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Heat Analysis in Friction Stir Welding Using Finite Element Method

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ABSTRACT

Heat is a key factor in friction stir welding (FSW) due to its capability to plasticize two stationary material (workpieces) in joining. The required heat energy is generated in such away by mechanical friction between rotating, traveling tool and workpieces itself. In this work the study which focused on the heat generation in FSW is done by using Finite Element Analysis software i.e. Altair HyperWorks. The generated and distributed heat across the workpieces of a 6mm thick Aluminium alloy 6061 during FSW is observed in this study. The objective of this study is to characterisize of the heat generation during FSW with respect to the welding parameters i.e. rotational and travel speed of the tool. In the analysis, a three dimensional symmetrical model was used to predict the generated and distributed heat by using the finite element method. Heat analysis and measurement during welding is carried out numerically and experimentally for validation. From the analysis and measurement is concluded that the maximum temperature gradients in longitudinal and lateral directions are located just beyond the shoulder edge. It can be seen that the heat flux is higher for higher tool rotation than the lower tool rotation. Both are set at constant travel speed. The maximum heat is proportional to the rotational speed. It is occured due to high frictional forces between the rotating tool and workpiece and increasing the heat generation around the tool. This study provided better

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insight about generated and distributed heat during FSW as a result of process parameters which can be used as reference to produced good quality of welding with less experiment.

Keywords: *Friction stir welding, Finite Element Method.*

Introduction

Throughout the years improvement to increase productivity related to aluminium alloy in the manufacturing industry, have been extensively researched and expanded. Friction Stir Welding (FSW), which has been proposed by The Welding Institute (TWI) in the UK since 1991, promissing high quality and high strength weld in potentially difficult to weld alloys are possible. Considered as a green technology emphasized on the process that is environmentally friendly due to requires no filler material, FSW is known as one of the solid state joining process which relied on the heat energy generated by mechanical friction between rotated tool and stationary work materials (work pieces). In this research, the model of heat generation in Friction Stir Welding (FSW) will be paid large of attention wich focusing on the contact area between tool pin and workpiece. The heat generation process that occurs at the side of the tool pin is the main focus of this research take place. The traversing process is the only area that is considered during the process and thus, the heat generated at the shoulder and the probe bottom surface is not in the project scope. Figure 1 shows a schematic drawing of friction stir welding of two plates. A rotated of a cylinder -shaped, shouldered tool with a profiled probe is gradually plunged into the weld joint in the middle of two pieces of sheet or plate that are to be joined[3]. The friction between the FSW tool and the material of the workpieces generates frictional heat. This heat softens the workpieces without reaching the melting point and lets the tool travel alongside the weld line. The resultant plasticized material from the foremost edge of the tool is transferred to the trailing edge of the tool and is forged together by the close contact of the shoulder of the tool and the pin profile. This will result in a solid-phase bond between the two pieces [4].

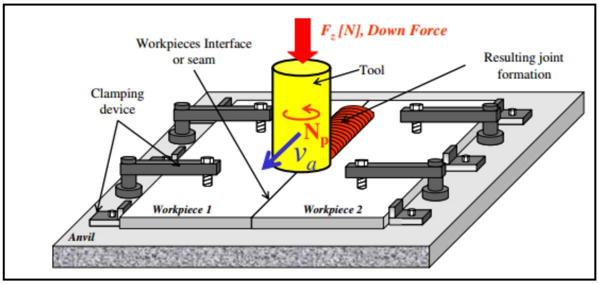

Figure 1: Schematic drawing of friction stir welding of two plates

The Process of Friction Stir Welding

The process of the FSW mainly consists of three parts that are plunging, traversing (traveling) and retreating or extracting. Figure 2 shows three main processes in FSW. For the plunging process, it is the process where inserting the tool into the workpiece that clamped together to weld. At the beginning, the tool rotates with constant rotational speed and move to the surfaces of the workpiece. The axial force applied to allow the pin and the workpiece surface contact slide against each other [5]. Because of that, the kinetic energy converts into heat energy caused from the friction of the tool pin and the workpiece and it will soften the workpiece and allow the rotated tool pin drill the workpiece into desired depth. After that, the heat generation and plastic deformation produced. It is because the localize TMAZ produced by the heat generation of the friction between the shoulder and the workpiece [5].

