to the ongoing efforts in refining FSW techniques, facilitating the development of high-performance welded joints.

KEYWORDS: Friction stir welding, solid-state welding, filler material, rotating tool, frictional heat, mechanical properties.

1. INTRODUCTION

In 1991, Wayne Thomas of The Welding Institute in the United Kingdom developed a solid-state welding technique known as Friction Stir Welding (FSW). It is a novel and relatively recent technique for joining metals and alloys without melting them. Conventional fusion welding processes are often unsuitable for materials with high melting points, distinctive metallurgical characteristics or other inherent difficulties. In such cases, FSW represents an effective alternative.

This welding technique involves the use of a rotating tool with a custom-designed profile, which is guided along the joint line while exerting a downward force onto the junction between two pieces of metal. The rotating tool's frictional heat softens the metal in the joint, allowing the tool to stir and mix the metal together. The tool establishes a solid-state bond between the two pieces of metal as it advances along the joint line. FSW provides various advantages over typical fusion welding processes, including less deformation, less porosity, and less cracking susceptibility. Furthermore, FSW can be automated and performed by robotic systems, making it a quick and cost-effective method of joining large, complex structures. When all factors are considered, friction stir welding can be defined as a flexible and innovative welding technique that offers numerous advantages over conventional methods. The advantages include an improved quality of the weld, a reduction in distortion, and heightened efficiency.

FSW offers a transformative approach to join metals, utilizing friction generated heat to weld without melting. This solid-state process circumvents fusion-related drawbacks, resulting in welds with superior mechanical properties. The absence of a fusion zone ensures heightened joint strength and fatigue resistance. FSW's low heat input minimizes distortion and residual stress, making it a preferred choice for industries prioritizing dimensional stability, such as aerospace and automotive. Its versatility spans diverse materials, from aluminum to titanium alloys. The absence of fumes, arc flashes, and spatter guarantees a safer work environment, while reduced energy consumption aligns with environmental concerns. The method's adaptability to complex shapes enhances its applicability across industries. FSW's potential to revolutionize welding technology underscores ongoing research and innovation.

In the field of welding, the use of additives is a fundamental aspect that enhances the quality of the welded joints and the efficiency of the welding process itself. In order to facilitate and enhance the fusion of

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the base metals, additives are introduced to the welding zone, frequently in the form of gases or filler materials. These materials are carefully chosen to complement the properties of the base metals and to address specific challenges associated with the welding process. In summary, additives in welding offer the potential to enhance joint strength, control fluidity, prevent defects, and influence metallurgical properties. Their careful selection and application are essential for achieving high-quality welds that meet the demands of various industries and applications.

1.1. Types of Additives

In Friction Stir Welding (FSW), additives play a vital role in tailoring the welding process and resulting joint characteristics. Several types of additives can be employed to enhance FSW outcomes:

• *Filler Materials:*
Filler materials can be introduced during FSW to improve joint strength, control microstructure, and compensate for material loss due to the process. The filler material is typically fed into the joint interface ahead of the rotating tool, where it is stirred into the base materials. This can be particularly useful when joining dissimilar materials or compensating for material thickness variations. Figure 1 illustrates the additive friction stir deposition (AFSD) process, which employs the use of filler material.

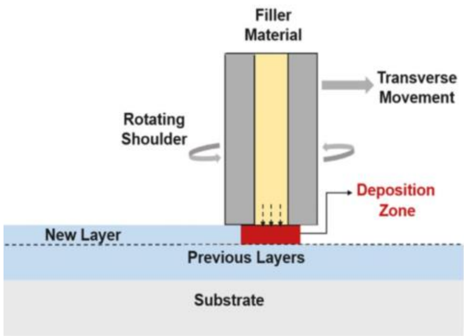


Fig. 1. Schematic of additive friction stir deposition (AFSD) [1]

• *Interlayers:*
Interlayers are thin sheets of material placed between the base materials to influence the welding process and the joint properties. They can act as thermal barriers, control heat input, and modify the metallurgical interactions during FSW. Interlayers can help prevent issues like hot cracking and can enhance the overall weld quality (Fig. 2).

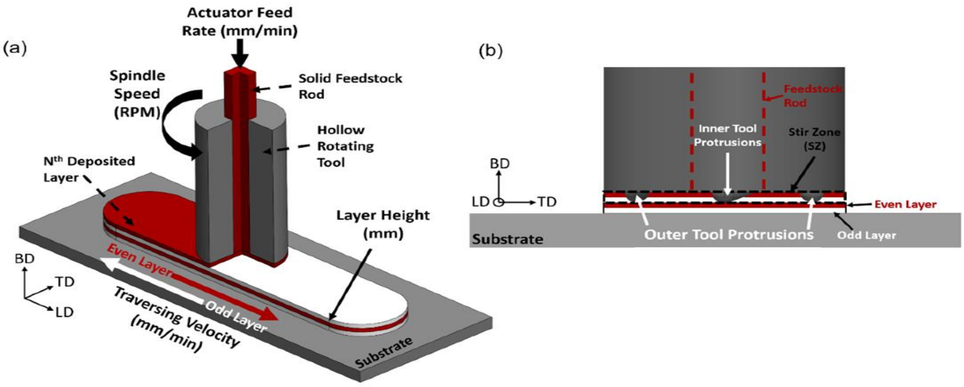


Fig. 2. a) Schematic of AFSD process parameters, illustrating the essential elements and variable parameters; b) Schematic of feature tool protrusions in interaction with layers that have already been deposited [2]

• *Coatings:*
Applying coatings to the surface of the workpieces before FSW can provide various benefits. Coatings can act as thermal barriers, reduce frictional heat, and prevent material interaction with the tool, which can extend the tool's lifespan and prevent wear-related defects. AFSD, as it is shown in figure 3, represents an emerging solid-state deposition manufacturing process rooted in the principles of FSW technology. The novel method is comprised of three principal modes, each of which employs a distinct set of instruments and techniques. The first mode involves the use of a consumable tool, while the second mode makes use of rods and a non-consumable tool. The third mode, finally, employs powder and a non-consumable tool. Figure 3 elucidates the fundamental concepts, emphasizing pivotal elements such as the substrate, feeding material, and hollow tool. In the AFSD process, the initial step is for the feeding rod to rotate with the tool as it progresses in the direction of the substrate. Subsequently, as the feeding rod interfaces with the substrate, intense frictional heating occurs. The resulting softened material, which has undergone significant frictional heating and widespread plastic deformation, creates a metallurgical bond by filling the space between the tool and substrate. As the deposition process reaches a state of equilibrium, the tool begins to move in accordance with the specified NC code. The morphology of the tool, the rate of material feed for powder or bar, the speed of the tool and the motion speed, and other contributing factors are important process characteristics [3].

