



A Numerical Study of Friction Stir Welding for AA5754 Sheets to Evaluate Temperature Profile and Plastic Strain

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HIGHLIGHTS

- A 3-D model based on a Lagrangian approach was built to study FSW's temperature distribution and plastic strain.
- A temperature measurement system was adopted to validate the model.
- Increasing the rotational speed resulted in increasing the peak temperature and plastic strain.
- Increasing the traverse speed resulted in lowering the peak temperature and plastic strain.

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ABSTRACT

A full-dimensions 3-D numerical model based on the Lagrangian approach has been employed to predict the peak temperature and the plastic strain distribution in the FSW of (AA5754) joints using ABAQUS software. The material's model utilizes the classical plasticity model in addition to defining the thermophysical properties of the alloy using JMatPro software to increase the accuracy of the numerical results. The basic variables of FSW were three rotational speeds (930, 1460, and 1860 rpm) and three traverse speeds (35, 65, and 95 mm/min). The influence of the rotational and traverse speed on temperature profile and plastic strain has been studied. The simulation results showed that increasing the rotational speed led to increasing the peak temperature, which concentrated under the tool's bottom surface while increasing the traverse speed decreased the peak temperature recorded. The highest peak temperature was (497 °C) at a rotational speed of (1860 rpm) and a traverse speed of (35 mm/min). It was also found that the rotational speed increased the plastic strain starting from the tool's neck and continuing along the pins' position and gradually decreasing towards the bottom. In addition, a V-shape pattern has appeared in the temperature distribution across the workpiece's cross-section, representing the heat loss during the FSW by the backplate due to heat conductance.

1. Introduction

Friction Stir Welding (FSW) is a recent solid-state joining method invented by Wayne Thomas at The Welding Institute (TWI) in Cambridge, the UK, in 1991[1]. FSW is a complex process that uses thermal and mechanical effects to make the material reach its flow stress and complete the joining process. It utilizes a non-consumable tool made of a shoulder with a specific diameter to generate the desired heat input to soften the material and a pin with different shapes to stir the material and complete the welding [2]. This process consists of four stages. The first stage is the rotation of the tool then, followed by plunging the tool slowly into the workpiece till the shoulder touches the workpiece's surface. Next, the dwelling stage follows, and its primary role is heating the workpiece by rotating the tool in the same position. Finally, a translation speed is applied to the tool to complete the welding, which is the welding stage [3].

FSW has proved effective in welding materials with poor weldability and eliminating the defects produced by traditional fusion welding methods. These defects are hot cracking, porosity, and embrittlement. It is also a sustainable welding method since it requires no filler material or shielding and does not generate toxic gases or fumes [4].

Aluminum alloy series 5xxx can be welded using traditional fusion welding like Metal Inert Gas (MIG) or Tungsten Inert Gas (TIG) using the appropriate filler materials. But using FSW to weld, this series can produce higher mechanical properties than the traditional methods [5].

The microstructure evolved from FSW is divided into three regions. The stir zone (SZ) includes the finest grains among other regions due to the severe plastic deformation made by the stirring and heat input generated by the tool. Thermo-

mechanically Affected Zone (TMAZ) this region is only exposed to partial dynamic recrystallization effect, and its grain size is larger than the SZ and rotates with the tool direction. Lastly, the heat-affected zone (HAZ) is only exposed to thermal cycles during the welding process. Therefore, its grain size is approximate to the base metal's grain size and has the lowest mechanical properties due to its elongated grains [6].

The influence of FSW parameters, tools' and joints' geometry on the temperature distribution and material flow around the tool has been studied experimentally and numerically. Numerical modeling of FSW has been utilized to investigate the temperature profiles across the weldment, evaluate plastic strain, and understand the complex material flow in this process. The numerical study can also avoid the parameters and conditions leading to defect formations. Material flow in FSW has been achieved using many approaches, such as Lagrangian, Eulerian, and Arbitrary Lagrangian-Eulerian (ALE) [7, 8].

Buffa et al. studied the temperature profile, strain rate, and welding forces numerically using visco-plastic material properties with an implicit Lagrangian approach [9]. Chao et al. considered the heat generated by FSW numerically using the Lagrangian modeling technique. They proposed steady-state conditions for the tool and transient states for the plates [10]. Finally, Khandkar et al. modeled the FSW using a 3D Lagrangian to predict the temperature profile and the welding torque of AA6061-T651 based on the temperature-dependent properties [11].

Cho et al. developed a CFD Eulerian model to explore stress distribution in the FSW of stainless steel 304L. However, they neglected the temperature influence on the viscosity and ignored the transient temperature conditions [12]. A. Savaş studied the effect of the tool's shoulder and pin shapes on the material flow in the FSW of AA2024-T3. Using the 3D CFD model, he used COMSOL Multiphysics Software Package [13].

Xu and Deng established a 2D FE model using ABAQUS to predict the material flow and estimate the plastic strain distribution using the ALE approach [14]. K.N. Salloomi et al. carried out a 3D numerical analysis for the FSW of (AA 7075-T651) to estimate the temperature and stress distribution during three stages using an ALE approach and adaptive meshing technique [15].

Previous studies showed that constant material properties strongly affect the numerical outputs, so using thermophysical properties will make FSW more realistic and yield better results [16-18]. However, after reviewing many numerical studies regarding the FSW, it was concluded that some studies built simplified models, such as 2D or half dimensions models, which can't predict accurate material flow, temperature profiles, and stress distribution values [17]. In addition, some studies don't use temperature-dependent properties and friction coefficients, leading to inaccurate outputs [18].

This work aims to build a 3D finite element with full dimensions model based on the Lagrangian approach. Since FSW requires temperature-dependent properties to produce accurate results and the lack of (AA5754) thermophysical properties, temperature-dependent properties for (AA5754) have been generated using JmatPro software to increase the results' accuracy. Furthermore, using JMatPro Software to generate thermophysical properties will pave the way for researchers to develop the needed properties if unavailable instead of adopting the properties of similar alloys and materials, which may not yield good results.

