Original Article

CFD modelling of friction stir welding (FSW) process of AZ31 magnesium alloy using volume of fluid method

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In this work, a validate couple-thermo flow model of the FSW process is generated using the CFD software FLUENT, with this model, then being developed to model the flash formation phenomena that occur during the FSW process using the volume of fluid method. From both models, pressure distribution on the tool surface was predicted at different radial positions. A comparison was made between single and multiple phase flow models. A significant reduction of the pressure values was seen when using a two-phase flow model. Volume fraction contour showed the changing in the metal phase when increased the welding time steps. A modelling procedure of this work is presented in details to utilize it in the further numerical investigation as a guide. This work could be used to afford more understanding of surface flash formation phenomena. Moreover, the outcome of this study can be a useful technique to aid the tool failure and increase the tool life during the FSW process.

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1. Introduction

It is well-known that friction stir welding (FSW) is a thermo-mechanical process, in which generates heat reaches to 0.8 from the work-pieces melting point. As the heat generates from friction contact between the tool and work-pieces material, a complex phenomenon occurs. This phenomenon includes high viscous flow motion with a large amount of shear deformation. Assidi, Fourment [1]. Many works have been achieved which initially start with a pure an experimental work to get a full understanding and to optimize the process parameters. Those works include flow visualization and producing less defect welding joints [2,3]. Nevertheless, it needs much effort in terms of economic perspective.

An alternative approach has been establishing since the invention of this friction base welding technique (FSW process), which is a numerical simulation. Numerical simulation approach started with a simple heat transfer model [4], follow that a couple-thermomechanical model. In which based on finite element method (FEM) or control volume method (CVM) [5,6]. It has been reported that a FSW process is considered to be a multiphase phenomenon that involves high plastic deformation, high viscous flow regime, and solid state joining.
method occurs at elevated temperatures [7]. Therefore, several numerical works have been carried out in the order to provide more understanding of the underlying physics of many observation that occurs during the process [8].

It is important to mention that the FSW process has three stages, which are plunge, dwelling and steady-state welding. The main points that have been investigated by the researchers and need to further understanding are flow patterns, void formation, flash formation (bulge formation), and tool work-piece interface conditions and microstructures evolution [9,10].

According to what has been reported in the literature since the invention of this welding process in terms of numerical simulation, a fully coupled thermo-mechanical model is widely used. In which, based on solid mechanics and fluid mechanics theories [11]. With regard, to solid mechanics, two main formulations have been utilized, Couple Eulerian–Lagrangian (CEL) formulation and Arbitrary Lagrangian (CEL) formulation. In which have the ability to simulate the three stages of the welding process and could model the free surface movement during welding stages (Defor- mation on the top surface of the work-pieces). Numerical simulation researches of the deformation at upper surface of the plate during the FSW process or two-phase flow behaviour have been reported in the literature relatively few since the last two decades. The body of these studies provides a useful information that can help to understand some phenomena that occur during the FSW process. Guerdoux and Fournent [12] developed a FE model using ALE formulation implemented in FORGE FE software. The study used re-meshing technology, Hansel Spittel as a material model and Norton’s Law for simulating the friction contact between tool and work-pieces. The main outcomes of the study were modelling the flash formation on the top surface of the welding plate and void formation during the welding process. The model was validated base on experimental data of the welding torque and welding force, the study predicted the flash and voids formation. The model provides more important details related to the welding stages and flow of the material. They suggested that further efforts are needed to study the friction contact and thermal profile.

The voids formed during the process were predicted by Schmid and Hattel [13] through the numerical simulation of the FSW process. ALE formulation with re-meshing tech- niques was utilized to perform the FSW process modelling. The model was implemented in the ABAQUS FE software. Coulomb’s Law of friction was used for implementation of the contact and friction. The model was validated with experiments data of temperature and plunge force. It provided an information and description about how the filling cavity behind the tool. Couple Eulerian–Lagrangian formulations were used by Hoßfeld and Roos [14] to simulate the FSW process, the model was implemented by ABAQUS FE software. The study used Johnson–Cook constitutive material law as a material model. The study focused on the voids formation and weld zone shape. The study showed that the FE model with CEL formulation was able to model the large deformations, void formation, and material flow during the FSW process. The results of the predicted temperature were not validated and more works are required to develop friction model by including the slip-stick condition.

