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Finite Element Analysis of Stress-Strain Response at the Tool Pin during Friction Stir Process

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Abstract

Friction stir welding (FSW) is a relatively new solid-state joining process which is considered energy efficient, eco-friendly and versatile. High stress and strain occur at the rotating tool, consisting of a pin (probe) and a shoulder, during the friction stir process. The geometrical design of the tool has some impact in terms of stress and strain once static load is applied against the tool. In this work, specific stress can be found on the tool due to the plunging and travel process that is analysed using finite element method. In the present work, a steady state finite element stress analysis of friction stir welding was carried out using CATIA V5 software. The critical points of the FSW tool are located mainly on the edge between the shoulder and the pin, where a large amount of stress is found and further leads to failure or tool defects. This critical stress and strain can be reduced by enlarging the diameter size of the pin and increasing tool life.

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Keywords: friction stir welding; finite element analysis; stress-strain simulation.

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1. Introduction to Friction Stir Welding

Friction stir welding is one of the most efficient joining processes. This joining process is known to be energy efficient, environmentally friendly, and versatile[1]. This technique can also be used to weld different types of metal which cannot be done using conventional welding processes. This joint process was invented and patented by The Welding Institute (TWI) in the UK in 1991[2]. FSW is considered to be a relatively important development in metal joining for decades. It is a solid state joining process facilitated by friction to produce heat and employs a rotating tool as the main element in the process consisting of a shoulder and a pin that simultaneously move along the butting surfaces of two rigidly clamped workpieces on a backing plate[3]. At the first stage of the welding process called plunging, the rotating tool, mainly the pin, slides on the work piece surface rotationally. After the workpieces become soft due to friction, the pin is continuously plunged down until the pin is completely positioned in the workpieces. Subsequently the rotating tool travels along welding path. This process is called traveling. The entire process is done by retracting the rotating tool at the end of the welding path.

2. FSW tool

The basic concept behind FSW is the following: A non-consumable rotating tool with a specially-designed pin and shoulder is inserted into the abutting edges of the two consecutive parts to be joined and travel along the joint line[4]. This process is forced completely into the adjacent mating edges of the workpieces[5]. Welding tools are one of the most important and critical components in FSW that can ensure the success of the process. Welding tools of various types, shapes, and sizes are considered based on how FSW being applied. The tool consists of 2 parts namely the shoulder and pin as shown in Fig. 1.

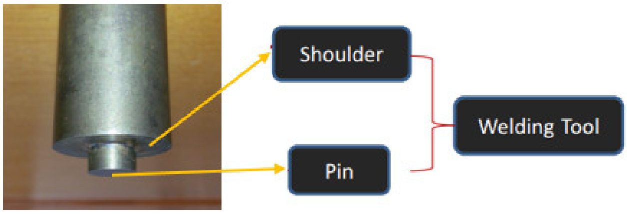

Fig. 1. FSW Tool Component

2.1. Tool Material

For this study, the material used for the tool is H13 steel. According to K. Kumar, and Satish V. Kailas, H13 or HDS have hardened to 55HRC[6]. Parameters such as welding speed of 80mm/min, tool rotation speed of 1400rpm and a tool tilt angle of 2°[6] were used. Fig. 2 shows some of the tools used in the friction stir welding process.

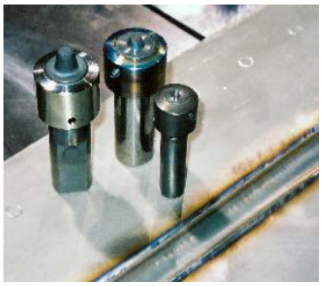

Fig. 2. Tools in FSW

The experiment done by Kumar and Kailas used tools of various shapes and explained the effect of shapes on the shoulder diameter, pin diameter and the pin profiles with respect to the size and location of defects, mechanical properties and final grain size. Kumar and Kailas also stated that there is not enough conceptual background available for designing the FSW tool geometry. Due to various reasons, research articles on tool geometry are mostly not reported[6]. Most of the tool designs are based on intuitive concepts, as pointed out by Mishra and Ma[1].