2. Numerical Modelling

2.1 . Computational Model

A 3D Lagrangian model using the ABAQUS package has been developed to numerically simulate the FSW of (AA5754) to predict the temperature profile and equivalent plastic strain. The model consists of two workpieces clamped together in a butt geometry and a rigid tool with a cylindrical pin. The model adopts the exact experimental dimensions for each workpiece and tool. Figure 1 shows the tool and workpiece dimensions and their assembly.

2.2 Defining Materials' Properties

The thermophysical properties of (AA5754) are generated using JMatPro. These properties have been adopted to simulate the FSW process. The JMatPro software is well-known for creating thermophysical properties for forging and casting simulations. Despite the software's credibility, it has been validated using experimental thermophysical properties from Mills [19]. Table 1 illustrates the validation of the JMatPro thermophysical properties with the experimental ones from Mills, while Table 2 shows the temperature-dependent properties used in the model for the workpiece. Defining the plastic behavior of the material was done by taking 10 points from the plastic true stress-strain curve of the alloy, as shown in Figure 2 and Table 3. The thermophysical properties were attributed to the workpieces to increase the temperature profile's prediction accuracy during the welding process and especially along the weld line. In addition, elastic and plastic properties were defined using the classical plasticity model to understand the plastic strain distribution during the FSW.

Due to the lack of the tool's X12M properties, it was given the properties of its equivalent in the ASTM, which is D2 die steel. Table 4 shows the D2 properties.

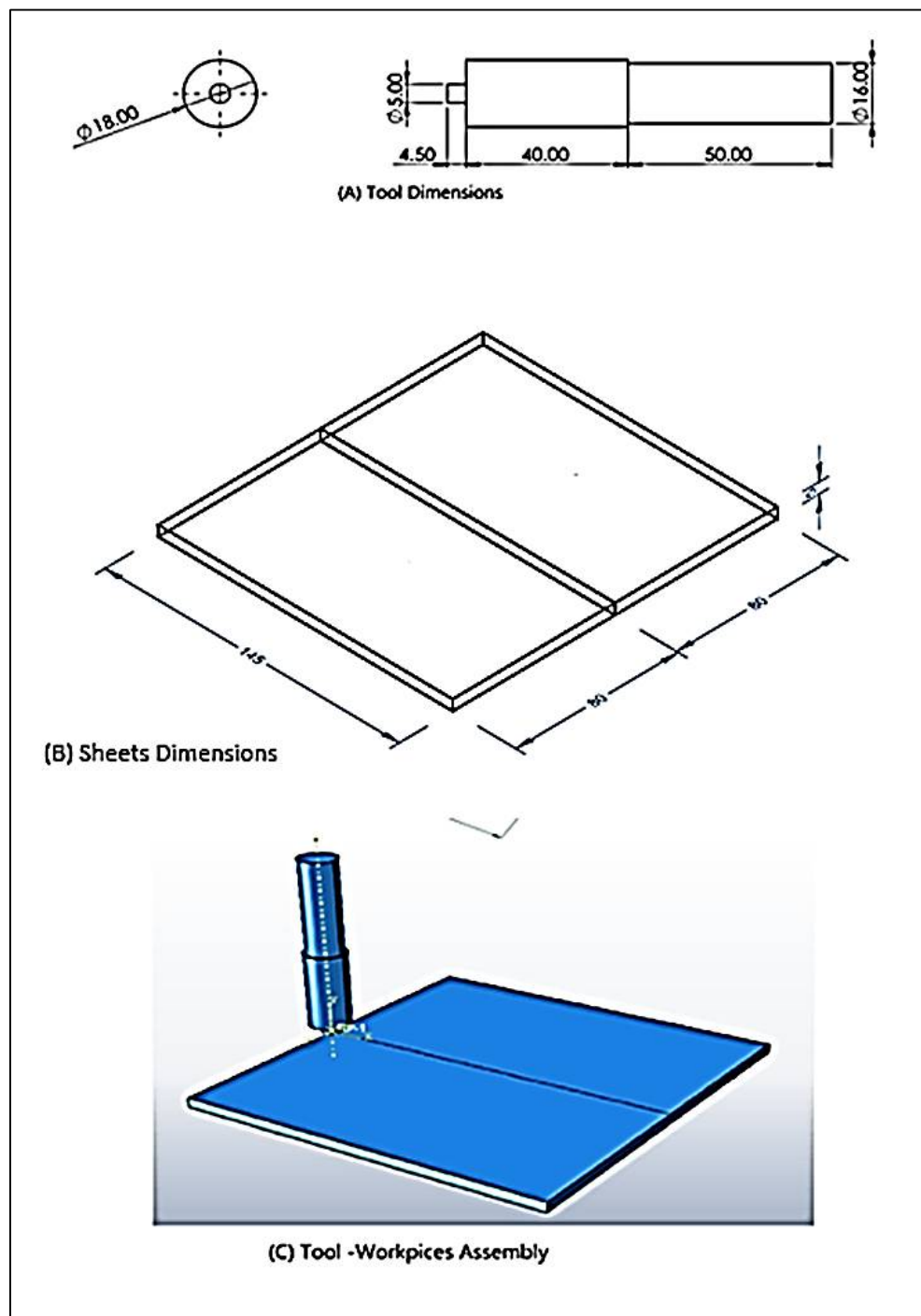


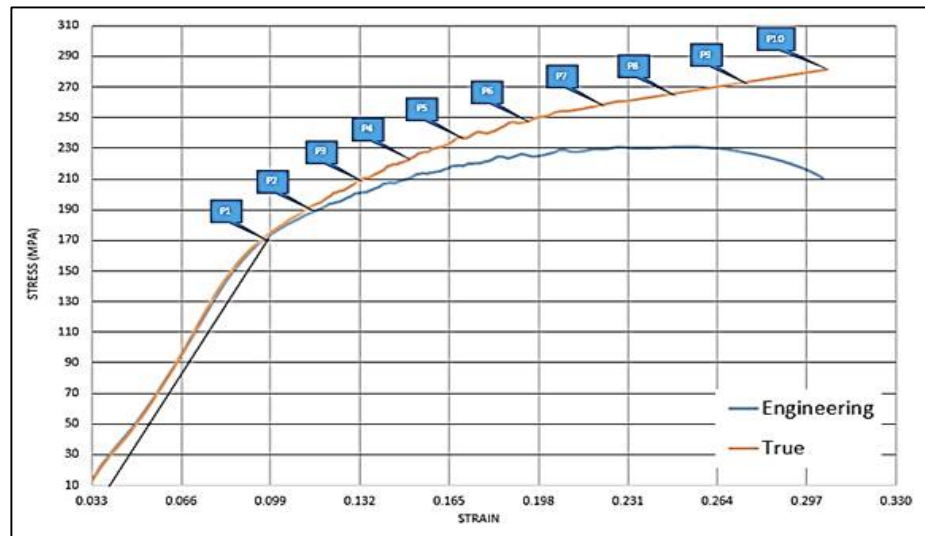
Figure 1: (A) Tool Dimensions (B) Sheets Dimensions (C) Tool Workpieces assembly