Assidi et al. [15] developed FE base model of the FSW process implemented by FORGE 3 FE software, employing ALE approach. The study focused on the contact conditions of the tool work-piece interface and flash formation that occurs during the welding process. For the constitutive model, the study used Hansel–Spittel material model and both of Norton’s and Colombo law for friction contact modelling. The study showed a good agreement for the predicted of welding forces and temperatures distribution with experiential data. The work provided a more insight into the FSW process in terms of surface flash occurrence and tool work-piece interface conditions.

Recently, Zhi et al. [9] predicted the voids formation and plastic deformation zone using the threaded and non-threads tool during the modelling of the FSW process. A couple thermo-mechanical model FEA based model was used employing a CEL formulation. The model taking in to account the elements distortion issue, high plastic deformation and flow behaviour that occurs during the welding process. Johnson–Cook constitutive material law was used to model the plastic material during the welding stage. Their results showed that it could be predicted the void formation and weld zone shape using different process parameters.

With regard to fluid mechanics theory, it used a Eule- rian approach that utilizes Computational Fluid Dynamics (CFD) technique, which showed a valuable understanding for the FSW process in terms of high viscous flow behaviour during the welding process. Generally, Couple Thermal Flow numerical modelling has been used to simulate the FSW process. It has been used to investigate the different regimes and prediction the thermal history during this process. A work by Colegrove and Shercliff [16] aimed to analyze the flow differences, temperature and pressure distribution using different tool geometries A slip-stick conditions were considered and Zener-Holman material model as a material model. The paper showed a useful information regarding the tool–material interface and the ability to use this model prevent the overprediction of the welding process power.

Nandan [17] used CFD based model to predict the velocity profile and temperature distribution during the welding process. In his work more insight was provided in terms of slip-stick interface conditions. Hasan, Bennett [18] modelled the FSW process using a CFD model to compare the flow behaviour and shape-size of the deformation zones using unworn and worn tool geometries.

More recently, a novel work can be considered was presented by Lin 2017, who developed a couple-thermo flow model using commercial CFD code FLUENT. He predicted the material distribution of the dissimilar material welded by FSW and temperature distribution during the steady-state stage of the welding process. The study adopted the multi-phase flow theory and Volume Of Fluid method (VOF) to highlight the stirring and distribution of the metals being welded as each metal assumed to be a different phase from the other metal. The two phases of the welding metals were assumed to be Non-Newton’s high viscous flow.
Hasan, Bennett [10] used a CFD based model to develop a methodology to predict the tool wear that associated with the high viscous flow during the FSW process. Their work analyzed the flow during the process and pressure predicted on the tool surface then used to calculate the tool wear based on the modified Richard equation. The study showed how the bifurcation of the flow around the tool causes an increasing pressure value on the tool surface. The methodology can be considered a novel work that predicted the tool wear associated with the high viscous flow behaviour during the welding process. While some inconsistency was seen in the results during the validation practically near the shoulder edge (Near the top surface of the work-piece). The study argued this duo for using single-phase flow model, which caused a localized pressure near the shoulder edge. The study highlights the fact that VOF can be used to model two-phase flow for further investigation to predict the flash formation which can cause a pressure drop at the top surface of the welding plate.

In the highlight of the literature discussed above, it can be seen that different modelling approaches have been demonstrated to predict the forces, torque and welding temperatures. Additionally, flow analysis has been also investigated in those approaches and some occurrence phenomena. This phenomenon such as void and flash formation, which have been investigated in these presented works. In contrast, research papers considering two-phase flow modelling and predicted pressure distribution on the tool surface associated with high viscous flow behaviour of the FSW relatively few.