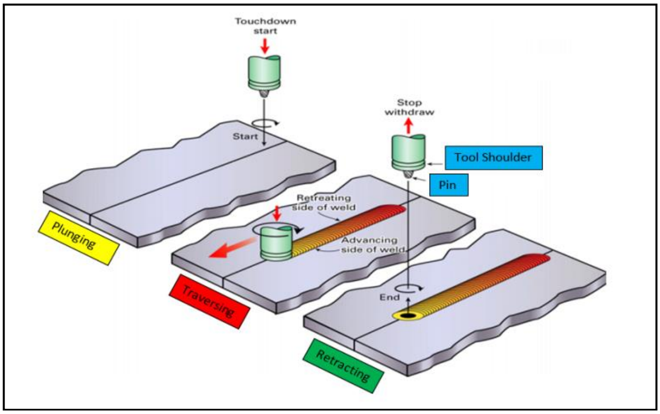

Figure 2: Schematic of three main processes in FSW [5].

For the travel process, it is the main process of the welding because this process is the majority of the joining process between two workpieces take place. Shoulder and pin tool synchronously undergo the friction stir welding process along the weld joint line. This process considers the travel speed, rotational speed, the axial force and also tilt angle of the tool pin. The weldment formation is by the behaviour of the material flow under the action of the rotating tool. The pin and shoulder work together consecutively and simultaneously to produce the weldment. The rotating tool is forced to the traversing on the welding line so that material continuously stirred , extruded around the tool and forced back to the back of the tool. The last phase of the process is extracting. It is the process where to extract the rotating tool from the workpiece. Then the process of the friction stir welding is ended [5].

Process Parameter of FSW

Friction stir welding involves complex material movement and plastic deformation. The welding parameter, tool geometry, and joint design exert a significant effect on the temperature distribution and material flow pattern, thereby influencing the microstructural evolution of material. In friction stir welding process have major factor such as size or shape of tool geometry, welding parameter, and joint design is addressed.

i. Tool geometry

For the aspect of process development, the tool geometry is the most influential aspect. The tool geometry plays a critical role in material flow and, in turn, governs the travel rate at which FSW can be conducted. In the initial stage of the plunging process, the heating results come from the deformation of material during the process. As mentioned earlier, the tool has two primary function such as localized heating and material flow. From the process, the tool is plunged till the shoulder touches the workpieces. The friction between the shoulder and workpieces results in the biggest component of heating. From the heating aspect, the relative size of pin and shoulder is important and the other design features are not critical. The shoulder also provides confinement for the heated volume material. The other function of the tool is to ‘stir’ and move the material.

ii. Welding parameter

For friction stir welding, there is two parameter that is very important: tool rotation rate (rpm) in clockwise or counter clockwise direction and tool travel speed (mm/s) along the line of joint. Stirring and mixing material occur when the tool rotating and the translation of the tool moves the stirred material from the front to the back of the pin and finished the welding process. In addition, the insertion depth of the pin into the workpieces or called target depth is important for producing sound welds with smooth tool shoulder. The insertion depth of pin is associated with the pin height. When the insertion depth is too shallow, the shoulder of the tool does not contact the original workpieces surface. The rotating shoulder cannot move the stirred material efficiently from the front to the back of the pin, resulting in the generation of welds with an inner channel or surface groove. When the insertion depth is too deep, the shoulder of the tool plunges into workpieces creating excessive flash.

iii. Joint Design

Butt and lap joint are the most convenient joint configurations in FSW. Two plates or sheets with the same thickness are placed on the backing plate and clamped firmly to prevent the abutting joint faces from being forced apart. While the initial process that is plunge of the tool, the forces are fairly large and extra care is required to ensure that the plates in the butt configuration do not separate. The joint line plunged with a rotating tool and travel along this line when the shoulder of the tool is in intimate contact with the surface of the plates, producing a weld along abutting line.

Heat Generation in FSW

Friction stir welding is a process that is strongly influenced by heat generation and heat flow. Heat generation is a process of energy transformation that takes place when one form of energy transforms into heat. However, the contact pressure inflicted by the welding tool, the friction coefficient, the change of thermomechanical properties, material flow around the probe and heat transfer coefficient are those important parameters that should be considered in understanding the heat generation in FSW [12]. The contact surface between the probe tip, the probe side and the shoulder tool with the workpiece, will generate heat. The research that has been conducted by D.M. Veljic in his journal revealed that the workpiece temperature will suddenly increase when tool shoulder establishes contact with it. The largest percentage of heat generated by frictional work occurred at the interface of the work piece and the probe [13].