Table 1: Thermophysical properties comparison between the JmatPro Software and experimental thermophysical properties from Mills

Temp. (°C)	Density (g/cm ³) Mills	Density (g/cm ³) JMatPro	Specific heat capacity (J/Kg.°C) Mills	Specific heat capacity (J/Kg.°C) JMatPro	Thermal Conductivity (W/m.°C) Mills	Thermal Conductivity (W/m.°C) JMatPro
25	2.805	2.950	0.85	0.83	-	130
100	2.795	2.940	0.91	0.87	186	139
200	2.770	2.910	0.96	0.91	197	148
300	2.750	2.890	0.98	0.95	194	154
400	2.725	2.860	1.04	1.27	196	148
500	2.700	2.820	1.10	1.26	196	142

Table 2: Thermophysical Properties of (AA5754) from JMatPro Software

Temp (oC)	Thermal Conductivity (W/m.oC)	Specific heat capacity (J/Kg.oC)	Density (Kg/m ³)	Young's Modulus (GPa)	Poissons's ratio	Coefficient of thermal expansion (10-6/K)
25	151	900	2670	67.2	0.337	22.5
50	155	920	2670	66.1	0.338	22.7
100	161	940	2660	64.7	0.340	23.2
150	166	970	2650	62.9	0.343	23.7
200	169	990	2640	61.1	0.345	24.2
250	172	1010	2630	58.8	0.348	24.8
300	174	1030	2620	56.8	0.351	25.3
350	175	1050	2610	54.5	0.354	25.9
400	176	1070	2600	52.2	0.357	26.4
450	177	1090	2580	49.7	0.360	26.9
500	177	1120	2570	47.1	0.364	27.5
550	177	1160	2560	44.4	0.368	28.1

**Figure 2:** Graph of True and Engineering Stress-Strain**Table 3:** True Plastic Stress and Strain Values for Ten Points

Point	True plastic stress	True plastic strain
P1	170E6	0.00
P2	190E6	0.0165
P3	206E6	0.033
P4	220E6	0.0495
P5	233E6	0.0693
P6	246E6	0.0953
P7	257E6	0.1223
P8	264E6	0.1485
P9	270E6	0.1782
P10	278E6	0.2094

Table 4: D2 Properties

Density (Kg/m ³)	Young's Modulus (GPa)	Poissons ratio
2770	205	0.3

2.3 Meshing and Boundary Conditions (Bcs)

The workpieces were meshed using a C3D8RT element with a (0.001m) mesh size, while the tool meshed with a C3D4T element of (0.001m) size. The plates were fully fixed at the bottom, as shown in Figure 3, and the tool was placed perpendicular to the welding line. The FSW at room temperature has been defined using a predefined thermal field of (25°C) as shown in Figure 4. A convective coefficient of (25 W/m².°C) has been utilized between the workpiece and the surrounding air. A coefficient of (1500 W/m².°C) between the workpiece's bottom surface and the backing plate has been defined to simulate the heat loss from the plates. Temperature-Dependent friction coefficient has been used to increase the results' accuracy, as shown in Table 5 [20]. Table 6 mentions the welding parameters that were used to simulate the FSW.

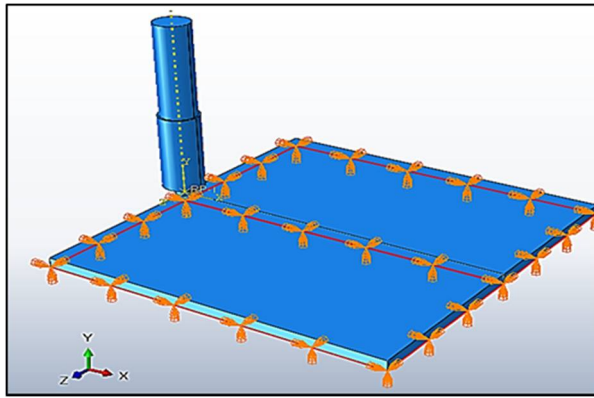


Figure 3: Fully Fixed Workpiece Bottom

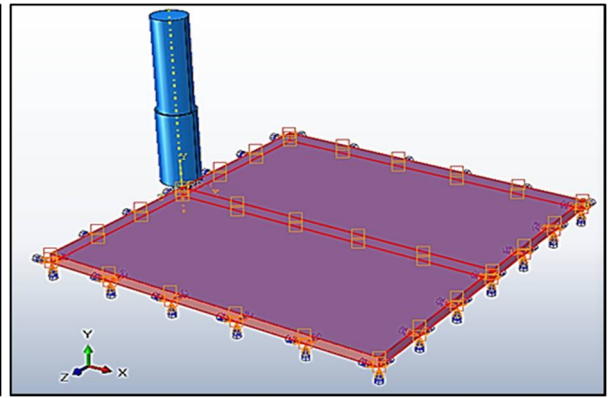


Figure 4: Thermal Predefined Field

Table 5: Temperature-dependent Friction Coefficient[20]

Temperature °C	Friction Coefficient μ
22	0.61
34.7	0.545
93.3	0.259
147.5	0.115
210.6	0.046
260	0.047
315.6	0.0350
371.1	0.020
426.7	0.007
582	0

Table 6: FSW parameters

Experiment No.	Rotational speed (RPM)	Traverse speed (mm/min)
1	930	35
2	930	65
3	930	95
4	1460	35
5	1460	65
6	1460	95
7	1860	35
8	1860	65
9	1860	95

3. Results and Discussion

3.1 Validation of The Model

A temperature measurement system based on the Arduino microcontroller board with two K-type thermocouples has been designed and manufactured. The thermocouple specifications are mentioned in Table 7. The Arduino Mega uses a 3.5" display; the system is programmed to measure the temperature and send the data to the PC using the USB interface or store the data on microSD. The system has four K-type thermocouples. The temperature readings are displayed on the 3.5" screen. Furthermore, when the system is connected to the PC through USB and data logging starts, the screen shows the current status of the measurement system. The measurement system has been implemented to measure welding temperature. The positions of the two thermocouples are (15 mm) from the welding line and (80 mm) from the start of the welding process. The validation has been done for two experiments with the lowest heat input (930/95) and the highest heat input (1860/35).

