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Friction Stir Welding: A green technology for welding joints with dissimilar metals (Al Alloy-Cu Alloy)

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Friction Stir Welding (FSW) extends its advantages due to its low energy consumption, reduced material waste and no harm in regards to radiation and hazardous fumes. Also, FSW process does not require any alloying elements, arc and filler wire. This process comes under the category of 'eco-friendly' and 'green' process, because of its zero pollution, larger efficiency and high productivity. The objectives of this study are: (a) to study the aluminium and copper alloy FSW joints, (b) to conduct the experiments of aluminium and copper alloy FSW joints using 'Full Factorial' Design of Experiment (DOE), (c) effects of process variables on power consumption during friction stir welding process. From this study, it can be concluded that FSW can be adopted across industries as it is an eco-friendly and more energy efficient over other fusion welding processes.

Keywords: Full factorial, axial force, power, rotational speed, welding speed.

Introduction

In conventional fusion welding process, various welding defects arises such as porosity, crack, lack of fusion, etc. due to addition of external filler material for joining the base materials. But, in case of FSW, the base materials get fused by itself without any addition of filler material. Therefore, as compared to other fusion welding processes, there is a very small chance of defects generation in FSW[1]. In the year 1991, FSW process was first invented at The Welding Institute (TWI), United Kingdom (UK) by Mr. Wayne Thomas. The working principle of FSW process is based on the frictional heat generated between two contacting surfaces. In this process a rotating non consumable tool with a profile pin is the main part to generate frictional heat. This rotating tool plunges inside the material in such a way that pin completely goes inside the material and shoulder makes a surface contact with material and starts generating frictional heat. The material around the tool get softens because of frictional heat, hence brings them to the plasticized effect. At the same time pressure is applied from upward direction and tool travels in the forward direction. In this way due to forward motion of tool contacting material comes in the plasticized zone and joining takes place. It is observed that an exit hole is being left at the end side of welding material. The diagramatic depiction of FSW process is shown in Fig. 1[1].

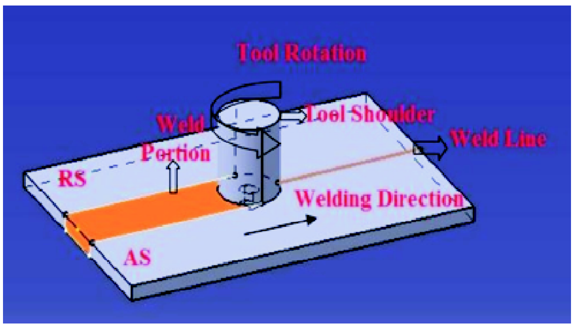

Fig. 1. Diagramatical representation of FSW[1].

Some advantages of FSW process over conventional fusion welding processes are mentioned below[2].

Eco-friendly process[2]: In today's world, it is very crucial for any process to be environment-friendly by reducing Carbon footprints, eliminating health hazards and preserving natural resources. The conventional welding processes generate hazardous fumes which is harmful for working environment. During friction stir welding process no fume is generated. In conventional welding processes, lot of hazardous waste is generated in terms of scales, spatters, stub loss etc. During this process no hazardous waste is generated. Whereas, no filler material is added, so no hazardous waste is generated during this process. In case of conventional welding, there are chances of rejection of materials due to various possible welding defects resulting wastage of scarce natural resources. As there is less scope of welding defects in case of FSW process, it helps in efficient utilization/preservation of scarce natural resources.

Energy saving FSW process[2]*:* The total energy consumption during a welding process is dependent on 3 parameters: (i) Energy consumed during the process, (ii) Energy consumed by the ancillary equipment and idling losses by machinery, (iii) Energy consumed during post weld treatment like grinding, finishing etc. Considering all these parameters, FSW process is more energy efficient compared to conventional welding processes.

Cost efficient[2]*:* As FSW process comes under the category of solid-state joining process, as there is no requirement of additional filler material, shielding gases, as well as gases used for brazing/soldering. As a result, other accessories such as gas fittings, gas cylinders, wire feeders etc. are not required for FSW process. Considering the expenses incurred, as compared to other conventional welding process FSW is more cost-effective process. The above factors define FSW process as a ‘green-process’ which can be adopted across industries as a sustainable process for the future. Considering its advantages, various industries such as ship-building, automotive industry, aerospace, railway, and construction have gradually adopted the FSW process. Though it is more convenient for joining the same materials, still dissimilar materials as well as dissimilar grades of same metal can be easily joined.

