A review of using Computational Fluid Dynamic in simulating of Friction Stir Welding and Parametric studies

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Abstract

Friction Stir Welding (FSW) is still gradually evolving where it is newer than most thermomechanical processes and due to its ability to avoid many of the common defects in other welding techniques it has become largely used, particularly for those materials that are soft.[1]

Since the invention of friction stir welding by The Welding Institute (TWI), Cambridge, UK, there have been many attempts to comprehend the physical phenomena that take place during this process. These phenomena can be affected by the welding variables and determine the quality of the welded joint as well. Numerous studies have been carried out based on the experimental approach. However, the experiments were often time-consuming and costly. As an alternative and to overcome these problems that accompany the experimental works, other approaches have been used such as numerical and analytical modeling. Numerical modeling was represented in two main methods, which are fluid dynamic (simulation of material flow and temperature distribution) and solid mechanics (simulation of temperature distribution, stress and strain).[2]

This paper focuses on applying Computational Fluid Dynamic (CFD) in modelling of FSW as its one of the most powerful numerical analysis technique. Whereas FSW is a complex process, the so important coupled physical phenomena such as heat generation, heat transfer, and metal flow are discussed. In addition, the latest developments in analysis of FSW using CFD are reviewed. Although, this technique is promising, there are still important issues need to be addressed. Thus, some factors that affect the reliability and applicability of CFD modelling are highlighted, and some future opportunities are identified.

1. Introduction

Friction Stir Welding is like any other welding process where careful choice of process parameters is vital for the attainment of welds without any defect and good micro-structural and mechanical characteristics. Parameters such as rotational speed, translational speed, and the tool geometry determine the amount of energy input to the weld and the rate of heat generation at the interface between the tool and the workpiece. Peak joint temperature and temperature profile in the region near the joint can have a significant impact on the plastic deformation zone, heat affected zones, and joint properties. Additionally, cooling rates are closely related to the joint temperature profiles and directly influence the final microstructure and residual stress state developed in the join which in role affect the global feature of the weld joint.[3-5].

Negative effects from the thermal cycle of welding might take place in the heat affected zone and the zone of plastic deformation. Thus, the information about temperature distribution is of great significance in estimating numerous thermal aspects that results in controlling the process and acquiring sound weld by avoiding the imperfection sources. The aspects of welding thermal cycles are distinguished in heat flux generated, rate of heating, peak temperature, time at temperature, temperature distributions, cooling endpoints and cooling rates of heated zones. Knowing the above aspects in detail, a lot can be done to explain how welding affects properties and microstructure of the given material.[6] However, when it comes to virtual measurements of temperature distribution in the stirring zone, there are difficulties because of the severe plastic deformation occurring when the tool is moving.[7]

Despite the complication of material flow in FSW, it is important to understand the nature of flow that aid in optimal tool design and to accomplish a sound weld. Material flow also relies mainly on process parameters (tool rotation rate and direction, that are anticlockwise or clockwise, travel speed, plunge depth, spindle angle), the tool geometry (pin and shoulder design, relative dimension of pin and shoulder), the characteristics of the material to be welded, and work piece temperature. Due to the thermomechanical interrelation, it is not the nature of deformation alone that affects the flow, but it is also strongly linked to the thermal cycle of FSW where they together determine the nature of metal flow.[2, 8] As a flow or geometric, the defects in FSW have been classified where lack of penetration takes place as a result of inadequate pin penetration depth or incorrect seam tracking is a major defect connected with the geometry while the nugget collapse or lack of consolidation, flash formation, lack of fill, surface galling and wormholes are all related to flow which are hardly unavoidable. Accordingly, it is useful having a means to understand and estimate the effects of friction stir welding parameters that leads to visualize the process and define the quality of

the weld.[3-5] Although the experimental work is a most common reliable approach in conducting the investigation studies, the obstacles of acquiring data from the weld zone still a question. Therefore, the necessity is to improve reliable alternatives.

2. Heat generation in Friction Stir Welding

The losses in the process of Friction Stir Welding resulting from the effects of microstructure are represented in the difference between the power input and the value of the generated heat which is profitable in the welding process.[9] Friction between the workpiece and the tool is one of the main sources of heat generation in the friction stir welding process. From an analytical point of view, the total heat generation **Qtotal** that is basically resulting by friction can be distinguished in the generated heat amount under the tool shoulder **Q1** and the generated heat amount around the tool pin **Q2** in addition to the generated heat amount under the tool pin **Q3**. [10] It is worth mentioning here that the tool shoulder plays a major role in generation of heat when dealing with low thickness workpieces while in the case of high thickness workpieces the tool probe shows more activities. Besides, the pressure under the shoulder is boosted either by value of the applied force or the shoulder form which both affect the heat generation.[2] Localised plastic deformation is the other main source to heat generation, which occurs in the tool faying layers of workpiece. Energy of deformation is divided into two parts; the first is stored in the material microstructure, and however, the other is transformed to heat. In spite of that, there are no experimental measurements for these two parts, but according to the numerical modeling, the values of the acquired heat from this plastic deformation fluctuate from 2% to 20%.[10]

It is a vital importance to know that the translational speed is much less than the peripheral speed of each of the shoulder and the pin, as well as the high shear stresses at the interface between the tool and the workpiece drive the viscous dissipation in the workpiece. Therefore, the behaviour of the contact interface is needed to be represented if we are modeling of heat generation in the presence of viscous dissipation. Actually, the contact condition at the interface can be different; whereas the material can slip or sticks to the tool. Sticking implies that the material moves at the velocity of the tool whereas slipping means the tool velocity may be higher than the material velocity. In this context, there is a model simulates the heat generation in friction stir welding was developed by Schmidt et al[9]. The model was by considering the shear forces between the contact surfaces; they described three diverse states of contact which are sticking condition, sliding condition and the partial sliding/sticking condition.

- Sticking condition. If the yield shear stress of the underlying matrix is less than the friction shear stress, the matrix surface will stick to the moving tool surface segment. An equilibrium state is established due to the accelerating of the matrix segment or in another meaning receiving of the tool velocity. The achieving of equilibrium means fulfilling of the sticking condition.

