Investigation on Heat Generation during the Plunging Phase of Friction Stir Welding for Different Rotational Speeds

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ABSTRACT: *Friction stir welding is a promising welding technology which has made its way to many industrial applications. It provides high quality welds by eliminating some defects like porosity and crack. The solid state joining process consumes comparatively less energy than some other welding technologies. The heat generated during the friction stir welding is responsible for the joining of the two base metals and also it has effect on the residual stresses of the workpiece. The residual stresses affect the fatigue life of the welded joints so it is important to control the heat generation in the friction stir welding. The heat generation is controlled by optimizing the parameters of the FSW tool. In this paper we will analyse the effect of the rotational speed of tool on the heat generation during the plunging state of FSW. Heat generation during the plunging phase has been chosen to be analysed since the highest possible temperature is attained at the plunging phase. A Coupled Eulerian Lagrangian technique is used for the numerical analysis using ABAQUS CAE.*

Key words: CEL, Friction Stir welding, microstructure, ALE, ABAQUS CAE.

1. INTRODUCTION

Friction stir welding (FSW) is a solid-state joining process mostly used for the joining of aluminium alloys. Invented in 1991 at TWI in England FSW has made its way to industrial application particularly in the last years. At first, this is because of the capability of producing welds with excellent properties like very good static and fatigue strength, low distortion and almost plain surfaces even in the as-welded condition. Furthermore, the possibility to join dissimilar materials such as aluminium and steel or aluminium and copper enables tailored blanks for lightweight designs or low resisting high current connections. But beside this there are other uprising advantages of FSW as in today's production environmental issues become more and more important.

This first commercial application of this welding technique is believed to be the joining of AA6xxx extrusions used for fishing vessels. Due to the low distortion FSW is optimal for welding flat panels and opens opportunities to be used also for welding bulkheads and decks components. The low component distortion is a major benefit in the case of shipbuilding applications. Aerospace has shown a fast adaptation of the friction stir welding process. The fact of FSW being able to weld high strength aluminium alloys, such as 2xxx and 7xxx series, when other welding technologies were not, has provided new opportunities to these alloys and increased the interest on this welding process in aerospace industry.

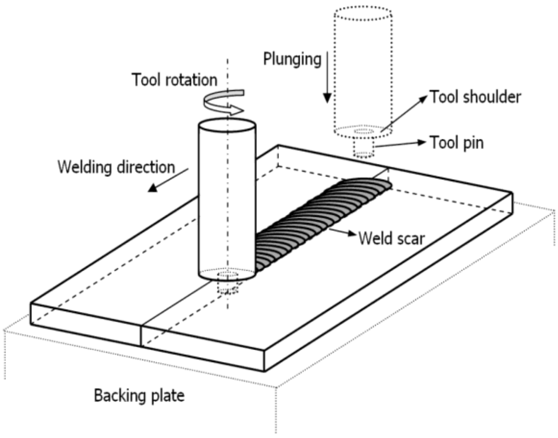

Fig-1: Schematic diagram of FSW

In friction stir welding the weld is produced due to heat which is generated by friction and the stirring action of the rotating tool. The primary factor which produces heat is friction and the secondary factor is plastic deformation of material which also produces a little amount of heat. The cylindrical tool is rotated and plunged into the abutting edges of the parts to be welded. As the tool is moved along the joint line as shown in fig 1, the friction from the rotating tool heats the materials to the extent that it plastically deforms and flows from the front of the tool to the back, where it subsequently cools and produces a weld. The rotation of tool heats the material to approximately 80 to 90% of the melting temperature of the alloy. The FSW process uses no outside (filler) material, no shielding gases, and requires low energy input when compared to other welding processes. And also in FSW the material does not get melted but instead it gets softened and hence all the peak temperature which attained by the friction between tool and workpiece will be and should be lesser than the melting temperature of the regarding workpiece materials. There are three main phases during the friction stir welding process which are the plunging stage, welding stage, and the retracting stage. During plunging the tool gets penetrated into the workpiece and it goes through a dwelling phase which is a preheating phase, then in welding phase the tool moves along the joint line, and at last the tool is pulled out in the retracting phase. In practical the plunging is done by forcing the tool through the workpiece the magnitude of the plunging force plays a role in the quality of weld. All the tool parameters involved in the FSW plays role in the amount of heat generation and the generated heat is responsible for the joining of metals. There are three important microstructure zones also in the welded workpiece named weld nugget, thermo-mechanically affected zone(TMAZ), heat affected zone(HAZ) which are shown in fig.2.