The validation of the numerical and experimental results of the temperature history has a good agreement, as shown in Figure 5 and Figure 6.

Table 7: Thermocouples specifications

Material	Temperature range	Accuracy
Made of a positive non-magnetic leg and a negative magnetic leg. The main constituents metals are Nickel, Chromium, and Aluminum.	-270 to 1260°C	+/- 2.2°C

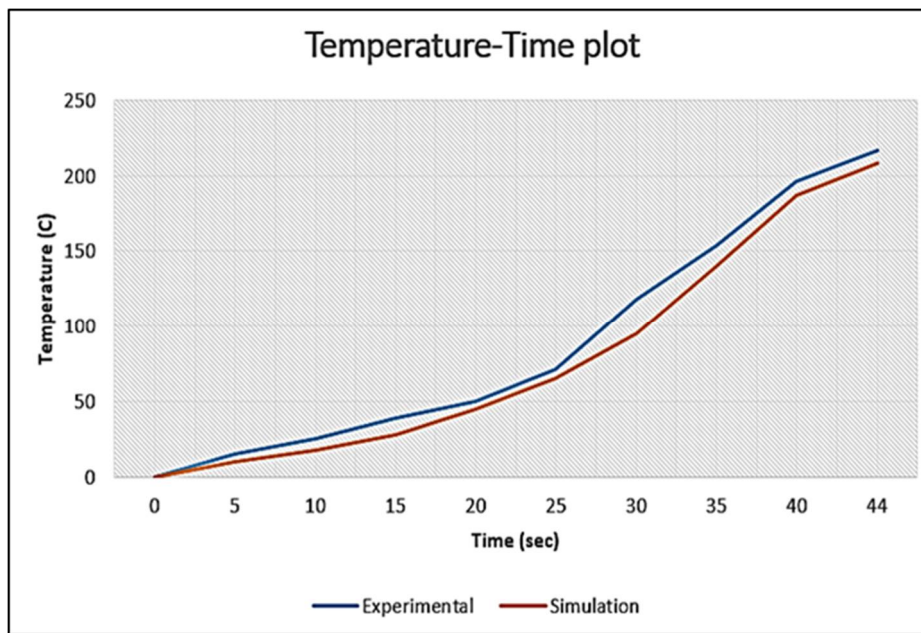


Figure 5: Temperature history agreement of (930/95) in experiment and simulation

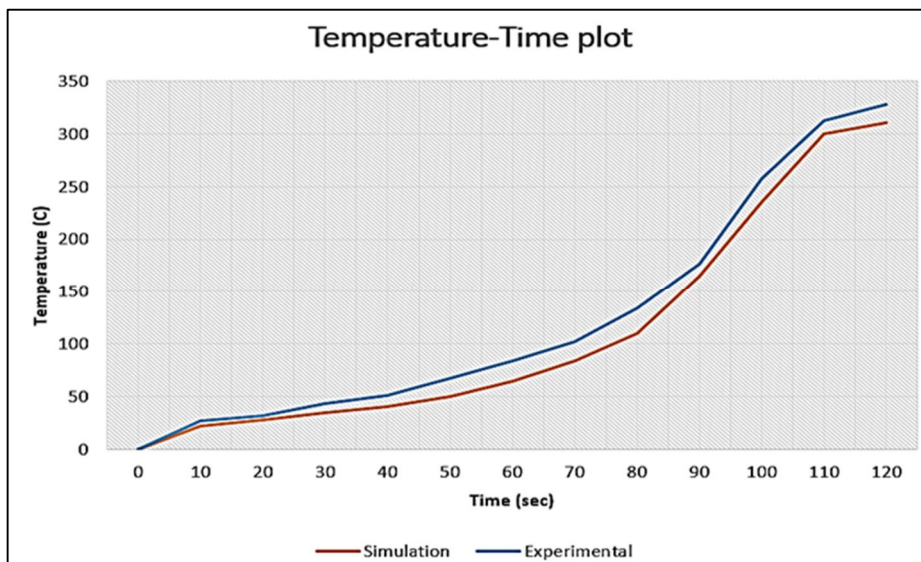


Figure 6: Temperature history agreement of (1860/35) in experiment and simulation

3.2 Traverse Speed Effect

Two speeds were simulated numerically to investigate the effect of the traverse speed on heat generation and plastic strain value. These speeds were 35 mm/min and 95 mm/min while keeping the spindle speed constant at 930 rpm.

The peak temperature has witnessed a drop by increasing the traverse speed from 35 mm/min to 95 mm/min due to the fast dissipation of heat from the workpieces at a higher traverse speed and the reduced heat input generated by the tool per unit length. On the other hand, when the traverse speed is low, the material in front of the tool is subjected to a higher temperature. Thus it is softer, and the tool needs less force to stir the material. Figure 7 a and b show the temperature profile of (35 mm/min) and (95 mm/min) traverse speeds, respectively. Figure 8 a and b show the conductance of the temperature generated by the friction of the tool's shoulder and the surface of the workpiece during FSW in the cross-section of the weldment. The V-shape pattern represents the temperature profile during the FSW due to the presence of high thermal flow at the interface between the shoulder and the weldment surface. The heat input starts at the workpiece's surface and is conducted gradually by the workpiece and downwards to be lost to the backing plate.