Analytical Estimation of Total Heat Generation in FSW

Heat generation is constantly being transferred within the system, portions of heat are distributed within the work material, the rotating tool, the holding fixture or backing plate and finally to the ambient. In-depth, heat generated is subjected to three-dimensional (3-D) heat flows away from the heat source under boundary conditions [14]. Heat input and heat transfer at the rotating tool are indirectly coupled at the rotating tool to work material interface into the work material through heat conduction and incorporated with convective heat transfer effect around the pin in the deformation zone [15]. For the work material, convective and radiative heat transfers are considered for heat exchange at the top work material surface, past the shoulder peripheral while at the same time only convective condition is considered for the bounding surfaces of work material [16]. For the case of backing plate, appropriate variable gap conductance is considered for work material to backing plate interface depending on specific thermal contact resistance condition; of temperature dependent or contact pressure dependent or surface contour of work material or any of the combinations [17].

Estimating the Value of Friction Coefficient during FSW

In finding heat generation during the plunging process, whereas the tool shoulder touches the workpiece, a major issue is to determine the suitable value of friction coefficient during the process. This is due to the difficulty of measuring the conditions under the tool and it is too extreme [16]. The friction coefficient is widely assumed in the range of 0.3-0.8, which reflect the experimental conditions [17]. Renju Mohan and N. R. Rajesh [18,19] investigated AA1100aluminum alloy with 6 mm thick and found that for the range of temperature of 400ºC-580ºC, the suitable range of friction coefficient is around 0.35-0.47. According to Song and Kovacevic [14], the friction coefficient for Al6061-T6, however widely published to be 0.4.

Heat Generated Results

This data report the effect of increasing pin rotational speed on heat generation and heat flux at shoulder and pin of the tool. Table 1 present the calculated heat generated at shoulder and pin affected by various rotational speed.

Table 1: Heat Generated At Shoulder, Pin And The Total

Rotational Speed (rpm)	Heat Generated, $\boldsymbol{Q_s}$ (Watt)	Heat Generated, $\boldsymbol{Q_p}$ (Watt)	Heat Generated, $\boldsymbol{Q_T}$ (Watt)
800	8796.63	173.29	8969.92
900	9895.94	194.95	10090.89
1000	10995.26	216.61	11211.87
1100	12094.57	238.26	12332.83
1200	13193.90	259.92	13453.82

Heat input is assumed to be linearly proportional to the distance from the center of the tool which is derived from the assumptions the downward force applied to the workpiece from the tool creates a uniform pressure between the shoulder and the workpiece. Moreover, the heat is generated from the work done by the friction force. The heat flux from the friction is applied at the bottom of tool shoulder and side of the pin. Figure 3 and figure 4 illustrate the trends of the heat generated at shoulder and pin with different rotation speed.

Figure 5 displays the combination of heat produced at shoulder and pin. In the simulation, the information already partitioned into two section those are for heat generated at shoulder and pin of the tool, so the total heat generated just want to show the values that calculated at shoulder and pin while the process occur. In the other word, no need to put the value of the total heat generated in simulation because the partition already divides into two sections that are heat generated at shoulder and pin, respectively.

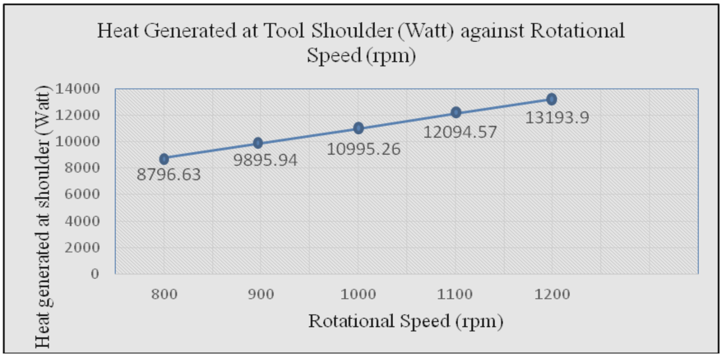

Figure 3: Heat generated at shoulder.

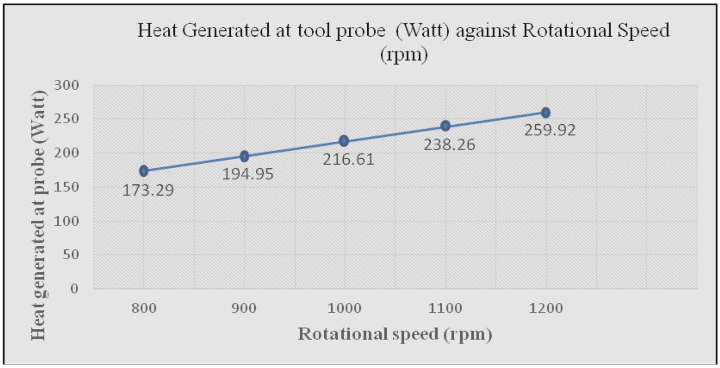

Figure 4: Heat generated at pin.