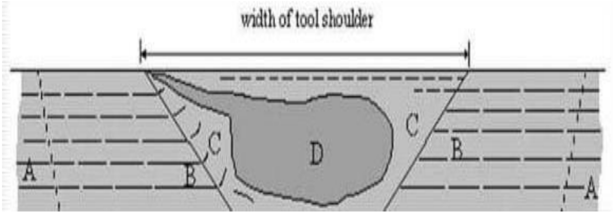

Fig-2: Microstructural zones of FSW

Where,

A – Unaffected zone

B – Heat affected zone (HAZ)

C – Thermomechanically affected zone (TMAZ).

In friction stir welding the temperature plays main role, usually the temperature on the workpiece is uneven and it is undesirable as it mainly affects the residual stresses. The residual stress affects the fatigue life of the welded members. The residual stresses are noted to be high in the thermo-mechanically affected zone (TMAZ) just beyond the tool shoulder this gives the importance of the temperature in friction stir welding. The peak temperatures in FSW are monitored during the plunging and dwelling of the tool. As the tool moves along the weld line the temperature starts decreasing. The values of the temperature are depends on the three welding parameters that are plunging force, rotational speed of the tool, and the welding speed. By varying these three parameters desirable temperatures can be obtained.

2. DETERMINATION OF MATERIAL PROPERTIES

The material properties of AA-6061 has been used for the numerical simulation since it has wide range of applications in the aerospace and shipbuilding domains. 6061 is a precipitation-hardened aluminium alloy, containing magnesium and silicon as its major alloying elements. Originally called "Alloy 61S", it was developed in 1935. It has good mechanical properties, exhibits good Weldability, and is very commonly extruded. It is one of the most common alloys of aluminium for general-purpose use. The chemical composition of AA-6061 has been shown in table.1.

Since thermal nonlinearity is involved in the simulation, the material properties should be temperature dependent. The material properties used by M. Hossfeld, E. Roos [3] have been used for the numerical model.

Table -1: Chemical composition of AA-6061

Mg	Si	Fe	Cu	Zn	Ti	Mn	Cr	Others	Al
0.8-1.2	0.4-0.8	0.7	0.15-0.4	0.25	0.15	0.15	0.14-0.35	0.05	Balance

3. GEOMETRY OF TOOL AND PLATE

The basic dimensions of the tool are mainly depending on the thickness of the workpiece (plates). The dimensions of the plates are 100mm x 40mm x 5mm.

The tool used for friction stir welding consists of a shoulder and pin as shown in fig 2. The length of the pin is usually a little bit smaller than the thickness of the plates (4.7mm in our case). The diameter of the pin is 6mm and the diameter of the shoulder is 18mm. Fig 3 shows the general nomenclatures of a simple FSW tool.

