Identification, Analysis and Optimization of Process Parameters of Friction Stir Welding: A Critical Review

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ABSTRACT

This review work is taken up to summarize and evaluate the past research works to identify the prominent process parameters of Friction Stir Welding (FSW). The effect of rotational speed, welding speed, tool pin profile, tool tilt angle, tool shoulder diameter, axial force and tool offset on the responses is evaluated. The summarization and evaluation of various optimization techniques employed to optimize the process parameters of FSW in various research works is also taken up. Taguchi and Response Surface Methodology (RSM) techniques are identified as most popular and effective optimization techniques. The integrated methods, design of experiments and the analysis of variance in Taguchi method and Response Surface Methodology are evaluated. The summarization of the effect of process parameters and optimization techniques helps to identify the explored materials, prominent process parameters, explored responses and effective optimization techniques that will open new insights into the FSW research.

Key words: Friction Stir Welding, Process Parameters, Responses, Optimization Techniques, Taguchi method, Response Surface Methodology.

INTRODUCTION

Friction stir welding (FSW) was invented by The Welding Institute (TWI) Ltd in 1991. The industrial usage of FSW in production was started in mid-1990's, makes it one of the welding techniques that progressed from invention to industrial usage in shortest time period. FSW is a solid state joining technique that uses the rotating tool to generate heat by friction and soften the materials to be joined [1]. The high-strength aluminium alloys up to 75 mm thick plates can be successfully welded by the FSW. Advancement of FSW with the well-developed tools facilitated wider usage of this joining method in aerospace, ship building and automotive industries. FSW is very popular technique to join the aluminium alloys of 2000, 5000, 6000, 7000, Al-Li series and aluminium matrix composites. Also, it is gaining prominent place in joining magnesium, copper, zinc, lead, titanium alloys and also for steel alloys [2].

A rotating and traversing tool shoulder (non-consumable) is pressed against the material. The heat is generated by friction that causes the softening and plastic deformation of the material. A probe protrudes from the shoulder and of a length slightly less than the thickness of the plates to be joined sweeps the softened material between the retreading side (tool rotation and tool traversing are in opposite direction) of the tool and the surrounding un-deformed material. The extruded material deposited behind the tool to form a solid phase joint behind the tool as shown in the fig.1 [3].

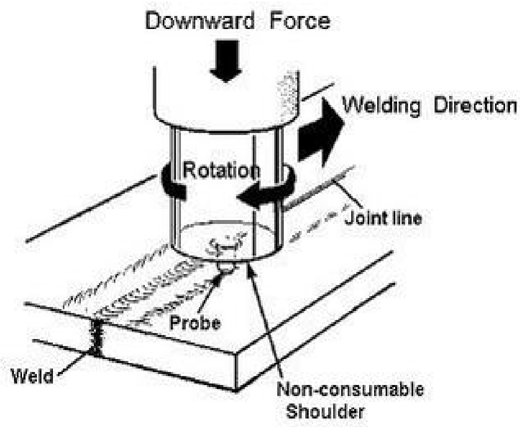

Figure 1. Schematic diagram of FSW process

A friction stir welding joint usually have four distinct regions as shown in the fig.2. They are (a) Unaffected base metal zone which is remote from the weld and microstructure and mechanical properties are unaffected by the heat. (b) Heat affected zone (HAZ) which experiences the thermal cycle and experiences the change in microstructure and/or the mechanical properties, but no plastic deformation occurs in this region. (c) Thermo-mechanically affected zone (TMAZ) in which plastic deformation occurs. The recrystallization also occurs in this region except in the aluminium alloys. In the aluminium alloys the recrystallization zone is a distinct sub-zone in TMAZ. (d) Stir zone (SZ) which is a recrystallization region in the TMAZ in aluminium alloys and also popularly being called as weld nugget [4].