- Sliding condition. This is the situation where the internal matrix yield shear stress is greater than the contact shear stress. When it comes to a stationary elastic deformation, the matrix segment volume shears faintly, and consequents in equality between the shear stress and the "the dynamic" contact shear stress.

- Partial sliding/sticking. The acceleration of the matrix segment to a velocity less than the tool surface velocity and becomes stabilized, the possible last state between the sticking and sliding condition occurs. The partial sliding/sticking condition is the equilibrium that is launched when the dynamic contact shear stress is equivalent to the internal yield shear stress as a result of a quasi-stationary plastic deformation rate.
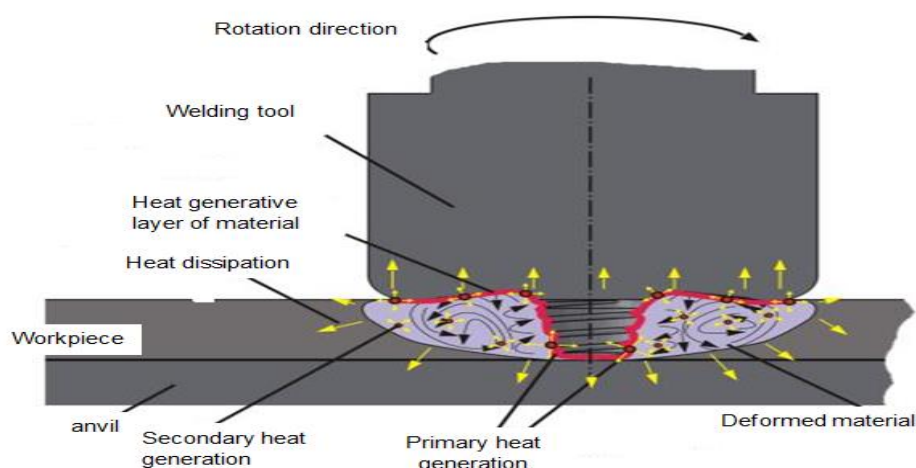
Figure 1 Mechanisms of heat generation and dissipation in FSW. [9]

3. Heat transfer in Friction Stir Welding

As it has been illustrated, the heat produced in FSW as a result of the effect of friction and plastic deformation, which is related to material stirring. The useful amount of the generated heat, that is utilized in welding and resulting in Heat Affected Zone (HAZ) and Thermomechanical Affected Zone (TMAZ) depending on the thermal conductivity of the base material. While the other parts of heat generated represent the losses.[9] During the FSW

process, the heat is lost through conduction and radiation, along with convection, which plays a role by changing the gradient in the temperature of air adjacent to the metal. Usually to produce a model characterized by accuracy, it is significant to rush out into define and consider the most important sources of heat loss. The main part of the heat losses is represented in the heat that dissipates through the tool and backing plate while the minor part can be found at the clamping metal and workpiece surfaces.**[11]**Compared to the heat input, the heat lost to the tool is a small portion which can be computed by measuring the temperature at two points along the tool axis and applying a simple heat flow model. Many writers have concluded that the percentage of heat losses is about 5%, after experimental assessments of the temperature distribution models. Heat loss from the workpiece top surface can be estimated by taking into account the convection and radiation heat transfer involved in the following equation.[2]

$$-k\frac{\partial T}{\partial Z} = \sigma\varepsilon\left(T^4 - T_a^{\,4}\right) + h(T - T_a) \tag{1}$$

Where σ is the Stefan-Boltzmann constant, is the emissivity, Ta is the ambient temperature and h is the heat transfer coefficient at the top surface.

The role of radiation is secondary; especially when the metal emissivity is very low; for instance, the emissivity of aluminium where it is most common welded material by FSW rarely exceed 0.3, even when it is oxidized. By considering an area equals to a twice of the shoulder area and temperature of 870K; the heat amount is around 1.2 W according to the Stefan-Boltzmann Low. Therefore, it is possible to ignore radiation while analysing.[11] Regarding the heat loss from the workpiece bottom surface, it is worth mentioning that the most of FSW process heat is dissipated through the backing because of the clamping action between the work piece and the backing plate. The contact conditions also greatly affect the transferred heat amount, and this is the reason why they have to be dealt with carefully particularly in the modeling process. Diverse possibilities have been recommended, for instance no backing plate where the lower surface of the work piece is assumed adiabatic or perfect contact between backing plate and the work piece. Moreover, the perfect contact under the tool region is also advisable and lastly, introducing the value of the convection coefficient between them as well.[2]
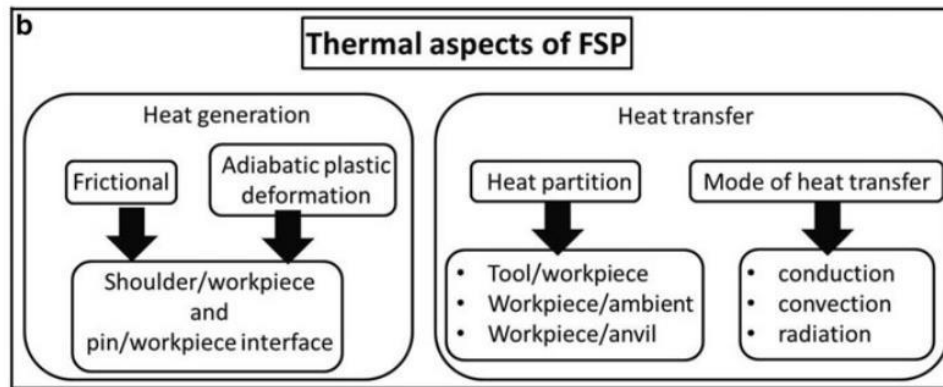
Figure 2 Thermal aspects of FSW. [10]

4. Metal flow in Friction Stir Welding

The non-Newtonian fluid flow approach has been used successfully to make out the deformation behaviour in FSW. That can be accredited to the constitutive behaviour of metals, which can appear a trend where the strain does not rely on the flow stress. This type of flow is treated on the hypothesis that it is the same as incompressible and presided over by energy equation, continuity equation and momentum equation.[7, 10]