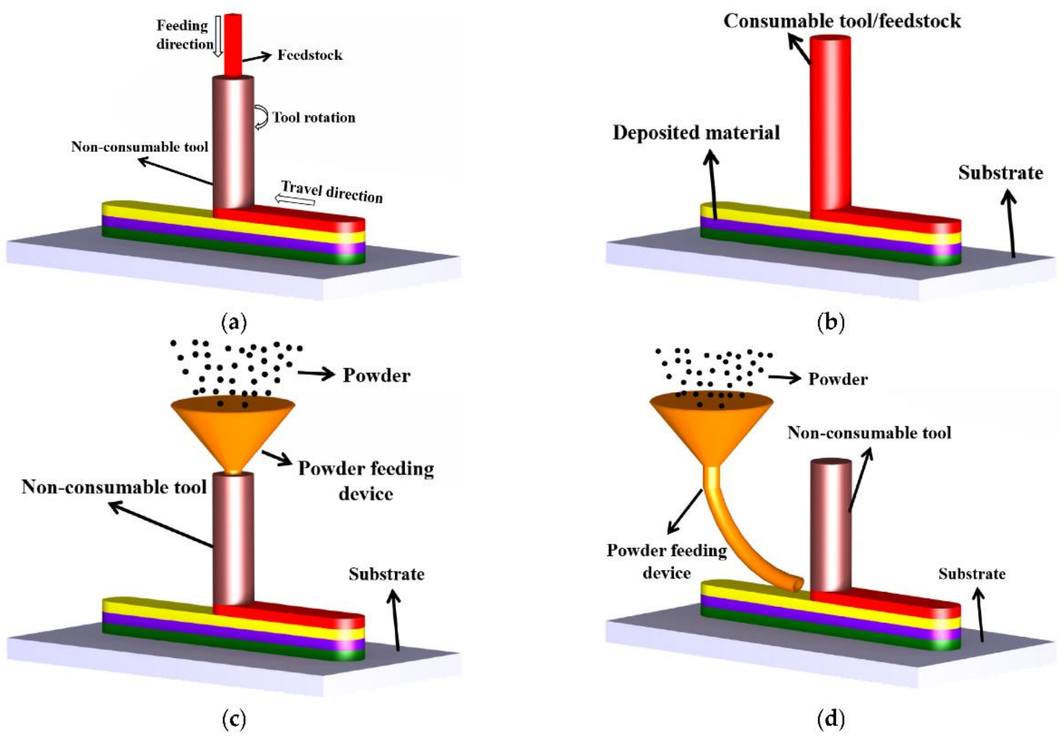


Fig. 3. Schematic of the AFSD process with different modes: a) rod with non-consumable tool; b) consumable tool; c) powder with non-consumable tool; d) powder with non-consumable tool [3]

• *Alloying Elements:*
Introducing alloying elements during FSW can modify the base material's composition in specific areas of the joint. This allows for tailoring the joint's properties, such as corrosion resistance, hardness, or thermal conductivity. Alloying elements are especially useful when certain properties need enhancements without altering the entire material's composition. Introduce alloying elements by mixing them with the base materials or using pre-alloyed sheets. Also, alloying elements can modify the microstructure and mechanical properties of the weld.

1.2. Filer Materials in FSW

Filler materials, often referred to as filler metals or welding filler rods, are materials that are used in welding to fill the joint gap between two base materials. They are melted during the welding process and solidify to create a continuous, fused connection between the base materials. Filler materials are commonly used in a variety of welding methods, such as friction stir welding, to improve joint quality, enhance mechanical properties, and ensure a complete and sound weld.

2. STATE OF THE ART OF FSW RESEARCH

2.1. Introduction

Friction welding is a solid-state welding process that joins two metal parts by applying frictional heat and pressure. It offers high-quality welds, the ability to join dissimilar metals, and is suitable for complex geometries. Friction welding is widely used in various industries and provides efficient and reliable welds.

One approach to overcome these challenges is the introduction of filler material during the FSW process. Filler material can enhance weld quality, improve mechanical properties, and expand the range of materials that can be successfully joined. In this study, we employ SolidWorks ® and Simufact Forming simulations to explore the potential benefits of incorporating filler material in FSW.

The utilization of friction stir spot welding (FSSW) may prove an invaluable substitute for conventional friction stir welding (FSW), with FSSW potentially superseding single-point joining techniques such as resistance spot welding and riveting.

2.2. The Development of FSW, FSSW, and RFSSW Techniques

A solid-state joining technique called friction stir welding joins two or more pieces of metal by creating friction rather than melting them together. Since its invention in 1991 at The Welding Institute (TWI) in Cambridge, UK, it has gained popularity as a method of joining metals.

This technique is a relatively new welding procedure, but it has grown in popularity in recent years due to the numerous benefits it offers over traditional welding methods. It can, for example, be used to combine incompatible metals like aluminum and steel, which presents a significant challenge when attempting to weld it using conventional techniques. FSW also creates a high-quality weld with low distortion and no filler material required.

FSW has a variety of advantages over other welding processes. It produces high-quality welds with minimal distortion and can be used to join several different metals, such as aluminum, copper, titanium, and steel. Additionally, Additionally, FSW is greener, as it doesn't produce the harmful fumes and emissions associated with traditional welding processes. Overall, FSW is a highly versatile and effective method of joining metals and is becoming increasingly prevalent in a multitude of industrial contexts.

Friction stir spot welding as an interesting variant of FSW presents several benefits. The FSSW has been the subject of numerous academic papers and a small number of mechanical applications. The approach elucidates the variations in characteristics, including those pertaining to scale and microstructure, as well as the mechanical properties of the resulting joints. Additionally, numerical recreations of FSSW in the automotive, aerospace, and aviation industries were examined based on the publicly available literature. In conclusion, the current challenges associated with FSSW were presented.

The application of finite element modelling to the thermophysical processes involved in welding, coupled with a programme of experimental work, has constituted a significant area of research.

The FEM can be applied in two distinct ways in the context of simulation studies pertaining for refilling friction stir spot welding (RFSSW) technology. The first category comprises the replication of the welded joint production process through the utilization of technological research.

By employing these simulations, researchers are able to attain a more comprehensive grasp of the welding process, encompassing alterations in the material's physical condition and configuration, thermal generation, friction phenomena, material mixing, and the dispersion of residual stresses and deformations within the joint region. In the second category, welded joints are represented as structural components within loaded construction models. The objective of these simulations is to investigate the response of a specific point to static or dynamic loads, with a view to developing an understanding of the behaviour of the structure as a whole [4].

In their study, Andres et al. [5] presented the findings of investigations into the welding of RFSSW lap joints at rotation rates between 1500 and 2000 rpm and tool sleeve plunge depths between 1.6 and 1.8 mm. The objective of the proposed experiment was to examine the effects of different parameters on the outcome. Moreover, the impact of the RFSSW process and surface preparation of the connected components on the mechanical properties and microstructure of lap joints was examined.

The influence of welding settings on welded AA7075-T6 single-lap joints' quality and load capacity was investigated by Kubit et al. [6]. The test results demonstrate that the utilization of inadequate welding process settings gives rise to the presence of defects, including voids, hooks, onion rings and bonding ligaments.

Shen et al. [7] employed the use of a grooved tool to examine liquation cracking, material flow, and intermixing in a number of aluminium alloys throughout the RFSSW process. The findings indicated that the vertical material flow and a combination of back extrusion and forging during the welding process facilitated the formation of a robust mechanical interlocking connection mechanism.

