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Thermo-Analysis of Friction Welding on High Density Polyethylene Sheets as a Single Point-A Review

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Abstract-Friction Stir Spot Welding (FSSW) is a rapidly evolving technology that is increasingly becoming one of the widely adopted technologies in the industries for joining alloys of various metals like titanium, aluminium, magnesium and even polymeric materials that are hard to weld by conventional fusion welding processes. This review paper presents an analysis of the thermo-mechanical conditions in Friction Stir Spot Welding (FSSW) of commercial High density Polyethylene sheets. As carried out on a Vertical Milling Machine, actual modified to work as a Friction Stir Spot Welding machine and lap joints were obtained on couples of HDPE sheets. The studies carried out using a set of tests to investigate how the friction stir spot welding process parameters namely tool rotational speed, axial feed rate, dwell time and the plunging depth effectthe temperature distribution in the weld zone and the resulting mechanical properties of the joints. The thermocouples inserted into the welding zone for measurement of the temperatures during tool plunging. The welded samples were subjected to lap shear tests for evaluation of their lap shear strengths. A mathematical model representing the correlation of process parameters with temperature distribution and lap shear resistance of the welds was developed.

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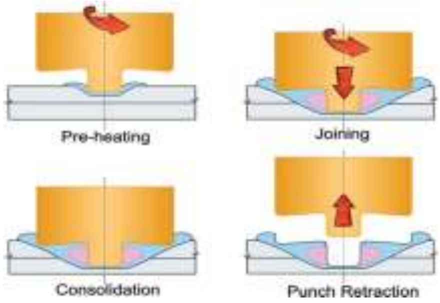
I INTRODUCTION

Thermoplastics materials are employed as structural components for replacing metals in a wide range of industrial fields including, building, automotive, aerospace, owing to a number of advantages including reduced cost of manufacturing, weight saving, flexibility and high thermal insulation. Besides the design flexibility, complex components usually involve many subparts being joined together. To this end, welding processes are generally employed; however, in order to overcome the principal limitations of such processes either improve the joint quality and reducing the processing time. Friction Spot Stir Welding (FSSW) are achieving growing interest since they produce joints with high mechanical performances (the strength of the stirred zone is close to that of the base materials), a reduced Heat Affected Zone and reduced temperature (as compared to that of material fusion). In addition, the simplicity of the required machines, low energy consumption, no cover gas or external heating sources requirement have contributed to the diffusion of these processes and have pushed the researches to discover new fields of application. The difference between FSW and FSSW concerns the absence of the transverse speed; therefore, FSSW produces spot joints rather than continuous welds. In FSSW, frictional heat is generated by the interaction of the tool pin with the material that becomes pasty and extrudes vertically. The tool shoulder then exerts an upsetting action on the stirred material to form the weld nut. Since their initial employment for joining materials being difficult to weld such as aluminium alloys, FSW and FSSW have been employed for a wider range of metals including titanium, magnesium, copper and even high-strength steels but also to different materials such as thermoplastics and composites. In addition, being semisolid, FSW and FSSW processes are less sensitive to physical either chemical compatibility of the materials to join; thus, they are suitable for joining even dissimilar materials.

Polypropylene is one of the popular polymers due to its availability and competitive cost. It is a thermoplastic with noticeable mechanical properties. However, the need to produce larger and more complex parts from polymers such as polypropylene has created an increased demand for joining. Furthermore, with the increasing development of engineering plastics, the demand for reliable, rapid, high productivity and cost effective joining methods.

A. FRICTION STIR SPOT WELDING

The basic concept of FSSW is extremely simple. The rotating shoulder and probe of a non-consumable tool heat and plasticize the surrounding material and a solid state joining is accomplished there. There, the tool serves three primary functions; heating of the work-piece, movement of material to produce the joint and containment of the hot material beneath the tool shoulder. The heating is generated by friction between the rotation tool (Shoulder & Pin) and the work-piece and by plastic deformation of work-piece. The localized heating softens material around the tool probe. The tool shoulder restricts metal flow upward.