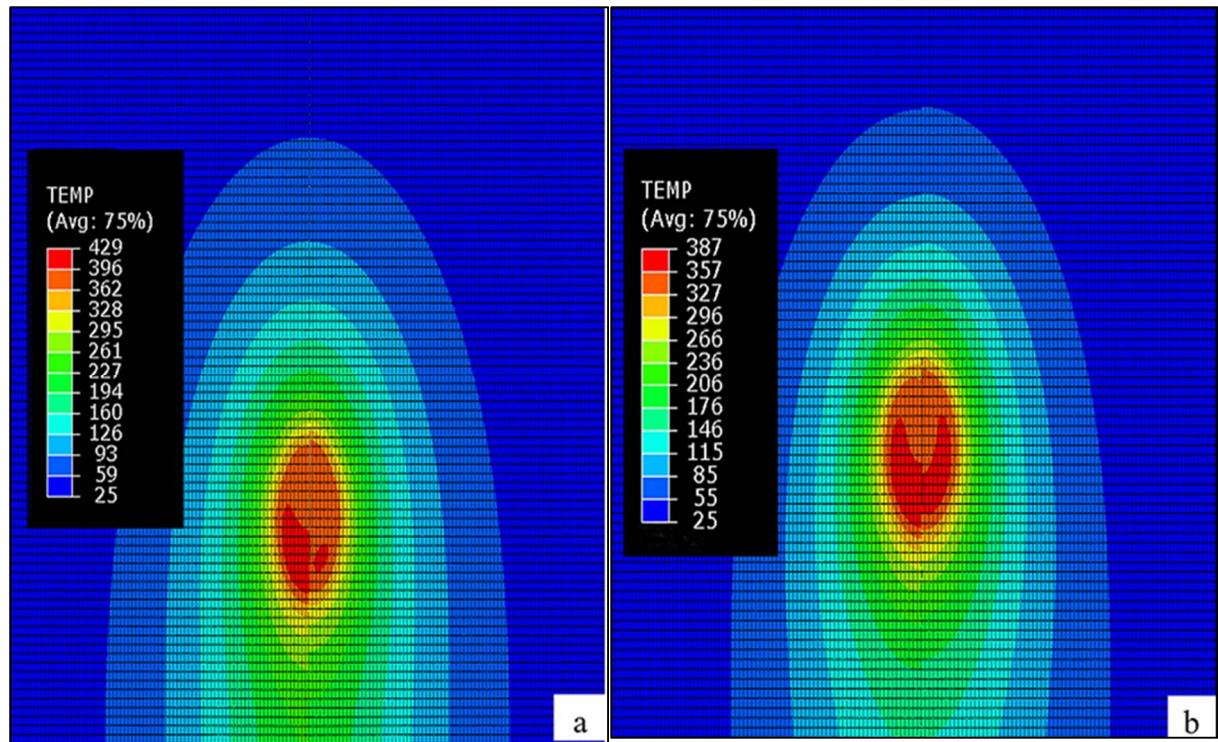


Figure 7: Temperature Profile at Different Traverse Speeds, a) 35 mm/min, b) 95 mm/min

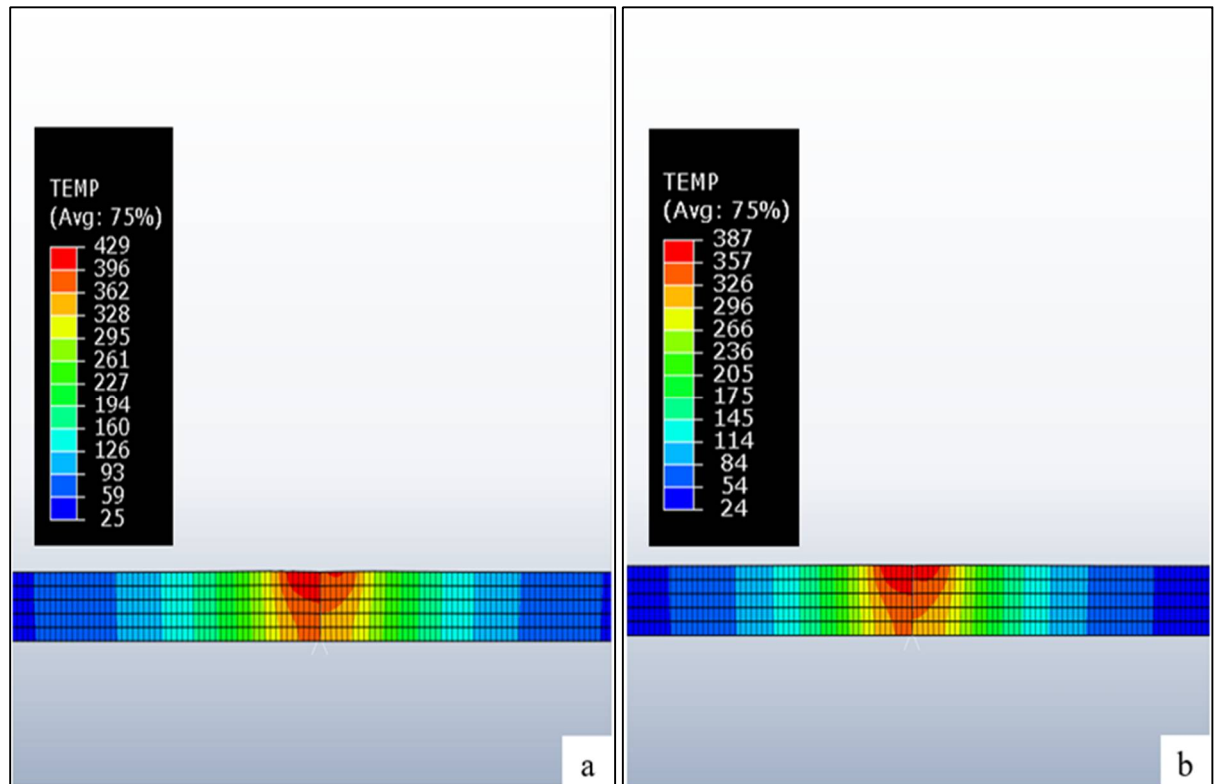


Figure 8: Temperature Distribution across the Cross-section at, a) 35mm/min, b) 95 mm/min

The equivalent plastic strain distributes along the welding seam on the retreating and advancing sides. Its maximum value starts at the tool's shoulder's neck, where the deformation is at its maximum due to the movement of the material by the tool and continues downwards along with the pin due to the stirring effect done by the tool's traverse movement along the welding line. The plastic strain is higher at low traverse speeds due to the higher heat inputs, making the materials softer, highly mixable, and having a longer mixing time. Figure 9 a and b illustrate the plastic strain distribution across the joint thickness.

