REVIEW ON THERMAL, THERMO-MECHANICAL AND THERMAL STRESS DISTRIBUTION DURING FRICTION STIR WELDING

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ABSTRACT:

Thermal has significant effects on the metal structure during welding process; it plays vital roles in rearranging molecular structure of the metal being welded. It is of great importance to have the knowledge of thermal, temperature, thermo-mechanical and heat distribution on the workpiece in friction stir welding as this will help in designing process and the model parameters for welding application in the following welded joints, edge butt, lap, square butt, T lap, fillet, multiple lap etc. The physics of heat generation must be explored in order to understand the workability of friction stir welding (FSW). The FSW process begun with initial friction of mechanical that took place between the tool and the welded surface resulting in the generation of heat. Since the discovery of Friction Stir Welding (FSW) in 1991, many researchers have done tremendous investigations into the process and many experimental, theoretical, numerical, empirical, computational and analytical methods have been carried out in order to analyse and optimize FSW and to understand the complex mechanism in friction stir welding at the same time to deal with effects of various parameters relating to thermal profile during the process of FSW.

Keywords: Thermal, Thermomechanical, Thermal stress, Friction Stir Welding, Temperature

1.0 INTRODUCTION:

The role of welding in manufacturing industries and the direct influence it has on the components integrity, thermal and mechanical behaviours during service cannot be overemphasized. Owing to the importance of the manufacturing process, significant progress in the development of various types of welding techniques has been achieved. The most vital development in the joining of metals in recent past is considered to be FSW and is a “green” technology as a result of its environmental friendliness, energy efficiency and versatile[1]. FSW consumes less energy, no flux or cover gas used as such the process is environmentally friendly, unlike the conventional welding process.

In some years back, FSW has become a prominent technique for joining structures of aluminium that are difficult to be welded by the use of traditional or conventional fusion welding technique[2]. This type of welding is a solid-state welding technique (in which the base metal does not melt during the process) that uses thermomechanical control of the rotating welding tool on the base metal (parent Material) resulting in monolith joint weld.

When the wedding tools and parent material are in contact, and there is significant stirring, parent material will deform as a result of the partial transformation of mechanical energy into thermal energy. FSW process makes use of a specially designed rotating pin that takes debut entrance into the adjoining edges of the blank plates with appropriate tilt angle and then navigated along the welding line (Fig. 1). This pin will then produce plastic and frictional deformation in the welded zone, it is paramount to know that no melting of material was observed in FSW. Besides, the movement of tool forced the material to flow around the tool in a complex flow pattern.

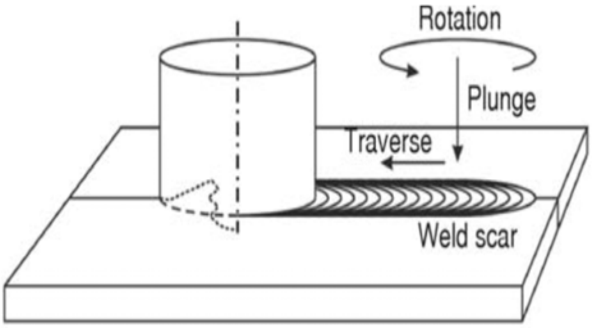

Fig. 1. The principle of the FSW[2]–[4]

Thermal has significant effects on the metal structure during a welding process; it plays vital roles in rearranging the molecular structure of the metal being welded. Researchers have done marvelous works in the area of thermal studies during the friction stir welding process, below is the review of great works carried out in the area of thermal, thermo-mechanical, heat and temperature distributions during FSW.

1.1 THERMAL AND HEAT EFFECTS

Despite notable advancement in the applications of FSW as the newest welding technique for welding aluminium and its alloys, the basic and the essential knowledge of the effects of thermal processes are still not well understood. A lot of studies have gone into investigating the effects of thermal on FSW using various means. Several researchers have done great works using various materials and methods in the course of their findings.

Hosseini et al.(2016)[5] investigated the optimization of thermal and simultaneous cooling on FSW using inverse approach. These findings centered on the experimental and numerical study of heat inputs of tools of Aluminium Al5052 which was based on limited measurement. Performance of cooling, optimization of normal force and other process parameters were carried out using finite element model of three dimensions to predict the results. It was recorded that numerical predictions agreed with experimental results.

Theoretical and experimental evaluations of the residual stresses and thermal histories of dissimilar friction stir welding of Aluminium Alloys 5058 and 6061was researched (Jamshidi et al., 2012)[6]. A three-dimensional model was employed and ABAQUS software was used for FE analysis (Abbasi et al., 2015; Ikumapayi et al. 2015)[7], [8] on AA6061-T6. The model results were compared with the experimental data and there was a reasonable agreement between the two which indicated that welding fixtures affect the tensile residual stresses significantly. In the same vein, (Raouache et al., 2016)[9] presented the effect of the tool geometries on thermal analysis of the friction stir welding. In this presentation, COSMOL MULTIPHYSICS was used in the investigation and analysis of temperature distribution of workpiece and tool during FSW operation. 3-Dimensional FE was developed to study the thermal transient as also demonstrated(Oyinbo et al., 2015)[10]. It was also established that analyzed results were the same as the one found in the literature. It was also concluded that as the temperature increases, holding time and speed of rotation also increase. The effects of thermal boundary conditions of 6.35mm thick plates of AA7050-T7 was conducted during FSW conducted by (Upadhyay and Reynolds, 2010)[11]. Welding process was carried out at a sub-ambient temperature of – 25^0C, this temperature measurement was made in the probe center and the least hardness location of the weld. Parametric variables such as joint strength, nugget grain size, and hardness distribution were recorded and compared with boundary conditions. It was concluded that submerged welds improve the tensile strength and elongation of the welds.