The optimized process parameters & temperature variations during the process are important to engineers for an appropriate designing of weld layout. Both experimental techniques & simulations using finite element analysis are to be utilized to optimize the weld strength. Optimum tool geometry, tool rotational speed, tool plunge depth & dwell time are the predominant factors to obtain better weld strength as these process parameters decides the formation of weld nugget. The high strength joint fails with pull nugget failure and the low strength joint fails with cross nugget failure. The tool pin geometry significantly affects the weld strength and nugget formation and plays an important role in the formation of good joints as they are directly associated with weld nugget formation.

B. NEED OF TEMPERATURE GENERATION ANALYSIS

The lap joint strength produced by FSSW is ultimately the function of temperature generation and temperature generated itself relies on the process parameters like tool rotational speed, tool plunge depth, dwell time and tool geometry. The FEM predicts the transient temperature distribution along the weld area with respect to boundary conditions and thus, helps to lay down the optimum weld layout and related process parameters. Therefore, thermal interaction is a very important aspect in FSSW since the process is dependent on the heat generated from the frictional force between tool and work piece to soften and join the workpieces. Although this welding technique has been successfully developed and applied in various cases in industries, the phenomena of thermal interaction between the PP and the tool should be fully understood. Therefore, this report addresses the study of thermal aspects between the tool and the workpiece interface using finite element analysis. Only a fewer published literature focuses on coupled thermal and mechanical phenomenon involved in FSSW of polymers. While others have recently started investigating the effect of process conditions and tool geometries on FSSW of polymers.

II LITERATURE SURVEY

M.K. Bilici*et al.* [4] studied the effect of Friction Stir Spot Welding parameters onthe weld strength of High Density Polyethylene (HDPE). Experiments were performedon 4mm thick HDPE sheet using a tool made of SAE 1050 with a taper cylindrical pinand a concave shoulder. Process parameters namely tool rotational speed, plunge rate,plunge depth, and dwell time were varied and their effect on the joint zone temperatureand shear strength of weld were studied. Tool rotational speed, dwell time and plungedepth were found to have a significant influence on the weld strength whereas plunge ratehad a negligible effect on the joint strength. Also failure modes namely pull nugget failureand cross nugget failure were encountered during shear testing of the weld samples.The melting of high density polyethylene occurred in the vicinity if tool pin reaching atemperature of 142*o*c at the 34th sec of dwell period, 1100 rpm tool rotational speed,3.3mm/s of tool plunge rate and 6mm tool plunge depth which shows that FSSW ofHDPE is not a solid state phenomenon.

MemduhKurtulmus[5] investigated the effect of welding parameters on joint formationand weld strength of polypropylene friction stir spot of welds. The effects of weldingparameters on welding joint formation were determined by metallographic studies. Thestrength of welds were determined by the lap-shear test. From the experiments, it wasfound that the tool plunge rate had no effect on FSSW of polypropylene sheets. The temperaturein the weld zone increased with the duration of the dwell time. The temperature reached its maximum level (190*o*C at 60s (melting point of polypropylene being 171*o*C).So, the material was melted. After 60sec, the temperature did not alter with the dwelltime. It was seen that the tool delay time has a significant effect on both weld quality and strength. FSSW with no delay period showed a poor weld strength and no characteristickeyhole is formed. A delay period of 20sec, tool rotational speed of 900rpm, plunge depthof 5.7(for a 5.5mm pin length tool) and 120sec dwell time showed the maximum shearstrength.

