Application of Design of Experiments to Plasma Arc Welding Process: A Review

K. Siva Prasad
kspanits@gmail.com
Assistant Professor
ANITS, Visakhapatnam, India

Dr. Ch. Srinivasa Rao
Associate Professor
Andhra University
Visakhapatnam, India

Dr. D. Nageswara Rao
Vice Chancellor,
Centurion University of Technology & Management
Odisha, India

Design of Experiment commonly referred to as DOE is one of the extensively used methods for experimental study of many manufacturing processes in engineering. DOE is a statistical approach in which a mathematical model is developed through experimental runs. DOE predicts possible output based on the input parameters of the experimental setup. In the present study, a review is made on DOE techniques that have been employed for various welding processes by other researchers. This study predominantly focuses on the usage of Response Surface Method, Taguchi's method and Factorial method in Welding.

Keywords: *Design of Experiment, mathematical model, Response Surface method, Taguchi method, Factorial method, welding*

Introduction

Design of Experiment (DOE) is an experimental or analytical method that is commonly used to statistically signify the relationship between input parameters to output responses, whereby a systematic way of planning of experiments, collection and analysis of data is executed. DOE has wide applications especially in the field of science and engineering for the purpose of process optimization and development, process management and validation tests. A mathematical model has been developed by Avinash and Vinod (2007a) using analysis techniques such as ANOVA and regression analysis whereby the mathematical model shows the relationship between the input parameters and the output responses (Montgomery, 1991). Among the most prominently used DOE techniques are Response Surface Methodology with Central Composite Design, Taguchi's method and Factorial Design. In DOE, synergy between mathematical and statistical techniques such as Regression, Analysis of Variance (ANOVA), Non-Linear Optimization and Desirability functions help to optimize the quality characteristics considered under a cost effective process. ANOVA helps to identify the effect of each factor versus the objective function, Wang et al. (2007b).

Experimental design was first introduced in 1920s by R. A. Fischer who developed the basic principles of factorial design and the associated data analysis known as ANOVA during research in improving the yield of agricultural crops, Alagumurthi et al. (2006a).

Factorial Method

Factorial design is used for conducting experiments as it allows study of interactions between factors. Interactions are the driving force in many processes. Vital interface may be unobserved without factorial design of experiments. In a full factorial experiment, responses are measured at all combinations of the experimental factor levels. The combinations of factor levels represent the conditions at which responses are measured. Each experimental condition is called a "run" and the response measurement is called an "observation", while factorial design can be run on two-levels, three-levels and multi-level factorial. The entire set of runs is the "design". According to Myers and Montgomery (2002a), Full Factorial Design is a design in which all possible combinations of the factor levels are fulfilled. The result from the full factorial experiments would be more reliable, but conducting the full factorial experiments is costly and sometimes prohibitive.

Paper received 21 March 2011. Paper accepted 13 October 2011.
Technical Editor: Marcelo Trindade

Response Surface Method

Response Surface Method or commonly known as RSM is an anthology of statistical and mathematical methods that are helpful in generating improved methods and optimizing a welding process. RSM is more frequently used in analyzing the relationships and the influences of input parameters on the responses. The method was introduced by G. E. P. Box and K. B. Wilson in 1951. The main idea of RSM is to use a set of designed experiments to obtain an optimal response. Box and Wilson used first-degree polynomial model to obtain DOE through RSM and acknowledged that the model is only an approximation and is easy to estimate and apply, even when little information is known about the process. Response Surface Regression method is an assortment of mathematical and statistical techniques useful for modeling and analyzing experiments in which a response variable is influenced by several independent variables. It explores the relationships between several independent variables and one or more response variables; the response variable can be graphically viewed as a function of the process variables (or independent variables) and this graphical perspective of the problem has led to the term Response Surface Method (Myers and Montgomery, 2002a). RSM is applied to fit the acquired model to the desired model when random factors are present and it may fit linear or quadratic models to describe the response in terms of the independent variables and then search for the optimal settings for the independent variables by performing an optimization step. According to Clurkin and Rosen (2002b), the RSM was constructed to check the model part accuracy which uses the build time as function of the process variables and other parameters. Asiabanpour et al. (2006b) developed the regression model that describes the relationship between the factors and the composite desirability. RSM also improves the analyst's understanding of the sensitivity between independent and dependent variables, Bauer et al. (1999a). With RSM, the relationship between the independent variables and the responses can be quantified (Kechagias, 2007c). RSM is an experimental strategy and has been employed by research and development personnel in the industry, with considerable success in a wide variety of situations to obtain solutions for complicated problems.

