

# Prediction of the Temperature Distribution During Friction Stir Welding (FSW) With A Complex Curved Welding Seam: Application In The Automotive Industry

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**Abstract.** Advanced welding of complex geometries promises significant development in the automotive industry. Friction Stir Welding (FSW) as a solid-state welding technique has spread quickly since its initial development by TWI in 1991. It has found applications in various industries, including railway, automotive, maritime and aerospace. Temperature during FSW plays a significant role, therefore thermal analysis of the process provides the opportunity to understand the process in detail, and also allows one to save energy and cost as well. However, experimental investigation of the thermal behaviour is challenging, because of inaccuracy in the measuring instruments. Thus, Finite Element Methods (FEMs) offer an appropriate approach for thermal modelling of the process. There is also a dilemma in defining the perpendicular movement of the tool on a curved surface. To clarify the problem, the tool needs to follow a regular pattern during curved movement, and it should have a perpendicular position to the surface at each point. However, previous literature modelled only a single point movement for the tool. Thus, the finite element package needs to be modified to develop a precise perpendicular movement for the tool. In this paper, a VDISP user defined subroutine is used to modify Abaqus<sup>®</sup> software for thermal analysis of a complex curved plate. The results of the paper show that the problem of the perpendicular movement of the tool is resolved and the thermal behaviour of the FSW is done with remarkable accuracy.

## 1 Introduction

In recent years, more research are being undertaken on methods of welding non-ferrous materials especially since the discovery of a novel friction welding method, the friction stir welding (FSW), which has been found commendable for welding lap and butt joints [1-3]. Since FSW discovery, it has proven useful for advance welding of different types of materials and creating high quality welds [4]. It need to be mentioned that according to the literature [5] in this welding method the welding temperature affects the welding quality and productivity. As such, the analyses of the thermal behaviour during the welding process has

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attracted enormous research interest [5]. However, it is always quite challenging to use experimental methods to analyse the thermal behaviour. This can be traced to the factors in which the measurements and accuracy of the results are dependent on. Some of such factors are; the temperature employed, type of thermocouple alloys, sensors, measured media and material state (gas, solid, or liquid), sheath material, and diameter of wire (thermocouple or sheathed). Thus, most investigations have adopted the finite element methods (FEMs), which is very efficient for solving complex problems with multiple input space and involving unseparated multiscale processes. In particular, the thermal behaviour of FSW under linear welding seam have been investigated using FEMs [6-10].

The thermal behaviour of FSW with a flat welding seam has been studied successfully in several studies [9, 11-13]. According to Schmidt et al. [14], heat can be generated using a general analytical model which is based on using the tool interface and two contact conditions (full sticking and full sliding). In the study, a flat welding seam was adopted, and a surface flux in the sliding condition and a shear layer with a volume flux in the sticking condition were used to apply heat. In another study by Mandal et al. [15], the process of flat FSW was augmented using a thermo-mechanical hot channel that was developed from a theoretical framework. A three-dimensional model was used to predict the heat transfer and the distribution of temperature in a rectilinear FSW by Song et al. [16]. In the study, plastic strain was found to be negligible while frictional heat occurred at the workpiece/tool shoulder interface where the heat was generated. In the study carried out by Zhang et al. [17, 18] a flat welding seam was adopted with employed two and three-dimensional thermo-mechanical models employed in analysing temperature history, mechanical features and flow of materials in the process of FSW. Nandan et al. [19, 20] developed a three-dimensional flat visco-plastic flow model of metals. The temperature fields and the cooling rates of FSW of 304L austenitic stainless steel and 6061 aluminium alloys were investigated by numerically simulating the non-Newtonian viscosity and the heat generation rates of the temperature fields in the thermo-mechanically affected zone (TMAZ). The heat generation rate was computed from the shear stress for yielding, rotational speed and tool geometry, while the spatial variation of the non-Newtonian viscosity was determined from the strain rate, the material properties, and the temperature. There was a good agreement between the independent experimental results and the generated plots of temperature against time as well as the geometry of the TMAZ region.