In their study, Zou et al. [8] investigated the impact of plunge depth and rotation speed on the mechanical characteristics and macro/microstructures of 2195/2219 aluminium alloy joints produced by RFSSW. The researchers observed that while a notable intensification of the depth of the plunge resulted in a notable elevation in the prevalence of hook defects, alterations in rotation speed demonstrated a negligible influence on the incidence of these defects. Additionally, they identified a correlation between elevated tensile shear strength and accelerated rotation speeds. However, the tensile-shear strength exhibited an initial increase followed by a decline with rising plunge depth.

An experimental investigation of the FSSW approach for lap-joining thin AA6061-T6 sheets was conducted by D'Urso et al. [9]. By modifying the rotational speed of the tool while maintaining the other parameters constant, The FSSW method was employed on sheets that were overlapped in pairs. The process parameters included dwell time, indentation depth, and axial feed rate. Further research confirmed the numerical findings.

As Andrzej et al. [10] stated the objective of the study was to assess the influence of diverse RFSSW parameters on the fracture load and failure processes of the manufactured joints. The authors employed a range of welding settings on 7075-T6 Alclad aluminium alloy sheets using RFSSW to ascertain the load capacity of the joints under tensile/shear loading. A numerical model was constructed for the purpose of simulating the joint-loading process, with due consideration given to the variation in the elastic-plastic properties of the weld material across the joint cross-sectional area. This objective was achieved through the utilization of finite element analysis.

A model of the RFSSW process using thermomechanical finite elements of 6061-T6 aluminium alloy was proposed by Muci-Küchler et al. [11] for the purpose of forecasting material movement, temperature fluctuations in the weld zone, deformation, and distributions of stress and strain across all process phases. By comparing the results with those obtained from the experimental study, the process' finite element analysis was validated.

Cao et al. employed the Abaqus program to model the material flow during the FSSW of AA6061 sheets, with a particular focus on the formation of the "hook" defect and onion structure around the sleeve's edge. This was achieved by making adjustments to variables such as temperature, stress, deformation, and deformation rate [12].

Kluz et al. put forth an optimisation strategy for process parameters in Refill Friction Stir Spot Welding (RFSSW) with the objective of ensuring optimal joint load capacity [13]. The results demonstrated that the rotational speed of the tool has a considerable impact on the load capacity, although excessive speeds may potentially compromise the integrity of the weld. Furthermore, it has been demonstrated that extending the duration of the welding process can enhance the quality of the weld and reduce the prevalence of defects. However, there are inherent limitations to the extent to which load capacity can be increased through prolonged welding. This can have a detrimental impact on the heat-affected zone (HAZ) and result in a sudden and significant decline in the joint load capacity. It is essential to achieve an appropriate balance between rotational speed and welding time in order to attain sufficient plasticisation, an adequate joint load capacity and the desired microstructure. The research findings confirm that RFSSW represents an effective method for joining aluminium alloys in the aerospace sector, reducing the labour requirements associated with the assembly of welded structures.

In their study, Ahmed et al. provided a comprehensive overview of the current knowledge regarding Friction Stir Welding (FSW) techniques, identifying areas that require further investigation, and the diverse range of materials utilized in aerospace applications [14]. The authors presented the essential methods and equipment for the creation of high-quality welded connections and reviewed a number of FSW techniques, including conventional FSW, underwater FSW, Friction Stir Spot Welding (FSSW), RFSSW, Stationary Shoulder FSW (SSFSW), and Bobbin Tool FSW (BTFSW). In addition, they provided recommendations for future research.

Finite element analysis was employed to gain insight into the intricate thermomechanical processes that occur during the welding process [15]. An optimisation model was developed using neural networks based on 98 parameter sets related to pin penetration depth, pin rotation speed, and retention time. To validate this model, ten parameter sets were tested, selected to minimise distortion and ensure uniform distribution in the training domain, with a particular focus on peak temperature and normal stress at the conclusion of the welding process.

2.3. Research Gap and Objective

Friction stir welding (FSW) research has focused on new materials and applications, dissimilar material joining, process optimization and modelling, tool design, and material advancements. Recent trends included exploring these aspects to improve the usability of FSW processes. Advances in tool materials, coatings, and geometries aimed to improve wear resistance, heat transfer, and joint formation, leading to more efficient and reliable welding processes.

The hybrid joining processes combining FSW with other welding or joining techniques are being explored to improve joint quality, strength, or enable new applications. Process monitoring and control techniques are being explored to better understand and control the FSW process in real-time. Sustainability and environmental impact are being improved to reduce energy consumption and environmental impact.

In the pursuit of advancing welding technology, this article unveils a groundbreaking exploration into a relatively uncharted realm, the incorporation of filler powder materials in the welding process. This innovative technique stands as a new frontier in welding research. As the focal point of this investigation, the article delves into the unexplored territory of how filler powder materials can intricately affect welding dynamics. This pioneering approach not only widens the horizons of traditional welding applications but also introduces a fresh perspective that challenges established norms.

Through meticulous research, this article aims to unravel the unique interactions between filler powders and the welding process, shedding light on their potential to enhance weld quality, structural integrity, and overall performance. In essence, this work represents a significant stride toward shaping the future of welding methodologies, emphasizing the innovative nature of this technique and its transformative impact on the field.

3. METHODOLOGY

While FSW has demonstrated numerous advantages, such as minimal distortion, low porosity, and improved mechanical properties, there are still challenges associated with welding certain materials and configurations. These challenges include the formation of defects in the weld zone, difficulties in achieving full penetration, and limited applicability to dissimilar materials.

3.1. Material

The base material chosen for this study was ENAW-AlMg3 (ENAW-5754), an aluminum alloy known for its favourable weldability characteristics. ENAW-AlMg3 is commonly employed in various industrial applications due to its excellent combination of strength, corrosion resistance, and formability (tables 1 and 2).

The mechanical properties of grade ENAW-AlMg3 (ENAW-5754) are given in reference [16].

Table 1. Chemical composition % of grade ENAW-AlMg3 (ENAW-5754) [16]

Be < 0.0003 for welding electrode, welding rod and filler wire only									
Fe	**Si**	**Mn**	**Cr**	**Ti**	**Cu**	**Mg**	**Zn**	**Others**	**-**
Max 0.4	Max 0.4	Max 0.5	Max 0.3	Max 0.15	Max 0.1	2.6-3.6	Max 0.2	each 0.05; total 0.15	0.1 < Mn+Cr < 0.6; Al – remaining

3.2. Experimental Investigations

An investigation was conducted to ascertain the influence of welding process parameters on the thermal distribution within the welding zone and the mechanical properties of lap joints produced by Refill Friction Stir Spot Welding (RFSSW) utilising 5754 aluminium alloy sheets.

The components, with dimensions of 45 x 35 x 1.5 mm (length x width x thickness), were overlapped and welded with a machine equipped with a cylindrical rotating tool. The welding tool is comprised of three distinct components, as illustrated in figure 4. These include a blank holder with an outer diameter of 18 mm, a sleeve with an outer diameter of 9.2 mm, and a pin with an outer diameter of 5.9 mm.