2.2. Tools and Material Parameters

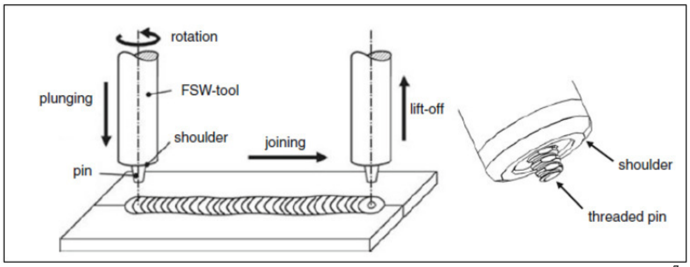

Fig. 3. Friction stir welding process and tool details by M.F.Zaeh and P. Gebhard [7]

Fig. 3 shows that for the dynamical behaviour of machine tools during friction stir welding, M. F. Zaeh and P. Gebhard used 0 tilt angle in their research, and for their geometrical setup of the tool, a shoulder diameter was 12mm and the pin diameter was 2.5mm[7]. 2.7mm was selected as the pin length[7]. Chen et al. did the experiment of joining the Al6061 to AISI1018 wtih 6mm thickness[8]. Watanabe et al. reported the joining of steel to an aluminium alloy with 2mm thickness[9].

3. Drafting and design geometry

This research was conducted using aluminium alloy with a thickness of 6mm as the workpiece, and the tool is made of H13 steel. Table 1 shows the material and dimension of the tool. The tool was designed using CATIA V5. Fig. 4 shows triangle elements with 6 nodes which support nonlinear direct coupled field analysis with both thermal and structural degrees of freedom used for mesh generation. The welded plates are made of rectangular-shaped Aluminium Alloy 6061 with dimensions of 200mm x 75mm x 6mm. The frictional and plastic heat generated during the FSW process propagates rapidly into remote regions of the plates also act as a boundary condition. On the top and side surfaces of the workpiece, convection and radiation account for heat loss to the surroundings. Conduction losses also occur from the bottom surface of the workpiece to the backing plate. The value of the convection coefficient is 250 W/m² °C for the workpiece and 200 W/m² °C for the tool.

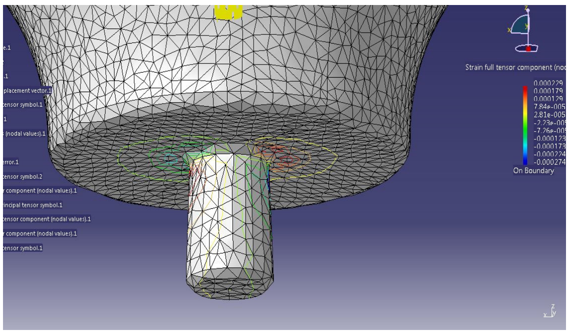

Fig. 4. Meshing of tool in CATIA V5

Table 1. Tool Material and dimension

Tool Material	**H13 Steel**

Shoulder Diameter	15mm
Pin Diameter	6mm
Pin Length	4.7mm
Density	7870 kg/m^3
Specific Heat	460 J/kg-K
Young Modulus	2.1 E+11
Poisson Ratio	0.35

4. Result and Discussion

In pre-processing, a constant downward force of 11kN and a 1.33kN longitudinal force in the direction of motion are applied during the plunge process. After applying the forces, the determination of stress in the tool is continually being done using the simulation. The result is obtained as the stress concentration of the force application. The appearance of a variety of contours and colours exhibits different stress values and points as shown in the Fig. 5.