Thermal effects of Butt Friction Stir Welded joints of Aluminium Alloys was characterized by (Beccari et al., 2005)[12]. Temperature distribution and Time were analyzed by the embedded thermocouples and thermography respectively in order to study the materials conditions during FSW process and also to analyze the process parameters such as feed rate, tool rotating speed as well as thermal effects on temperature distributions.

Su and Wu, 2014 [13] did work on thermal energy generation and distribution in friction stir welding of aluminum alloys. In this work, the coefficient of friction and slip rate was measured with the new methods of integrative calculation. The energy required to plastically deform and interfacial friction were considered. It was also observed that the predicted maximum temperature values were in agreement with the experimentally measured ones.

Experimental and Numerical investigation of heat transfer in Friction Stir Welding was studied by Chao et al. (2003)[14]. It was revealed that the quality of the weld, distortion and residual stress in the workpiece will be determined by the amount of the heat conducted. Two boundary value problems (BVP) was adopted in formulating heat transfer processing which is transient BVP and steady-state BVP. It was further revealed that heat generation that was transferred into the workpiece was about 95% and the remaining 5% flow into the tool. The BVP for the tool and workpiece is as depicted in Figure 2 and the Energy balance during FSW at any time in the tool and workpiece is as shown in equations 1 and 2 respectively.

$$Q_3 = Q_4 + q_1 \qquad 1$$

$$Q_1 = Q_2 + q_2 + Q \qquad 2$$

Where Q_3 is the heat flux to the tool from the friction between the tool and the workpiece;

q_1 is the heat lost from the surface of the tool to the environment convection;

Q_4 is the heat transferred to the machine head in which the tool is mounted;

Q2 is the heat conducted from the bottom surface of the workpiece to the backing plate on the machine;

q_2 is the heat lost from the surface of the workpiece to the environment through convection;

Q is the increase of the heat content in the workpiece

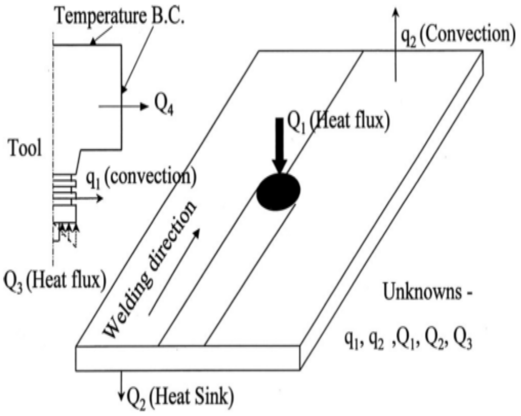

Fig. 2: Heat transfer in tool and workpiece in friction stir welding, One-half of the tool model is shown due to symmetry [14].

Akinlabi and Akinlabi (2012) (Akinlabi and Akinlabi 2012) investigated friction stir welding between Aluminium and copper and examined how heat input affects the properties of the materials under study. In this research, dissimilar welding between aluminium and copper was made by the help of three shoulder diameter tools which are 15, 18 and 25mm, the rotational speed was varying between 600 and 1200rpm and that of transverse speed was also varying between 50 and 300mm/min. Microstructural, Microhardness and grain size were characterized and electrical resistivities of the joints were also measured. It was concluded that electrical resistivities increased with increase in heat input.

1.2 THERMOMECHANICAL EFFECTS

The thermal computations are coupled to the mechanical ones – this is called thermomechanical. Heat generated by material deformation and by the friction with the tool during FSW produced thermal effects which can be in form of conduction, convection, and radiation.

Several findings have been done in the modeling of thermomechanical effects during friction stir welding. Malde (2009)[16] Stated that the first step towards the knowledge of thermomechanical interaction that takes place in the Friction Stir welding process is to first understand the heat generation as well as temperature history during the welding process.

Finite Element Analysis (FEA) was used by Chen and Kovacevic (2004) [17] to model force and thermomechanical effects during FSW. In this work, a parametric study of the effects of the longitudinal and rotational speed of the tool on the vertical, lateral and longitudinal forces was investigated in order to estimate appropriate applied clamping force on the plates. It was revealed that the measurement values by the load cells of vertical, longitudinal, and lateral directions are in agreement with numerical calculations. Similarly, finite element modeling of friction stir welding—thermal and thermomechanical analysis was also conducted by Chen and Kovacevic (2003)[18]. The research used the 3D thermomechanical model to study the effects of mechanical and thermomechanical actions on the FS welded 6061-T6 Al alloy. It was concluded that the higher the transverse speed, the higher the stress zone at the longitudinal; and the lower the stress zone at the lateral of the weld.