In this current study, a validate couple- thermo flow model (single-phase flow) is presented. The outcome of this model is to predict temperature and dynamic viscosity values on the deformation zone. After that, they will be used to conduct a two-phase flow model (Air-Metal phases). This work could be used to provide more understanding of surface flash formation phenomena. Moreover, hopefully, the outcome of this study can be used in further instigation to develop tool wear model.

2. Model description

In this work, two 3D FSW process models are generated and implemented in commercial CFD software FLUENT. The first one is used for the validation process and to determine some variables that will be used later in the second model. Model 2 is used for modelling the two-phase flow approach and for predicting the pressure distribution on the tool surface.

2.1. Assumptions

In the current pieces of work, the study focuses on the modelling of a steady state welding stage based on Eulerian formulation. The flow model that used in this study viscous laminar with an incompressible fluid flow. As the tool has been considered to be a main heat source of the heat generation, therefore, thermal model is implemented with transit model and the temperature value will be predicted and compared with an experimental study that has been generated by Albakri et al. [19], with using same sensors locations.

In order to avoid the differences length scale, double precision is used to avoid convergence error as was recommended [11,20]. Regarding the solver, a pressure-velocity coupling algorithm (Semi-Implicit Method For Pressure Linked) SIMPL is utilized to solve pressure gradient, incompressible flow and a viscous term as used previously [21]. In order to state the gradient of the cells variables the least squares cell base approach is selected for spatial discretization.

The convergence of the solution is assessed by using points monitoring, two points were used. They are located in the deformation zone for the velocity and temperature, while for the second model (VOF model) the point is located at the interface between the two phases. Essentially those locations represent the interested area and were monitored throughout the solution until the difference reach less than 0.05% per iteration for any particular variables that specified.

The blocking strategy is used for generating the mesh with ICEM software. The hexahedral cell shape is used for the two models. The total numbers of the first model are 1,350,000 cells. While for the model two is 2,350,000 cells. It is worth to mention that the study maintained fine mesh near the deformation zone and the interface with a minimum cell size of 0.2 mm and the average aspect ratio for both models is kept below 7 as recommended by [20,22].

2.2. Geometry

In this study, two geometries of the computational domain of the FSW models were used, both of there were rectangular cuboid. The model parts of model 1 consist of a welding work-piece, tool and a backing plate. While model 2 tool includes air domain and neglected the backing plate. The dimensions of both models are shown in Table 1; while, Figs. 1 and 2 represent the geometries that were used for both models.

Model 1 has been used to conduct the validation study and to extract the average viscosity and temperature values in the deformation zone. After that, those values were used to implement the two-phase flow model (VOF model) with an isothermal assumption to avoid any complexity might occur during the modelling.

2.3. Boundary conditions

It is important to mention that the boundary conditions of the CFD model play a significant role in the prediction of the results. It should represent the real physical situation of the welding process. The parts and boundary conditions of both models are presented schematically in Figs. 1 and 2.

Flow inlet boundary condition has been defined as:

\[ u = u_{\text{inlet}}, \quad v = 0, \quad w = 0 \]  

(1)

where \( u, v, \) and \( w \) are the magnitude of the velocities in the \( x, y \) and \( z \) directions respectively, \( u_{\text{inlet}} \) is the welding traverse speed. Work-pieces upper, lower and sides surfaces of the
domain have been defined a free slip wall. A pressure outlet was assumed for the outlet boundary with a zero pressure value.

In this paper, the velocity components on the tool surface are specified as tool angular translation in x and z directions \((u \text{ and } w)\) that are shown in Eqs. (2) and (3):

\[
u = (1 - \delta) (\omega r \sin \theta - u_{\text{weld}}) \tag{2}
\]

\[
w = (1 - \delta) (\omega r \cos \theta) \tag{3}
\]

where \(\omega\) is the tool speed rotation, \(\theta\) represents the angle from the direction of the tool movement with the x-axis, and the value of \(r\) between the range of \(r_{\text{pin}} < r < r_{\text{shoulder}}\).

