Finite element analysis of electrically enhanced friction stir welding

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ABSTRACT

This article presents a novel variant of conventional friction stir welding (FSW). This welding process involved in chemical and pharma industries with numerous applications like low level joining process. Moreover, in this article investigate about effect of electrical enhancement with friction stir welding is studied by using commercially available finite element analysis solver ANSYS. In this investigation 2D axis symmetric thermal, thermoelectric and thermo mechanical finite element model is developed to analyse the mechanical behaviour of electrically enhanced friction stir welding process of stainless steel plates by using tungsten tool. It is compared with conventional friction stir welding by using commercially available finite element analysis (FEA) solver ANSYS. In conventional Friction stir welding (FSW), joining of higher harder material results in high tool wear, tool breakage and low weld speed during plunge stage to gain heating to plastically soften the work piece. High harder material has problem of high tool wear, tool breakage and low weld speed during plunging stage because material is cold during plunging stage, therefore more axial force is required to plastically soften the work piece. Electrically enhanced friction stir welding (EHFSW) is one of the new technique in which electric current is passed to work piece from top of the tool. As electric current is passed from the tool, work piece get localised heating which will help material to reach the plastic stage quickly when tool rotates over it, so tool can easily plunge into work piece, which will reduce axial force acting on tool therefore tool wear and tool breaking problems can be minimized and weld speed can be increased. This finite element analysis results shows axial load acting on tool can be reduced when electric current is passed therefore reducing the tool wear, tool breaking and increases weld speed.

KEY WORDS: Finite element method, conventional friction stir welding, electrically enhanced friction stir welding.

1. INTRODUCTION

Friction stir welding is invented in the year 1991 by The Welding Institute (TWI), it is a solid state welding process in which metals are joined without melting and FSW can be used where the material property of work piece should remain same before and after welding process. In FSW rotational movement is given to tool and is forced to move downwards until tool shoulder makes contact with work piece and moved along contacting surface (Zhu and Chao, 2004; Prasanna, 2010) as rotating tool shoulder makes contact with work piece friction heat is generated which softens the work piece (Zhang and Zhang, 2008). As tool moves forward, region around the tool get softens and material is stir from side to back and material from both plates combine together to form weld. In friction stir welding of high harder materials which having high melting point has high tool wear, tool breakage and low weld speed problems (Long and Sanjeer khanna, 2005) during plunging stage, because more axial force acts on tool to generate the required frictional to plastically soften a material and also downward axial force is having influence on weld speed and tool rotation (Zhang and Zhang, 2008)

Electrically enhanced friction stir welding process is a new process in which electric current is passed from top of the tool to work piece (Arnaud, 2007; Jie Shen, 2011.), where tool and work piece contacting region get localised joules heating (Long and Sanjeer Khanna, 2005) which will be distributed throughout the work piece. As metal at high temperature have low yield strength, therefore less axial force is enough (Xu wei, 2009) to thermally soften the work piece, as the axial force acting on tool is reduced, tool wear can be reduced and also weld speed can be increased, which has influence on the weld quality. Previously Long and Sanjeer Khanna (2005), proposed 2D axis symmetric model and performed transient thermoelectric and thermal analysis and given temperature relationship existing between friction heat from conventional FSW and Joules heating from EHFSW. But their work is limited with thermal analysis itself and they did not perform thermo mechanical analysis to find the relationship on effect of joules heating on mechanical parameters such as axial load, contact pressure and stress distribution. In this investigation, transient thermal and thermoelectric analysis is first performed for the 2D axis symmetric model and by using sequential coupling method static thermo mechanical analysis is performed using the same model by giving the temperature obtained from thermal and thermoelectric analysis as thermal load at each node (Chen and Kovacevic, 2003; 2004) to find the effect of joules heating from EHFSW and frictional heating from FSW on axial load, contact pressure stress distribution were calculated by employing temperature obtained from both thermoelectric and thermal analysis as thermal load.

Equation governing heat flow in EHFSW process: EHFSW has three heat sources such as frictional heating which is produced when rotating tool makes contact with work piece, heat generated due to plastic work and heat generated by joules heating when electric current is supplied. Since thermal, electric and mechanical heat sources are involved, Fourier's second law of heat transfer equation can be used for heat flow analysis in EHFSW (Long and Sanjeer Khanna, 2005).

$$\rho c \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+q_0 \quad (1)$$

Where ρ is material's density, c is heat capacity, t is time, k is thermal conductivity and q_o is internal heat source. In this present study q_o has three kinds of sources

$$q_o = q_{oF} + q_{oP} + q_{oR} \quad (2)$$

Where q_{oF} is friction heat, q_{oP} plastic work heat and q_{oR} is electrical resistance heat.