The following two designs are widely used for fitting a quadratic model in RSM.

Central Composite Designs

Central composite designs (CCDs), also known as Box-Wilson designs, are appropriate for calibrating the full quadratic models described in Response Surface Models. There are three types of CCDs, namely, circumscribed, inscribed and faced. The geometry of CCDs is shown in Fig. 1.

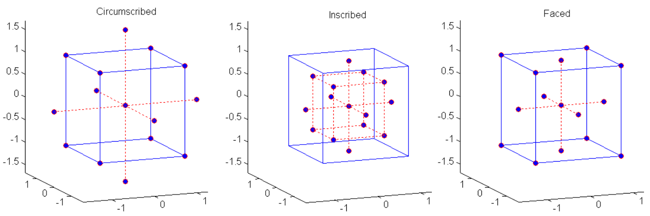

Figure 1. Circumscribed, inscribed and faced designs.

Each design consists of a factorial design (the corners of a cube) together with *center* and *star* points that allow estimation of second-order effects. For a full quadratic model with *n* factors, CCDs have enough design points to estimate the $(n+2)(n+1)/2$ coefficients in a full quadratic model with *n* factors.

The type of CCD used (the position of the factorial and star points) is determined by the number of factors and by the desired properties of the design. Table 1 summarizes some important properties. A design is rotatable if the prediction variance depends only on the distance of the design point from the center of the design.

Table 1. Comparison Of CCDs.

Design	Rotatable	Factor Levels	Uses Points Outside ±1	Accuracy of Estimates
Circumscribed (CCC)	Yes	5	Yes	Good over entire design space
Inscribed (CCI)	Yes	5	No	Good over central subset of design space
Faced (CCF)	No	3	No	Fair over entire design space; poor for pure quadratic coefficients

Box-Behnken Designs

Box-Behnken designs (Fig. 2) are used to calibrate full quadratic models. These are rotatable and, for a small number of factors (four or less), require fewer runs than CCDs. By avoiding the corners of the design space, they allow experimenters to work around extreme factor combinations. Like an inscribed CCD. However, extremes are then poorly estimated.

Some extensions of RSM deal with the multiple response problem. Multiple response variables create difficulty, because what is optimal for one response may not be very optimal for other responses. Other extensions are used to reduce variability in a single response while targeting a specific value, or attaining a near maximum or minimum while preventing variability in that response from getting too large.

Significant criticisms of RSM include the fact that the optimization is almost always done with a model for which the coefficients are estimated and not known. That is, an optimum value may only look optimal, but be far from the truth because of variability in the coefficients.

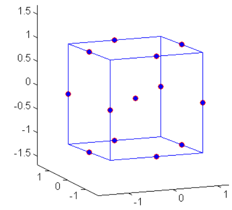

Figure 2. Box-Behnken design.