Thermomechanical modeling of steady state of friction stir welding was conducted by Bastier et al. (2006)[19]. The work aimed at predicting material flow, final residual stresses and temperature field during final joining with FSW. This work incorporates Eulerian model with 3D FEM to establish the flow of material, pressure field, and temperature distribution during FSW. It was concluded that the steady state phase of the FSW was simulated which eventually lead to a drastic reduction in time of computation.

Other great researchers that have done tremendous works in the area of thermomechanical effects and modellings of FSW are (Butan and Monaghan, 2009; Hilgert et al., 2011;Schmidt and Hattel, 2008) (Butan & Monaghan, 2009; Hilgert, Schmidt, Dos Santos, & Huber, 2011; Jacquin et al., 2011; Nourani, Milani, & Yannacopoulos, 2014; Schmidt & Hattel, 2008). It is worthy of note that (Butan and Monaghan, 2009; lammlein, 2010 and Okokpujie et al., 2018) [23], [25], [26] used thermomechanically coupled, as well as rigid-viscoplastic of DEFORM 2D and DEFORM 3D to analyse and predict the force, strains, stresses, strain rates as well as temperature distribution in the FSW of 4.89mm thick sheets of Aluminuim 2024-T3 (Alclad) and AA6061-T6 . Input/output of 2D and 3D models flow diagram is as depicted in figure 3.

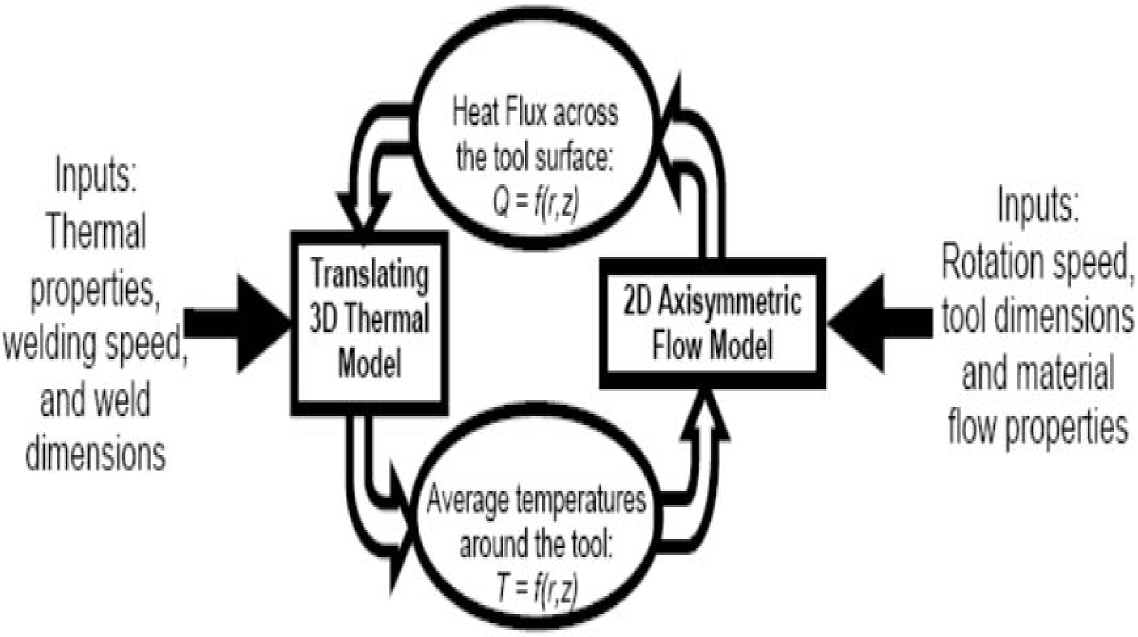

Figure 3: Input/output flow diagram for the 2D and 3D models[25].

A review on thermomechanical models of friction stir welding was carried out by Nourani et al. (2014)[20] and it was summarized in this findings that the commonness used thermomechanical models during FSW and their characterizations are Fluid Dynamics-based models, Mechanics-based models, and hybrid or multiphysics models. Thermomechanical model using simple Eulerian method during friction stir welding was studied[24]**.** The 3D thermomechanical model was employed to investigate the tribological properties of AA2024-T351 sheet metal. It was concluded that the amount of sliding seems to be greatly influenced by the speed of rotational and welding.

A thermomechanical hot channel (THC) approach for friction stir welding was studied by Mandal and Williamson, 2006 [27]. In this paper, THC aimed at lowering wear tool by decreasing the demand for frictional heat from the pin and tool shoulder. 2D analytical model based on Rosenthal's model was employed in this study for analysis of thermal distribution. The main aim is to integrate FSW which has a pre-heat source that creates a thermomechanical hot channel (THC) ahead of the welding tool. The reason behind this is to have the workpiece preheated as well as reducing the quantity of frictional heat which in-turn reduce the wear rate (Fig. 4).