Many researchers conducted various experiments of FSW of dissimilar metals/materials based on various Design of Experiment methods such as RSM, Taguchi, Factorial design (FD), and so on. Also, some of the researchers investigated the energy consumed during friction stir welding process.

Based on design of experiment technique: M. Shunmugasundaram *et al*. conducted the experiments on FSW of AA 6063 and AA 5052 using Taguchi method. From the analysis of variance (ANOVA), it was noted that as compared to feed and tilt angle, welding speed has more influence on the dissimilar joint. K. P. Vasantha Kumar *et al.* formulated a mathematical model to investigate the tensile properties of FSW joint of AA 6061 and AZ31B Mg alloy using Taguchi method.

From the ANOVA analysis, it is concluded that the tool tilt and rotational speed has less effect as compared to welding speed. H. M. Anil Kumar *et al.* performed an experiment on FSW of dissimilar material AA 5083 and AA 6082 using Response Surface Methodology. They developed a model and established a relation between output and input parameters of welding.

Based on weldability of FSW among Al alloy and Cu alloy: Friction stir welding has been done on annealed pure cu and Al 1060. The above-mentioned materials can be comfortably joined by FSW process. Tan has conducted the experiments of FSW on 5A02 Al-alloy and pure copper. It was noted that the joint was welded successfully. P. Xue *et al*. joined copper with Al 1060 using FSW at various process parameters. It was analyzed that when Cu plates were put at advancing side, defect-less joints were produced. But, lots of defects were found when Al plates are put on advancing side. Vahid M. Khojastehnezhad *et al.* performed experiments of FSW on AA 6061-T6 and pure Cu. It is observed from their experiment that defect-less joints can be obtained if rotational speed is high and welding speed is low.

Based on consumption of power: Woongjo Choi *et al.* conducted the experiments on power and energy consumption of FSW of 6061-T6 aluminium alloy. It is analyzed that consumption of power increases with increase in weld speed and rotational speed. So, it can be concluded that power consumption is minimized at low spindle speed and rotational speed. Researchers analyzed the consumption of energy in GMAW (gas metal arc welding) and FSW of different materials. From their analysis, it can be concluded that consumption of energy is very much less in FSW as compared to GMAW. Researchers analyzed the effect of consumption of energy on FSW of aluminum alloy of 2024-T4. It was noted that with increase in velocity power absorbed during the weld increases slightly. Also, at faster speed the overall consumption of energy can be highly reduced.

The current experimental work examines the weld ability for FSW for joining of dissimilar metals. From this study, the objective is to carry out the FSW process for dissimilar metals AA 6061-T6 and Cu B370 using 'Full Factorial' Design of Experiment. Also, the total power consumption of friction stir welding is analyzed during the experiments.

Experimental detail

To conduct the FSW, a numeric controlled FSW machine (ETA, WS004) had been used. In this experiment, AA 6061-T6 and Cu B370 alloy (having dimension 150 mm×50 mm×3 mm) was used as the work-piece material. In this experiment conical shaped pin with threads tool manufactured from H13 material was used (Fig. 2). Some experiments were conducted at rotational speed 1400 rpm, 1000 rpm, and 710 rpm. In this experiment welding speed is taken as 65 mm/min, 40 mm/min, and 25 mm/min. During this experiment, load cells embedded strain gauges were used to capture the quantum of force and torque. Fig. 3 depicts the pictorial view of FSW AA 6061-T6 and Cu B370 alloy Joint.

Fig. 2. Friction stir welding tool.

In this current investigation, 'General Full Factorial' Design with two variables i.e. rotational speed and welding speed with ranging to three levels was adopted.