Taguchi Method

Since the last four decades, there were limitations when conventional experimental design techniques were applied to industrial experimentation. Dr. Genichi Taguchi, a Japanese engineer, developed a new method that is known as orthogonal array design, which adds a new dimension to conventional experimental design. Taguchi's DOE's are denoted by '$L_a b_c$', where 'L_a' are the orthogonal arrays of variables or design matrix, 'b' the levels of variables and 'c' numbers of variables. Taguchi method is a broadly accepted method of DOE which has proven to produce high quality products at subsequently low cost. This method is regularly used in automobile, electronics and other processing industries. The objective of the Taguchi method is to determine the optimum settings of input parameters, neglecting the variation caused by uncontrollable factors or noise factors (Sivarao, 2010). Factor here refers to an input variable whereby the state can be controlled during the experiment. Taguchi method (Juang et al. (2002c), Wu et al. (2004a)), a systematic application in design and analysis of experiments, is used for designing and improving product quality. However, the original Taguchi method was designed to optimize a single performance characteristic. Furthermore, optimization of multiple performance characteristics is much more complicated than optimization of a single performance characteristic (Lin. Z.C et al. (2003d), Fung et al. (2003b), Tarng et al. (2002d), Lin T.R. et al. (2004b), Huang et al. (2003c)). Although similar to DOE, the Taguchi design only conducts the balanced (orthogonal) experimental combinations, which makes the Taguchi design even more effective than a fractional factorial design. By using the Taguchi technique, industries are able to greatly reduce product development cycle time for both design and production and thus reducing costs and increasing profit (Julie Z. Zhang, 2007d).

Taguchi proposed that engineering optimization of a process or product should be carried out in a three-step approach: system design, parameter design and tolerance design. In system design, the engineer applies scientific and engineering knowledge to produce a basic functional prototype design. The objective of the parameter design (Ross, 1988) is to optimize the settings of the process parameter values for improving performance characteristics and to identify the product parameter values under the optimal process parameter values. The steps included in the Taguchi parameter design are: selecting the proper Orthogonal Array (OA) according to the number of controllable factors (parameters); running experiments based on the OA; analyzing data; identifying the optimum condition; and conducting confirmation runs with the optimal levels of all the parameters (Julie Z. Zhang, 2007d). The main effects indicate the general trend of influence of each parameter. Knowledge of the contribution of individual parameters is the key to decide the nature of the control to be established on a production process. ANOVA is the statistical treatment most commonly applied to the results of the experiments to determine the percentage contribution of each parameter against a stated level of confidence (Ross, 1988). According to Roy (1990), Taguchi suggests two different routes for carrying out the complete analysis. In the standard approach, the results of a single run or the average of repetitive runs are processed through the main effect and ANOVA (raw data analysis). The second approach, which Taguchi strongly recommends for multiple runs is to use the Signal-to-Noise (S/N) ratio for the same steps in the analysis.

The Grey system theory proposed by Deng (1989) has been proven to be useful for dealing with poor, incomplete and uncertain information. The Grey relational analysis can be used to solve complicated interrelationships among multiple performance characteristics effectively (Lin, 2003d). By this analysis, a Grey relational grade is obtained to evaluate the multiple performance characteristics. As a result, optimization of the complicated multiple performance characteristics can be converted into optimization of a single Grey relational grade.

An advantage of the Taguchi method is that it emphasizes a mean performance characteristic value close to the target value rather than a value within certain specific limits, thus improving the product quality. Additionally, Taguchi's method for experimental design is straightforward and easy to apply to many engineering situations, making it a powerful yet simple tool. It can be used to quickly narrow the scope of a research project or to identify problems in a manufacturing process from data already in existence (Fraley, 2006c).

It is probably unfortunate that the important concepts advocated by Taguchi have been overshadowed by controversy associated with his approach to modeling and data analysis. There have been many papers and several books explaining, reviewing, or criticizing Taguchi's ideas (Nair, 1992; Parks, 2001a). Most of these, however, have not adequately captured the diverse views on the topic and their underlying rationale. In particular, the Taguchi methodology has not been well represented in statistical journals. These considerations led to a published "panel discussion" by a group of practitioners and researchers (Nair, 1992). The topics covered include the importance of variation reduction, the use of noise factors, the role of interactions and selection of quality characteristics, S/N ratios, experimental strategy, dynamic systems, and applications. Panelists provided comments on topics on which they have worked or with which they had practical experience. Their comments were organized into sections to give readers a balanced picture of the different views on each topic. In this panel discussion, Shin Taguchi proclaimed: "Pure science strives to discover the casual relationship and to understand the mechanics of how things happen. Engineering, however, strives to achieve the result needed to satisfy the customer". In the same paper, Box among others, declared his profound disagreement with this claim. Jeff Wu, one of the panelists, pointed out that the S/N ratio was an objective of the analysis.