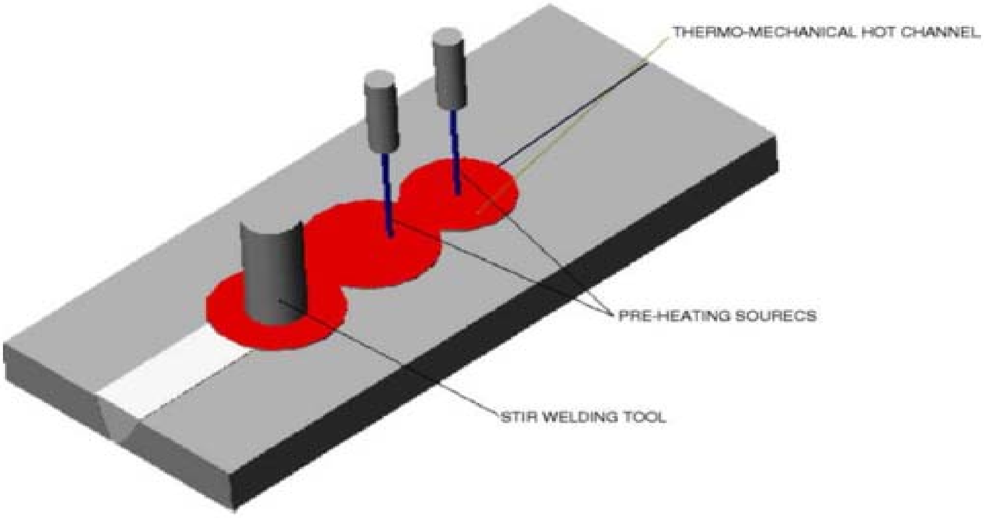

Fig. 4. Diagram of FSW coupled to THC[27].

Thermal modeling of friction stir welding of stainless steel 304L was investigated Darvazi and Iranmanesh, 2014 [28]. The thermal equation was solved using nonlinear FE code ABAQUS, and the measurement of heat generated at thermomechanically affected zone by dissipation of plastic strain energy by the conventional heat transfer coefficient and the new technique was also adopted. The numerical and experimental results shown that asymmetric nature of temperature distribution of both results is in agreements. It was concluded that the heat convection coefficient has a greater impact on the temperature distributions.

1.3 THERMAL AND HEAT MODELLINGS AND GOVERNING EQUATIONS

Many researchers have done great and mighty works in the area of FSW from one material to the other. This aspect will only focus on the review of modeling of thermal effects during FSW processes. Several theoretical approaches have been adopted in the past in order to solve thermal effects on FSW varying from numerical, empirical, computational and analytical methods. Thermal Modeling during FSW process is crucial in order to have better knowledge of welding mechanism and optimizing process parameters. It is also found useful to predict temperature near tool shoulder/workpiece interface. Lammlein, 2010[25] affirmed that the heat produced during the welding process is amounting to the input power into weld tool, minus some losses as a result of microstructural and other potential effects. Schmidt and Hattel, 2008 ; Hilgert et al. 2011[21], [22] investigated thermal pseudo-mechanical (TPM) model in which heat generation is controlled by the temperature-dependent yield stress of the weld material.

A steady-state algorithm was used Bastier et al., 2006 [19] to measure the state of residual induced by the process. This measurement must be accountable for the whole mechanical history of the material, this is because of the algorithm by the integration of the particles of trajectories. The values of residual stress of FS welded assembling was obtained.

Another important investigation was the thermo-mechanical model of AL6061 with adaptive boundary conditions for friction stir welding was carried out Soundararajan et al., 2005 [29]. This model was to predict the active stress as well as thermal history with adaptive contact conductance at the workpiece interface as well as the backing plate. Considering the uniform contact conductance, the developed stress at the interface are used to evaluate the contours of the contact conductance

Heat transfer modeling during friction stir welding of 12.7mm thick A6061-T6 plates by the use of a meshless particle method was studied by Xiao et al, 2017[30]. The research used a particle approximation with first-order consistency to discretize the governing heat transfer equation. It was also proposed a penalty method to impose different thermal boundary conditions, numerical stability was also enhanced by smoothing algorithm. The verification of the accuracy and the effect of parameters of the meshless particle methods was first carried out by two examples. The measured and computed FEM of temperature distributions were compared. There was a good agreement in thermal cycle obtained from experimental and theoretica

To save computational cost and to consider problem symmetry, only one of the two workpieces was modeled. The diagrammatic representation of heat transfer model for FSW with boundary conditions for various surfaces of the workpiece is as shown in Fig. 5 and the heat transfer governing equation (eqn 3) was also presented Medhi et al., 2015; Phanikumar et al., 2011 and Xiao et al., 2013[30]–[33].

$$\rho c\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + Q \qquad 3$$

Where T is the temperature, ρ is the density, t is the time, c is the specific heat, k is the thermal conductivity, and Q is the volumetric heat source term consisting of two parts i.e. Qs and Q_b, which are the heat resulted from the friction between the tool pin’s side and the workpiece and the friction between the tool pin’s bottom surface and the workpiece, respectively and x, y, and z are the coordinates.