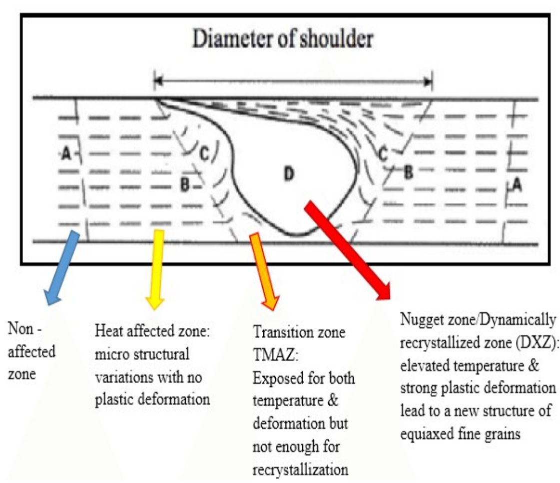

Figure 2. Different zones of FSW

Loureiro *et al*., (2007) detailed the advantages of FSW of thin aluminium alloy sheets compared to other fusion welding processes. FSW minimizes porosity and cracking problems and reduces welding cost [5]. R.Nandan *et al.*, (2008) discussed about the metallurgical, environmental and economic benefits of FSW compared to other fusion welding techniques. Higher quality welded joints are resulted by FSW method because the absence of distortion and solidification defects, which are common in fusion welding techniques. FSW gives dimensional stability and better mechanical properties resulted from fine recrystallization microstructure. FSW is also a green technique as the process is energy efficient (2.5% of energy needed by laser beam welding), produces no fumes, does not use shielding gas, and does not use filler material [6]. A.K.Lakshminarayanan *et al.*, (2009) compared the mechanical properties of welding joint of aluminium alloy AA 6061 by different welding processes. The joints prepared by gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) exhibited poorer mechanical properties and resistance to hot cracking compared to friction stir welding. They cited the reason for this as the microstructure in the weld zone was coarse and columnar in GMAW and GTAW, whereas in FSW it was fine and equiaxed [7]. S Malarvizhi *et al.*, (2010) experimented and evaluated the tensile properties, fatigue performance and corrosion resistance of square butt joint of AA 2219 prepared by gas tungsten arc welding (GTAW), friction stir welding (FSW) and electron beam welding (EBW). FSW joints exhibited superior tensile properties, better fatigue performance and higher joint efficiency than the EBW and GTAW joints. However, the corrosion resistance offered by GTAW was better among the three welding method joints [8]. G.Padmanaban *et al.,* (2010) compared the tensile properties of the weld joint of magnesium alloy AZ31B by three different methods namely gas tungsten arc welding (GTAW), laser beam welding (LBW) and friction stir welding (FSW). They concluded that joint prepared by the LBW exhibited better tensile properties compared to the other two methods because of formation of very fine grains in the fusion zone and absence of heat affected zone in the LBW [9]. S Raghunathan *et al.*, (2015) compared the mechanical properties and micro structural features of friction stir welding (FSW), gas metal arc (GMA) and shielded metal arc (SMA) welding joints of naval grade HSLA steel. They concluded from the experimental results that the FSW welded joints showed better mechanical properties and also the joints were free from the specific defects arise in the fusion welding methods [10].

P. L. Threadgill *et al.,* (2003) discussed the drawbacks of FSW. More substantial clamping is required in FSW compared to arc welding methods, as the work piece has to withstand downward and traversing forces. At the withdrawing position of tool from the material exit hole is left. FSW is not suitable for the cases where metal deposition is required. FSW which is fully mechanised hence cannot be used in the cases where manual process is suitable because of complex weld shape [11].

EFFECT OF PROCESS PARAMETERS IN FRICTION STIR WELDING

The process parameters of the FSW can be classified as tool design parameters and operating parameters. The tool design parameters surfaced in the literature survey were tool pin profile, shoulder diameter, tool pin diameter, tool pin length and shoulder profile. The operating parameters considered in the works were rotational speed, welding speed, axial force and tool tilt angle. The operating parameters such as offset distance and rotation direction were exclusively considered when the welding was performed on the dissimilar materials. The various responses considered in the works were microstructure of the weld, tensile strength, percentage elongation, hardness, temperature distribution, weld defects, formation of intermetallic compounds, fatigue strength, residual stresses and tool wear. The interface microstructure was also studied in the cases of dissimilar material welding. Most of the works were carried on the aluminium alloys, dissimilar aluminium alloys. Few works had taken up on the magnesium alloys, Ti-6A-4V, Polyolefin composites, aluminium based composites and joints of aluminium and steel. The effect of prominent process parameters on the responses is discussed below.