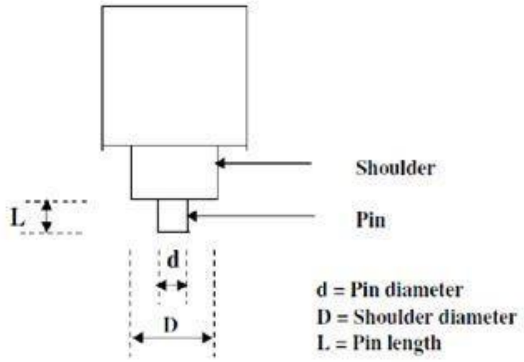

Fig-3: nomenclature of simple FSW tool

3. NUMERICAL MODELLING

In the past years various methods and commercial finite element packagers have been used to analyse the friction stir welding. Model built by using Lagrangian elements are used to analyse the temperature and thermal stresses in friction stir welding as they provide better results. But in the case of using Lagrangian elements the problem is element distortion and the authors deal with it by mesh refinement. But with the use of Arbitrary Lagrangian-Eulerian some authors found good results and the problem of element distortion is not anymore with ALE. In the case of Lagrangian both the material and element moves togethor i.e.) the Lagrangian mesh is attached to the material point. In Eulerian the mesh (element) is held and the material flows through the mesh.

Here we use Coupled Eulerian Lagrangian technique with the analysis package ABAQUS-CAE version 2016. CEL also uses Eulerian and Lagrangian elements, with the help of CEL we can analyse the temperature and thermal stresses and also the material flow during the friction stir welding as stated by Bahman Meyghani and Mokhtar B. Awang [8] in their comparison study of various solvers used for FSW.

3. 1 Discretization of model and boundary conditions

The tool has been modeled as Lagrangian part with rigid constraints. And the plate (workpiece) has been modeled with the Eulerian elements **EC3D8RT.** The mentioned element type with ABAQUS can only be solved by explicit method. The discretized model with plate and tool is shown in fig 4.

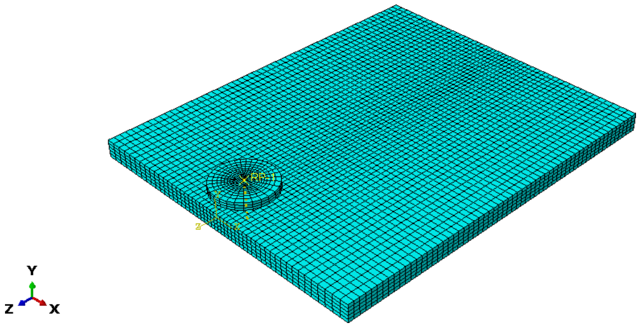

Fig-4: discretized model

Table-2: tool boundary conditions

Case.no	Plunging velocity	Rotational velocity
1	4.7 mm/sec	38 rad/sec
2	4.7 mm/sec	40 rad/sec
3	4.7 mm/sec	42 rad/sec

The plate is fixed as similar to the experimental. The tool has a rotational velocity and a linear velocity (plunging). There are three cases formed to analyse the effect of rotational velocity on heat generation. In each case the linear velocity is maintained constant. The difference cases are shown in table 2.

3.2 Material modeling

A strain rate and temperature dependent material law is implemented by using Johnson cook material law. The temperature dependent material properties and the Johnson cook material model properties are extracted from the literature [3]. The Johnson cook material model relates the stress with experimentally obtained material properties of AA-6061 and also with the melting and transition temperature that's how a combined effect is provided by the Johnson cook material model. The Johnson cook constitutive equation is shown below.

Where, σy- the equivalent stress, A is the yield strength of the material, B is the strain hardening constant, n is the strain hardening coefficient, C is the strengthening coefficient of the strain rate and m is the thermal softening coefficient. T is the deformation temperature. Tref and Tmelt are the reference and melting temperature of the material.

3.3 Interaction

The interaction between the tool and plate is defined by general contact algorithm with the "ALL* with self". This algorithm determines the contact condition for every single node. When contact between nodes is detected friction, frictional heating etc. are respected. The heat generation by friction is defined by the coulomb's law of friction with the coefficient of friction value of 0.3. To stop the generation of heat before the melting temperature the coefficient of friction value is set as near zero at a particular temperature.

4. RESULTS AND DISCUSSIONS

The investigation on heat generation of FSW during the plunging phase was done and the results are presented below.

4.1 Heat generation by tool pin

When the tool pin makes contact with the plates the heat is generated between the tool pin and the plates as shown in fig 5. When pure Lagrangian method is used this particular portion is often ignored as it always ends up in element distortion but with CEL it can be achieved.