2. EXPERIMENTAL

Finite element model: 2D axis symmetric model is employed to perform thermoelectric, thermal and coupled thermo mechanical analysis is shown in Fig 1. Commercial FEM solver ANSYS 11 is used to simulate FSW and EHFSW process. Element type PLANE 67 and PLANE 42 is used and model is meshed with 21630 elements. Contact is given between tool and work piece (Zhigang Hou, 2007). Work piece used for this analysis is stainless steel 304L and tool is tungsten.

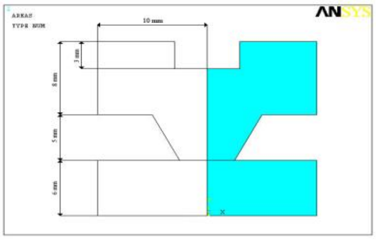

Fig.1. 2D axis symmetric model

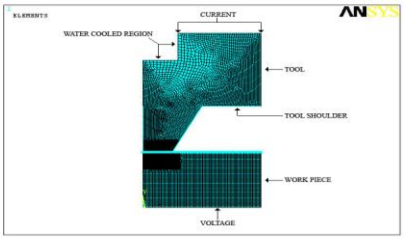

Fig.2. Meshed 2D axis symmetric model

Thermal analysis: In transient thermal analysis tool is rotated over the work piece to produce friction heating for that following (given) thermal boundary conditions are given for a period of 10 seconds. Thermal boundary conditions are used. Convection value of 300 $Wm^{-2} K^{-1}$ on the surface of material in water cooled area in tool and 30 $W m^{-2} K^{-1}$ is given to surface of material exposed in air. Heat flux of 2 x 10^6 $W m^{-2}$ is assumed to simulate friction heating generated by tool when rotated over work piece is given as input. Suitable contact conductance is given for tool work piece contact. Temperature obtained from this analysis when heat flux value of 2 x 10^6 $W m^{-2}$ is shown in fig.3.

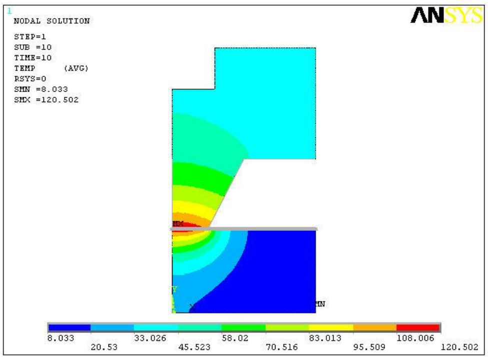

Fig.3. Temperature obtained when friction heat is applied for 10s

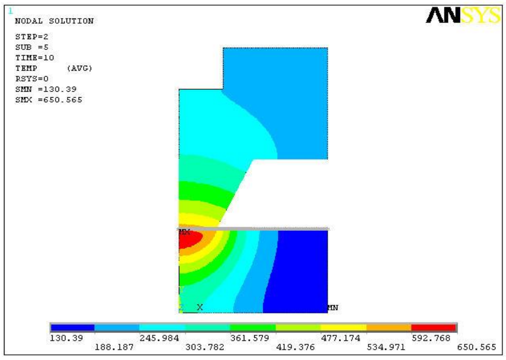

Fig.4. Temperature obtained when 1000A current is applied for first 5s and friction heat for next 5s

Thermoelectric analysis: In transient thermoelectric analysis for first 5 seconds electric boundary condition such as current value of 1000A is applied on top of tool (Jie Shen, 2011) and voltage is to be zero at bottom of work piece (Arnaud Monnier, 2007) is applied in order to produce joules heating as shown in Fig.2 and now tool is rotated to produce friction heat for that a heat flux value of 2 x 10^6 $W m^{-2}$ was assumed and simulate friction heating is applied, now thermal boundary condition as used in above thermal analysis is applied along with electric boundary condition for next 5 seconds. Temperature profile obtained from in thermo electric analysis is shown in Fig 4. Material properties applied for both of this analysis are collected from various literatures and it is shown in table 1. The voltage difference created the current flow and the material near the top surface is heated up to 650^0C. Since it is applied for a small period, the mechanical properties will be unaltered.