Figure 3 metal flow patterns and metallurgical processing zones developed in FSW.[10]

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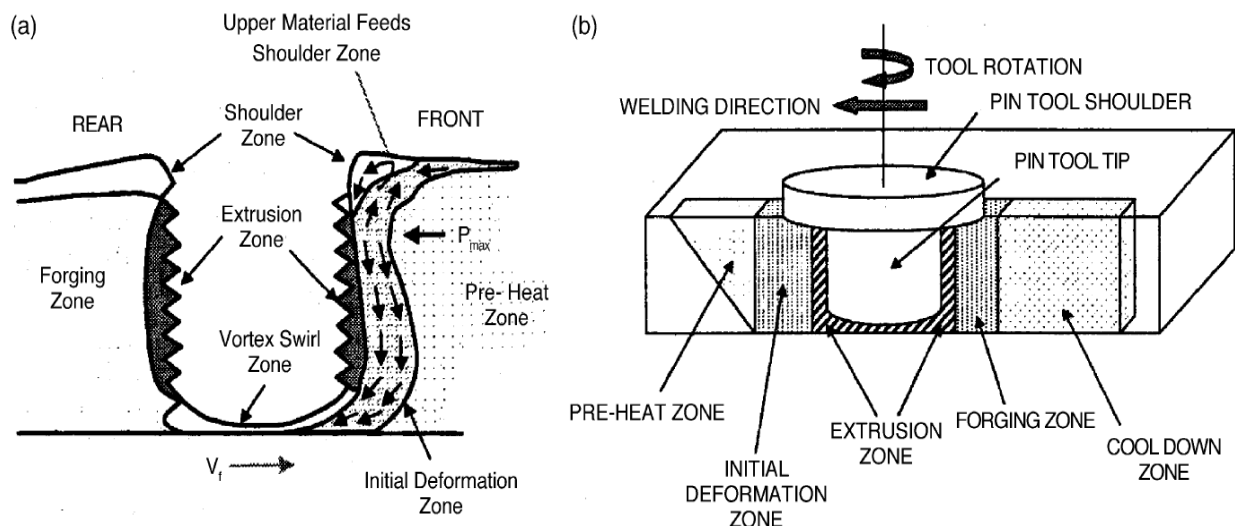Many experiments have been performed to mark out the deformation and to understand the flow behaviour by using marker materials implanted into the workpiece. The majority of these experiments have, however, depicted two types of deformations. The first one occurs at the interface between the work piece and the tool shoulder, whereas the second is at the interface between work piece and the tool pin. As presented in the figure 4,a,b the marker material indicates how the material deforms in the retreating and advancing sides at the shoulder and work piece interface. The marker is transferred from advancing side to the retreating side by the tool and vice versa, even so; the dissimilarity is that the direction of advancing side material movement is vertically downwards into the work piece while the movement of retreating side material is vertically up pushed to the work piece surface. Some of the material may also be pushed out as a flash depending on the welding conditions.[10]

In the figure 4, c and d shows the movement of marker material caused by the deformation at the tool pin and the work piece interface. At the advancing side, the marker material is moved close to its initial position. The marker material at the retreating is pushed, which is the same as the case of work piece interface and the tool shoulder. Concerning the deformation at the tool pin bottom and for some extent, it is same as deformation at the shoulder where the dissimilarity is accredited to the anvil constraint. [10]
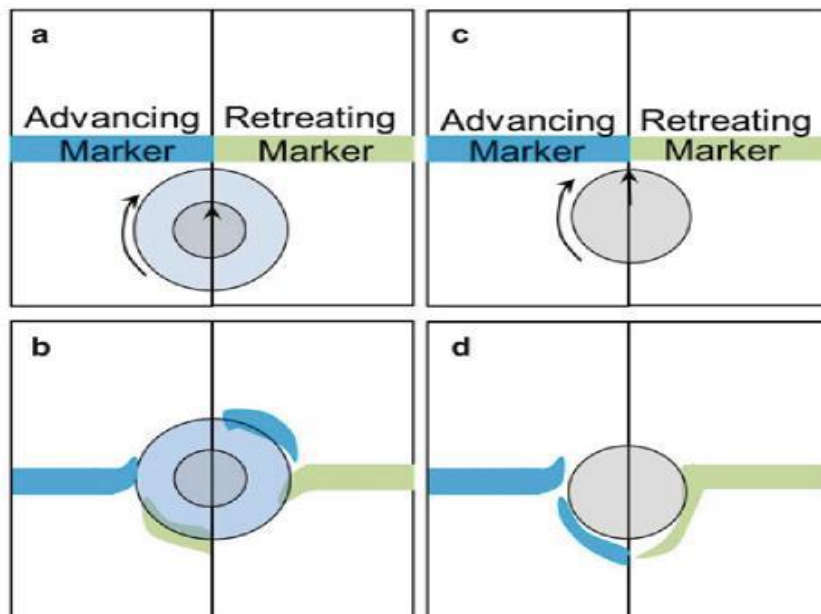

Figure 4 the material transport in the shoulder/workpiece interface region and in the tool pin/workpiece interface region interface. [10]

The kinematic describing of the metal motion was applied in introducing a physical model for the metal flow. The figure below demonstrates how three incompressible flow fields are

merged to form two different currents. The model has a ring vortex field which is laid over on a rotation field, and the two talked about fields are translated along the weld panel.[8]
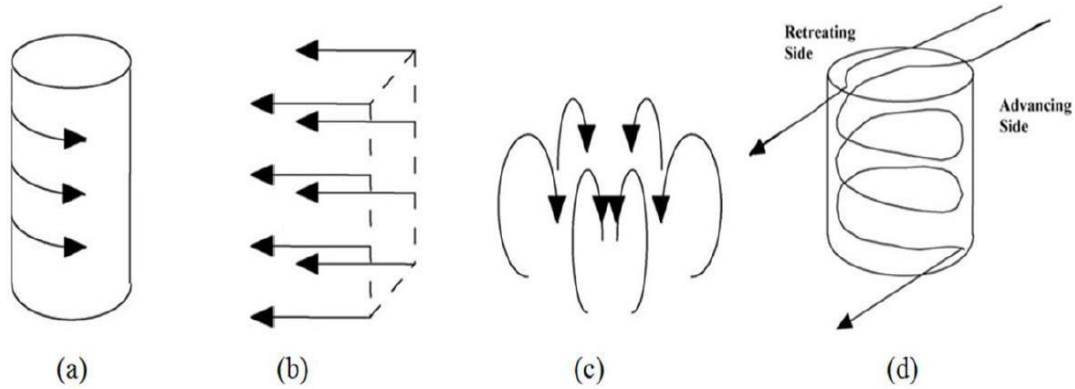

