Experimental study of effect of process parameters for heat generation in friction stir welding

Rajnish singh*1 and Anshul yadav2
Department of Mechanical Engineering, Kamla Nehru Institute of Technology, Sultanpur, U.P. - 228118, India.
*Corresponding Author: rajnish.singh.knit@gmail.com

Abstract. In this study, experiments have been performed with three tools of cylindrical pin type for three sets of rotational speeds and feed rates, and the effect of processes parameters on heat generated at different zones of friction stir welded plate is examined. In friction stir welding, the base material is heated at elevated temperature for which heat generation is an important factor. Less heat reduces the rheology and mixing of material whereas more heat reduces the strength of the welded material. From this study, it was concluded that more heat is generated at higher tool rotation rate and tool shoulder diameter whereas less heat generate at high tool traverse speed. This study also reports the optimum tool shoulder diameter, rotational speed and transverse feed for having maximum joint strength.

1. Introduction
Friction stir welding (FSW) was invented by W.M. Thomas at The Welding Institute (TWI) of UK in 1991. It is a technique of joining metal parts by a solid state technique in which a non consumable tool having a specific designed pin and shoulder in rotating state is inserted into the faying surface of clamped sheets or plates to be welded and traversed along the line of joint [1,2]. FSW process is environment friendly and advantageous over conventional fusion welding process as it exhibits low distortions and residual stresses and has no arc flash, fumes or spatters [3]. The welding sheets or plates which are on the fixture base plate are clamped in a manner such that it prevents the faying surface from being forced apart.

In FSW, heat affected zone (HAZ) is also less thus reducing residual stresses, distortion of welded material and thermal cycle related micro structural changes [4,5]. The process parameters in FSW plays an important role in deciding the output parameters and researchers are continuously trying to enhance the weld quality and process efficiency of welding joint [3,4,5].

In FSW, wear resistant rotating tool is inserted into the workpiece mating edge and traversed, thus generating frictional heat and plastic deformation. This causes the material to stir and soften below the melting point of the material [6]. This softened material is transferred from tools leading edge to tools trailing edge and being forged by tool shoulder underneath and pin profile contact thus leaving a solid phase bonding between workpiece [7].

The area of tool development for FSW process is growing and with this progress, tool materials are becoming better in properties and further improvement is needed as growing demand of high temperature melting point with high strength and hardened materials. For achieving desirable product quality by design, Taguchi suggested a three-stage process: system design, parameter design, and tolerance design. The preferred parameter settings are determined through analysis of the “signal-to-
noise” (SN) ratio where factor levels that maximize the appropriate SN ratio are optimal [4,8]. Loftus et al. [9] examined the effect of FSW parameters on temperature and reported that for a given tool geometry and depth of penetration, the maximum temperature was observed to be a strong function of the rotation rate (ω, rpm) while the rate of heating was a strong function of the traverse speed (v, mm min\(^{-1}\)).

In this study, an attempt is made to study the effect of FSW process parameters (tool shoulder diameter, tool rotation rate, tool traverse speed) on the heat generation for welding of material at the distance of R+9 mm from abutting edge, where R is the tool shoulder radius.

2. Experiments
The converted vertical milling machine is used for FSW processes. A new fixture, fixed on milling bed was designed and fabricated for clamping of workpiece as shown in figure 2. The friction stir welding tool is shown in figure 3. For temperature measurements, brazed thermocouple was used along the weld centre line at different positions. The specifications for the FSW setup is mentioned in Table 1.

Nine sets of experiments were performed for different conditions of welding and these parameters were optimized for better performance of welding. The welding conditions are tabulated in Table 2. Cylindrical pin type tool having shoulder diameter of 22 mm, 20 mm and 18 mm, Tool rotation speed of 2000 rpm, 1600 rpm and 1250 rpm and tool traverse speed 15 mm min\(^{-1}\), 20 mm min\(^{-1}\) and 25 mm min\(^{-1}\) is selected for Taguchi optimization technique. The fixture, clamps and stopper is made of mild steel whereas die steel is used for tool. The complete FSW setup as shown in figure 1.