Raghu Kacker suggested that it should be kept in mind that Taguchi method is not a universal approach. The role of interactions has been debated vigorously since Taguchi's approach to experimental design for robust products and processes became known in United States. A perception persists in the statistical literature that Taguchi's approach assumes that interactions are absent and hence the method is unscientific. The presence of interactions implies that a much larger number of experiments would be needed to study the same number of control factors (Parks, 2001a). Understanding contributions to noise factors is very difficult. Knowledge of the noise factors and their behavior is an important prerequisite to an efficient experiment. If the noise factor exhibits variation and further experimental detail is required using an outer array configuration, then understanding of the range of variation of the noise factor will be required, to select the factors levels. Often noise factor cannot be controlled during the experimentation (Nair, 1992). Jeroen de Mast (2004c) compared three methodologies (Shainin system, Taguchi methods, Six Sigma) for quality improvement and concluded that Taguchi methodology falls short in the exploration phase – for which it provides only limited guidance and the focus on picking optimal settings (as apposed to gaining insight in the system) is debatable.

The main disadvantage of the Taguchi method is that the results obtained are only relative and do not exactly indicate what parameter has the highest effect on the performance characteristic value. Also, since orthogonal arrays do not test all variable combinations, this method should not be used with all relationships between all variables. Taguchi method has been criticized in the literature for its difficulty in accounting for interactions between parameters. Another limitation is that the Taguchi methods are offline, and therefore inappropriate for a dynamically changing process such as a simulation study. Furthermore, since the Taguchi methods deal with designing quality rather than correcting for poor quality, they are applied most effectively at early stages of process development (Unitek Miyachi Group, 1999b).

Other Methodology

DOE is a method that revolves around experimentation for optimization and modeling. The other methods that are commonly used for this purpose are analytic methods and Artificial Intelligence (AI) based techniques. Some of the commonly used analytical methods are exact solution and numerical solution while artificial neural network (ANN) and fuzzy logic are widely used AI techniques, Zhang et al. (2000) and Sheng-Chai Chi et al. (2001b).

Advantages and Disadvantages of DOE

DOE became a more widely used modeling technique superseding its predecessor one-factor-at-time (OFAT) technique. One of the main advantages of DOE is that it shows the relationship between parameters and responses. In other words, DOE shows the interaction between variables which in turn allows us to focus on controlling important parameters to obtain the best responses. DOE also can provide us with the most optimal setting of parametric values to find the best possible output characteristics. Besides, the mathematical model generated can be used to predict the possible output response, based on the input values. Another main reason for using DOE is savings on time and cost in terms of experimentation. DOE can determine the number of experiments or the number of runs before the actual experimentation is done. DOE allows to handle experimental errors while still continuing with the analysis. DOE is excellent when it comes to prediction of linear behavior, however, when it comes to nonlinear behavior, DOE does not always give the best results. DOE is extremely helpful in discovering the key variables influencing the quality characteristics of interest in the process. A designed experiment is a test or sequence of tests in which purposeful changes are made to the input variables of a process so that one can observe and identify corresponding changes in the output response. The progress of various statistical methods is shown in Fig. 3.

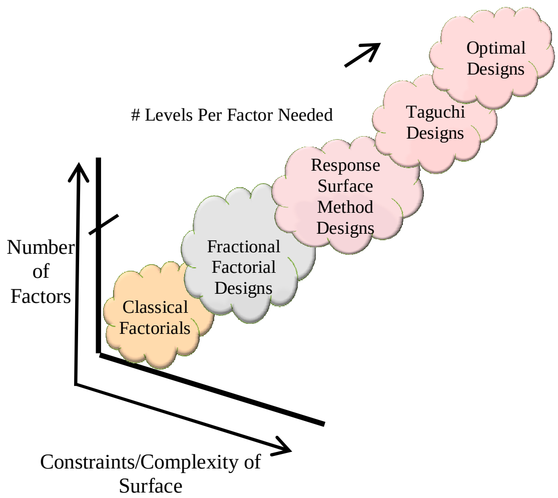

Figure 3. Progress of various statistical methods.