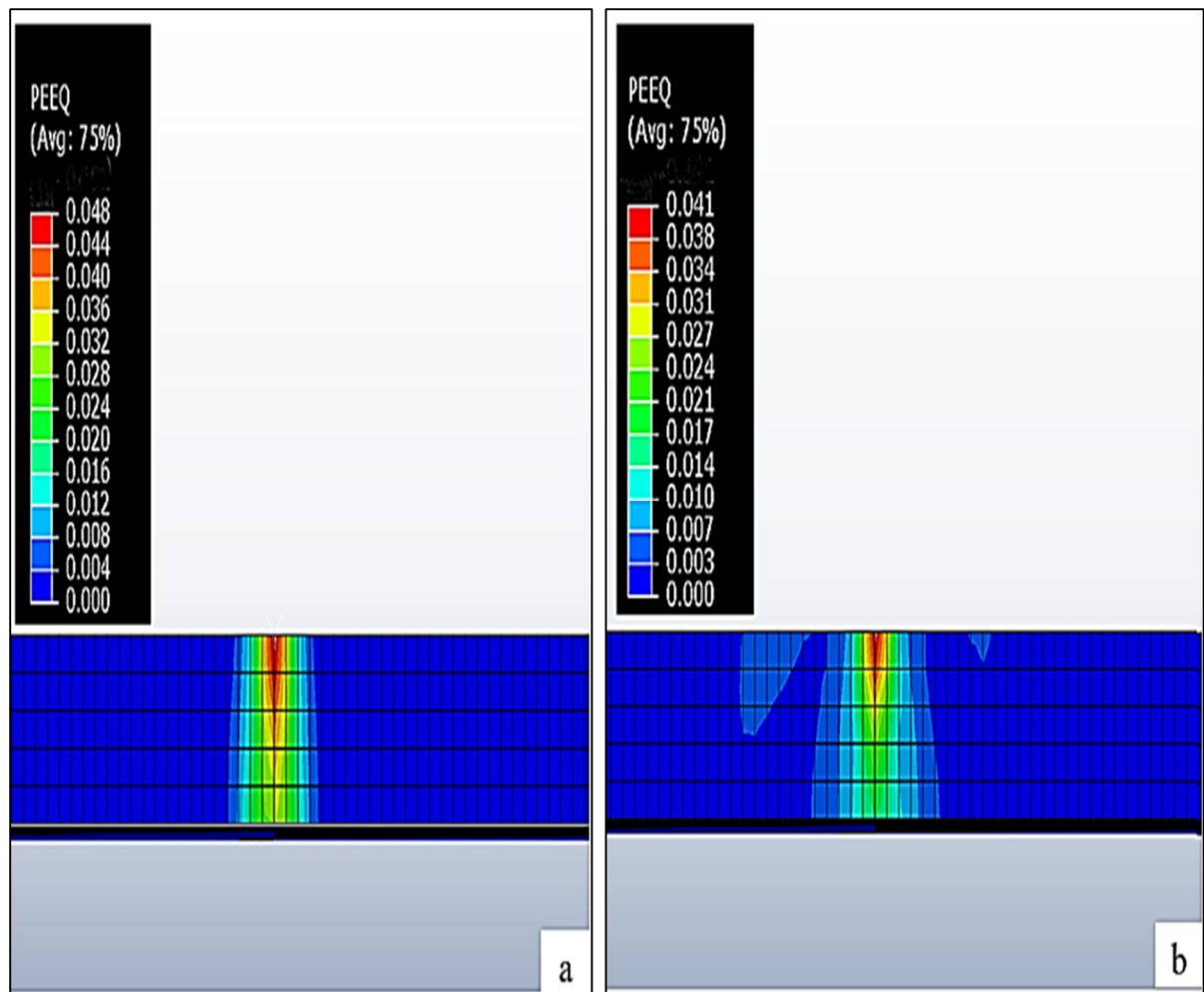


Figure 9: Plastic Strain Distribution, a) at 35 mm/min, b) at 95 mm /min

Backar et al. [20] adopted a 3D finite element model built using ABAQUS software with thermo-physical properties of the workpiece to yield accurate results. They used an elastoplastic Johnson–Cook model to simulate the material behavior. The peak temperature results acquired from the simulation showed that increasing the traverse speed has led to decreasing the peak temperature of the FSW. This is due to the shorter time of contact between the tool's shoulder and the workpiece's surface, which is mainly responsible for the heat input generation due to friction. Their study also showed that increasing the traverse speed resulted in smaller plastic strain values. The study results are in good agreement with our results.

3.3 Rotation Speed Influence

Two simulations were executed to consider the rotational speed's effect on the temperature profile and plastic strain. These simulations were performed with two rotational speeds, 930 rpm, and 1860 rpm, while the traverse speed is 35 mm/min.

The numerical results show that the rotational speed mainly influences heat generation since it is responsible for the amount of friction between the tool's shoulder and the workpiece's surface. Increasing the rotational speed allows more contact time between the shoulder and the workpiece. Therefore, at 930 rpm the peak temperature was 429°C; at 1860 rpm, the peak temperature was 497°C. Figure 10 a and b show the influence of rotational speed on heat generation in FSW. The cross-section area of the welded joints in Figure 11a and b shows the V-shape pattern formed due to the larger diameter of the tool's shoulder compared to the pin. This difference results in higher heat generation on the upper surface than on the bottom. This pattern is also formed due to the smaller convection coefficient between the weldment and the air compared to the convection between the weldment and the back plate, which allows more heat loss.