Figure 5 incompressible flow fields in FSW. [10]

As mentioned before, it is not the nature of deformation alone that affects the flow, but also due its strong linking to the thermal cycle of FSW. The thermal history that relies on the value of heat generated by the friction between the tool shoulder/pin and the work piece, together with the heat generated by the plastic working of the material determine the nature of metal flow.

5. Survey of using CFD in simulating of Friction Stir Welding and Parametric studies

Several aspects of the FSW process have not yet been fully understood despite the fact that lots of experimental investigations have been carried out particularly those interested in adjusting input FSW parameters. For the same purpose also, the numerical investigations are rarely used. Computational tools are very important for comprehension of the effects of input parameters. That is to say, that, using simulation's results than experimental one's results in visualization and analysis of the material flow with ease, stress and strain and temperature field involved in FSW process. As a result, best weld properties are accomplished by exploiting simulations in optimizing the process parameters and the tool design. [2]

Analytical and numeric methods have a vital function in the sense of keeping the goals of the model in view and taking on a suitable level of complication. For numerical modeling, the two adopted methods are the computational fluid dynamic (simulation of

material flow and temperature distribution) and solid mechanics (simulation of temperature distribution, stress and strain). Numerical FSW flow modeling is possible basing on analyses and methods applied in the other processes like friction welding, machining, extrusion, rolling, and forging. Since Computational Fluid Dynamic (CFD) formulations are applied in simulation of the material flow in FSW, the material is analysed as a viscous fluid interacting with a rotating tool and considering Eulerian mesh. About heat flow analysis, Eulerian or Lagrangian, formulations are used by numerical flow models for the mesh. The combination of hybrid solution and Lagrangian- Eulerian is also a way out. The mesh is mostly divided into zones because the steep gradient of flow velocity presents complexities in the numerical analysis. Impossibility of residual stresses predicting is a major disadvantage of CFD models. [2]

In the published work by Colegrove and Shercliff [12] , the application of the computational fluid dynamics (CFD) code, was described to modelling the 3-dimensional metal flow in friction stir welding(FSW). The primary goal was to gain a better understanding of the material flow around a complex FSW tool and demonstrate the effects of tool rake angle and the rotation speed. To do this, a flow model was developed that included coupled thermal and flow analysis, heat generation by viscous dissipation, heat loss to the backing plate and the tool, convective heat loss from the top surface of the plate. As it is able to handle the high strain rates that occur near the tool surface, the CFD package FLUENT [16] was selected for the modeling work. To solve the model, the problem was considered a steady state, and the material sticks to the tool surface. As a result, it was noted that streamlines are instantaneously tangential to the flow and the particle tracks are much more difficult to calculate and require a full transient analysis. Regarding the longitudinal streamlines show very little deviation in height as the material passes the tool. This contrasts with the quite large vertical movement of material as compared to the literature. The problem is caused by the model's over-prediction of the deformation region size.
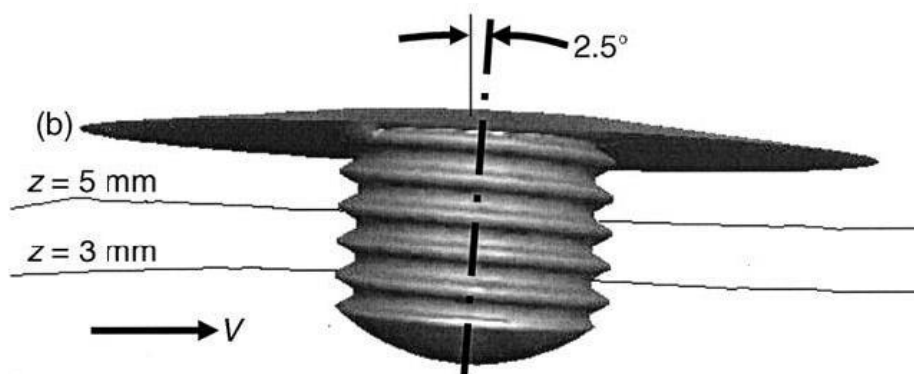

Figure 6 longitudinal streamlines [12]

The peak temperature of all the thermal models (isothermal and non-isothermal) that used a welding speed of 90 mm/min and a rotation speed of 500 rpm was approximately 860 C˚, which is well in excess of the welding temperature of 550 ◦C expected for this material. Whereas the model type a little effect on the peak temperature value, the reason can be attributed to that in a real weld slip may occur between the tool and the material, which leads to reduce the heat input and avoids material melting. Additionally, the rotational speed has shown a greater effect than the welding speed on the peak temperature. Although, this work has demonstrated how the CFD package, FLUENT can be used to analyse material flow in FSW; It was noted that the size of the deformation zone was much larger than that observed experimentally. Futurity, In order to improve the model, transient state can be considered.
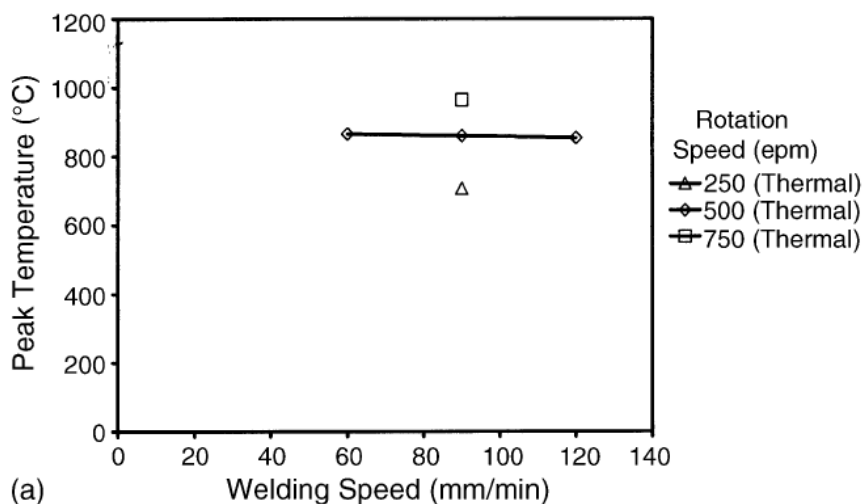