Rotational speed and Welding speed

Welding speed was more significant factor compared to rotational speed while evaluating the tensile strength of the aluminium alloys and aluminium composites [15] [22] [24] [43]. Whereas rotational speed was more significant factor compared to welding speed while evaluating the tensile strength of magnesium alloys and polypropylene composites [14] [25] [32]. The temperature under the tool and the peak temperature were highly dependent on the rotational speed than the welding speed [16] [42]. Rotational speed and welding speed had contradicting effect on the transient temperature distribution [27]. Forging force depends on the tool shoulder diameter and tool rotational speed. Welding force depends on tool pin profile and welding speed [22]. The grain size was decided by both rotational speed and welding speed [42].

Tool pin profile

Regarding the parameter 'tool pin profile', the studies were aimed to find the suitable pin profile for the weld material. Over 70% of the FSW studies were on the similar aluminium alloys and dissimilar aluminium alloys. For these materials straight cylindrical profile [12] [30], taper cylindrical profile [23] [33] [35] and straight square profile [18] [19] [20] were identified as most suitable tool pin profiles to produce mechanically sound, defect free joints. Tool pin profile along with welding speed was more significant process parameter in FSW of aluminium metal matrix composites [24]. While welding the metal matrix composite Al-TiB2 straight square profile gave better mechanical properties and tapered square profile yielded better metallurgical properties [21]. Taper cylindrical profile resulted in defect free, finer microstructure and optimum mechanical properties of friction stir weld joint of magnesium alloys [32] [36] [37].

Tool tilt angle

Tilt of the welding tool leads to stronger stirring action of the material and generates higher frictional force at the work piece-tool interface. Tool tilt angle is one of the significant factors that control the weld properties by altering the plastic material flow in the nugget zone [17] [25] [26] [28]. The increase in tool tilt angle increased the thickness of the intermetallic compounds at the interface of the joint of AA5083 and SS400 [13].The weld joint of AA5052 and SS304 at higher tilt angle and pin depth resulted in defect free, high strength joint [40].

Tool Shoulder diameter

The increase in shoulder diameter increased the peak temperature and heat generated under the tool. With the increase in shoulder diameter, the temperature gradient became less steep and reached a minimum value for 18 mm and beyond 18 mm there was a moderate decrease in the temperature gradient up to 24 mm. At constant rotational speed, the volume of shoulder driven material flow reduced marginally with the increase in shoulder diameter. Welding force increased steeply with shoulder diameter up to 18 mm; further increase in shoulder diameter caused negligible variation [29]. Forging force largely depended on the tool shoulder diameter and the tool rotational speed [22]. Mechanically sound and defect free joints were prepared at 18 mm shoulder diameter [19] [39].

Axial force

In evaluation of tensile strength of friction stir welding joint of aluminium material matrix composite, out of the parameters selected (welding speed, rotational speed, axial force and tool pin profile) tool pin profile and welding speed were more significant [24]. Higher axial forces and higher rotational speeds resulted in higher weld joint efficiencies. Lower axial forces and lower rotational speeds resulted in voids in the weld nugget [31].

Tool offset

The tool offset was provided in the case of dissimilar material friction stir welding. It was observed that the softer material was placed on the retreading side and the harder material on the advancing side. It was also observed that the offset was into the softer material to avoid excessive heat generation. Thicker intermetallic compounds formation resulted when the offset was into the harder material. Maximum tensile strength was obtained with 2 mm tool axis offset towards AA5052 in a joint of AA5052 and HSLA steel [33]. Tool pin offset of 0.4 mm into AA5083 along with lower rotational speed and lower welding speed resulted in maximum tensile strength joint without defects [34]. Wrong selection of tool offset distance along with other process parameters lead to formation of thicker intermetallic compounds which initiate the crack nucleation and formation of defects which causes the stress concentration [38]. In the recent investigation of friction stir welding of AA6061 and AZ31B, the tool offset was into the AZ31B. The tensile strength reached maximum at 1.5 mm of offset and defects were appeared when the offset reached 2.5 mm [41].

OPTIMIZATION OF PROCESS PARAMETERS IN FRICTION STIR WELDING

After careful examination of the research works carried over a decade on the optimization of process parameters of FSW, it is observed that the Taguchi method was the most used optimization technique followed by response surface methodology. As a part of continuous improvement, integrated methods involving the above two methods were evolved. The literature survey concentrated on identification of the type of design of experiment, method used to develop models for the responses, techniques used to optimize the responses and analysis employed to find the significance of the process parameters.