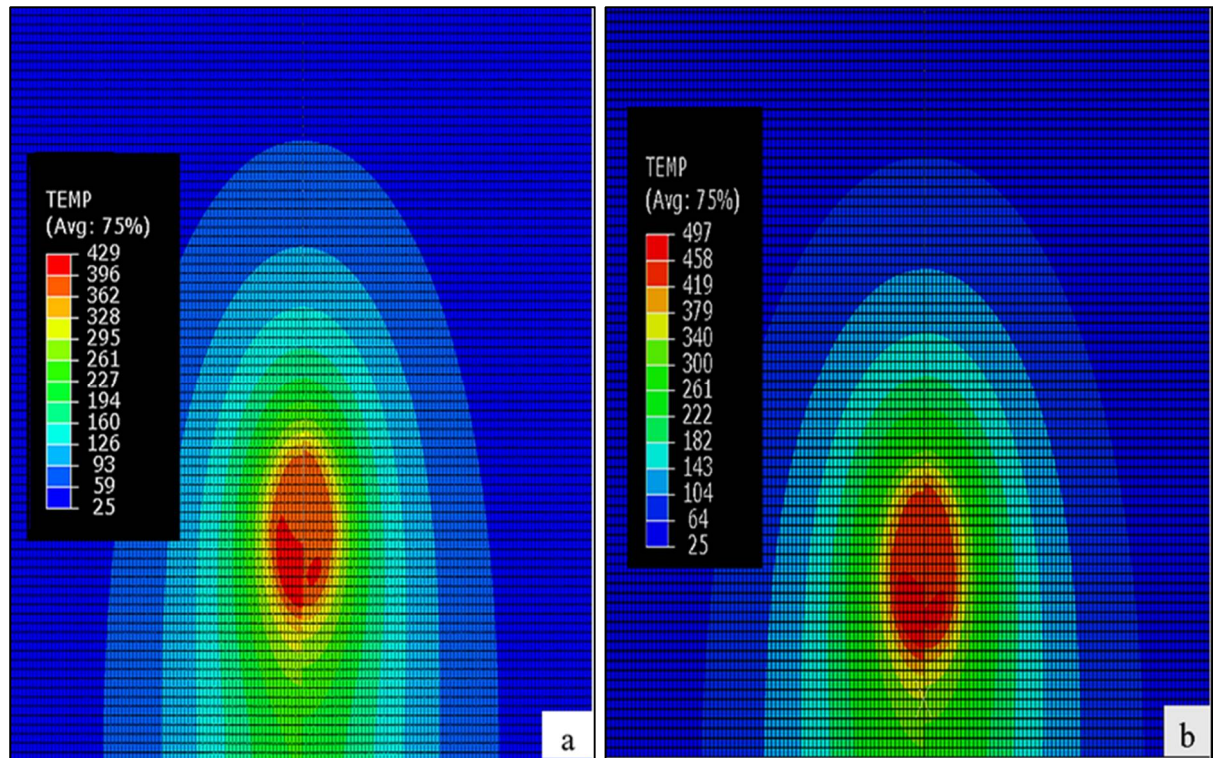


Figure 10: Temperature Profile at Different Rotational Speeds, a) 930 rpm, b) 1860 rpm

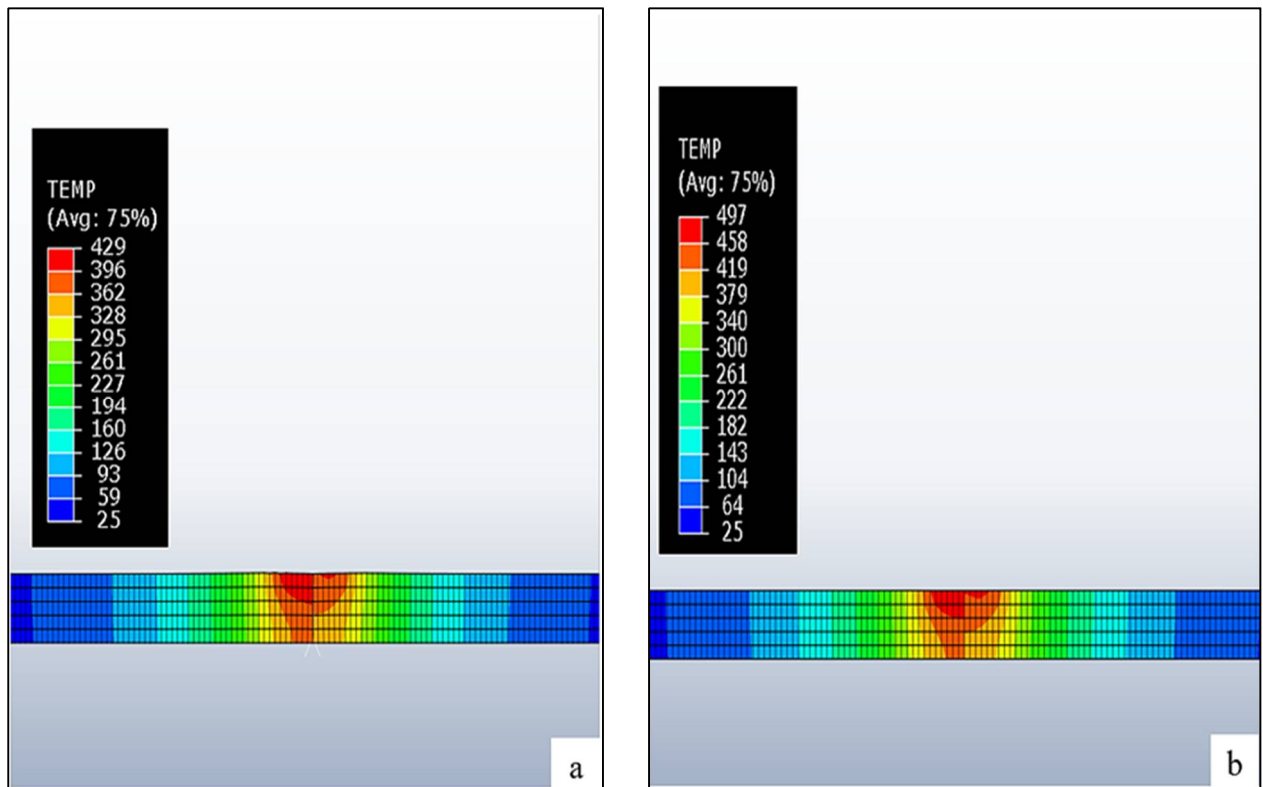


Figure 11: Temperature Distribution across the Cross-section at a) 930 rpm, b) 1860 rpm

Plastic strain values increased by increasing the rotational speed due to generating more frictional heat thanks to the longer contact time between the tool's shoulder and the workpiece, which results in more softening of the material, thus more mixing effect by the pin. The highest plastic strain is located at the tool's neck and gradually decreases downwards along the pin. Figure 12 a and b show the plastic strain profile in the cross-section of the joints.