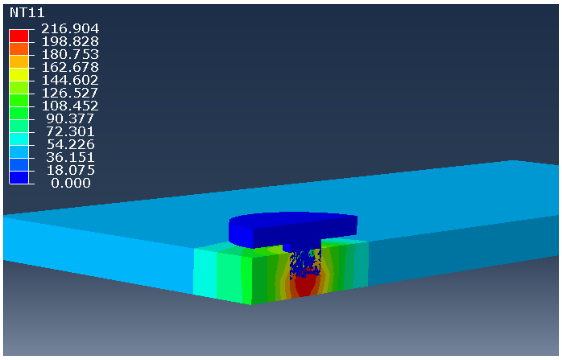

Fig-5: Temperature near tool pin during plunging.

$$\sigma_y = \left[A + B(\bar{\varepsilon}^{pl})^n\right]\left[1 + C\ln\frac{\dot{\varepsilon}^{pl}}{\dot{\varepsilon}_0}\right]\left[1 - \left(\frac{T - T_{ref}}{T_{melt} - T_{ref}}\right)^m\right]$$

5.2 Microstructural zones of the plate

As it was mentioned earlier the plunging is a crucial phase where the highest temperature of the FSW occurs and it decreases as the tool moves along the weld line. The different microstructural zones of FSW have been shown in fig.4 the temperature variation differentiates the zones clearly.

The temperature contours for all the cases have been shown and the comparison of the cases has been shown in fig.5 in similar material welding the temperature field is almost symmetrical yet there will be a little asymmetry when the tool moves on the weld line.

At the initial state of plunging heat is generated between tool pin and plate, as the tool shoulder makes contact with the plate the generation increases more and the maximum value is obtained.

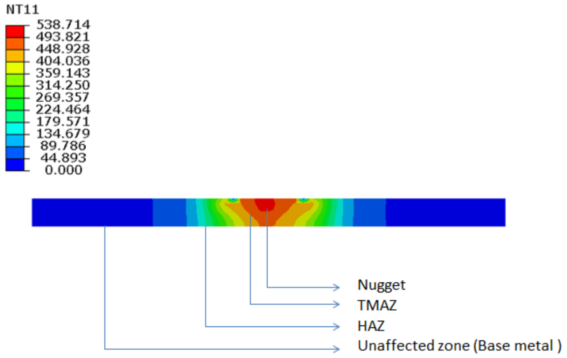

Fig-6: Micro structural zones of FSW

From the analysis the magnitude of temperature seems to be increasing as the rotational speed of the tool is increased. At 42 rad/sec of the tool's rotational velocity the maximum temperature among all the three cases is obtained near the tool shoulder. The temperature contour grows as the dwelling phase continuous.

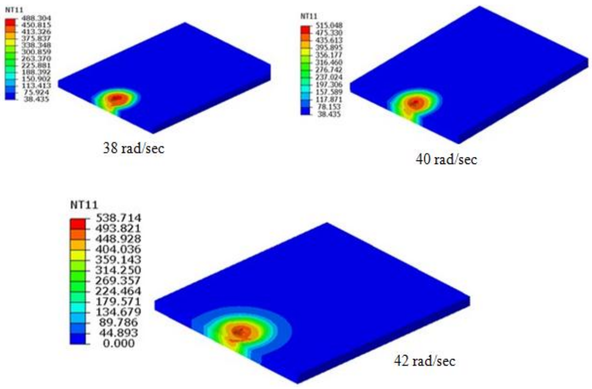

Fig-7: Temperature results for different rotational speeds.

6. CONCLUSIONS

The analysis was performed for three different speeds by using the method CEL from that the following conclusions can be drawn.

- The element distortion problem can be eliminated by using CEL.
- When the rotational speed increases the heat generation also increases.
- Maximum amount of heat is generated when the tool shoulder makes contact with the plates as the contact region becomes bigger and directly proportional to heat generation.

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