Taguchi and integrated Methods

Taguchi method and integrated Taguchi methods are the most popular techniques used to solve the optimization problems of FSW. More than half the studies in the literature survey belong to this category. Taguchi approach uses the well balanced robust experimental design called Orthogonal Arrays (OAs) to study a large number of parameters with a small number of experiments. Signal-to-Noise (S/N) ratios which are logarithmic functions of responses, serve as objective functions for optimization [46]. The S/N ratio is a measure of robustness that identifies the control factors that reduce the variability in a process [72].

Taguchi – Grey Relational Analysis

To overcome the limitation of the traditional Taguchi method in solving the multi-objective optimization problems, the grey relational analysis was combined with the Taguchi method [46] [72]. Grey systems are complex multivariate systems, in which the relationship among the factors is unclear and contain incomplete information. Grey relational analysis compensates the short comings of inexact experiments with statistical regression [61]. In the first approach, initially the grey relational coefficients for the responses were calculated and then grey relational grades. Later S/N ratios were calculated for the grey relational grade to decide the optimum values of process parameters [46] [78] [86]. In the second approach grey relational coefficients were calculated for the S/N ratios of responses. The grey relational grade which is the mean sum of the grey relational coefficients for each experiment was calculated. The optimum values of parameters were decided with the grey relational grades and mean effect for each level of parameters [58] [72] [74]. In the third approach Taguchi method was limited to the design of experiments. The grey relational coefficients were calculated for the responses and from that data grey relational grade were calculated for each experiment [60] [87].

Design of Experiment (DoE)

Design of experiment is a statistical procedure to find the number of runs required to develop a model for response. A DoE contains "level" and "factor". Factor is a parameter and level is the number of different values of a factor based on its discretization [91]. DoE can be conveniently divided into full factorial design and fractional factorial design. Full factorial design considers all the combinations of the parameters, whereas fractional factorial design considers only statistically important combinations for the experiments. Taguchi designs are usually highly fractionated. Two-level full factorial design is represented as 2^k, where 'k' is the number of factors. Two-level fractional factorial design is represented as 2^{k-f}, where 'f' is the fraction considered. To save cost and time, fractional factorial designs are preferred to full factorial designs. Three-level, two-factor full factorial design (3^2) [51] [89] and three-level, three-factor full factorial design (3^3) were considered in a few works [44] [57] [61] [87]. The L9 orthogonal array for three-level, three-factor fractional factorial design (3^3) [45] [56] [60] [66] [69] [74] [78] [84] and for three-level, four-factor fractional factorial design (3^4) was used extensively [59] [86] [91]. In the four-level experimentation, for three-factor fractional designs (4^3) [58] [63] [88] and for four-factor fractional designs (4^4), L16 orthogonal array was considered [47] [49] [52] [81].

Analysis of variance (ANOVA)