(a)

Figure 7 effects of rotation speed and welding speed on the peak temperature [12]

Aljoaba et al. [13]have developed a three dimensional (CFD) model to simulate FSP using the STAR CCM+ CFD commercial software. To investigate the effects of process parameters on temperature, strain rate, flow stress and material velocity fields in, and around, the processed nugget, User defined subroutines were developed and implemented, In addition to calculating the dynamic viscosity of the material which is mainly a function of local values of temperature and strain rate. As the temperature contours were calculated for different stirring conditions, they assumed that the heat generated at the interface between the tool and workpiece to be a heat flux which is a frictional heat. Furthermore, the heat loss from the top and bottom of the workpiece was considered. However, temperatures of workpiece sides were kept fixed at the room temperature as the thickness was low enough.

The information obtained from the model revealed that not only the temperature increased as the rotational speed increased, but it was also noticed that the temperature of stirred material increased with the increase in distance to the tool's outer edge. As illustrated in the figure 8 below, there was a small difference in the temperature distribution between the advancing and the retreating sides.

Figure 8 temperature distribution at 1750rpm (perpendicular section).[13]

A good estimation for the material behaviour was provided where the velocity fields appeared dissimilar in all directions around the tool which means that movements of the material are not in the same speed and direction. In general, this CFD model represents a useful tool. However, it can provide more accurate results if the model improved to better simulation of the reality, in addition to the proper providing of the conditions and the assumptions.

Atharifar et al. [14] used computational fluid dynamics (CFD) to numerically analyse the material flow and heat transfer of the FSW process. They assumed a tool with a one-way, right-handed threaded pin and a rake-angle of 2.5 degrees. In this study, frictional and viscous heating are the two heat input sources assumed and FLUENT is employed to solve the coupled thermal and fluid flow equations. The thermal model was validated by the measured temperature and the material flow as well which was by conducting axial force measurements for different welding parameters. The results of this model have shown that the accuracy was promoted by including the sliding/sticking behaviour. However, not all welding parameters have been adjusted during modeling. Therefore, it is possible to perform a sensitivity analysis to present the contribution of the parameters on the final results.

To understand how seriously affected the simulation of velocity distribution by the pin geometry, San-Bao Lin et al. [15] have developed a three-dimensional FSW model based on fluid mechanics with three kinds of pin geometry. Authors have assumed that the material transport in the welding process laminar, viscous, and non-Newtonian liquid flows past a rotating pin. To divide the welding zone, a criterion has been given on the basis of combining of velocity and viscosity field. Thermally, the tool surface was presumed adiabatic while

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there was a convective heat transfer from all workpiece sides. As the simulation result well agreed with the "marker insert technique" experiments. That mean the flow zone can be considered as the criterion to optimize the friction stir tool design.

In an advanced step, a three-dimensional transient (CFD) model of FSW of Mg alloy was proposed by Zhenzhen Yu et al.[16] The model was to investigate the material flow and heat transfer during FSW process and to build this model; there have been assumptions such as considering the material to be a non-Newtonian viscoplastic fluid, and the Zener-Hollomon Parameter has been used to define the dependency of the viscosity on the temperature and the strain rate. To capture the material flow induced by the movement of the threaded tool pin, a dynamic mesh method, combining both Lagrangian and Eulerian formulations was used. Moreover, in the simulation domain and to track the detailed history of material flow, massless inert particles were embedded.

Experimentally, temperature profiles were recorded to validate the predicted transient temperature and finally; two kinds of pin (threaded and smooth) were used to study the influence of the threaded on the simulated results thermal history and material flow. The used tool was steel with dimensions of 19.05mm diameter shoulder, and threaded pin 6.35mm diameter and 5.72mm high. The rotational speed and travel speed were 600rpm, 1.1mm/s respectively. In addition, eight holes 1.5mm diameter and 3mm deep were drilled to insert the K-type thermocouples.

In the transient model, the governing equations were treated using the finite volume method and solved using the computational fluid dynamics solver, ANSYS/ FLUENT. To describe the heat generation at the contact surface between the tool and the workpiece, the radius dependence heat flux used, which was proposed by Schmidt and Hattel[9]. Additionally, the process efficiency was applied to estimate the portion of the heat generated that is lost to the tool though conduction. To reduce the physical computation time required for the simulation, the actual plate length was reduced. A good agreement was shown by the results with the experimental measurements, however; the model can be improved to account the temperature distribution in the tool and describe the effects of other parameters on the thermal history, especially the cooling rate that is one of the determining factors for the final microstructure and material properties.
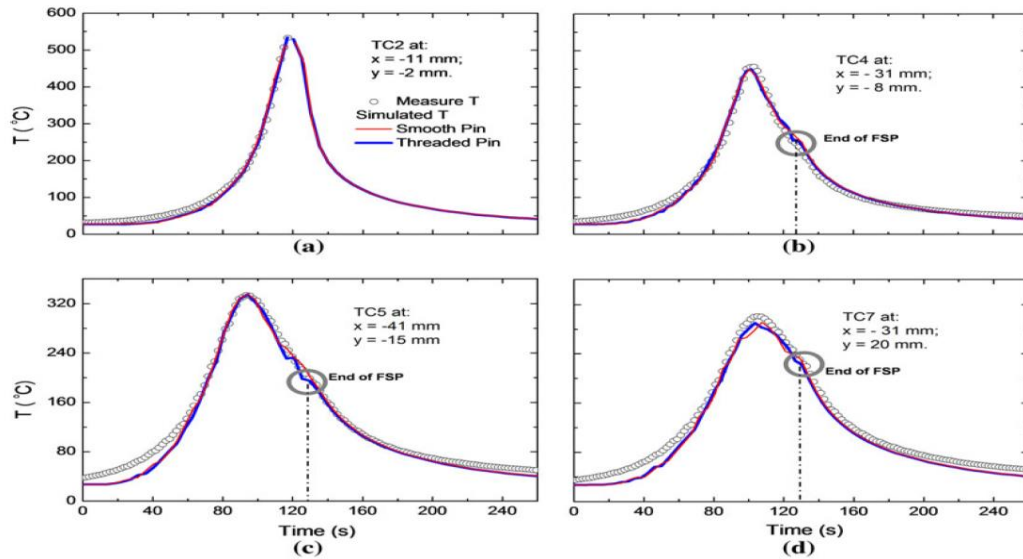
Figure 9 measured and predicted temperature profiles corresponding positions [16]