M.K. Bilici*et al.* [6] investigated the effect of tool geometry on friction stir spot weldingof polyethylene sheets. The highest tensile strength was obtained with a threadedpin tool (pitch length 0.8mm, 7.5mm pin diameter, 5.5mm pin length, 30mm shoulderdiameter and 6 degree shoulder angle). The weld strength obtained with a threaded pindecreases with the pitch. Pitch length of threaded pin of threads on the pin were foundto be very important for the weld quality and the weld strength. The optimum straighttool geometry for 4mm thick sheets was determined as 7.5mm pin diameter, 15 degree pintaper angle, 5.5mm pin length, 30mm shoulder diameter and 6 degree shoulder concavityangle.

Amir Mostafapour*et al.* [7] investigated the weldability of high-density polyethylenesheets via heat assisted friction stir welding and effect of process parameters onmicrostructure and mechanical properties of welded plates. The parameters under studywere pin rotational speed, transverse speed of tool and shoulder temperature. Tensile andbend tests were done in order to evaluate mechanical behavior of material. The resultsshowed that polyethylene plates could be welded with joint characteristics similar to basematerial. This could be accomplished by operating with a high shoulder temperature androtational speed as well as low transverse speed. They conclude that by utilizing heatassisted friction stir welding, polyethylene sheets could be joined with ultimate tensilestrength of higher than 95% of base material strength.

R. Sakano*et al.* and S.G. Arul *et al.* [8] have demonstrated that thelap shear load for the welded specimens first increased and decreased with increasingvalues of tool rotational speed. While, authors T. Freeney*et al.* and Y. Tozaki*et al.* [43, 44] observed that the higher value of weld strength can be due to large stirzone size, achieved by reduction in the tool rotational speed.

M. Merzoug*et al.* [8] found that the shearing strength of the weld increases for decreasingvalues of tool rotational speed and increasing values of tool plunge rate. it was declared that the weld lap shear strength can be increased by increasing the spanof dwell period or by optimizing this parameter**.**

Bozziand **A.L. Helbert-Etter*et al.*** Found that the shear resistance of the jointsdecreases with decreasing tool rotational speed.

III EXPERIMENTAL SETUP

The experimental setup of Friction stir spot welding has developed on vertical Milling machine (VMM). VMM is converted into FSSW machine with certain required modification. For performing the FSSW process milling machine requires some extra attachments.

A. Design and Development of Mechanical Fixture

The main purpose of a fixture for FSSW is to holding the Sample plate in position during welding. The main reason for having appropriate clamps or fixtures is to prevent the specimens from moving while being welded shown in below.

- ***Clamping requirement***

The forces that act on the base plates as a result of transverse and rotational movement of the tool can be summarized and built into a clamping design. The initial plunge of the tool, before welding feed, transfers forces to the base material. Firstly the tool generates a moment while rotating against the frictional surface of the base material. This frictional moment or shearing force is assisted by the downward thrust of the tool increasing the linear force vector at every increment of rotation. The probe that is sunk into the joint line wants to push the two base plates apart. Movement of the tool through the joint line also produces translational forces that tend to push the plates in the x-axis direction. The magnitude of these forces will depend on the viscosity level reached as well as the feed rate that the process commences at. The other forces to be under attention are the transverse forces produced by the rotating tool due to the shearing action.

- ***Clamp Design***

A recommended advantage on the engineering design side was a universal clamp that would characterize easy manufacturing; good stability and quick disassembling characteristics. The clamp was only bolted down with one T-nut it could not prevent any rotational (moments) movement of the clamp base.

- ***Backing Plate-***

The design of the fixtures had to be based around a backing plate size. This backing plate is a piece of material, normally made out of a medium carbon steel, placed at the bottom (back) of the plates to be welded. The main purpose of this backing plate is to prevent the welded material being forced out of the joint line during a weld run. Since the tool shoulder applies a downward force on the plasticized material the backing plate must support the welded plate and resist any thermal deflection.

IV WELDING PARAMETERS

The welding parameters are the key art of FSSW process. They decide what materials that can be welded by this new technology and determine the thickness of work piece with the help of literature. The important input process parameters in FSSW are listed below.