The analysis of variance is conducted to find the adequacy of model developed and to find the significance of parameters on the response(s). In optimization of the tensile strength of weld joint of cast aluminium alloy A319, the rotational speed and welding speed were the dominant parameters followed by the axial force [44]. Analysis of variance showed that rotational speed was most significant parameter followed by tool pin profile and tool tilt angle in optimizing the responses (tensile strength and hardness) of FSW joint of dissimilar aluminium alloys AA6061 and AA6082 [50]. The significance of process parameters (tool rotational speed and tool tilt angle) of FSW of thermoplastic-polyethylene sheets was evaluated by analysis of variance. The response considered was the ultimate tensile strength of the weld joint. It was found that the tool rotational speed was more influential parameter, whose contribution was 73.85% [51]. In the work of finding the optimum process parameters (traverse speed, tool rotational speed, ratio of shoulder diameter to pin diameter (D/d) and tool geometry) of FSW of dissimilar aluminium alloys AA2219-T87 and AA5083-H321 plates, analysis of variance showed that the significance of D/d was predominant followed by pin geometry and traverse speed. The weld joints were tested for tensile strength [52]. Out of the three parameters (rotational speed, travel speed and tool tilt angle) the tool tilt angle is most prominent variable on the tensile strength of low alloy steel plate joint [56]. Analysis of variance was carried to find the percentage contribution of parameters on the responses (ultimate tensile strength and %elongation) of FSW joint of dissimilar aluminium alloys AA6082 and AA7075. The significance was in the descending order of welding speed, tool type and rotational speed [58]. Analysis of variance was carried to find the significance of process parameters (downward forging force, tool travel speed and probe length) on the tensile strength, bending strength and hardness of weld joint of aluminium alloy AA2024-T351. The probe length was the highest contributing parameter on the tensile strength and the tool travel speed was the most significant parameter on the bending strength as well as on the hardness [59]. The significance of the parameters on the maximum strength of weld joint of polypropylene was in the descending order of tool pin profile, feed rate and rotational speed [63]. It was concluded that the feed rate was the most influential factor followed by rotational speed. The pin diameter and the shoulder diameter have no considerable influence on the residual stresses in weld joint of aluminium alloy AA5086 plates [65]. In the investigation of the effect of process parameters of FSW on mechanical properties (tensile strength, hardness and impact energy) of magnesium alloy AZ31B, it was concluded that welding speed and rotational speeds were more significant, followed by the tool material [69]. In the investigation of optimization of FSW process parameters (tool pin shape, traverse speed, rotational speed, shoulder diameter, pin diameter, depth of penetration, tool tilt angle and shoulder concave angle) of AZ91 alloy sheets. The optimal process parameters were determined with respect to hardness, ultimate tensile strength, yield strength and grain size of the weld joint. Analysis of variance showed that traverse speed was the most significant parameter followed by the shoulder diameter, tool pin shape and rotational speed in the order [73]. The weld joints of dissimilar aluminium alloys AA6061 and AA6082 were tested for tensile strength and percentage elongation. The rotational speed was the most dominant factor followed by tool tilt angle and tool pin profile. [74]. Optimization of the process parameters (welding speed, tool rotational speed and tool tilt angle) of FSW of aluminium alloy AA5083-H321 for maximum ultimate tensile strength, % elongation and micro-hardness had taken up and concluded that the rotational speed and welding speed were the most significant parameters [78]. Investigation of the effect of process parameters of FSW on mechanical properties (tensile strength, hardness and impact energy) of magnesium alloy AZ31B through analysis of variance yielded that welding speed and rotational speed were more significant, followed by the tool pin profile [84]. The multi-response (tensile strength and tensile elongation) optimization of FSW of dissimilar alloys AA8011-H24 and Ti3Al2.5V carried and the analysis of variance concluded that the rotational speed was most significant contributing parameter followed by welding speed and tool pin profile [87]. Investigation of the influence of process parameters of FSW of AA7075 to maximize the responses (ultimate tensile strength and hardness) were carried by Taguchi's method. Analysis of variance showed that the welding speed was more significant parameter than the tool rotational speed [89].

Response Surface Methodology and integrated methods

Response surface methodology (RSM) is a group of mathematical and statistical techniques used to develop a functional relationship between a response of interest and a number of independent variables. RSM treats the interaction of independent variables as surfaces to which mathematical model is fitted [68]. RSM designs a set of experimental runs and carries regression analysis on the experimental data that develops a model for the response. Further analysis is carried to find the optimal set of parameters that produce a maximum or minimum value of the response [70]. The response surface and contour plots are drawn between any of two process parameters and response to visualize the variation of the response. The apex of the surface gives the maximum value of the response and the nadir of the surface gives the minimum value of the response [90].

Meta-heuristic techniques

Meta-heuristic algorithms are effective techniques used to optimize the multi-response problems with many parameters [67]. They are used to optimize the mathematical models developed for the responses in terms of process parameters. The literature survey shows that genetic algorithm (GA) and simulated annealing (SA) were the most popular heuristic algorithms. Genetic algorithm over comes the problem of getting local optima by selecting the population points randomly from the large number of generated population points [79]. Genetic algorithm was used to find the optimum values of rotational speed and welding speed of FSW of AA5083-AA7075, that yield the maximum tensile strength [76]. The model for tensile strength of FSW joint of AA1100 was developed by response surface methodology in terms of welding speed, rotational speed, shoulder diameter and pin diameter. The optimization was carried by genetic algorithm [77]. The mathematical models for ultimate tensile strength and tensile elongation of FSW joint of AA2024-AA6061 in terms of welding speed, rotational speed, axial load and pin shape. Single objective optimization (SOO) and multi objective optimization (MOO) were carried using genetic algorithm and simulated annealing algorithm separately [79].