![Figure 1. Experimental setup of friction stir welding](image)

Table 1. Specification of experimental setup

| Specification         | Description                      |
|----------------------|----------------------------------|
| Power                | 5 kW                             |
| Weld position        | Flat                             |
| Power source         | AC current                       |
| Type of Joint        | Butt Joint                       |
| Maximum spindle speed| 3000 rpm                         |
| Tool shoulder diameter| 18 mm, 20 mm and 22 mm           |
| Tool Pin diameter    | 4 mm                             |
| Tool material        | Die steel                        |
3. Results and discussion

The experiments are designed with Minitab 17 software in which L9 Orthogonal arrays is employed. Based on L9 orthogonal array 9 experiments of FSW on aluminium alloy 1100 material performed with the tool shoulder diameter of 18 mm, 20 mm and 22 mm, tool rotation rate of 1250 rpm, 1600 rpm and 2000 rpm and tool traverse speed of 15 mm min\(^{-1}\), 20 mm min\(^{-1}\) and 25 mm min\(^{-1}\). The welded workpiece is shown in figure 4, respectively.
Temperature is measured at distance R+9 mm (R is the tool shoulder radius in mm) from mating edge, by using alumel-chromel type thermocouple at various positions along and away from the centre line. The temperature obtained by the measurement are shown in Table 2.

Table 2. FSW temperature generation result

| Expt. No | Tool Shoulder Diameter (mm) | Tool rotational speed (rpm) | Travel speed (mm/min) | Temperature at (R+9 mm) (°C) |
|----------|---------------------------|---------------------------|----------------------|-----------------------------|
| 1        | 22                        | 1250                      | 25                   | 141                         |
| 2        | 22                        | 1600                      | 20                   | 149                         |
| 3        | 22                        | 2000                      | 15                   | 181                         |
| 4        | 20                        | 1250                      | 20                   | 120                         |
| 5        | 20                        | 1600                      | 15                   | 135                         |
| 6        | 20                        | 2000                      | 25                   | 105                         |
| 7        | 18                        | 1250                      | 15                   | 160                         |
| 8        | 18                        | 1600                      | 25                   | 108                         |
| 9        | 18                        | 2000                      | 20                   | 132                         |

3.1. Effect on heat generation

The FSW results were analysed by Taguchi robust design method to obtain the temperature changes and their effect at different parameters. The results obtained by ANOVA (analysis of variance) and DOE is shown in Table 3 by SNRA, MEAN column and graph. The controlling factors are tool shoulder diameter (TSD) (mm), tool rotation rate (TRR) (rpm) and tool travel speed (TTS) (mm min\(^{-1}\)) and response is heat generation or temperature obtained.

Table 3. SN ratio and mean result for heat generation of FSW experiments

| Run | TSD (mm) | Tool rotation (rpm) | TRR (mm/min) | Temperature at Radius+9 mm (°C) | SN ratio | MEAN |
|-----|----------|---------------------|--------------|---------------------------------|----------|------|
| 1   | 22       | 1250                | 25           | 141                             | 42.9844  | 141  |
| 2   | 22       | 1600                | 20           | 149                             | 43.4637  | 149  |
| 3   | 22       | 2000                | 15           | 181                             | 45.1536  | 181  |
| 4   | 20       | 1250                | 20           | 120                             | 41.5836  | 120  |
| 5   | 20       | 1600                | 15           | 135                             | 42.6067  | 135  |
| 6   | 20       | 2000                | 25           | 105                             | 40.4238  | 105  |
| 7   | 18       | 1250                | 15           | 160                             | 44.0824  | 160  |
| 8   | 18       | 1600                | 25           | 108                             | 40.6685  | 108  |
| 9   | 18       | 2000                | 20           | 132                             | 42.4115  | 132  |