The experiments were conducted with and without the addition of filler material, while the remaining welding parameters were held constant. The rotational speed of the FSW tool was set to 2200 revolutions per minute (RPM), which had a significant impact on the generation of heat and the flow of material within the weld zone. An axial force of 20 newtons (N) was applied to ensure optimal tool penetration into the AlMg3 material, which is vital for achieving high-quality welds. Furthermore, the plunge depth of the tool was maintained at 1.45 mm, and the welding cycle comprised a plunge time of 1.2 seconds and a retraction time of 1 second.

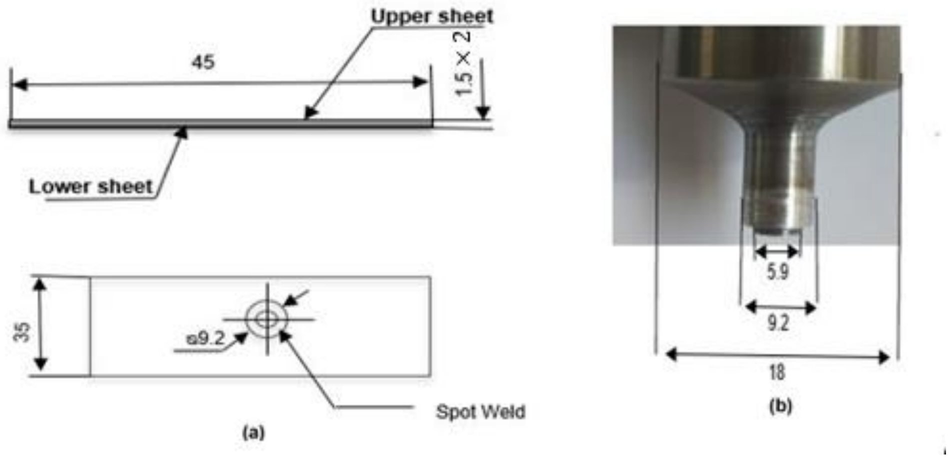


Fig. 4. Welding equipment: (a) sheet metal dimensions, (b) FSW tool dimensions

3.3. Numerical Investigation

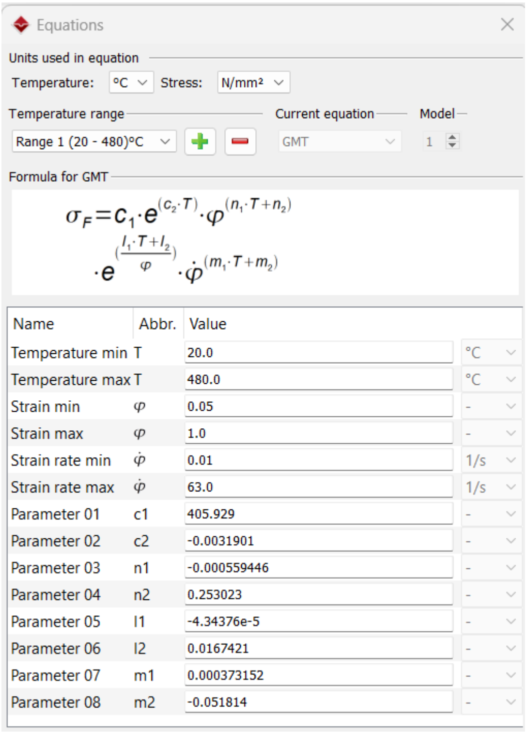
In this investigation, a single numerical model was employed to examine the welding process under two conditions: with and without filler metal. The model, developed using a finite element method (FEM), includes precise geometrical parameters such as workpiece dimensions and welding tool characteristics. The properties enumerated in Table 2 were derived from the material database accessible within the Simufact Forming software, version 2022.1 [18]. Equation 1 shows the mathematical model of the material used. The values of the parameters of equation 1 are given in table 3.

$$\sigma_F = C_1 . e^{(c_2 . T)} . \varphi^{(n_1 . T + n_2)} . e^{\left(\frac{l_1 . T + l_2}{\varphi}\right)} . \varphi^{(m_1 . T + m_2)} \quad (1)$$

Table 2. A summary of the fundamental mechanical characteristics of the aluminium 5754 alloy [16]

Yield stress Rp0.2 [MPa]	Ultimate tensile stress R_m [MPa]	Elongation at fracture A [%]	Melting point [°C]
80	190-240	12 min.	600

Table 3. The values of the parameters of equation 1 in the plasticity model


Equations

Units used in equation

Temperature: °C Stress: N/mm²

Temperature range: Range 1 (20 - 480)°C | Current equation: GMT | Model: 1

Formula for GMT

$$\sigma_F = C_1 \cdot e^{(C_2 \cdot T)} \cdot \varphi^{(n_1 \cdot T + n_2)} \cdot e^{\left(\frac{l_1 \cdot T + l_2}{\varphi}\right)} \cdot \dot{\varphi}^{(m_1 \cdot T + m_2)}$$

Name	Abbr.	Value	
Temperature min	T	20.0	°C
Temperature max	T	480.0	°C
Strain min	φ	0.05	-
Strain max	φ	1.0	-
Strain rate min	$\dot{\varphi}$	0.01	1/s
Strain rate max	$\dot{\varphi}$	63.0	1/s
Parameter 01	c1	405.929	-
Parameter 02	c2	-0.0031901	-
Parameter 03	n1	-0.000559446	-
Parameter 04	n2	0.253023	-
Parameter 05	l1	-4.34376e-5	-
Parameter 06	l2	0.0167421	-
Parameter 07	m1	0.000373152	-
Parameter 08	m2	-0.051814	-

The equation 2 and the equations 3 to 7 given in table 4 are used to analyse the friction stir welding process:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial T}{\partial z}\right) + q_p \quad (2)$$

where q_p is the heat generated by the dissipation of plastic energy, while x, y, and z are the spatial coordinates. T, t, K_x, K_y, and K_z are taken from the software database.

The variation of the material's physical-mechanical properties, such as Young's modulus, Poisson's ratio, coefficient of thermal expansion, conductivity coefficients, radiation and heat capacity as a function of temperature, was taken into account in the Simufact Forming software's material database.

In the Simufact Welding simulation, the mesh undergoes automatic adjustments throughout the welding process, ensuring an adaptive and responsive representation of the evolving geometry. As the simulation progresses, the software dynamically refines the mesh to accurately capture changes in material flow, deformation, and contact conditions. This adaptive meshing strategy is crucial for maintaining computational efficiency and accuracy in modelling the intricate details of the Friction Stir Welding (FSW) process. By automatically adapting the mesh based on the evolving geometry, Simufact Welding facilitates a realistic simulation, providing a high-fidelity representation of the welding operation while efficiently managing computational resources. This dynamic meshing approach contributes to the reliability and precision of the simulation results, allowing for a thorough analysis of the FSW process with varying conditions and parameters.

The 3D model in figure 5, designed for the Friction Stir Welding (FSW) simulation in Simufact Forming encapsulates the intricate details of the welding setup. The model includes key components such as the pin, sleeve, blank holder, upper sheet, lower sheet, and the worktable. Each element's position is meticulously defined to accurately replicate real-world welding conditions. The pin and sleeve represent the FSW tool, with their precise placement and dimensions crucial for simulating the stirring and deformation of the material. The blank holder ensures stability during the welding process, while the upper and lower sheets constitute the workpieces being joined.