It is important to mention that in the current work the slip-stick condition is implemented on the tool surface as in Eqs. (2) and (3) by including contact slip condition \(\delta\) term, \(u\) and \(w\) refer to the velocity of the welded material at the tool interface. It was assumed the value of contact slip to has a value of 0.07 according to the study of Chen et al. [24].

Another important point that needs to be specified correctly in the most powerful CFD model of the FSW process is a dynamics viscosity \((\nu)\). It is well-known that during this welding process the material is subjected to sever strain rate with high plastic deformation. The viscosity of the non-Newton’s fluid in this model temperature-strain rate dependent. Therefore, the most powerful material model that has been used and suggested in such case of process modelling is the one that developed by Sheppard and Jackson [25]. This constitutive material model includes Zener-Hollomon parameter, flow stress \((\sigma_f)\), strain rate and temperature as shown in Eqs. (4)–(7). Table 2 presents the most material properties that needed to be specified in such model.

In this paper, the equations of the material constitutive model, tool velocity and heat generations model have been
formulated and implemented in the commercial software (ANSYS-Fluent); as User Defined Functions (UDF).

\[ \mu = \frac{\sigma_e}{3e} \]  
\[ \varepsilon = \left( \frac{2}{3} \varepsilon_{ij} \varepsilon_{ij} \right)^{1/2} \]  
\[ \sigma_e = \sigma_R \sinh^{-1} \left[ \left( \frac{Z}{\alpha} \right)^{1/m} \right] \]  
\[ Z = \varepsilon \exp \left( \frac{Q}{RT} \right) \]

where dynamics viscosity (\( \mu \)), flow stress (\( \sigma_e \)), \( \varepsilon \) effective strain rate and \( \varepsilon_{ij} \varepsilon_{ij} \) are strain rate tensor. As presented earlier, the current work is couple-thermoa fluid model that means heat generation equations need to be specified. A transient thermal model was implemented and the temperature was calculated in the domain at specific locations as shown in Fig. 1 to validate the model with the work by Albakri et al. [19]. Full details of this heat generation model has been presented by the author elsewhere [10]. The heat flux \( Q_{\text{pin or shoulder}} \) was obtained from Wang et al. [28] to had a total value of 1300 W. (0.75 from shoulder and 0.25 from pin) and heat input rate \( q_r \) (pin or shoulder) is used to implement the heat generation during the FSW process which is given by Eq. (8):

\[ q_r (\text{pin or shoulder}) = \frac{3Q_{\text{pin or shoulder}} r}{2\pi (r_{\text{shoulder}}^3 - r_{\text{pin}}^3)} \]

This model has been widely effectively used in the literature [4,29]. Besides, free air convection was assumed for the convection thermal boundary condition, it was applied on the top surface and sides of the work-piece and took a value of 40 W/(m² K⁻¹). While the backing plate heat transfer coefficient had a value of 35 W/(m² K⁻¹) e m² K⁻¹. Those values were taken from [28,30]. In order to assess convergence of the steady-state solution, the value of velocity at two points (upstream near the tool and in the free stream) was monitored throughout the solution until the change in the velocity was less than 0.05% per iteration.

3. Modelling procedure

A description of the modelling procedure for this paper is listed in these steps as shown below:

- Generate a CFD model (Single phase model); replication of Albakri et al. [19] work. This step included CAD geometry and mesh.
- Solve the CFD model for the stated parameters (Traverse speed values 3, 7 and 15 mm s⁻¹).
- Validation the predicted data with Albakri et al. [19] work in terms of peak temperature.
- Estimated the average temperature and dynamic viscosity values in the deformation zone.
- Run Model 1 (single phase) predicted the pressure values on the tool surface using 3 mm s⁻¹ translation velocity, 1000 rpm tool rotation speed, dynamic viscosity 2.3E5 Pas and 706 K as welding temperature.
- Generate CFD model 2 (two-phase flow), VOF, using the same parameters for mode 1.
- Processing pressure data as described below:

Once the CFD model has been solved for both models, a data file was exported to CFD post software in order to extract the pressure distribution on the tool surface. To do this, eight polylines were set on the tool surface, which represent the pressure profiles, as shown in Fig. 3. By using a MATLAB code that was written to process the data; in which, the tool surface data is in the Cartesian coordinate system then it was converted to the cylindrical coordinate system in order to get tool surface data as a function to radial position. It has been used to obtain an average data file, which provides a set of values as a function of tool radial position, demonstrating one tool surface as shown in Fig. 4.

4. Results and discussion

4.1. Model validation results

It is important to get a validated CFD model results that can be used to predict confident results for this study. Generally,
many numerical studies have validated their models through the comparison of the temperature distribution. In this part, the study started with a replication of the work by Albakri et al. [19] to validate the peak temperature that measured at sensors locations that showed in Fig. 5. Model one was used to predict the peak temperature at specific locations as determined by the experiments. The model was run at three welding traverse speeds and then temperature values were taken on the advancing and retreating sides.

In Fig. 5 the results of the predicted and experiments values were plotted at 3, 9 and 15 mm s\(^{-1}\) welding traverse speed with a constant rotation speed of 1000 rpm. From the figure, it can be seen that peak temperature decreased with increasing the traverse speed of the weld this due to the inverse proportional between peak temperature and traverse speed which was determined by the study of [31,32]. Also, it has been found that by increasing the welding traverse speed, heat input rate decreased and causes an increase in the cooling rate during the welding stage.[31]. Another observation from the figure is that the peak temperature on the advancing side was higher than the retreating side which was showed an agreement with what has been reported by the [33]. It can be argued to the material in the advancing side existence in the solid state then it undergoes to deform with high plastic deformation in the entire shear zone and more heat is generated there. In addition, the tool components (traverse and tangential) are in opposite which leading to low friction forces resulting an increase in the temperature value in the advancing side [30,34]. From the figures, it can be seen a difference between predicted and experiments values. The average differences were calculated to have a value of 11%. This miss matching could probably due to experiments setting or (data noise) or further developments need to be done for this model in terms of heat generation model and the assumption that has been made.

4.2. **Obtaining the average temperate and viscosity**

Fig. 6 shows the predicted temperature contour on the top surface of the welding work-pieces. Clearly, it can be observed that circular contours were seen and the peak temperature
is 750 K, which is slightly higher than Albakri et al. [19], the predicted contour is consistency with work conducted by [19] for the temperature distribution. It is necessary to note that the validation of the peak temperature has been done for the specific location as in experiments. Function calculator was used in CFD post to estimate the average temperature using volume average method. In which, volume (volume of cells) has been generated in the deformation zone. The deformation zone was approximately chosen as a conical shape with a radius slightly higher than shoulder radius as it has been reported and investigated by [18].

Correspondingly, the value of dynamic viscosity was estimated in a similar way by using function calculate and volume of cells. Fig. 7 shows the iso-viscosity surface using the average value of the dynamic viscosity of 2.3E5 Pa. It worth to mention that the value of volume was selected to has a value of slightly less than the shoulder diameter, due to what has been reported in the literature in terms of size and shape of weld deformation zone [18].

4.3. Predictions of the pressure

The pressure distribution on the tool surface was predicted for the two models, (single and two-phase) and a comparison has been presented. A comparison of the pressure distribution on the tool surface is shown in Fig. 8 for both models. From the graph, it can be seen that for both models there is no significant difference in pressure trends from a radial value from 0 to 3 mm, this distance is a pin bottom surface. However, for the single phase model the pressure trend is slightly decreasing; thereafter, the trend showed similar behaviour as in the pin bottom surface. Following that, at $r = 6.5$ mm the pressure values decreased to has a value of 2.8 E6 Pa. Regarding the two-phase model, the pressure trend at $r = 3$ mm is in contrast with what has been seen in a single phase model. In this model, the pressure at that radial position increased to reach a value of 0.6 E6 pa. Flowing that, decreased slightly to reach a similar trend as in the single-phase model.