In the work that carried out by H. Mohanty et al. [17] a CFD model using FLUENT software was introduced to analyse of material flow and heat transfer of series 1100 aluminium alloy, with respect to different tool geometries. In this model, the partial slip-stick condition of heat generation was incorporated and in order to reduce the simulation time; the dimensions of the computational region were smaller than those used for the plates in the in the experimental work. Heat convection between workpiece and the surrounding was assumed and the conduction heat transfer to the tool as well. But heat transferred to the supporting tables was ignored. The CFD solver condition was set to be laminar and steady. Although the results depicted most features of the FSW, the model can be improved by replacing the assumptions were taken by others that are more realistic.

In terms of quantitatively describing the three-dimensional material flows, FSW process with a conical pin was simulated by W.U.Chuan-song et al. [18] the computed results were compared with FSW experiments of 2024 Al alloy that were conducted using marker inserted method and evaluated in metallographic ways. The model assumes that the material sticks to the tool surface, so the material velocity is the same as the tool surface. The calculated overall mode of material flow was consistent with the visualized results. However, authors assumed that the pin surface as an adiabatic wall.

In order to account for material softening phenomena at elevated temperatures and extremely high strain rates that occur during the FSP process, A.N.Albakri et al. [19] experimentally measured peak temperatures were utilized to introduce a correction function in the flow stress constitutive relation. That was inserted in the CFD, fully coupled, 3D, thermo-mechanical model, which was built to understand the effects of FSW process

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parameters on the temperature, material flow and strain rate. Furthermore, an attempt was made to relate the thermo-mechanical aspects with the evolution of grain size in the FSW processed AZ31 Mg alloy. In the simulation, commercial software STAR-CCM-V.5 was used, where the full sticking (no slip) conditions assumed, and temperature-dependent specific heat was employed. During model set up, polyhedral cell type which has an average of 14 faces per cell was used for meshing whereas the denser mesh is employed in the stirring region. The results reasonably investigated the effects of the considered parameters on the temperature profiles, material flow, and the grains size. However, in the future extra efforts can be done to predict the effect of other parameters even with alternative software.
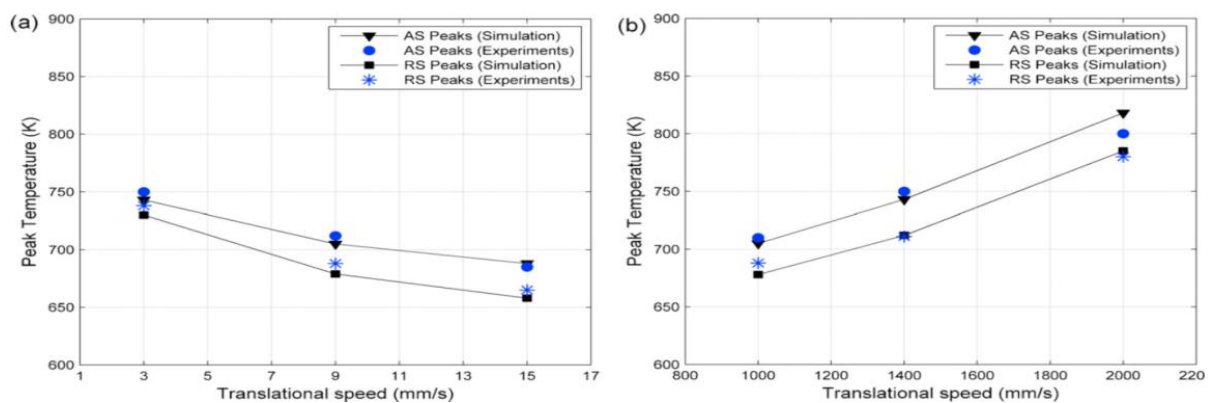

Figure 10 Temperature peaks: (a) simulated and experimental asset value values at constant rotational speed of 1000rpm and (b) simulated and experimental values at a constant transitional speed of 9mm s^{-1}.[19]

G.Chen et al. [20] have quantitatively studied both the total heat generation and the spatial distribution of the heat flux. For doing that, a thermomechanical coupled model based on computational fluid dynamics using ANSYS Fluent was presented. Moreover, simulations using different welding parameters were carried out to examine the effect of those parameters on both the total heat generation and the spatial distribution of heat flux. In the study, the geometric model was obtained by subtracting the tool from the workpiece, whereas the tilt angle and the concave shoulder were not employed, and Aluminium alloy 6061 was selected as the target material. The density was kept constant and temperature-dependent thermal physical properties were considered, while the viscosity calculated based on the following formulation:

$$\mu = \frac{\sigma}{3\dot{\varepsilon}} \tag{2}$$

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Where, σ is the flow stress and $\dot{\varepsilon}$ is the strain rate. The relationship between the total heat generation and the rotating rate was found to be proportional to $\omega^{0.75}$ and a radial distribution function was defined to describe the heat flux. Furthermore, the model could show the slight difference between the temperature on the advancing side and the retreating side.