The worktable provides the foundational support for the entire assembly. Parameters such as rotational speed, movement velocity, material properties, and tool geometry are configured to align with the desired welding conditions. This comprehensive 3D model enables a comparative simulation, allowing for an in-depth analysis of the FSW process with and without filler material. Through systematic parameter adjustments and meticulous modelling, the simulation aims to provide valuable insights into the impact of filler material on the welding outcomes.

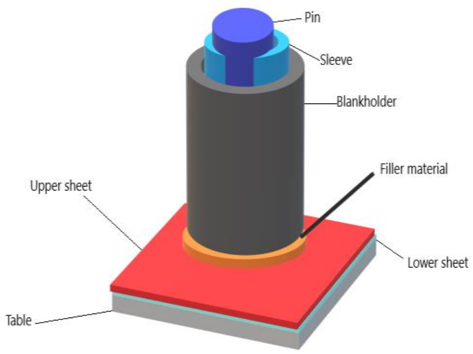


Fig. 5. The model used in the numerical modelling

Table 4. The friction stir welding process analysis equations

q_p -The rate of heat generation resulting from the dissipation of plastic energy: τ is the shear stress, ε_p is the factor of conversion of mechanical to thermal energy.	$q_p = \tau . \varepsilon_p$ (3)
q_f - the heat generated by friction between the tool surfaces and the workpiece where: μ is the coefficient of friction, p is the contact pressure, and ω is the rotational speed.	$q_f = \mu . p . \omega$ (4)

q_c - convective heat loss where: h_f is the convection coefficient (h_f = 50 W/m^2°C), T_s is the temperature at the plate surfaces and T_∞ is the absolute temperature of the surroundings.	$q_c = h_f(T_s - T_\infty)$ (5)
q_r - heat loss by radiation where: κ is the Stefan-Boltzmann constant (κ = 5.67·10^{-8} W/m2°C), *Tr* is the absolute temperature of the radiating surface, and ε_r is the emissivity of the radiating surface.	$q_r = \kappa.\varepsilon_r(T_r^4 - T_\infty^4)$ (6)
M - The shortest time interval during which the circular tool is required to rotate in relation to the workpiece surface during the plunge phase. where: *R* represents the contact surface radius, *F* denotes the force, and *μ* is the coefficient of friction.	$M = \int_0^R 2\pi.\mu.F.r^2\,dr$ (7)

Table 5. Upper sheet characteristics

Type	Workpiece
Model range	45 x 35 x 1.5 mm
Material	ENAW-AlMg3
Mesh	Mesher Type: Advancing Front Quad Element Type: Quads (10) Element size: 0.25 mm Mesh created: Yes Element: 1300
Minimum workpiece temperature	20 °C
Maximum workpiece temperature	1200 °C

Table 6. Lower sheet characteristics

Type	Workpiece
Model range	45 x 35 x 1.5 mm
Material	DB. 1B_u (Simufact library) D5-
Mesh	Mesher Type: Advancing Front Quad Element Type: Quads (10) Element size: 0.18 mm Mesh created: Yes Element: 1000
Minimum workpiece temperature	20 °C
Maximum workpiece temperature	1200 °C

4. RESULTS AND DISCUSSION

4.1. Results of Simulation without Filler Material

The simulation-derived effective stresses and plastic deformations of the material are presented in the figures 6 and 7. The material's response to applied forces is comprehensively elucidated in the simulation findings through the utilization of a stress-strain analysis, which also offers significant insights into the material's mechanical behaviour and deformation properties under the simulated settings.

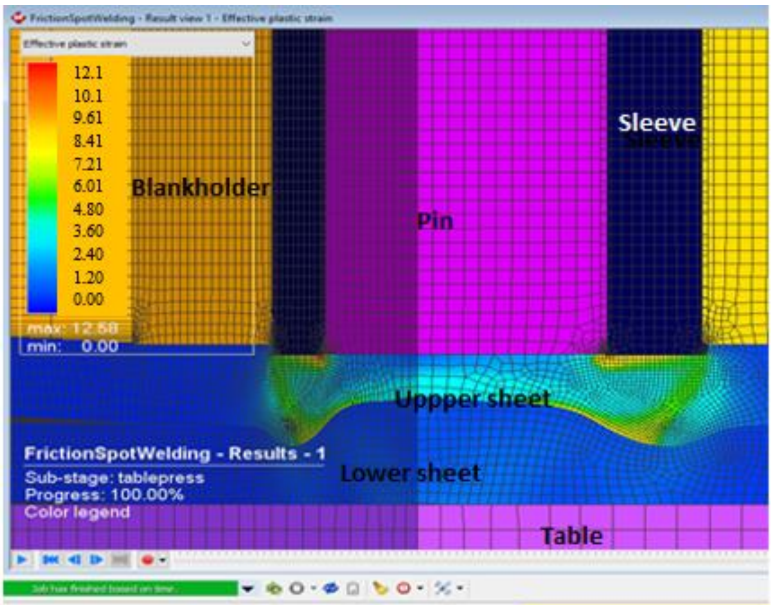


Fig. 6. Effective plastic strain during FSW without filler material

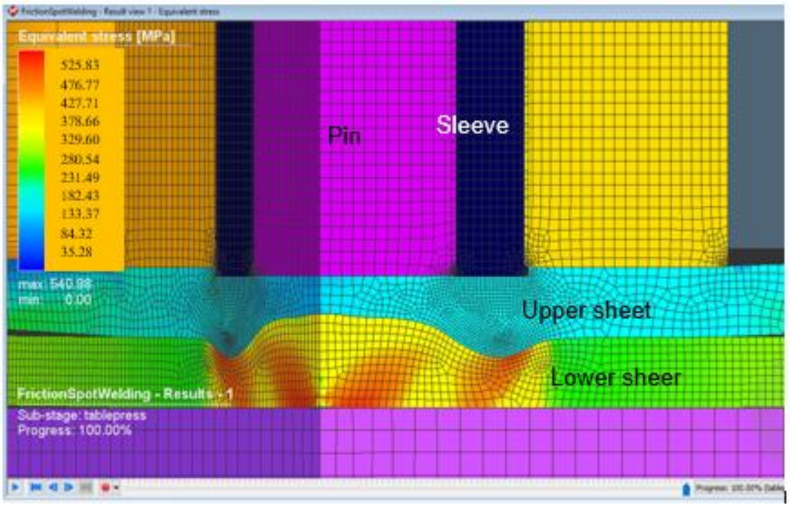


Fig. 7. Von Mises equivalent stress during FSW without filler material

The default result shown for this process type is the effective plastic strain. The final recorded value for plastic deformation is 12.58%. Figure 7 depicts the von Mises equivalent stress. It can be noted that the interface between the pin and sleeve exhibited an equivalent stress of 540.98MPa (illustrated by the red area). Moreover, the upper plate material adjacent to this region displays a distinctive fine-grained structure.