Simulated annealing (SA) is a random search technique that is not trapped in a local minimum. It is analogous to annealing process in metal working, in which heating to high temperature causes the atoms in the molten state move freely and subsequent slow cooling attains a minimum stable energy state [79]. A model for tensile strength of FSW joint of AA2024-AA7075 in terms of rotational speed and welding speed was developed by response surface methodology. The optimum values of process parameters to get maximum tensile strength were obtained by the simulated annealing algorithm [64]. Simulated annealing algorithm was used to optimize the responses (tensile strength, yield strength and hardness) of FSW joint of AA7075 plates. The adaptive neuro-fuzzy inference systems (ANFIS) had been used to develop the models for responses [67]. The mathematical model was developed by response surface methodology in terms of process parameters (rotational speed, welding speed, axial force and tool pin profile). Simulated annealing algorithm was used to optimize the corrosive resistance of FSW joint of AA2219 [71].

Design of Experiment (DoE)

The popular designs for fitting the second -order models are central composite design and Box-Behnken design. Central composite designs are augmented with axial or star runs ($2k$) and center runs along with fractional factorial runs (2^{k-f}). Rotatable central composite design gives same predicted value for response in all directions whenever it is estimated at same distance from center. The central composite design with the star points represent mid-levels of all the factors is referred as face-centered central composite design, which is non-rotatable. Box-Behnken design is highly fractionated, resulted from combination of two-level factorial design with incomplete block design. These designs are very efficient in terms of number of runs required and are rotatable or near rotatable [93]. Rotatable central composite design was the most extensively used design [53] [55] [62] [70] [71] [75] [80] [83] [85] [90], followed by face-centered central composite design [48] [64]. Box-Behnken design does not contain any points at the vertices of the cubic region (upper and lower limits of variables). This is advantageous when the physical process constraints prohibit the selection of these extreme points in design [79].

Analysis of Variance (ANOVA)

After developing the mathematical model for the response, the analysis of variance largely used to evaluate the adequacy of the model alone without bothering about the evaluation of significance of the process parameters [53] [55] [64] [70] [77] [80] [85]. Analysis of variance showed that rotational speed was the most dominant parameter and tool pin diameter was the least dominant parameter on the tensile strength of FSW joint of AA5083-AA6061. Rotational speed and welding speed play more significant role in generating heat than pin diameter and shoulder diameter [54]. The rotational speed had more influential effect than the welding speed on the mechanical properties (tensile strength, yield strength, impact strength and hardness) of FSW joint of AA6061-AA7039 [62]. The analysis of variance gave the percentage contribution of the process parameters (welding speed-35%, rotational speed-19%, pin shape-23% and axial load-15%) on the tensile strength and tensile elongation of the FSW joint of AA2024-AA6061 [68]. The effect of process parameters on the tensile strength and tensile elongation of FSW joint of AA2024-AA6061 was in the descending order of pin shape, rotational speed, welding speed and axial load [82]. The effect of parameters on the tensile strength of FSW joint of AA7075 was in the descending order of welding speed, rotational speed, shoulder diameter and pin diameter [83]. The most influential parameter on the intergranular corrosion rate of the FSW joint of AA5086 was the rotational speed [90].

CONCLUSIONS

The relative significance of rotational speed and welding speed on various responses depends on the material that is welded and the responses that are evaluated. The cylindrical, taper cylindrical and straight square tool pin profiles are more suitable for welding of aluminium alloys. Higher tilt angles up to a certain limit produces higher frictional force at the tool – work piece interface. Both the welding force and forging force depend on the tool shoulder diameter. Tool offset is provided in the welding of dissimilar material and usually the softer material was placed on the retreading side. Wrong selection of offset leads to defects in the weld that causes the stress concentration. Taguchi method and response surface methodology are the two basic optimization techniques employed widely and successfully. Grey relational analysis is integrated with Taguchi to solve many optimization problems. Genetic algorithm and simulated annealing are the two meta-heuristic techniques coupled with response surface methodology to solve many multi-objective optimization problems with many parameters. Fractional factorial orthogonal array designs in Taguchi method are successfully applied, thus saving time and money by reducing experimental runs. Central composite designs and Box-Behnken designs are used to design the fractional factorial runs in response surface methodology. Analysis of variance evaluates the adequacy of the model developed and significance of each parameter. It is also used to find the percentage contribution of each parameter on the given response. Though we can say that rotational speed and welding speed were the most significant factors in many cases, we cannot conclude that these factors are significant in all the cases. The significance of parameters depends on the material, combinations of parameters and the responses selected.

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