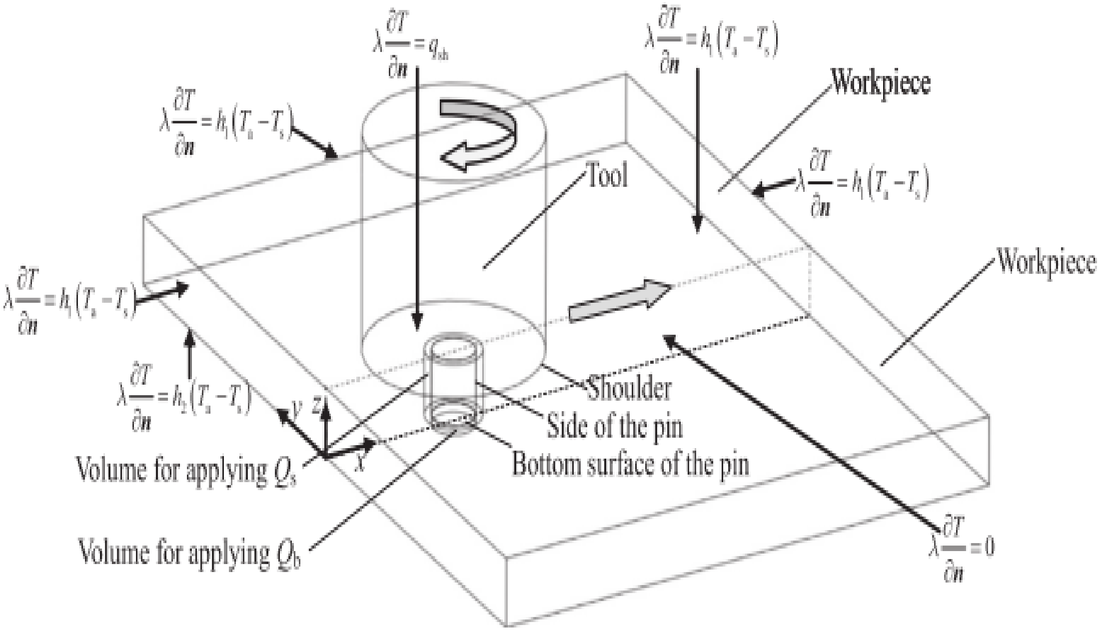

Fig. 5. Schematic diagram for heat transfer model of FSW process[30]

Numerical simulation of thermal history, as well as residual stresses in friction stir welding of Al 2014-T, was investigated by rajamanickan and balusamy, 2009[34] and it has been established that during service life, residual stresses can affect the welded components. ANSYS package was used to model a 3-D non-linear thermo-mechanical finite element (NLTMFE) for 2014-T6 butt-welded aluminium alloy. Experimental validation was done with NLTMFE and it was concluded that there was a close agreement in the experimental and modeling values for residual stress patterns and temperature history.

The study provides prior knowledge about residual stress contour along with thermal history in order to design stress relief techniques, while designing FSW based aluminum alloy structures. A monolithic solution technique or an implicit nonlinear consistent (INC) was used to dictate shear band formation and to evaluate the absorption energy and strain failure of a friction stir welded aluminium joint by McAuliffe et al., 2014 [35] during FSW. Different high strain loading conditions using plasticity model that is rate dependent and thermal softening was investigated. This model accounts for thermal diffusion which maintains the problem in the softening region and it was evaluated by the method of the monolithic nonlinear solver. It was shown that the initiation of material failures at the interface can be predicted, and that abruption of materials properties gradients greatly contribute to the failure of joints during FSW.

Song and Kovacevic, 2003 [36] used A 3-D heat transfer to model FSW and introduced a moving coordinate to reduce the difficulty in the modeling of moving tool. Heat input from the tool shoulder and that of tool pin are the parameters considered in the model. The control equation was solved by the application of finite difference. According to Song and Kovacevic[36], the heat generated by the tool pin consists of the following three parts as depicted in equation 4; (1) heat generated by material shearing; (2) heat generated by the frictional threaded surface of the pin; and (3) heat generated by frictional vertical surface of the pin.

$$Q_{pin} = 2\pi r_p hk\bar{Y}\frac{V_m}{\sqrt{3}} + \frac{2\mu k\bar{Y}\pi r_p hV_{rp}}{\sqrt{3(1+\mu^2)}} + \frac{4F_p\mu V_m \cos\theta}{\pi} \qquad 4$$