J.Shude et al. [21] have published a study included an investigation of the effect of flute geometry in the tool pins on material flow velocity by using ANSYS FLUENT. A tool with half-screw pin and a tool with a tapered-flute pin were suggested in order to improve material flow behaviour during FSW and avoid the root flaws of welds, which are the most common defects. Three kinds of a rotational tools were discussed; two of them are designed to improve material flow velocity between the tip of the tool and the bottom of workpiece.
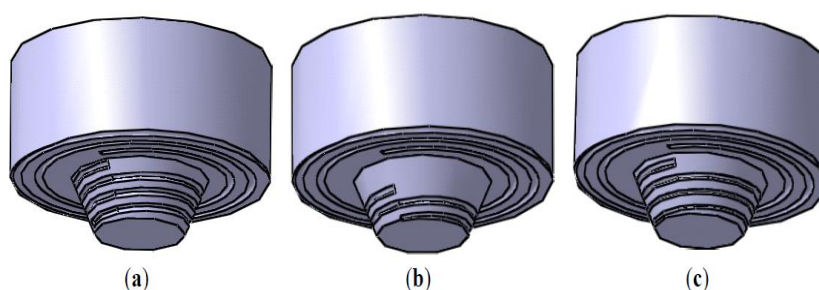

Figure 11 (a) The conventional tool; (b) The tool with half-screw pin; (c) The tool with tapered-flute pin.[21]

Ti6A14V titanium alloy was chosen as studied subject; where it was supposed to be fused liquid, and their properties were kept unchanged. To solve the model, the RNG k-ε and non-slip boundary conditions were used. In the results, it was seen that the tool with half-screw pin, and the tool with tapered-flute pin increased material flow velocity near the bottom of the workpiece. However, the results still need to be validated.

C.Pierpaolo et al. [22] reported a numerical and experimental data on the influence of rotating and welding speed on microstructure, mechanical properties, and joint quality in 4mm-thick AA2024-T3 friction stir welded butt joints. The eventual defects in the welded specimens were evaluated through microscopic analysis, in addition, grain size, microstructure in the welding zone, and microhardness profiles were evaluated as well by metallographic observation. By taking into account numerical results provided by a CFD Eulerian model, experimental data have been analysed. In order to solve the computational model, ANSYS CFX commercial finite-element package was used and then validated by comparison with the thermographic observation of the process. Authors have considered partial sticking/sliding contact state to define the processing material-tool interface and

modelled the heat generation due to frictional effects and plastic deformation as a heat flux applied on shoulder and pin contact surfaces. The heat flux formula was written by considering the Treska model ($\mu_f p = m\tau_y$) as follows

$$q = \eta_m \delta \omega r \tau_y + (1 - \delta)\eta_w \omega r \mu_f p \qquad (3)$$

$$q = \omega r \tau_y (\eta_m \delta + \eta_w m(1 - \delta)) \qquad (4)$$

Where, r the radial distance from the tool axis, μ_f the friction coefficient, p The contact pressure, τ_y the yielding shear stress, m the proportional coefficient, η_m the mechanical efficiency (amount of mechanical energy dissipated as heat),and η_w the frictional heat transferred to the workpiece.

The aspiration of the published work by H.Wang et al. [23] was detecting the influence of applying slip and stick boundary conditions to the FSW process model. In terms of assessing whether such conditions are likely to exist in practice, the estimated heat generation, temperature, and material flow around the tool for various boundary conditions were examined. Additionally, a new combination method was presented for characterising the contact conditions that occur during FSW, and the results were experimentally validated. In modeling, the parameters for heat generation were calculated differently for different contact conditions, likewise; several model types were investigated to compare the influence of stick and slip contact conditions. To this end, three major factors affecting the heat generation have been varied: the contact condition, the contact shoulder radius ratio (CSRR), and the softening regime. It was found that the strain rate, and the heat generation can be reduced by applying the slip boundary condition rather than the stick one. Experimentally that the average temperature difference between the two sides (advancing and retreating) was found to be 13 K° and the slip contact method combining CSRR and the slip coefficient is able to yield a close thermal profile.
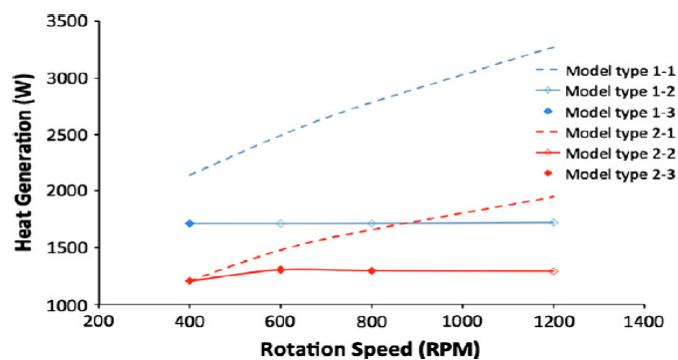

Figure 12 the obtained heat generation with model type groups.[23]

H.H.Cho et al. [24] utilised an Eulerian finite volume under steady-state conditions to simulate FSW processes are carried out for 409 ferritic stainless steel, then with the measured temperature and obtained microstructure; the simulation results were compared. Spatially variable heat generation rates and non-Newtonian viscosity were considered in the model as a function of local strain rate, temperature and characteristics of material. Likewise, the texture around the FSW tool was predicted from the computed velocity gradients along the streamlines of the flow field by using a viscoplastic self-consistent (VPSC) approach for polycrystal. Researchers considered the partial sticking contact condition and dependent temperature properties. Thus, all formulations were incorporated into a FLUENT using a user defined function (UDF). Moreover, formula for the heat generated at the interface between the vertical and horizontal surfaces of the tool, and the workpiece was given and the fractional slip as well. Although, the model used to demonstrate sufficient possibilities, some assumptions that taken in the account could be weaknesses the model or cause uncertainty of the results.