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Heat input as indicated by heat generation and heat flux are examined. In FSW, the melting and solidification process does not occur, so there will be no shrinkage or hot cracking. The heat flux depict higher value at higher rotation speeds. Figure 4 represent the trends of the heat flux against different rotational speed at shoulder and pin, respectively.

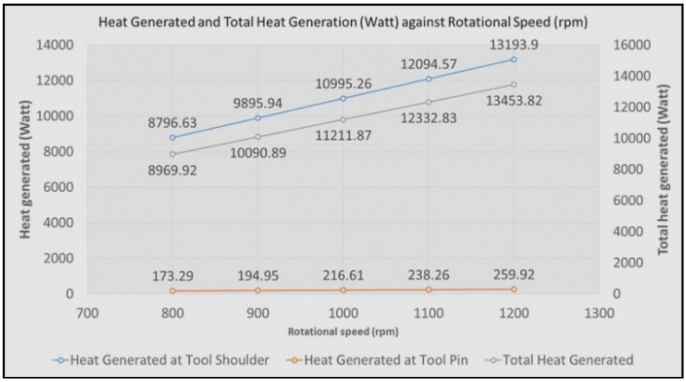

Figure 5: Combination of heat generated at shoulder and pin.

Simulation and Experimental Results

To see the effect on temperature, heat transfer coefficient were changed, which could predict the rate of temperature increase in the model. Boundary conditions were specified in Altair HyperWorks templates in FSW throughout this simulation model.For example, steady state thermal finite element analyses are performed at rotational speed of 900 rpm with travel speed of 2.5 mm/s, in order to obtain the temperature distribution in the welded aluminium plates during the welding operation which is shown in Figure 6.

The variation in the temperatures recorded by thermal imaging camera are seen, which may be due to difference in rotational speed and travel speed during the process. The thermal imaging data measured by IRT Cronista shows well distributed and maximum temperature at the edge contact between shoulder and workpieces which will be used for validation. The temperature distribution in the workpieces predicted by FEA model is compared with experimental values. Calculated temperatures were collected at locations 10 mm away from the weld center as shown in Table 2. The simulation results matched reasonably well with experiments, even though the simulations slightly lower predict temperature in most cases compared to experiment because it may be due to assumption of a constant temperature of backing plate and the constant of friction coefficient.

Table 2: The Comparison of Peak Temperature At The Edge of Shoulder

Rotation Speed (rpm)	**Transverse Speed (mm/s)**	**Simulation (°C)**	**Experimental (°C)**	**Percentage Difference (%)**
800	1.5	427	478.7	11.42
	2	404.6	423.2	4.35
	2.5	386.3	407.4	5.21
	3	371.2	353.4	4.91
	3.5	358	336.8	6.10
900	1.5	448.2	463.9	3.44
	2	424.8	455.4	6.95
	2.5	406	426.7	4.97
	3	390.3	415.9	6.35
	3.5	376.8	392	3.95
1000	1.5	469	492.9	4.96
	2	444	476.8	7.12
	2.5	424.5	445.1	4.73
	3	408.1	421.4	3.21
	3.5	394.2	378.5	4.06
1100	1.5	491	520.8	5.80
	2	462.9	496.8	7.06
	2.5	441.9	423.2	4.32
	3	425	398.1	6.56
	3.5	410.5	372.9	8.43
1200	1.5	521.5	494.2	5.52
	2	483.2	473.8	1.89
	2.5	459.2	484	5.30
	3	441	455.8	3.34
	3.5	426.3	440.7	3.22

Reasonably good agreement between experimental results and FEA results are found validating the numerical model. The initial results for the thermal imaging camera temperature comparison for the same weld rotation for various weld trials compare fairly well, suggesting better result, whereas the last indicate a few difference. Possible influences could be any of the following such as the angle and distance of camera changes further out on the weld line, therefore emissivity value might be different. Besides that, a few reflective temperature has an influence on final temperature result as well.