1. Tool rotational speed (N)-Tool rotation speed is one of the most important parameter using FSSW process. In this process Tools speed are used 225, 560, 900 and 1400 rpm. The motion of the tool is generate frictional heat on the work pieces such a HDPE Sheet, to extruding the softened plasticized material around it and forging the same in place so as to form a solid-state seamless joint. As the tool rotates and moves deep along on Z axis of the lap surfaces and heat is being generated at the shoulder work piece and to lesser extend at the pin work-piece contact surfaces, as a result of the frictional-energy dissipation.

2. Plunge rate (f)- The Plunge rate depends on several factors, such as polymers and alloy type, rotational speed, penetration depth, and joint type Higher tool rotation rates generate higher temperature because of higher friction heating and result in more intense stirring and mixing of material. Plunge rate are define from when wheel is one rotation into convert reciprocating moves 2 mm at z-axis of machine.

*3. **Dwell Time (Td)***-Dwell time is the time for which the tool is continue to rotate on the spot of the joint with no movement or no further plunge of the tool. Actually, the dwell time is the parameter responsible for the melting of the HDPE. During this time, stirring of the material occurs. The temperature of the weld increases with the dwell time. This is due to fact that the friction heat produced in the vicinity of the tool increases with the dwell time, so the temperature of the material increases. The temperature of the material reaches to the melting temperature but it does not change with extended dwell time. The values of the dwell time taken in this study are in the range of 30 to 90 seconds.

*4. **Axial force (F)-***During traversing, softened material from the leading edge moves to the trailing edge due to the tool rotation and the traverse movement of the tool, and this transferred material, are consolidated in the trailing edge of the tool by the application of an axial force.

*5. **Tool Plunge Depth (Z)-***The tool plunge depth is the depth to which the tool penetrates into the weld joint. In this study, the tool plunge depth is kept constant to a value of 9mm which is equal to the value of pin length of the tool.

*6. **Tool Delay***-Tool delay is also a parameter which mainly decides the macrostructure of the weld nugget. It is the delay made in the withdrawal of the tool as soon as the dwell time is over. The cross section of the weld nugget depends upon the waiting time of the tool after the end of the dwell time. The values of the tool delay have been taken for the studies are in the range of 5 to 9 seconds.

*7. **Nugget Formation***-Nugget Formation is the thickness of solid molten material which takes place around the tool pin. The nugget thickness increased with the dwell time. There is a direct relationship between the nugget thickness and weld bond area. The weld bond determines the strength of a weld in metals. The high friction heat affects the nugget formation. The nugget gets thicker with tool rotational speed. The friction heat produced in the weld area increases with the tool pressure and obtaining thicker weld nuggets.

*8. **Tool Design-*** Tool design influences heat generation, plastic flow, the power required, and the uniformity of the welded joint. Tool geometry such as probe distance, probe diameter and shoulder shape & size are the key parameters because it would affect the heat generation and the plastic material flow. Finally tool geometry and design standard base size given by the probe diameter is 0.8 times the sample thickness plus a constant of 2.2 mm, shoulder diameter is 2.1 times the probe diameter plus 4.8 mm according to rivet joint consideration. Friction stir welds are characterized by well-represent weld nugget and flow contours, almost spherical in shape, these contours are dependent on the tool design and welding parameters and process conditions used.

9. Fixture and clamping plate-Obtaining good stability during the process is important since any deflection or major vibration would affect the quality of the weld.

V THERMAL ANALYSIS IN ANSYS

A thermal analysis calculates the temperature distribution and related thermal quantitiesin a system or component. Typical thermal quantities of interest are:

- The thermal distributions
- The amount of heat gained or lost
- Thermal gradients
- Thermal fluxes.