Using CFD package, Fluent; a model was established by G.Q.Chen et al. [25] based on the interactive force between the tool and the material. The heat generation, temperature distribution, were calculated and experimentally verified while the velocity on the tool material boundary, and the shape of the stir zone is investigated based on the simulation results. The authors assumed that the quasi-steady state was reached during the process. However, the boundary between the workpiece on the advancing and retreating sides was not considered. The tetragonal grids were used to mesh the calculation domain and the heat dissipation to the air and the fixtures were assumed. It's noteworthy in the model that the interactive shear stress on the boundary was assumed to be equal to the shear flow stress of the material next to the boundary, which depended on the temperature and strain rate of the adjacent material. Accordingly, as a vector; the shear stress direction at the boundary was defined by the relative velocity vector between the tool and the adjacent material.

As defining the fluid region in FSW simulation is a key issue for an accurate modeling, S.Kang et al. [26] modelled FSW by imposing a rotational affected zone. In this research, a CFD finite volume method (FVM) with the Eulerian description approach was implemented beside the full sticking condition. Two models were assumed to define the rotational zone, the first one is in which only the contact area is forced to rotate, and the plastic zone grows as heat spreads; while the second is in which the rotational region around the tool was defined as plastic deformation zone and named rotation affected zone(RAZ). Additionally, a parametric study was carried out for finding out the best shape of the (RAZ).
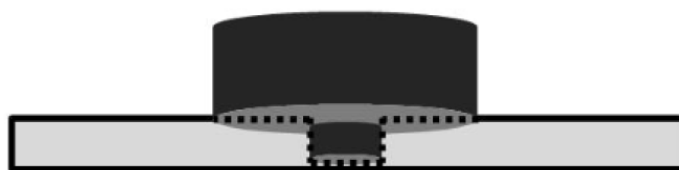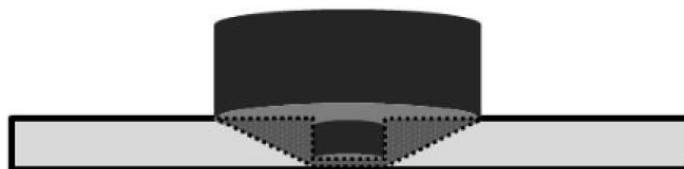
Figure 13 model I: contact surface.[26]

Figure 14 model II: rotation region.[26]

In another study, S.Kang et al. [27] constructed a 3D numerical model to analyse the heat transfer of FSW using Fluent and. For doing that, three different methods of the heat-transfer analysis were employed. Case I and II were implicit finite-element methods (FEMs) for transient heat transfer analysis while case III used CFD for heat transfer analysis under a steady state. Subsequently, the simulation result was used to calculate welding deformation and residual stress.

A novel modified process has been invented, which is called Reverse Dual-Rotation Friction Stir Welding (RDR-FSW). In this process, the tool pin and the assisted shoulder are separated and rotate in the opposite direction. L.Shi et al. [28] developed a 3D, CFD model to quantitatively analyse the effects of the pin and shoulder on the material flow and heat transfer during the process. The model was validated experimentally by comparing the predicted peak temperature at some typical location with the recorded ones. In another research that was carried out on the same technique, L.Shi et al. [29] developed a numerical analysis using CFD for heat generation, temperature field, and material flow, whereas friction heat, plastic deformation heat, and their partition coefficients were analysed. The numerical simulation results revealed that through adjusting the rotating speed of the tool pin and the assisted shoulder independently, the heat input and the temperature field can be optimised to achieve a sound weld. Recently, L.Shi et al. [30] continued their efforts and highlighted the effect of welding parameters on temperature distribution and the geometry of the thermo-mechanically affected zone during (RDR-FSW).

A computational fluid dynamic model for FSW was presented by Z.Zhang et al. [31] the model interested in calculating the forces acting on the welding tool according to the obtained pressure. After experimental validation of the force distribution, two analytical

methods were proposed for the calculations of the fatigue stress on the welding tool. Then, the analytical methods were validated by the finite-element model. For modelling, the velocity of material at the contact surface was given and User defined function compiled by C language to define the material properties and heat generation.

For its ease and less computational cost to perform parametric studies V.Kishore et al. [32] introduced a two-dimensional CFD code, Fluent, steady-state and visco-plastic model for friction stir welding od dissimilar metals. Two different material combinations were simulated. Likewise, for different position of materials, process parameters, and tool profiles; the temperature distribution and the material flow were studied. Multi reference frame has been used for the computation as the rotating wall is a surface of revolution, while the mesh was defined in a stationary frame. The temperature –dependent thermal conductivity and the specific heat were given in the picture of third order equations.

6. Conclusion

In general, CFD modelling of FSW can play a significant role in visualising of the fundamental behaviour of the welded materials, in addition to avoid the cost experiments that are performed to analyse the influence of different welding parameters and boundary conditions. It seems that the CFD analysis of friction stir welding is still facing challenges as the process involves complex phenomena representing in the interrelated mechanisms and thermal processes. For illustration, the steep gradient in flow velocity near the tool is one difficulty in the analysis. However, the CFD models have achieved positive results in terms of simulating the thermal cycle. Additionally, avoiding the unnecessary assumptions in CFD modelling of FSW should be considered to achieve an applicable model. For instance, very high levels of deformation and Elastic-Viscoplastic material models are important to be taken into account.

Although steady-state CFD models that have been used in simulating of FSW helped to explain and understand the thermal and deformation history, a basis for calculating the detailed thermal and deformation history can be provided by the transient models. For instance, before and after a steady state and the cooling stage. The transient models can be improved as the literature indicated to that they have not yet reached full maturity. Therefore, the rotating zone concept with the aid of sliding and dynamic mesh techniques can be exploited to improve the model. [26] From another angle and in order to facilitate the simulating process most of the published work considering the whole workpiece as a fluid region. Nevertheless, some recommend selecting a strip along the workpiece to represent the weld zone, which means closer to the real world situation. The question still being raised is for what extent the selected strip width affects the model results.

Regarding using CFD based tools in optimisation of FSW parameters; some defects that could practically take place, which cannot be modelled and the high computational costs are still the main reasons for the lack of the optimization studies. Conversely, as the processors are witnessing continual improvements, there might be an opportunity to conduct the costly computational processes, particularly with employment of the practical limitations of the process parameters which in role replacing the experimental trials actually used and promoting to use FSW in a wider range of applications. So far, the optimisation studies have remained largely based on the experimental data.

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