Application of Design of Experiments to Plasma Arc Welding

In the present days fabrication industry, welding has become one of the major manufacturing processes frequently used in all types of works. Quality of a weld joint is influenced by welding input parameters that are to be controlled to establish a proper weld. The input parameters selected vary with the type of welding process, thickness and type of base material used. In order to establish the correct combination of input weld parameters trail experiments are to be performed which consumes lots of time and manufacturing cost. Hence statistical techniques are utilized to avoid trial experiments and reduce the manufacturing cost. For that purpose experiments are to be conducted in a sequential manner according to the type of statistical technique selected. Statistical techniques like Factorial Method, Response Surface Method and Taguchi Method are adopted in Design of Experiments to optimize the required output parameters. A thorough review on application of Response Surface Method and Taguchi Method on Plasma Arc Welding is presented in the following sections.

Zhang et al. (2000) studied the influence of welding current, arc voltage, welding speed, wire feed rate and magnitude of ion gas flow on front melting width, back melting width and weld reinforcement of Alternating Current Plasma Arc Welding process using Artificial Neural Network- Back Propagation algorithm. Orthogonalising design matrix was used to perform the experiments. Sheng-Chai Chi et al. (2001b) developed an intelligent decision support system for Plasma Arc Welding based on fuzzy Radial Basis Function (RBF) neural network. Experiments were conducted based on Taguchi method. They reported that the developed neural network can be trained to establish a quality prediction system for PAW.

Marimuthtu and Murugan (2003e) used five-factor, five-level factorial technique to predict the geometry of the weld in the deposition of Stellite 6 (Co - Cr - A) alloy onto carbon steel valve seat rings using PTAW process. They reported that optimizing the process parameters reduced the amount of metal deposited and enhanced the mechanical and metallurgical properties of the hardfaced layers. Ming-Der Jean et al. (2005) proposed the application of an artificial neural network to a Taguchi orthogonal experiment to develop a robust and efficient method of depositing alloys with a favorable surface morphology by a specific microwelding hardfacing process. The experimental results reveal that the hardfacing roughness performance of the product of PTA coating is greatly improved by optimizing the coating conditions and is accurately predicted by the artificial neural network model. The combination of the neural network model with Taguchi-based experiments is demonstrated as an effective and intelligent method for developing a robust, efficient, high-quality coating process.

Wurikaixi Aiyiti et al. (2006d) presented a direct metal rapid prototyping process based on micro-plasma arc welding. The impact of the ratio of width to height of the deposited track cross-section on part quality(R) is investigated. Taguchi method is adopted to analyze the effect of each process parameter on R and the optimized process parameters are obtained. The results show that the quality of the parts with larger R is better than that with smaller R and the pulse current, wire-feeding speed, scanning speed and plasma gas flow rate exert significant effects on R. The overlapped surface smoothness, tensile strength and elongation of the parts fabricated with the optimized parameters are measured to show the obviously better performances than those of the parts in the ordinary technological process. Hsiao et al. (2007e) studied the optimal parameters process of plasma arc welding (PAW) by the Taguchi method with Grey relational analysis. Torch stand-off, welding current, welding speed, and plasma gas flow rate (Argon) were chosen as input variables and welding groove root penetration, welding groove width, front-side undercut were measured as output parameters. Taguchi orthogonal array is employed for the experiment and different levels were considered among the major welding parameters. After the experiment is completed, the S/N ratio and Grey relation of each evaluation indicator of the welding groove were computed respectively and then major parameters were assessed through ANOVA for selection of optimal parameters and prediction of the welding quality. Taguchi orthogonal array of L_{18} was used. Utilization of the optimal welding parameter combination enhances a significant improvement of the Grey relation.