Thermal simulation plays an important role in the analysis and design of manyengineering applications including welding, forging, heat exchangers, internal combustionengines, turbines, piping systems, and electronic components. Usually, engineerscouple the thermal analysis and structural analysis with a view to calculate the thermalstresses (*i.e.* stress caused by thermal expansions and contractions). Basically, ANSYS
Supports two types of thermal analysis:

- A steady-state thermal analysis that determines the temperature distribution andother thermal quantities under steady-state loading conditions. A steady-stateloading condition is a situation where the heat storage effects varying over a periodof time can be ignored.
- A transient thermal analysis that determines the temperature distribution and otherthermal quantities under conditions that vary over a period of time.

HEAT GENERATION IN FSSW

The approach followed for friction heat generation calculations in Friction Stir Spot weldingis based on the analytical model proposed by Frigaard [55]. This scheme is reportedin Figure 4.3.2.1. The major hindrance in modelling the heat flow in friction stir spot.

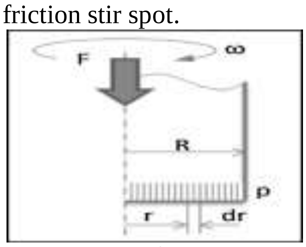


Figure 1-Scheme of Analytical Model

Welding(and FSW) is to account for the adequate description of the energy input. This is because the friction coefficient μ is changes continuously, from about one at the start of dry sliding to about nearly negligible (or zero) when the local melting temperature has been reached at the tool-work piece interface. Considering an ideal case as shown in Figure 4.3.2.2, the torque required for rotating a circular shaft against a surface under the action of an axial load is given in equation

$$M_t = \int_0^{M_t} dM = \int_0^R \mu P(r) 2\pi r^2 dr = \frac{2}{3}\mu\pi P R^3$$

Where, *Mt* is the frictional torque, μ is the coefficient of friction at the interface, *P*(*r*) is the pressure distribution (here considered uniform) across the surface and equal to *P* (Pa) and *R* is the surface radius.

If all the shearing work is converted into frictional heat then the average heat input per unit area per unit time can be represented as:

$$q_0 = \int_0^{M_t} \omega \, dM = \int_0^R \omega 2\pi\mu P r^2 dr$$

Where, *q*0 is the net frictional power in Watt and is the angular velocity in rad/s.

Expressing the angular velocity in terms of the rotational speed, *!*= 2_*N*, we get:

$$q_0 = \int_0^R 4\pi^2 \mu P N r^2 dr = \frac{4}{3}\mu\pi^2 P N R^3$$

it is clear that the heat input depends on the tool rotation speedand the shoulder radius, leading to a non-uniform generation of heat during the process.In this work, the coupled-field simulation for prediction and validation of the peaktemperature outcome was performed for the welding condition representing N=980rpm,*f* =20mm/min, Z=6.8mm and *tdw*=30s. The values of friction coefficient μ for sliding contactbetween High Density Polyethylene and Steel materials was taken equal to 0.12±0.02 from [56].The axial load exerted at the end of a dwell phase of 30s at 980rpm by a tool with taper cylindrical pin was found to be 3.997kN from experiments. This load was used for the calculation of the axial pressure *P* exerted on a projected area A with surface radius.

VI COUPLED-FIELD ANALYSIS

Some types of coupled-field analyses, such as thermal-structural and magnetic-thermal analysis are used for representing thermal effects coupled with other phenomena. A coupled-field analysis can use matrix-coupled ANSYS elements, or sequential load-vector coupling between seperatesimulations of each phenomenon. The computational analysis procedure adopted in this work represents a Coupled-Field Structural-Thermal analysis with elements shifting from thermal (SOLID87) to structural (SOLID187).