In this meantime, the need for welding of curved surfaces is increasing in different industries such as automotive and aerospace. However, all of the studies mentioned above have only talked about the tool linear movement across the welding seam. Moreover, in modelling terms there is a need to consider the tool as a rigid body in order to simplify the model, minimize computational time and decrease of error probabilities. During simulation the tool need to be considered as a rigid body, because compared to the work piece, the deformation of it can be ignored. On the other hand, based on the definition of the boundary condition, only one single point movement can be described for a rigid body, which this issue will not allow the perpendicular movement for a rigid body. Furthermore, considering the tool the as a part that can be deformed will maximize the mesh distortion, resulting in the termination of the simulation. Thus, the tool curved movement is still a complex aspect which could garner high level of interests among scholars and a thermal analysis of the complex curved Friction Stir Welding (FSW) would bring a better understanding of the thermal behaviour of the process. Thus, according to the objective of this study the thermal distribution of a curved plate is done using ABAQUS/Explicit®.

## 2 Methodology

### 2.1 Numerical model description

In the Lagrangian finite element model, the domain is created using nodal points of materials and elements. During the analysis, the nodal points and the elements can move and deform. In the Eulerian method, the domain is created using spatial material nodes and elements, and they remain in the same space position during the analysis, but in this method, the material has the freedom to flow through the element boundaries. Field variables, including velocity, strain rate, and temperature, can be computed at these stationary points and elements. For FSW simulation, each available software has its own distinct capabilities. For instance, Abaqus® commercial code has the capability to predict material flow, temperature etc. Based on previous studies by different authors on FSW modelling and the ability of software to simulate the process this software was used by many researchers [6]. The model which is created regarding to the above-mentioned modification is shown in Figure 1. The arbitrary-Lagrangian–Eulerian formulation (ALE) was used, because it can improve the model to simulate the process large deformations and the heat generation.



**Fig 1.** The model and the mesh

The parts are discretized into various sizes using Brick C3D8RT (8-nodes thermally coupled brick, trilinear displacement and temperature, reduced integration, hourglass control) elements. Fine meshes are used around the weld zone and coarse meshes are applied away from the weld line. Simulations are evaluated using coupled temperature-displacement analysis. For the simulation, the workpiece is kept fixed, while the tool is made to rotate freely around Y-axis and move along X, Y. In addition, the angular movement of the tool is also modelled (using VDISP user defined subroutine). The simulation involved three steps; the plunging, the preheating, and the traversing, with different time periods, traverse and rotating speeds limited to previous experimental works [21, 22]. For the simulation process, the probe is allowed to plunge until the shoulder contacts with the workpiece. Consideration is given to the contact surfaces between the tool and workpiece using the Coulomb's law of friction with the friction coefficient obtained from the dependent temperature values [23]. Then, Johnson-Cook law (where the yield stress is a function of strain rate and temperature) is used to determine the material behaviour [4]. Moreover, temperature dependent film coefficient, material and mechanical properties are obtained from literature [4, 24].

### 3 Results and discussions

According to the model considerations, the plunging phase can be observed between 0 and 3 s and dwelling phase between 3 and 5 s, while the welding step time was 20 s. Figures 2–5 present the temperature distribution of five individual time points in the welding step including 4, 8, 12.8 and 19.6 s. It should be mentioned that the plunging out step time is 1 s.

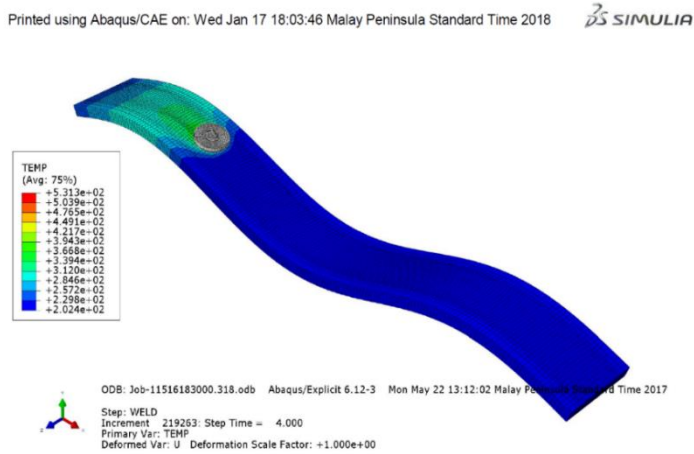


Fig 2. Welding step (step time of 4 s)