The results obtained in figures 5 and 6 at different TSD, TRR and TTS for SN ratio and mean shows that as TSD changes its SN ratio and mean for heat generation first decreases then increases from tool shoulder diameter 18 mm to 22 mm and is maximum for tool diameter 22mm, though the slope from tool diameter 18 mm to 20 mm is less than from 20 mm to 22 mm. The reason for this is that less shoulder diameter creates less friction and as vertical force by tool is also applied on workpiece so heat generation changes by both effect. In graph 2 as TRR increases, the temperature generation first decreases and then increases. The decreasing slope for TRR 1250 rpm to 1600 rpm is more than increasing graph 1600 to 2000 rpm due to vertical force applied by tool. In this difference in vertical force is also affected a lot. In graph 3 as TTS increases from 15 to 25 mm min\(^{-1}\) heat generation decreases continuously. This occurs because at high TTS less friction and less time generate less heat. Result obtained by comparing graph 1, 2 and 3 in figure 5 shows that tool shoulder diameter 22 mm,
tool rotation speed 2000 rpm and tool transverse rate 15 mm min\(^{-1}\) is the best choice for welding to generate more heat.

![Main Effects Plot for SN ratios](image1)

**Figure 5:** SN\(_{11}\) versus Tool no, Tool rotational and Tool transverse speed graph for temperature generation

![Main Effects Plot for Means](image2)

**Figure 6:** Mean versus tool no, rotation and transverse speed graph for temperature generation
The interaction plot heat generation is generated for temperature generation. Two factors (A and B) are considered to have interaction between them when one has influence on the effect of the other factor respectively as it is shown by graph.

Figure 6 reveals that TSD, TRR and TTS interference has an impact on mean heat generation. The plot clearly indicate that TSD 22mm, TRR 2000 rpm and lowest TTS 15 mm/min is the best option for obtaining maximum heat generation among these parameters. At this parameter, the heat generation is maximum due to more friction and enough time that generates more heat. The complete interaction of all parameters shown in figure 7 reveals that as friction and rheology increases, heat generation increases.

![Interaction Plot for Temperature at (R+9mm)(OC)](image)

**Figure 7:** Interaction plot b/w TSD (tool shoulder diameter, TRR (tool rotational rate) and TTS (tool transverse speed) for temperature generation

### 3.2. Microstructural study

Figures 8(a) through 8(i) corresponding to experimental data set of Table 4 shows microscopic images of friction stir welded Al alloy at the position where temperatures were measured. This shows that grain size is refined after friction stir welding. These microstructure images are near the thermocouple brazed point. In Figures 8 (c), 8(f) and 8(i) images are more segregated points of constituent of aluminium alloys. These microstructure are at 2000 rpm, therefore more strength can be obtained due to this hardening. It can be observed that more fine grains can be obtained at high rotational speed and at large temperature gradient.
Figure 8: Microstructural images of friction stir welded Al alloy at the position where temperatures were measured. (a) through (i) corresponds to experimental data set of Table 4

Scanning electron microscopy (SEM) was performed on the welded workpiece after their tensile test and base metal to obtain its morphology different magnification. Figure 9 shows that after FSW, ductile to brittle transformation is very less or negligible because material is heated at elevated temperature below melting point of welding material. The sample three shown in figure are at optimised welding parameters conditions. At high resolution of SEM images more dimples are shown.
4. Conclusions

In this study, FSW experiments were conducted to join Al workpiece and an attempt was made to study the effect of process parameters (tool shoulder diameter, tool rotation rate, tool traverse speed) on the heat generation. From the study it was concluded that FSW leads to significant microstructural refinement and homogenization. Increase in traverse speed reduces the heat generation, stirring time, and area of stir zone with its grain size, rheology (deformation & flow of matter) of the plastic material but tool rotation rate and tool shoulder diameter affect inversely. At higher TRR and TSD, heat generation increases which enhances better particle distribution with this grain size, stir zone area also increases. The strength of welded plate obtained maximum in case of 22 mm shoulder and 15 mm
transverse feed for maximum TRS. The microstructure revealed that fine grains structure obtained at high rotational speed and very slow traverse rate. SEM images of fractured sample also predicted brittle to ductile transitions was resulted at optimum welding parametric conditions of welding of friction stir welded aluminium alloys.