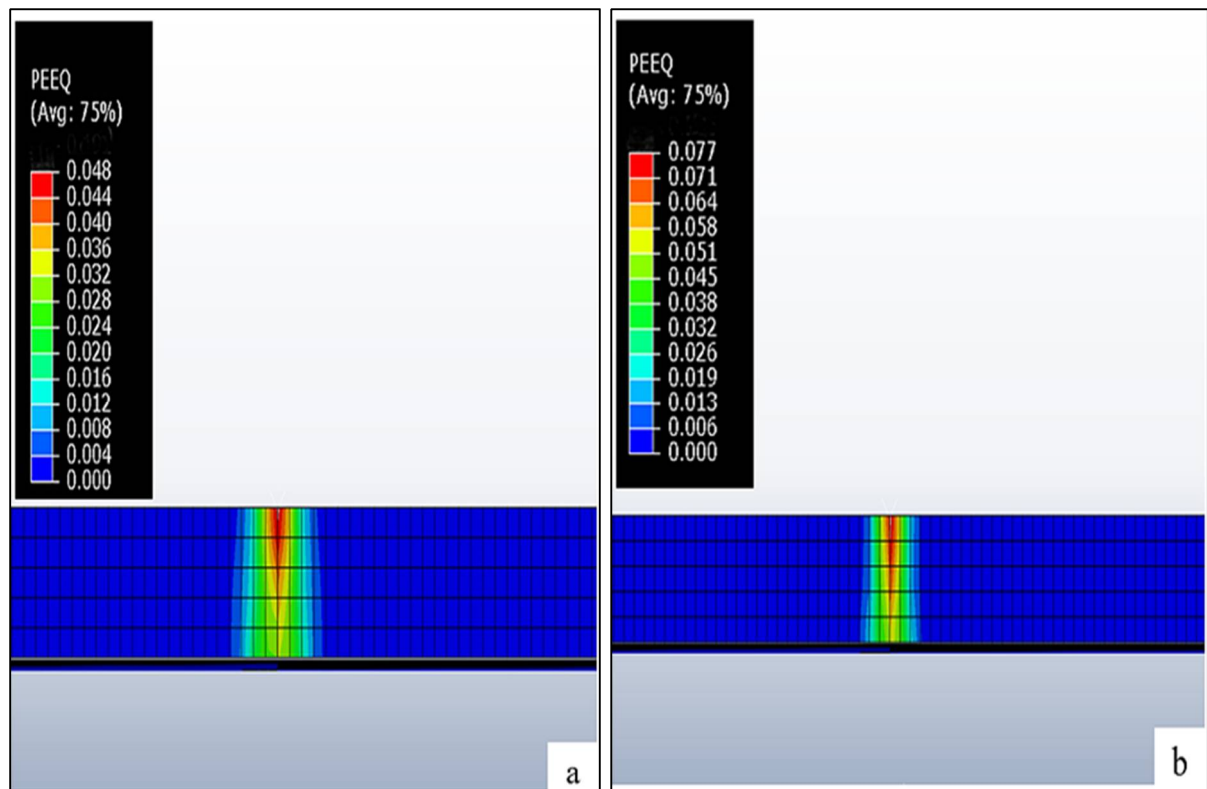


Figure 12: Plastic Strain Distribution, a) at 930 rpm, b) at 1860 rpm

The rotational speed influence during the FSW has shown good agreement with Siddharth et al. [21]. They built a 3D thermophysical properties model to study the peak temperature profiles and plastic strain distribution. The peak temperature results showed a significant rise with increasing the rotational speed due to increased heat generated from friction and the slow dissipation of heat across the workpiece. The plastic strain witnessed an obvious increase by increasing the rotational speed due to the softening of the welded material by the higher heat input, which makes the material highly mixable. Vignesh et al. [22] studied the peak temperature distribution in FSW using a model built using COSMOL software. The findings showed that the rotational speed directly affects heat generating in the FSW but is still lower than the influence of the traverse speed. The amount of heat was found to be dependent on the contact area of the tool and the workpiece.

4. Conclusions

A 3D numerical model based on the Lagrangian approach has been developed to predict the temperature profiles and equivalent plastic strain development in the (AA5754) weldments. The material's model is a classical plasticity model, and thermophysical properties have been generated using JmatPro software. The numerical results led to the following conclusions:

- 1) The proposed model based on the Lagrangian approach agrees with the experimental results of the peak temperature history.
- 2) The JMATPro software has good reliability in generating thermophysical and thermomechanical material properties, which is noted by the accurate output results of the simulation.
- 3) Increasing the traverse speed in FSW decreases the peak temperature. It reduces the plastic strain due to generating less frictional heat by the tool's shoulder and the workpiece, which also means less softening of the metal and, thus, smaller plastic deformation.
- 4) Increasing the rotational speed of the tool increases the heat input, leading to an increase in the peak temperature, resulting in a softened metal that is highly mixable by the tool's pin.
- 5) Creating a full dimension model and using thermophysical properties increases the model's ability to yield accurate outputs since using thermophysical properties mimics the natural behavior of the FSW process at high temperatures.
- 6) The maximum peak temperature range recorded by the model is (66-85) % of the base alloy melting point, and this range has a good agreement with the FSW principles.
- 7) The designed and manufactured temperature measurement system based on the Arduino has good performance, making it suitable to be used as a validation technique to verify the simulation result.

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Author contribution

Mustafa Mahdi Hadi and Mohammed M. H. AL-Khafaji; Numerical Analysis using ABAQUS Software. Mohammed M. H. AL-Khafaji designed, programmed, and manufactured the temperature measurement system. Mustafa Mahdi Hadi and Akeel Dhahir Subhi; generated thermophysical properties using JMatPro Software; Writing-Original Draft Preparation, Mustafa Mahdi Hadi and Mohammed M. H. AL-Khafaji; Writing-Review & Editing, Mustafa Mahdi Hadi, Mohammed M. H. AL-Khafaji, Akeel Dhahir Subhi, "All authors have read and agreed to the published version of the manuscript."

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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