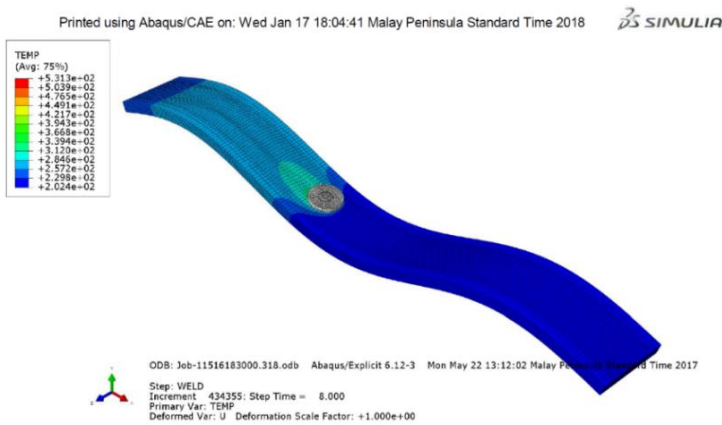
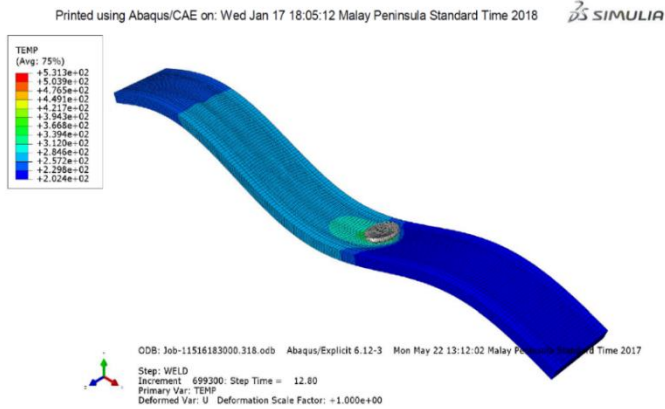
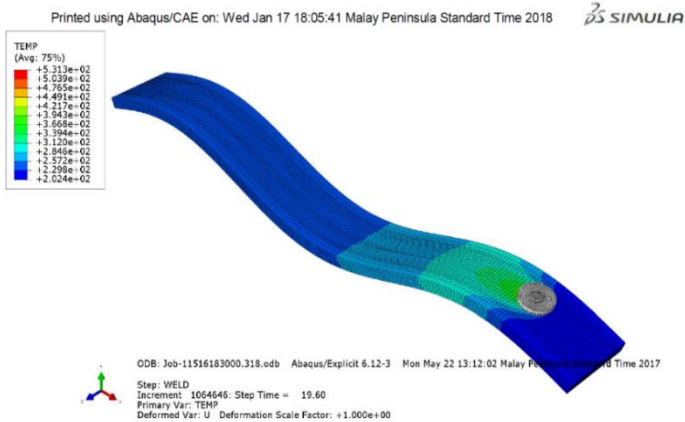


Fig 3. Welding step (step time of 8 s)