As illustrated in figure 8, during the compression phase of the plunge stage, the aluminium plates undergo deformation beneath the pin area, resulting in the material flowing towards the pin within the sleeve region.

Simufact Forming outputs the peak temperature for friction spot welding operations in addition to the typical outcome numbers. This result value can be used to trace the areas of the process with the greatest temperatures (Fig. 9).

The maximum temperature of 488.86°C can be seen just under the pin. Because the rotating velocity of the sleeve and the friction between the spin and the upper sheet generate the maximum heat in this area.

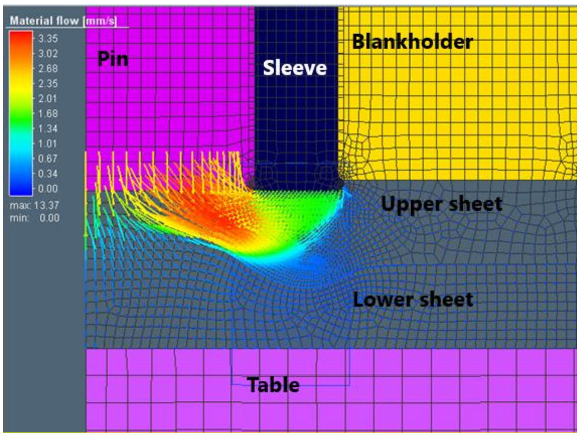


Fig. 8. Material flow during FSW without filler material

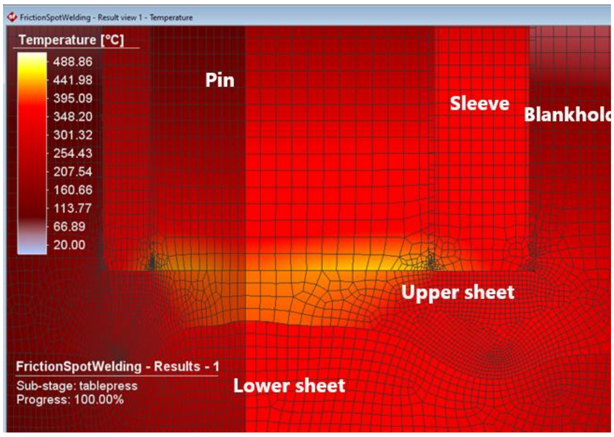


Fig. 9. Temperature field during FSW without filler material

Figure 10 illustrates the temperature change over time at the interfaces between the sleeve and the upper plate and between the pin and the top plate. One potential explanation for an incomplete refill is that, following plastic deformation, the material may reflow in the horizontal plane, where dimensional constraints are absent. The differing friction between the tool and the workpiece in these locations may also result in a discrepancy in the flexibility of the material in comparison to the material beneath the sleeve.

The simulation results of Friction Stir Welding (FSW) using Simufact Forming have demonstrated promising outcomes, showcasing a commendable level of accuracy and reliability. However, while these results are notable, they fall short of achieving the desired perfection in the welding process. Recognizing the potential for enhancements, the subsequent section of this report will explore the integration of a filler material. This strategic addition aims to augment the welding process further, addressing any imperfections observed in the initial simulations. The forthcoming section will delve into the specific parameters, conditions (with filler material), and simulations with filler material to comprehensively understand its impact on elevating the FSW process to an even higher level of precision and effectiveness.

4.2. Results of Simulation with Filler Material

The filler material used in this case is AlMg5. AlMg5 is an aluminum-magnesium alloy commonly used in welding applications. The use of AlMg5 powder filler section will delve into the specific parameters, conditions (with filler material), and simulations with filler material to comprehensively understand its impact on elevating the FSW process to an even higher level of precision and effectiveness.

AlMg5 powder filler, being an aluminum alloy, typically has good thermal conductivity. This can positively influence the heat generation and dissipation during FSW Improved thermal conductivity can help in maintaining controlled temperatures, reducing the likelihood of overheating, and contributing to a more uniform temperature distribution (Fig. 11). The maximum temperature decreases to 424.12°C compared to the previous result without filler material with a maximum temperature of 488.86°C.

The use of AlMg5 powder filler can enhance the material flow and mixing during FSW. This alloy is compatible with the base material, and its addition can promote better metallurgical bonding between the workpieces. This, in turn, can lead to a more homogeneous microstructure in the welded region.

According to the figure 12, the maximum of the material flow is 2.21mm/s which explains the impact of the filler material on the welding process compared to the result found in the simulation without it.

AlMg5 powder filler may contribute to the reduction of residual stresses in the welded structure. This is beneficial for minimizing post-weld distortions and improving the overall structural integrity of the joint (Fig. 13).

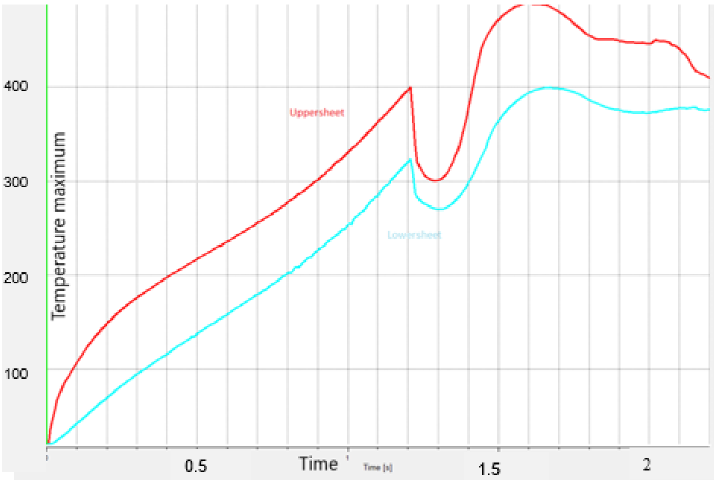


Fig. 10. Maximum temperature for the upper sheet and the lower sheet during the process (the Time [s] and Temperature maximum [°C])