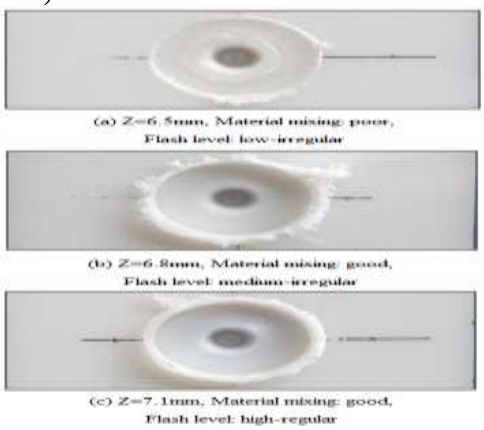


Figure 2-Weld Appearance at Different Tool Plunge Depths

VII SIMULATION DATA AND RESULTS

For the simulation of the weld joints, particularly select tool profile with concavity of specimen was chosen on the basis of their experimental strength and temperature generated. The specimen number was prepared at the available type of tool rotational speed. The temperature distributions of specimens obtained such as shown in below.

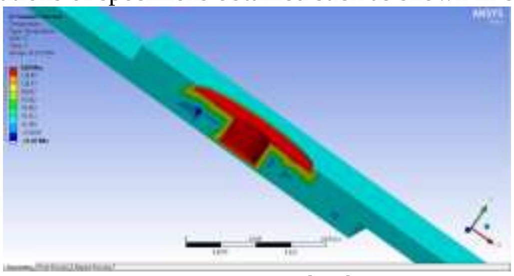


Figure 3-Temperature distribution

Temperature distribution for specimen

1. Total heat input as per applying in KW
2. Convective coefficient as per applying in W/m °C
3. Ambient temperature as per applying in 23°C
4. Maximum temperature attained during the process in °C.

TOTAL HEAT FLUX

For the simulation of the weld joints, particularly tool pin profile with concavity of specimen choose on the basis of their experimental strength and temperature generated. The specimens willprepare at the tool rotational speed. The temperature distributions of specimens obtained:

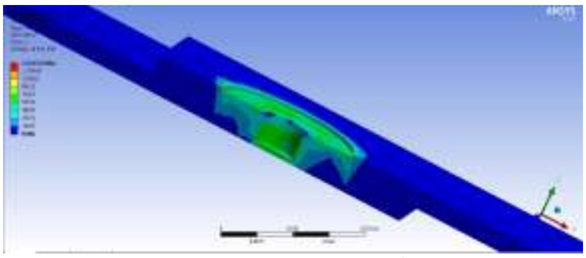


Figure 4-Total heat flux

STATIC STRUCTURAL ANALYSIS

For the simulation of the weld joints, particularly type of pin profile with concavity of specimen was chosen on the basis of their experimental strength and temperature generated. The specimens will have prepared at the tool rotational speed. The lap shear analysis on ANSYS 14.5 of specimens obtained will have presented as follows:

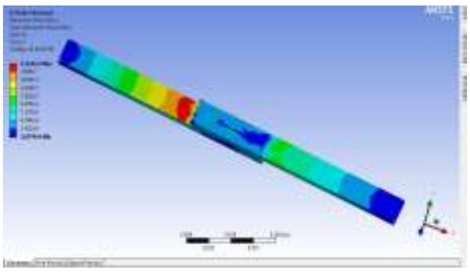


Figure 5-static structural analysis

CONCLUSION

Heat generation and heat transfer play a major role in FSSW in determining the success of the joining process as well as predominantly establishing the joint characteristics and properties. 9. In this work, the computational analysis was performed using commercial FEM code ANSYS 14.5 and the heat generation calculations were based on a simplified analytical model. The resultant temperature distribution shows a good agreement with the experimental temperature outcomes. Experiments in welding present a unique set of challenges, and modelling efforts are used extensively in all branches of welding research to investigate welds on scales and in ways that are impossible or practically no feasible experimentally.

Many of these challenges in FSSW are magnified

• It is a short duration and transient process.
• It involves high forces, of the order.
• The rotational speeds are high, of the order of 100 to 1500 rpm
• The material flow patterns during the weld are quite complex
• Steep thermal gradients occur, both in time and space
• The volume of the total weld zone is small
• FSSW is generally executed on thin sheets which make contact type temperaturemeasurements quite difficult.

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