Thermo mechanical model: In coupled thermal-electric-mechanical analysis, temperature obtained from above thermal and thermoelectric analysis for the heat flux value of 2 x 10^6 $W m^{-2}$ is used as thermal load at each node and temperature dependent material properties (Jie Shen, 2011; Hou Zhigang, 2006; Dong, 2001; Grujicic, 2009) is used for analysis and it is shown in table 1. Boundary condition used for mechanical analysis are symmetric boundary line of model is allowed to move only in vertical direction and movement at bottom of work piece is arrested in all direction. Rotation of 600 rpm is applied on tool along with displacement of 0.5mm in downward direction is shown in fig.5.

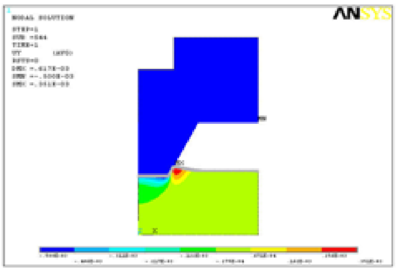

Fig.5. when displacement of 0.5mm is applied in downward direction on tool

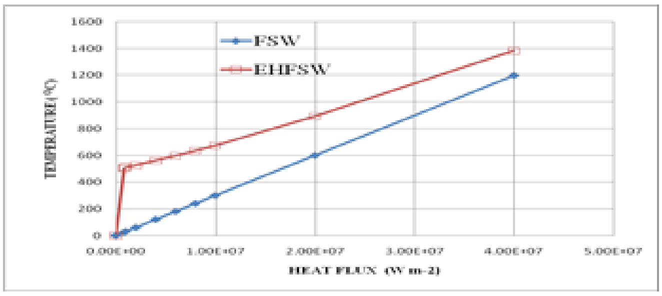

Fig.6. Temperature vs heat flux

Table.1. Thermal and mechanical material properties of stainless steel 304L and tungsten

Temp. (ºC)	Youngs modulus (GPa)		Yield strength (MPa)		Specific heat (J kg-1 K-1)		Thermal Conductivity (W m-1 K-1)		Electrical resistivity (x10-8 Ω m)	
	304L	Tungsten	304L	Tungsten	304L	Tungsten	304L	Tungsten	304L	Tungsten
24	195	400	485	3500	460	130	14.9	130	70	5.5
90	192	396	483	3210	-	-	-	-	-	-
200	183	392	401	2760	520	150	17.5	120	81.9	10.5
370	170	384	332	-	-	-	-	-	-	-
430	165	385	308	-	-	-	-	-	-	-
480	159	379	288	1605	-	-	-	-	-	-
600	150	373	244	-	-	-	-	-	-	-
700	140	368	145	700	-	200	-	110	-	24.3
800	-	-	50	-	580	-	25.9	-	114	-

3. RESULTS AND DISCUSSION

Comparison temperature obtained from EHFSW and FSW: Temperature obtained from both FSW and EHFSW for various heat flux values is shown in fig.6. Here temperature increases linearly in conventional FSW where as in EHFSW the temperature increases rapidly during initial stage and slowly in later stages, because as temperature increases resistance to current value also increases because of coefficient of thermal expansion of material. It is also evident from the graph that high temperature profile is obtained in EHFSW when compared to FSW. So less axial force is enough for tool to thermally soften the work piece which can result in reduced tool wear and tool breakages. As axial force is reduced, weld speed can be increased which has great influence on weld quality (Nandan, 2006; Zhang and Zhang, 2009).

Axial Load acting on tool: Axial load obtained for the displacement of 0.5 mm in both FSW and EHFSW is shown in fig 7. When rotating tool makes contact with the workpiece, the axial load acting on tool from both the process is having only negligible difference in their values in intial stage. But when rotating tool starts plunging into work piece, axial load acting on the tool in EHFSW started to decrease decreses because three heat sources such as friction, plastic deformation and joules heating are acting on EHFSW process, which can thermally soften the material easily whereas in FSW only friction heat and heat from plastic - plastic deformation of material is are acting.So more plunging force is required to produce the enough friction heating to thermally soften the material to reach plastic stage in FSW.Where as in EHFSW axial load is reduced, therefore high weld speed can be obtained while welding high harder material and tool wear, tool breakage can be reduced because the axial load is the main causes for these problems.