Where $\theta = 90° - \lambda - tan^{-1}(\mu)$, $V_m = \frac{\sin\lambda}{\sin(180^{\circ} - \theta - \lambda)}v_p$, $V_{rp} = \frac{\sin\theta}{\sin(180^{\circ} - \theta - \lambda)}v_p$,

and $v_p = r_p\omega . r_p$ is the pin tool radius, h is the workpiece thickness, $\bar{Y}$ is the material's average shear stress, F_p is the Welding translation force, and λ is the helix angle of the thread, and μ is the coefficient of friction. The tool pin is assumed to be a cylinder with no thread, only the first item in Eq. (4) is calculated as the heat input from the tool pin. The dissipated heat by the tool can be compared with some measured values of the cumulative heat input to produce the ratio of weld efficiency as given in equation 5 by lammlein, 2010 [25]. ($\eta_{weld\_thermal}$) is used here for clarity). It is expected that this ratio varies with parameters and experimental set-up.

$$\eta_{weld\_thermal} = \frac{Q_{shoulder} + Q_{probe}}{Q_{shoulder} + Q_{probe} + Q_{tool_{shank}}} = \frac{Q_{weld}}{Q_{total}} = \frac{Q_{weld}}{\eta_{power\_to\_heat}Q_{dissipated\_mechanical}} \qquad 5$$

Thermal modeling and process parametric effects in friction stir welding were experimented by Medhi et al., 2015 [31]. In this investigation, a Tribometer was used to understand the variation of coefficient of friction between a high strength tools (die steel) with a base metal of 6061-T6 aluminium alloy, in order to develop a realistic thermal model. A thermomechanical model using the obtained value of the coefficient of friction was also developed using Finite Element software, Comsol Multiphysics. Analysis of thermal was done and welding parametric effects were investigated.

Both the thermal and mechanical modeling of Friction Stir Welding of AA2024-T351 alloy was researched by Heurtier et al., 2006 [37], like every other thermal modeling, a three-dimensional thermomechanical model was employed in this study. The model provides the trajectory of each elemental material for the strain, the weld, strain rates and as well estimates the micro-hardness and temperature in the welded zones. It was established that to optimize welding conditions, there must be a good interrelationship between thermal modeling and kinetic modeling and that heat increase comes from the following sources:

- the friction of the shoulder on the surface of the workpieces
- the plastic strain
- the friction of the pin on the material

Thermal optimization of friction stir welding with simultaneous cooling using inverse approach was investigated by Mir et al., 2016 [38]. This research studied how heat input was obtained with the help of simultaneous cooling during FSW using inverse heat transfer approach. 3D finite element model was used to dictate the parametric conditions. It was established that normal force and cooling performance of FSW of Al5052 sheet were optimized. It was concluded that numerical results were in agreement with the experimental measurement of temperatures and optimization and the results were acceptably near to the desired highest value of the temperature, which is practically obtainable.

The prediction of temperature by Finite Element Method during Friction Stir Welding of AA6061-AZ61 was examined by (Afolalu et al., 2015; Dhas et al, 2015)[39], [40]. Finite Element Analysis was developed to model the residual stress and the temperature characterization. ANSYS was developed to simulate the effects of thermal history, lateral residual stresses, and evolution longitudinal stresses during FSW. Coordinate Measuring Machine (CMM) was used to measure the residual stress of the weld plate and also via the contour. It was found that the developed model which is FEM can be used as one of the correlating tools for the temperature as well as residual stresses on the weld.

Temperature distribution was experimentally investigated and FSW of Al7075-T651 was characterized by Shah and Badheka (2016)[41]. It was established in this study that the weld quality, residual stresses and the tool life of the workpiece are determined by heat generation. Metallographic characterization and tensile strength distribution were evaluated, at the same time thermal histories were explored. The transient temperature during FSW was measured with different thermocouple layouts.

Thermal modeling of underwater friction stir welding of the high strength aluminum alloy was conducted by Zhang et al., 2013 [32]. A 3-D heat transfer model was adopted to model temperature dependent properties of the materials and vaporizing characteristics of water were analyzed to illuminate the boundary conditions of underwater during FSW. It was discovered that underwater maximum peak temperature is drastically lower than that of a normal joint and that the width of the underwater weld is a bit smaller compared to that normal weld. It was also established that high-temperature distributing area is sufficiently narrowed hence the welding thermal cycles in different zones are effectively controlled, unlike the normal joint. It can also be seen from Figure 6 that underwater weld exhibits smoother appearance than the normal weld as a result of a reduction in oxidation in the water environment.

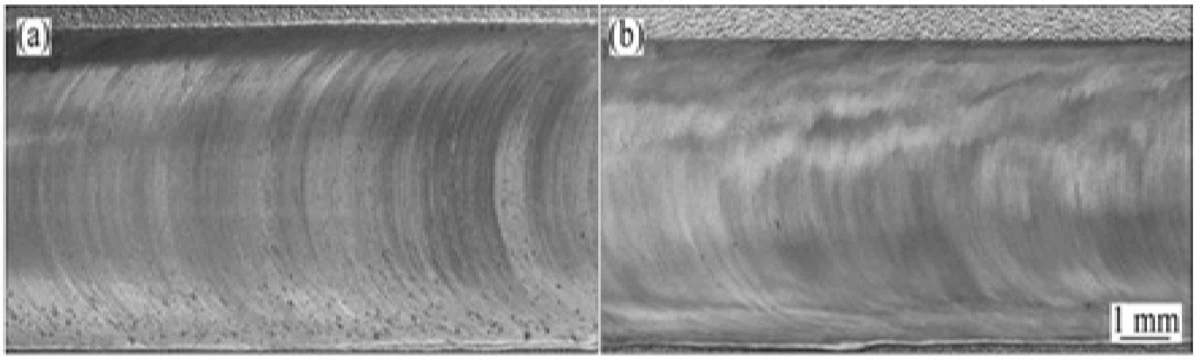

Fig. 6. Weld appearances formed under different welding conditions: (a) Normal weld; (b) Underwater weld[32]