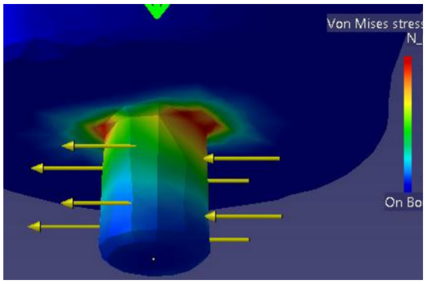

Fig. 5. Stress analysis contour colour

As we can see from Fig. 6, stress increases gradually corresponding to rotational speed. From the result, it is clear that the critical stress is located on the tool edge between the pin and the shoulder as shown in Fig. 5. This critical stress is represented by the colour contours. As expected, the highest stress or the maximum stress is concentrated in between the shoulder and the pin edges.

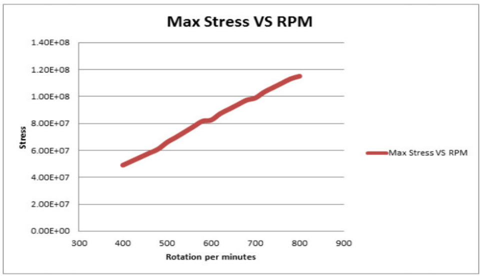

Fig. 6. Maximum Stress vs Rotation per minute

In Fig. 6, red represents the maximum value of stress. The minimum value and the maximum value of stress are clearly displayed. According to table 2, the maximum value of stress is 4.90x10^7N/m2 for 400 rotational speeds (RPM),. This maximum value increases to 6.60 x10^7N/m when the rotational speed is set at 500rpm. All points can be referred to in table 2.

Table 2. Maximum stress value

RPM	Max Stress (N/m2)
400	4.90E+07
500	6.60E+07
600	8.25E+07
700	9.89E+07
800	1.15E+08

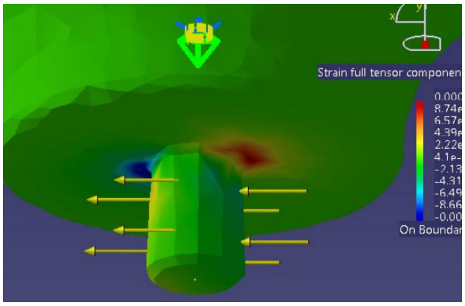

Fig. 7. Strain effect in simulation

From Fig. 7, the phenomenon of strain is observed. Strain is a description of deformation. The data taken out from the simulation reveals the strain effect in Fig 8. In Fig. 7, the red area indicates the area with the highest strain. It showed that its effect occurred on the flat surface of the shoulder area in contrast to the stress effect that happened at the edge between the pin and the shoulder.

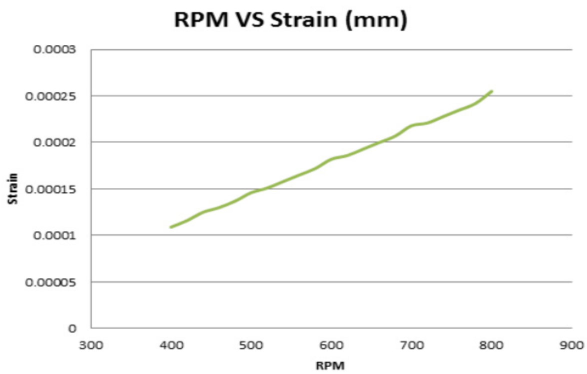

Fig. 8. Rotation speed versus Strain

Table 3. Value for maximum strain from simulation data

RPM	Max Strain (µm)
400	0.109
500	0.146
600	0.182
700	0.218
800	0.255

The results in table 3 were obtained from the simulation. From Fig. 8, strain increases according to the rotation speeds. It shows here that strain and stress take place in the same situation once the rotational speed is increased. It will also increase stress force and strain in the tool.

5. Conclusion

Finite element analysis in the case of stress-strain at the rotating tool pin during friction stir process can be deployed to ensure that the tool is able to withstand tremendous load during the process. This work revealed that the critical stress in the tool pin is a consequence of the rotational speed applied on the tool. When the rotational speed increases, the stress and strain in the tool pin will also increase. Another further consideration of this study is expected to be used to measure the tool performance for joining dissimilar material or even hard materials such as steel or titanium alloys. In this case, good tool performance is required to ensure a successful process.

Acknowledgements

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