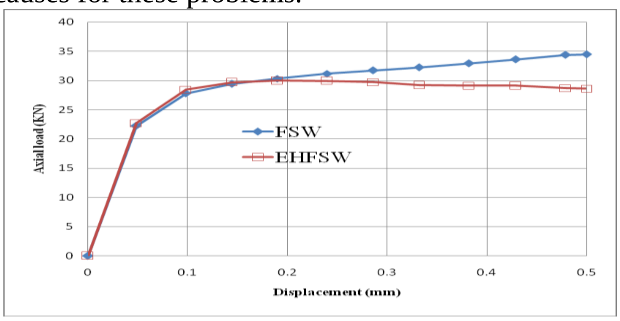

Fig.7. Axial load for displacement of 0.5mm

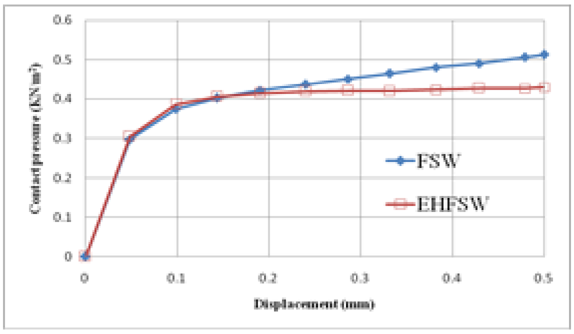

Fig.8. Contact pressure for tool displacement of 0.5mm

Contact pressure between tool and work piece: Contact pressure between tool and work piece for a tool displacement of 0.5mm is shown in Fig 8. Contact pressure obtained from EHFSW is less than that obtained from FSW, as axial load is reduced contact pressure existing between tool and work piece also reduces because at high temperature yield strength of material reduces (Xu Wei, 2009) which results in material to reach plastic stage easily,so tool can plunge into work piece with less plunging force which results in less contact pressure therefore tool wear, tool breakages can be reduced and weld speed can be increased**.**

Von Mises stress: Stress value obtained for tool displacement of 0.5mm is shown in fig 9 from the figure it shows that stress obtained in FSW process is high when compared to EHFSW, which shows high tool wear occurs in this process because high stress acting on tool is main reason for tool wear and tool breaking whereas in EHFSW less amount of stress only acting occurs which can tool wear .

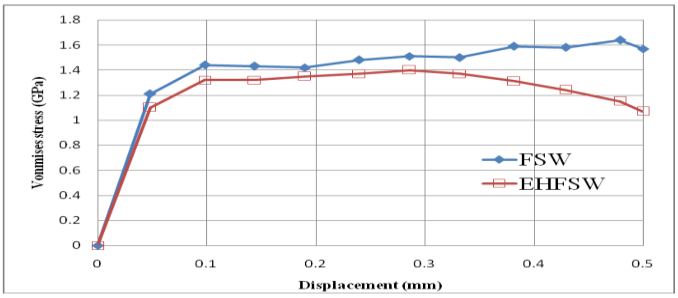

Fig.9. vonmises stress for tool diplacement of 0.5mm

4. CONCLUSION

Finite element model has been developed using ANSYS 11. Thermal and thermoelectric analysis is performed and temperature distribution from both analysis is studied. Temperature obtained from above analysis is used as temperature load in Thermomechanical analysis to find out the consequence of electric current on mechanical behaviour of EHFSW and compared with FSW. Following are results obtained from above analysis. From thermal analysis, high temperature is obtained in EHFSW when compared with FSW because at high temperature yield strength of material is less. so material can reach plastic stage easily, so tool plunging force can be reduced which can minimise the tool wear, tool breakages and weld speed can be increased. From thermomechanical analysis,less downward axial force,contact pressure and stress values obtained in EHFSW for the displacement of 0.5mm when compared with FSW, as plunging force,contact pressure and stress values is reduced,high plunging force acting on the tool is the main reason for tool wear therefore tool wear can be reduced. High stress acting on tool is main reason for tool breakages so it can also be reduced in EHFSW. When plunging force acting on the tool is reduced means which can automatically increases the weld speed.

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