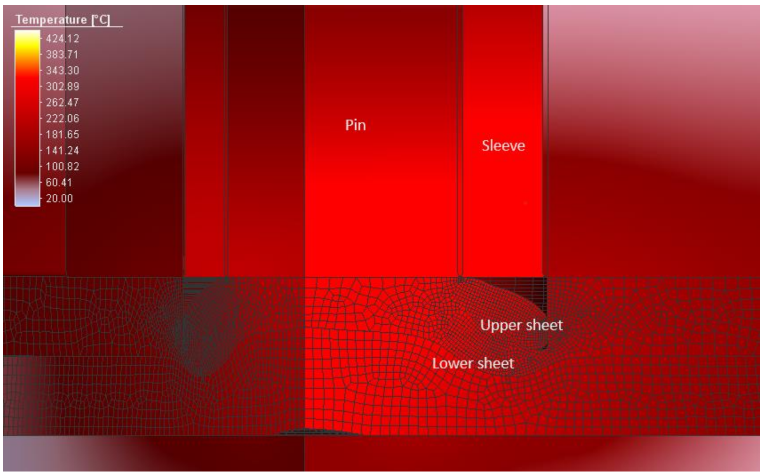


Fig. 11. Temperature field during FSW with filler material

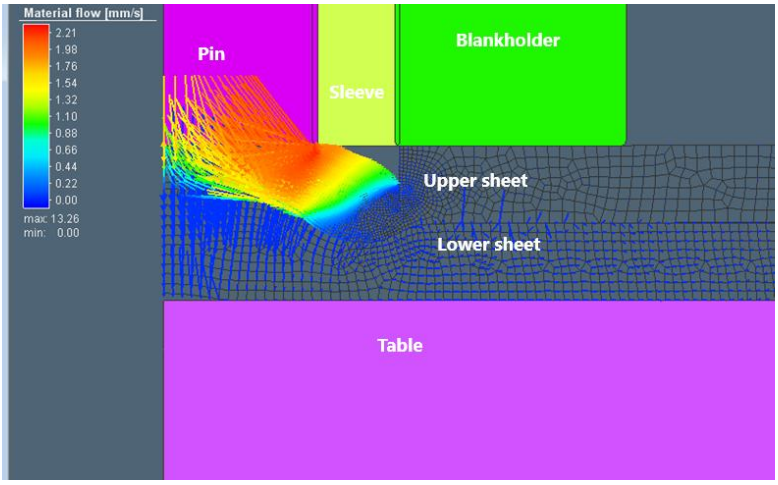


Fig. 12. Material flow during FSW with filler material

The effect of filler material is clearly shown as the von Mises equivalent stress was 540.94MPa without filler material and is only 441.25MPa for the equivalent stress. Figure 14 illustrates the impact of AlMg5 powder filler material on temperature control during the friction stir welding process, showcasing a reduction in maximum temperatures for both the upper sheet and the lower sheet.

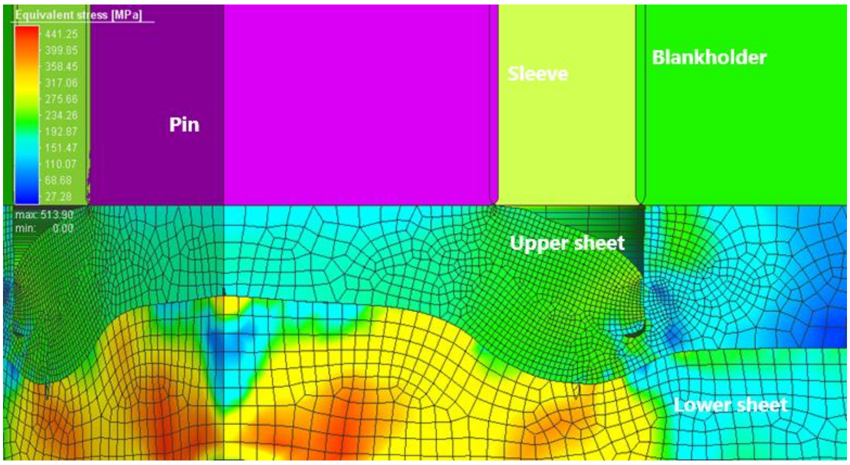


Fig. 13. Equivalent stress during FSW with filler material

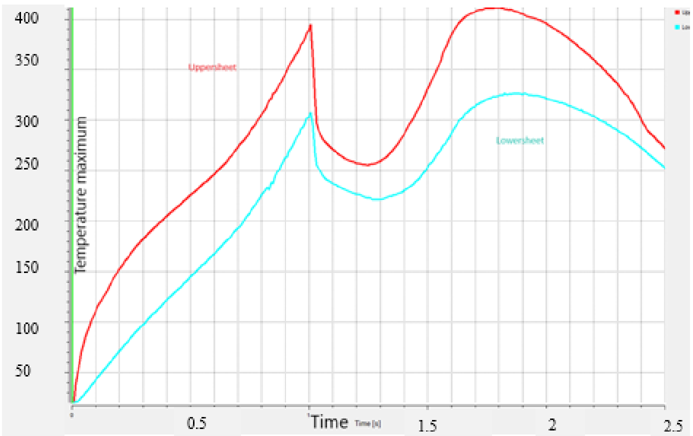


Fig. 14. Maximum temperature for the upper sheet and the lower sheet during the process (Time [s] and Temperature maximum [°C])

In summary, the incorporation of AlMg5 powder filler material in the friction stir welding process has yielded notably improved results, particularly in terms of temperature control. The observed variation in maximum temperatures reveals a significant reduction, showcasing the effectiveness of AlMg5 in mitigating thermal effects during the welding operation. Specifically, the upper sheet temperature decreased from 488.86°C to 424.12 °C, and the lower sheet temperature exhibited a decrease from 400°C to 328.20°C. These findings underscore the positive impact of AlMg5 powder as a filler material in enhancing the thermal characteristics of the welding process, contributing to a more controlled and optimized manufacturing environment.

4.3. The Supply of Temperature

In this section, we will conduct experimental validation of our results based on the work of the team referenced as [15], which was performed in the same laboratory and utilized the same process parameters.

Two Type K thermocouples were employed for the purpose of measuring temperature during the course of the welding process. The aforementioned thermocouples were connected to the K-EVIDASBUN-ESS-QX440 data acquisition system. As illustrated in the schematic of figure 15, the thermocouples were positioned in a strategic manner on the upper valve of the top plate, at a distance of 4.8 mm and 6mm from the centre of the pin. Measurements were taken at 200ms intervals. To ensure accuracy, ten samples were assessed, and the finite element analysis was validated using the average of these observations.

The friction and plastic deformation that occur in the weld zone during the welding process result in the production of heat. The temperature data obtained from the finite element analysis are compared with those obtained from the thermal sensors mounted on the top plate, as illustrated in figure 15.

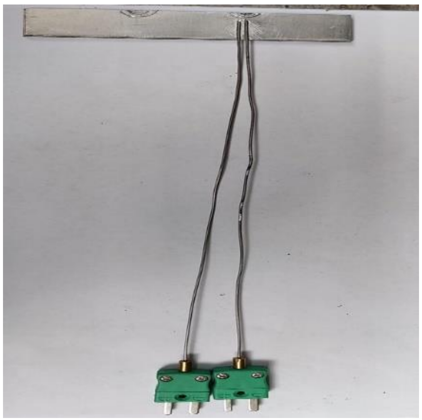


Fig. 15. The wiring diagram for thermocouples

In order to replicate the ambient conditions in the hall during the welding operation, the numerical model was initiated at a temperature of 20 degrees Celsius.