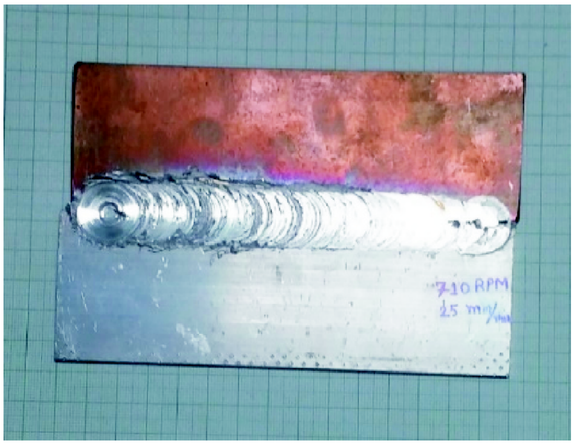

Fig. 3. FSW Joint (AA 6061-T6 and Cu B370).

'MINITAB 17' has been used for data interpretation under this DOE[13]. The Table 1 represents the DOEs considering process variables.

Table 1. Design of experiments

Sr. No.	Std. order	Run order	Pt type	Blocks	Rotational speed (rpm)	Welding speed (mm/min)
1.	1	1	1	1	710	25
2.	4	2	1	1	1000	25
3.	2	3	1	1	710	40
4.	3	4	1	1	710	65
5.	9	5	1	1	1400	65
6.	8	6	1	1	1400	40
7.	6	7	1	1	1000	65
8.	7	8	1	1	1400	25
9.	5	9	1	1	1000	40

Results and analysis

Investigation of axial force applied during FSW process: The variation of applied axial force on FSW process with time has been investigated during the joining of AA 6061-T6 and Cu B370. The observations during the process are mentioned below.

Fig. 4 depicts the graphical presentation of axial force (Fz) with time. The graph represents the variation of axial force at different stages of the welding process. Initially the force starts at sub-zero point (A) due to the softening of the material. With further insertion of pin, the applied force in-

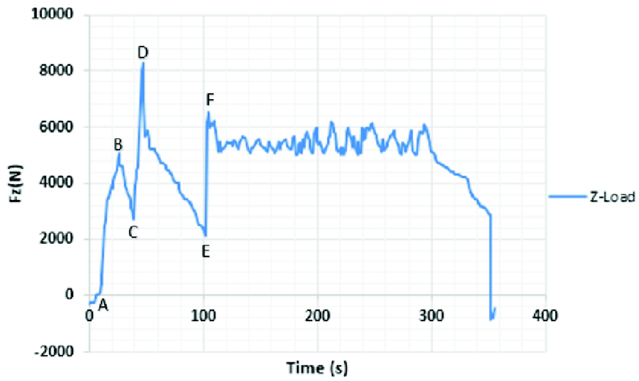

Fig. 4. Axial force vs time.

Table 2. Experimental results – process power

Specimen No.	Rotational speed (rpm)	Welding speed (mm/min)	Power consumed (W)
1	710	25	78.378
2	710	40	78.707
3	710	65	80.541
4	1000	25	74.761
5	1000	40	81.995
6	1000	65	82.653
7	1400	25	52.073
8	1400	40	74.103
9	1400	65	93.832

creases up to point B to overcome the resistance offered by the work piece. But there is a sudden decrease in applied force at point C due to the deformation of material into elastic stage below the rotating tool surface. This stage is known as dwelling[14]. Again, the applied force increases up to point D, when the work-piece makes the surface contact with rotating tool's shoulder portion. Later, applied force further decreases up to point E due to higher deformation occurred after complete contact of the tool shoulder. Thereafter, the applied force increases up to point F and gets stabilised within a certain range till completion of the welding process. During this time, the fluctuation of applied force is less due to only traverse movement of the tool. At the end the applied force drops down once the tool is drawn back from the joint surface[15].

Instruments for measuring power consumption: During the FSW of AA 6061-T6 and Cu B370, a PS100 montronix power sensor was used for capturing the consumption of power. All data of power are captured through LABVIEW software[15]. During FSW process, the force is exerted on the tool to plunge into the abutting edges as well as tool's transverse movement along the weld line. So, power is consumed due to the axial movement of tool to generate frictional heat between tool and base material. Apart from that the additional power is consumed for creating torque by rotational movement of the tool/spindle. So, sum of power consumed by the tool for both axial motion as well as rotational motion is total consumed power during the process. The process power required for the spindle rotation as well as the linear motion of the tool were investigated at different rotational speed and weld speed as mentioned in the Table 2[11].

The graphs depicted in Fig. 5 and Fig. 6 represents the process power consumed at various process variables (weld speed and rotational speed). From the figures (Fig. 5 and Fig. 6), it can be concluded that process power increases at constant rotational speed with increase in welding speed. On the contrary, at constant weld speed, as rotational speed of tool increases process power decreases.