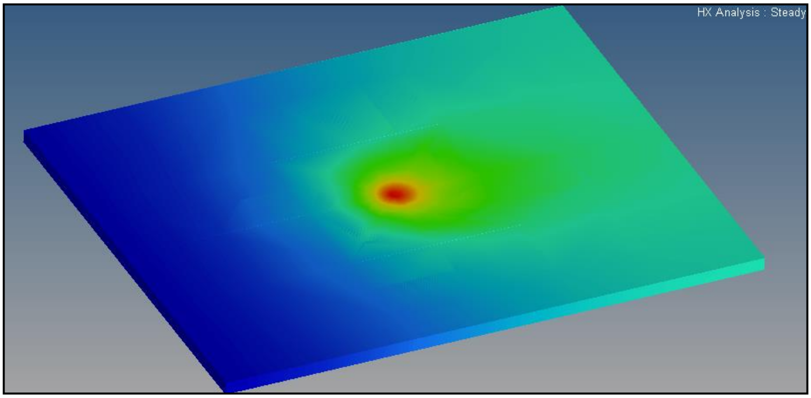

Figure 6: Temperature distribtion in welded plate

Peak Temperature near Pin Area Results

Recall from the Table 3, the melting range of Aluminium 6061 is 582 to 652 ºC. Since most studies revealed that, the optimum welding temperature required in FSW process is usually 80% to 90% of the melting temperature of the material in order to minimize and avoid some of the welding defects and large distortion associated with fusion welding [18]. Therefore, the appropriate temperatures for a successful FSW process are between 456ºC to 587ºC.

The peak temperature around the pin was predicted by simulation analysis. From the simulation analysis results it is known that the temperatures at the pin can be regarded as a uniform distribution and that the heat transfer starts from the edge of the pin. These simulation results of temperature histories can offer useful knowledge for an FSW process of aluminium alloy 6061 butt joining especially when to determine the peak temperature near the pin area. Because the temperatures at the joint line under these different welding parameters are quite close to one another, there is no large difference for the temperature distribution of the welds, especially in the stir zone. With a higher rotational speed, the temperature should increase, but increased temperature reduces the metal flow stress and the torque which limits any power generation increase. Nevertheless, with higher temperature the normal force between pin tool and the workpieces may relax as the material becomes hotter, thereby reducing friction force and power generation due to relative slippage. The results of the temperature comparison prove to be challenging but fair relationship can be determined in that the temperature for each are increasing in a similar manner, which concludes that model developed is a good representation of the FSW process in this regard. The difference of maximum temperature and temperature distribution will exert a significant effect on the heat force coupling analysis of the welding pin. Therefore, the welding parameter is a deciding factor for the state of the welding process, which is significant for the quality of the weld bead and life time of the friction stir welding tools.

Table 3: Maximum temperatures obtained from the numerical modelling near the pin

Rotation Speed (rpm)	**Transverse Speed (mm/s)**	**Peak Temperature Near Pin Area (°C)**
800	1.5	518.6
	2	507.0
	2.5	497.9
	3	490.4
	3.5	484.4
900	1.5	544.5
	2	532.3
	2.5	523.1
	3	515.6
	3.5	509.1
1000	1.5	569.6
	2	556.3
	2.5	546.7
	3	538.9
	3.5	532.6
1100	1.5	597.3
	2	579.5
	2.5	568.7
	3	560.7
	3.5	554.1
1200	1.5	643.0
	2	604.5
	2.5	590.3
	3	581.3
	3.5	574.5

Conclusion

Modeling and measurement of the temperature in the FSW of 6061 Aluminium alloy is conducted, and the experimental values validate the efficiency of the proposed model. The prediction and measurement show that the maximum temperature gradients in longitudinal and lateral directions are located just beyond the shoulder edge, and it can be seen for higher tool rotation, the heat flux is higher than for lower tool rotation, both are also set at constant travel speed. The calculating method for the heat generation during is proper, and the assumption of the contact state variable within the different region is reasonable. The maximum temperature proportional to the rotational speed that is the peak temperature increase when the rotational speed increases. It is because, rotational velocity between the tool and workpiece is high and cause frictional forces also increases and due to that, the heat generation also increase. It shows the good similarities with the experiment that had done.This provides better insight about peak temperature developed at different tool speeds by numerical modelling without conducting costlier experiments.

In summary, the computed results from a well-tested three dimensional heat transfer model show that the model can predict peak temperatures for the FSW of aluminium alloy for various welding conditions. The computed results are used to construct contour maps of peak temperatures in good temperature range. As the conclusions, the travel speed and the rotational speed of the tool will affect the temperature distribution. The result of the temperature distribution will affect the quality of the weld that be joined. So, to get the good quality of the joining process, the travel and the rotational speed of the tool must be controlled.

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