From the figure, it can be observed that the average single phase pressure value has an order of magnitude of 3.2E6 Pa, while for the two-phase model the value is 0.25 E6 Pa. It is worth to highlight the difference between both models, in terms of pressure distribution trends on the tool surface at different radial positions. The main differences that have been seen are in the order magnitude of the pressure value, a significant reduction on the pressure values has occurred when using two-phase flow model. It can be attributed to the surface flash formation phenomena that occur during the process; as it has been reported by [28,35]. In that case, the VOF model allows to the welded material to flows on the upper surface of the work-pieces that causing a reduction on the pressure profile. However, in the case of single-phase model, the top surface of the plate was assumed a non-deforming wall, which prevents material flow past the boundary and causes an increase in the pressure at that position.

It has been seen another interesting point in Fig. 8, at $r = 3$ mm it is a sharp edge between the pin side bottom region. There is a drop in behaviour was seen in a single-phase model, while an increase in pressure trends was observed in the second model. It might be argued that to a spiral motion and flow separation at that particular position that occurs when using such tool design as investigated by [11,36] when using tool has a sharp edge at the intersection between tool bottom side and shoulder intersection. Finally, the drop in pressure values at shoulder outer edge ($r = 6.5$ mm) is due to the high velocity gradient with increasing in the slip velocity. It is clear that the peripheral velocity of the welding tool has the highest value out towards shoulder edge which, leading to decreasing in pressure at the outer edge. To summarize the main key point that was seen in this graph is that the VOF model seems to be more realistic to predict the tool wear in a future study.

4.4. Predictions of the volume fraction

As mention earlier, the simulation is for the steady-state welding stage. To get an understanding for the surface flash formation that occurs during this welding process, transient simulation of the two-phase flow (metal-air) is shown in Fig. 9. It can be seen that there is two colour; blue which represents the air phase and red for metal phase. Fig. 9 shows the initialized case when $t = 0$, and the then when welding started with the time Fig. 9a to d, the gradient of the volume fraction (phase change) started to change within increasing the time.

In Fig. 9 it can be seen the time-dependent VOF formulation that utilized to track the formation of the surface flash formation during this welding process. It can be observed how the pattern of the metal and air around the tool shoulder outer edge have changed. Fig. 9 explains the volume fraction contours at different time steps. Fig. 9a to d, show the changing in the metal phase when increasing the time. The metal phase
near the shoulder outer edge has risen above the initialized level. The formation of the flash occurs due to tool rotation which, leading to metal rising up at that particular position. This behaviour has been reported in the literature during the FSW process as in [28].

Unworn tool velocity vectors at 2 mm plane below the shoulder

5. Conclusions

From the study, some findings can be summarized as shown below:

- The results of the temperature distribution on the welding plate were experimentally validated and the average difference was seen with experiments to had a value of 11%.
- For both tool models, pressure distribution on the tool surface is almost similar, with differences near pin-bottom side intersection.
- The time-dependent volume fraction contour showed how the metal phase near the shoulder outer edge has risen above the initialized level.
- From the study, it can be concluded that the VOF model seems to be more realistic to predict the surface formation.
- Further efforts are needed to develop the VOF model, which could include a mesh sensitivity study at the interface and more simulation using range of time steps.
- Utilizing the ANSYS FLUENT-CFD code to study the effect of the high viscous flow, which has not widely drawn attention in the previous studies in order to predict the tool wear in the FSW process. That could be a useful technique to aid the tool failure and increase the tool life during the FSW process.

Conflicts of interest

The author declares no conflicts of interest.

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Fig. 9 – Volume fraction contour of the two phases (Air and metal) for the (a) initialize case and (b, c and d) time steps of 150, 250 and 350 s respectively; (e) is a magnification of the right shoulder region for case (d).