1.4 THERMAL STRESSES IN FRICTION STIR WELDING

The thermal stresses contribute a greater portion of the cumulative stresses developed during the FSW process by Soundararajan et al., 2005 [29]. FSW induces thermal residual stresses resulting in distortions in thin-walled structures. It is also of significance to know that thermal stress generated during FSW processes can result in the failure of welds joints, critical degradation of the structural integrity and performance of components. The ability to accurately predict thermal stresses is necessary to adequately understand the behaviour of the FSW joints, to ascertain safety, efficiency, quality, and reliability of such joints. The expansion and contraction of material during heating and cooling resulted in thermal stress and occurs in the constrained welded plates by Riahi and Nazari, 2011[42].

Prediction, as well as measurements of thermal residual stresses in Aluminium Alloy 2024- T3 Friction Stir Welds as a Function of Welding Parameters, was investigated by Dubourg et al., 2010[43] ; Similar investigation was carried out by Khandkar et al., 2006 [44]. Application of 3D FEM model was used in both cases to predict the process and was validated by neutron diffraction. It was discovered that "the application of 'hot' welding conditions such as high rotational speed and reduction in the speed of welding increased the residual stresses and temperatures significantly mainly in the transverse direction. Meanwhile, 'cold' welding conditions reduced the residual stresses". The result of this research shown that there is a cordial agreement between the recorded and the predicted residual stresses in Aluminium Alloy 2024-T3 studied.

Analysis of transient temperature and also that of thermal residual stresses in friction stir welding of aluminum alloy 6061-T6 via numerical simulation as depicted in figure 7 was also conducted by Riahi and Nazari, 2013 (Riahi & Nazari, 2013) and it was discovered that heat distribution varies along the thickness and is asymmetrical and it was also established that longitudinal residual stresses in the weld zone increases as speed of process and tool movement decreases, this is in agreement with the work of Dubourg et al. (2010)[43]

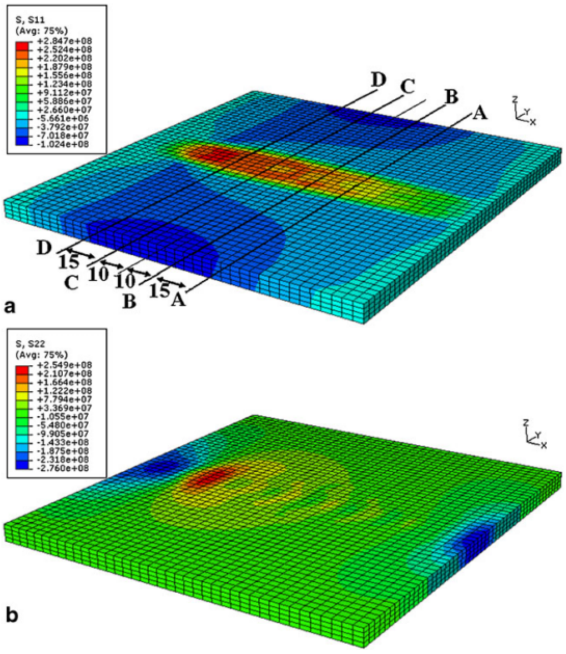

Fig 7: Predicted 3-D residual stress distribution in the welded plate. (a) Longitudinal residual stress and (b) transverse residual stress (ν = 280 mm/min; ω = 1,250 rpm)[42]

Buglioni et al.(2015) [45] presented an article on the thermal cycles and residual stresses in FSW of 7075-T651 aluminum alloys plates of 150x75x4 mm. Experimental measurements and numerical models were carried out to analyze stress distribution. The Stress variation, residual strains, and stress values were calculated against weld centerline distance and null stress position vary in different ways for each method. It was concluded in this research that the prediction of the numerical model is higher than measured longitudinal stress gradient. It was also noted that higher travel speed will lead to higher longitudinal stresses until certain value.

The Evaluation of residual stresses in AA2024-T3 Friction Stir Welded Joints was carried out by Milan et al., 2007 [46]. In this study, inverse weight function method was used to measure initial residual stress profile. It was concluded in this work that predominant region for fatigue crack nucleation to occur for the longitudinal direction will be the location on the advancing side of the heat affected zone or thermomechanically affected zone (TMAZ).