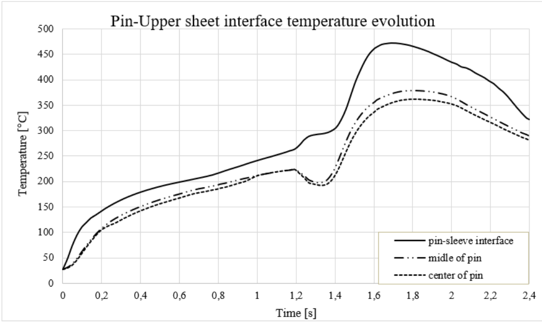


Fig. 16. Temperature at pin-upper sheet interface – FEM [15]

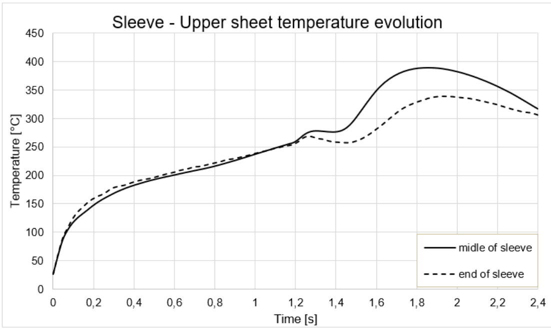


Fig. 17. Temperature at sleeve-upper sheet interface – FEM [15]

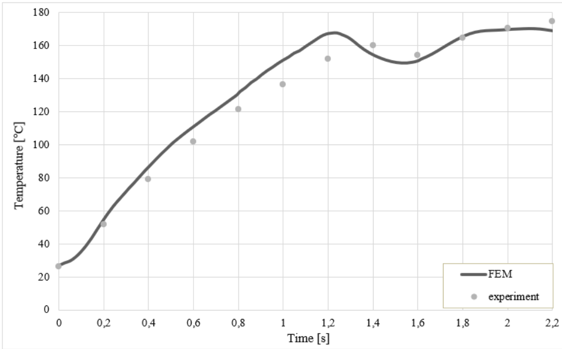


Fig. 18. Variation in temperature throughout the welding process at the specified measuring point, Sensor 1 [15]

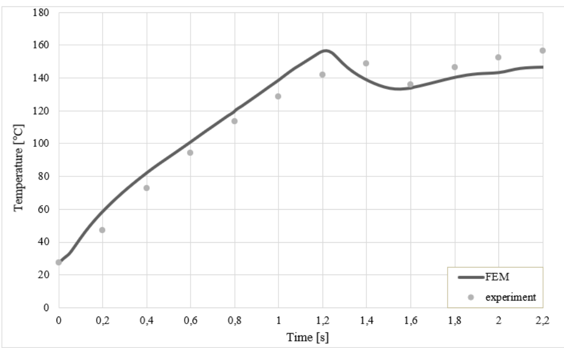


Fig. 19. Variation in temperature throughout the welding process at the specified measuring point, Sensor 2 [15]

The insertion of the sleeve and elevation of the pin resulted in a rapid increase in temperature within the welding zone during the initial phase, which lasted for a duration of 1.2 seconds. Sensor 1 recorded a peak temperature of 472 °C at 1.7 seconds into the welding process (see Fig. 16), followed by a maximum temperature of 390°C at 1.8 seconds (see Fig. 17). As illustrated in figures 18 and 19, the discrepancy between the simulation and the experimental results is insignificant.

4.4. The Impacts of Thermo-Mechanical Zones in RFSSW Technology

Figure 20 presents a schematic representation of four distinct regions, each characterised by a unique microstructure resulting from the welding process. The identified regions are as follows:

The Stir Zone (SZ) is defined as the region where the materials are subjected to intense mechanical and thermal action during the welding process. This area is directly affected by the welding operation, whereby the base materials are mixed and plasticised due to the application of intense heat and mechanical action, resulting in a homogeneous microstructure.

The Thermomechanically Affected Zone (TMAZ) is situated in the vicinity of the stir zone and is subjected to both thermal and mechanical influences, which result in modifications to the microstructure due to the interaction of heat and deformation, without complete melting.

The Heat-Affected Zone (HAZ) is a region that has been subjected to elevated temperatures during the welding process yet has not undergone significant mechanical deformation. This region is subjected to elevated temperatures during the welding process, yet it does not undergo significant mechanical deformation. The application of heat results in alterations to the microstructure, which may manifest as changes in hardness and strength characteristics.

The Base Material (BM) is defined as the original material that remains unaffected by the welding process. This is the material from which the sample was originally constructed, and which remains unaffected by the welding process. It serves as the reference point for the evaluation of the effects of welding on microstructural properties.

An appreciation of the specific characteristics of different regions is essential for the comprehensive assessment of a welded joint, including its overall integrity and performance.

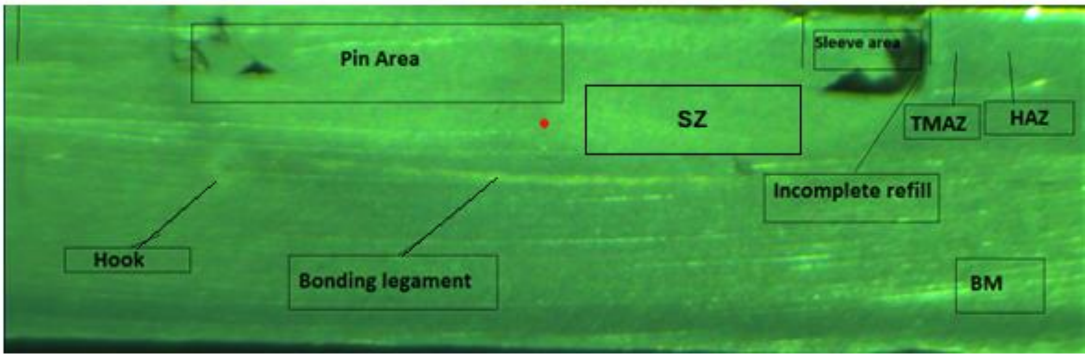


Fig. 20. Cross-section through the welded joint

5. CONCLUSIONS

This article has focused on elucidating the influential role of filler material in leveraging the capabilities of Simufact Forming. The investigation of the impact of filler material has revealed a substantial transformation in the welding joint's quality. By comparing scenarios with and without filler material, the results unequivocally demonstrate a noteworthy improvement in welding outcomes when filler material is introduced. The integration of filler material proves instrumental in obtaining a level of welding excellence that surpasses the limitations observed in its absence.

The integration of AlMg5 powder as a filler material in FSW brings forth a range of positive outcomes. Simulations, especially those conducted using an advanced software like Simufact Forming, play a crucial role in understanding and optimizing the intricacies of this process. These simulations reveal insights into temperature distributions, material flow, and residual stresses during the welding operation.

The use of AlMg5 powder offers promising results in terms of enhanced thermal conductivity, favourable mechanical properties, improved material flow, and reduced tool wear. These factors collectively contribute to the production of high-quality welds with superior mechanical characteristics. The corrosion resistance inherent in aluminum-magnesium alloys further underscores the applicability of this technology in diverse industries.

As a new technology, the exploration of AlMg5 powder in FSW represents an initiative at the forefront of materials science and manufacturing engineering. Researchers and practitioners alike are investing efforts to unlock its full potential, aiming to refine the process parameters and advance our understanding of how this innovative filler material influences the welding dynamics. This endeavor is not only a testament to the continuous evolution of welding technologies but also an acknowledgment of the need for sustainable and efficient methods in joining dissimilar materials.

By delving into the complexities of FSW with AlMg5 powder, researchers are contributing to a growing body of knowledge that has the potential to revolutionize fabrication techniques across various industries. This initiative is driven by a pursuit of more robust, cost-effective, and environmentally friendly alternatives to conventional welding methods, positioning FSW with AlMg5 powder as a transformative force in modern materials joining technology.

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