5. References

[1] R.S. Mishra, Z.Y. Ma 2005 Friction stir welding and processing, Materials Science and Engineering. 50, 1-78.
[2] A. Meilinger, I. Torok 2013 The importance of friction stir welding tool, Production Processes and Systems. 6, 25-34.
[3] P.H. Shah, V. Badhe 2016 An experimental investigation of temperature distribution and joint properties of Al 7075 T651 friction stir welded aluminium alloys, Procedia Technology. 23, 543 – 550.
[4] S.K. Karna, R.V. Singh, R. Sahai 2012 Application of Taguchi Method in Indian Industry, International Journal of Emerging Technology and Advanced Engineering. 2, 387-391.
[5] S. Wei, C. Hao, J. Chen 2007 Study of friction stir welding of O1420 aluminum-lithium alloy, J. Mat. Sci. Engg. A 170, 452-453.
[6] V.B. Sivakumar, , D. Raguraman, D. Muruganandam 2014 Review Paper on Friction Stir Welding of various Aluminium Alloys, IOSR Journal of Mechanical and Civil Engineering. (IOSR-JMCE) 46-52.
[7] A.R.S. Essa, M.M.Z. Ahmed, A.K.Y.A. Mohamed, A.E. El-Nikhaily 2016 An analytical model of heat generation for eccentric cylindrical pin in friction stir welding, Journals of Material Research and Technology. 5, 234–240.
[8] R.A. Wysk, B.W. Niebel, P.H. Cohen, T.W. Simpson 2000 Manufacturing Processes: Integrated Product and Process Design, McGraw Hill New York.
[9] Z. Loftus, W.J. Arbegast, P.J. Hartley 1998 Friction Stir Weld Tooling Development for Application on the 2195 Al-Cu-Li Space Transportation System External Tank.
[10] A. Ghosh, A. Yadav, A. Kumar 2017 Modelling and experimental validation of moving tilted volumetric heat source in gas metal arc welding process, Journal of Material Processing and Technology. 239, 52–65.
[11] W.M. Thomas, K.I. Johnson, C.S. Wiesner 2003 Friction stir welding–recent developments in tool and process technologies, Advanced Engineering Materials. 5, 485-490.
[12] A. Yadav, A. Ghosh, A. Kumar 2017 Experimental and numerical study of thermal field and weld bead characteristics in submerged arc welded plate, Journal of Materials Processing Technology.248, 262–274.
[13] A. Scialpi, L.A.C. De Filippis, P.Cavaliere 2007. Influence of shoulder geometry on microstructure and mechanical properties of friction stir welded 6082 aluminium alloy, Materials & Design. 28, 1124-1129.
[14] P. Reddy, V. Patel, A. Yadav, S. Patel, A. Kumar 2018 Modelling and simulation of equilibrium and non-equilibrium solidification in laser spot welding, IOP Conf. Series: Materials Science and Engineering. 310, 012092
[15] J.M. Piccini, H.G. Svobod 2015 Effect of the tool penetration depth in Friction Stir Spot Welding (FSSW) of dissimilar aluminium alloys, Procedia Materials Science. 8, 868 – 877.
[16] R.A. Bates, R.S. Kenett, D.M. Steinberg, H.P. Wynn 2006 Achieving Robust Design from Computer Simulations, Quality Technology & Quantitative Management. 3, 161-177.
[17] S. Ugendor, A. Kumar , A.S. Reddy 2014 Microstructure and Mechanical Properties of AZ31B Magnesium alloy by Friction stir Welding, Procedia Materials Science. 6, 1600 – 1609.
[18] O.S. Salih, H. Ou, W. Sun, D.G. McCartney 2015 A review of friction stir welding of aluminium matrix composites, Materials and Design. 86, 61–71.