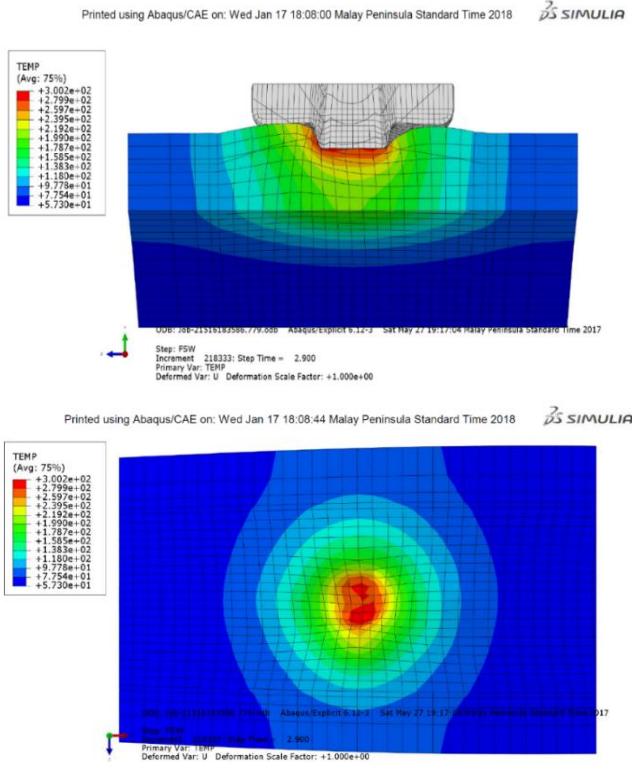


**Fig 4.** Welding step (step time of 12.8 s)



**Fig 5.** Welding step (step time of 19.6 s)

Meanwhile, Figure 6 presents the top view of the workpiece and the cross-section. Here, the highest temperature is recorded adjacent the bottom edge of the stir-pin when there is a complicated contact behaviour between the stir-pin and the workpiece. The shoulder and the workpiece got in contact at the plunging step (2.8 s) where the peak temperature of 300 °C is observed below the shoulder. At 2.9 s, the contact area of the workpiece upper surface and the tool shoulder is fully established. It should be noted that, the highest temperature occurs around the interface between the shoulder and the workpiece (peak temperature of 300 °C during the plunging step and 531 °C during the welding step).



**Fig 6.** Cross section and top view of the workpiece

A “V” form temperature field is appeared in the workpiece centre line, indicating the presence of the high-intensity heat flow at the boundary layers between the plate and the shoulder. It needs to be noted that, the distribution of the temperature becomes more intense at the area located between the tool leading and trailing sides after a few seconds of dwelling. Subsequently, the tool moved laterally to join the plates together.

Figure 4 and 5 show the gradual change of temperature at 12.8 s, and 19.6 s, respectively, as the welding process quickly reached a steady state. Here, there is an asymmetrical temperature contour among the advancing and the retreating sides. In the advancing side, the maximum temperature difference can reach about 30-50 °C. Meanwhile, the highest temperature recorded during the steady-state transverse phase is around 531 °C which is slightly lower than the melting point of AA6061-T6 at 580 °C. In this condition, welding defects could be minimized completely as the material solidity retains.

In this regard, the workpiece fully reflects the advanced nature of FSW. Larger deformation normally takes place in the elements adjacent to the tool during the simulation process, particularly in the plunging stage. Moreover, the reduction in the certain element length causes to small global time increment and whereby the working time would be increased. Meanwhile, reducing mass can substantially decrease the computational cost in the analysis. Thus, based on the considered assumptions the final time of the simulation was around 12 days, to reduce the computational time, the mass reduction is employed to find a solution within a reasonable timespan.

## 4 Conclusions

In the work presented, FE-method was employed in evaluating the thermal properties of FSW process of aluminium alloy AA6061-T6 using the Abaqus® software and VDISP user defined subroutine application. The distribution of temperatures obtained through the simulation were observed at the cross section and the top view of the workpiece. The results show that, the region under the shoulder has a high temperature gradient which is unsymmetrical with the weld centre line. For the welding zone, the rotating tool was found to sweep the surface materials from the advancing side to the retreating side, while the material continues to rotate under the shoulder of the tool before it gets deposited towards the trailing edge (behind the tool). The tool then captures the material as it rotates under the shoulder, and the material gets drawn into different welding zones. Finally, materials at the bottom plane and the mid-plane migrated downward due to the rotational movement of the tool.

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