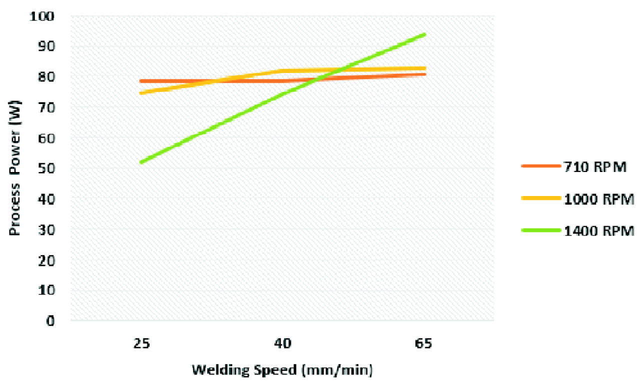

Fig. 5. Weld speed vs process power.

Variation of spindle power with time: Fig. 7 represents the relationship between the time during the FSW process and spindle consumption of power. The graph defines different points where the spindle power consumption changes abruptly such as at the start of rotation of the tool, plunging point of the tool into workpiece, during transverse motion of the tool and at the point of retraction after the joining is completed. The pick power consumption occurs at the point when

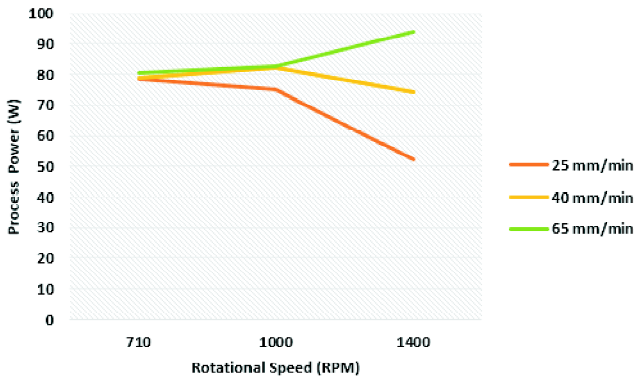

Fig. 6. Rotational speed vs process power.

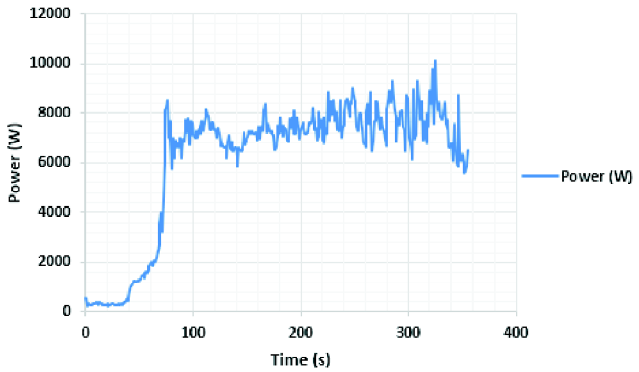

Fig. 7. Variation of spindle power with time.

top surface of base material makes surface contact with the shoulder portion of tool.

Conclusions

In the current study, 'Full Factorial Design' DOE was used for the experiments of FSW for dissimilar metals of AA 6061-T6 and Cu B370. Also, the power consumed during this welding process was measured using a power sensor (Montronix, PS100). From this experimental work, the following important conclusions are derived:

(1) From the experimental work, it is noted that AA 6061-T6 and Cu B370 are joined successfully by FSW by keeping at advancing side Al plate and at retreating side Cu plate at various rotational speed (1400 rpm, 1000 rpm, and 710 rpm) and weld speed (65 mm/min, 40 mm/min and 25 mm/min).

(2) From the experimental investigation of time dependency on axial force, it is observed that the axial forces attain a highest value at the point when work-piece makes a surface contact with shoulder portion.

(3) With increase in welding speed keeping rotational speed constant, power consumption increases. On the contrary, at constant weld with increasing rotational speed of tool power consumption decreases. So, it is concluded that for less power consumption low welding speed and high rotational speed is suitable.

(4) As FSW process does not generate hazardous waste, fumes, UV rays which is harmful for the working environment, this process can be widely adopted across industries for a greener future and healthy workplace.

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