Dresbach et al. (2015) [47] investigated the Simulation of thermal behavior during friction stir welding process for predicting residual stresses. Transient Thermal FEA was adopted to carry out thermal behaviours during FSW process. This paper established that in order to determine the quantity of deformation caused by the thermal residual stresses, thermomechanical material properties, temperature history, and thermal contact must be known. It was observed that the calculated values of the distortion were lower compared to experimental measurements. Figure 8 shows the principle procedure of the simulation process chain.

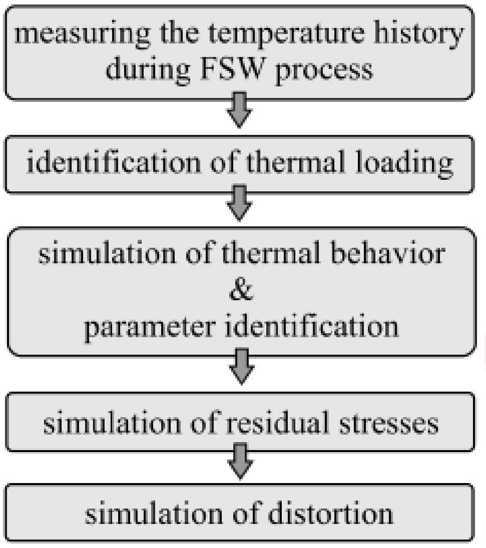

Fig. 8: Simulation flowchart process for calculating the thermal behavior, distortion as well as residual stresses in FSW process[47].

The effect of hardening laws, as well as thermal softening on modeling residual stresses in FSW of aluminum alloy 2024-T3, was conducted by Sonne et al., 2013[48]. In this study, heat transfer analysis based on the thermal pseudo-Mechanical (TPM) model for heat generation was employed by numerical method. A sequentially coupled quasi-statics stress analyzer was implemented in ABAQUS and Isotropic and kinematic rules of hardening were used in order to study the effects of the hardening on the residual stresses. At the same time, the 1D satoch test was modeled. It was concluded that there was a good agreement regarding temperatures and there were discrepancies in residual stresses while comparing cold and hot welding conditions

Khandkar et al., (2006)[44] researched on the prediction of residual thermal stresses in friction stir welded metals. In this study, three different materials were considered and they are AA2024, AA6061, and SS304L. Residual stresses caused by the thermal cycle during FSW were modeled using a sequentially coupled FEM, this was used to predict residual thermal stresses. It was concluded that the shapes of the simulated stress profiles were in good agreement with stress profile reconstructed through equilibrium-based weighted least square method.

A microstructure, as well as residual stress distributions of dissimilar aluminium alloys during friction stir welding, was studied by Jamshidi Aval (2015) (Jamshidi Aval H., 2015). This study was aimed to examine the effect of welding heat input and post weld natural aging on residual stress microstructure, and precipitation distribution in different zones of dissimilar FSW between Aluminium Alloy 6082-T6 and 7075-T6. It was concluded that atomic diffusion occurs at the interface of the materials in the stir zone of the joints.

The relationship between Welding Rates as well as Residual Stresses in Friction Stir Welding of Aluminium Alloy 6056-T4 was conducted by Dada and Cornish (2013)[50]. Residual Stress at the top of the weld in the longitudinal direction was measured by the standard electric gauge based technique. It was concluded that the minimum and the maximum tensile longitudinal residual stress at the retreating side of the weld lowered with increased translational velocity as well as advance per revolution.

Numerical simulation of residual stresses, as well as transient temperature in friction stir welding of 304L stainless steel, was also investigated by Zhu and Chao, 2004 [51]. Nonlinear 3D thermal and thermomechanical numerical simulations were conducted. WELSIM was the Finite Element Analysis Code developed. The study aimed at the residual stress and variation of transient temperature in FSW of 304L stainless steel. Neutron diffraction technique was employed to measure residual stress which was compared with the 3D elastic-plastic thermos-mechanical simulation results and they were found to be in agreement.

CONCLUSION

An overview of the effects of thermomechanical, thermal stresses and thermal/heat distribution during Friction Stir Welding (FSW) process have been summarized. The study centered on the experimental and theoretical review such as modeling of thermal stresses and thermal effects as well as temperature distribution during FSW.

From the literature review gathered, it can be concluded that thermal, thermal stresses and thermomechanical played vital roles when it comes to FSW as they all affect both the process and model parameters.

It can also be inferred from the review that most modeling on thermal and thermomechanical use either 2-Dimensional or 3-Dimensional model criteria. It was also reported in the review that thermal modeling can either be Solid Mechanics (SM) which compute strain, temperature, and residual stresses distributions, such SM is computational solid mechanics (CSM), examples are Abaques, Deform 3D, Ansys and Fatigue 3 etc. Another Model use mostly in the review was Fluid Dynamics (FD) which was able to predict strain rate e.g. computational fluid dynamics (CFD) such as fluent; lastly Multiphysics (CSM-CFM) model that was capable of modeling both residual stress from different elastic and thermal strain across the welded part as well as predicting temperature distribution and thermal coefficients of expansion.

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