Kueng-Hueng Tseng et al. (2008a) investigated the effect of welding parameters on the weld quality to develop guidelines for a selection of suitable parameter ranges for micro plasma welding. A series of experiments was conducted to explore how changes of welding parameters affect the strength of the weld for the thin stainless steel most often used in the industry. The experiment results show that work piece exposure height must be above a minimum limit in order to prevent undesired joining. The strength increases as the current increases with fluctuations, but still in the sufficient range. The minimum sufficient current for quality welds increases, while the minimum sufficient heat input decreases, as the travel speed increases. Siva et al. (2008b) used central composite rotatable full factorial design matrix and conducted experiments for optimization of weld bead geometry in Plasma transferred arc welding using Genetic Algorithm. The experiments were conducted based on five factors, five-level CCD matrix to optimize the experimental conditions. Lakshminarayan et al. (2008c) predicted the Dilution of Plasma Transferred Arc Hardfacing of Stellite on Carbon Steel using RSM. CCD of second order was employed to establish the mathematical relationship of the response surface using the smallest possible number of experiments without loss of accuracy. The experiments were conducted based on five factors, five-level CCD matrix to optimize the experimental conditions.

Balasubramanian et al. (2009a) used RSM to predict and optimize the percentage of dilution of iron-based hardfaced surface produced by the PTA (Plasma Transferred Arc Welding) process. The experiments were conducted based on five-factor five-level CCD with full replication technique and a mathematical model was developed using RSM. Furthermore, the RSM was also used to optimize the process parameters that yielded the lowest percentage of dilution. Ramachandran et al. (2009b) studied the effects of different experimental conditions on the dry sliding wear behavior of stainless steel surface produced by PTA hardfacing process.

Mathematical models were developed to estimate wear rate incorporating with rotational speed, applied load and roller hardness using statistical tools such as DOE, regression analysis and analysis of variance. It is found that the wear resistance of the PTA hardfaced stainless steel surface is better than that of the carbon steel substrate. Siva et al. (2009c) reported the modeling, analysis and optimization of weld bead parameters of nickel based overlay deposited by plasma transferred arc surfacing. The experiments were conducted based on a five-factor, five-level central composite rotatable design and a mathematical model was developed using multiple regression technique. The direct and interaction effects of input process parameters of PTA Hardfacing on weld bead geometry are discussed. Siva et al. (200d) developed mathematical equations using multiple regression analysis, correlating various process parameters to weld bead geometry in PTA hardfacing of Colmonoy 5, a nickel-based alloy over stainless steel 316 L plates. The experiments were conducted based on a five-factor, five-level central composite rotatable design matrix. A genetic algorithm was developed to optimize the process parameters for achieving the desired bead geometry variables. Mohan and Muragan (2009e) analyzed the effect of various parameters such as welding current, open circuit voltage, travel speed, nozzle to work distance, shielding gas flow rate and welding position on bead width, height of reinforcement, depth of penetration and percentage of dilution of PTAW tungsten carbide hardfacing of 316 stainless steel plates. The experiments were conducted based on five-factor, five-level CCD design matrix.

Abhishek Jivrag and Shashikant Pople (2010b) studied the effect of Inconel625 as wear resistant material to control erosion wear. They established the mechanisms of erosion wear on Inconel625, by considering impacting angles of particles at different temperature of Inconel625 substrate as process parameters and wear rate as response parameter. Fractional Factorial Regression method is used for developing relationship between process parameters and response parameter. Yan Bai et al. (2010c) used orthogonal experimental design to study the influence of plasma-MIG welding parameters on the aluminum weld porosity. The mixed orthogonal matrix $L_{16}(4^4 \times 2^3)$ and analysis of variance (ANOVA) technique were employed to optimize the welding parameters. Siva Prasad et al. (2010d) studied the effect of various process parameters like welding current, torch height and welding speed on front melting width, back melting width and weld reinforcement of PAW welded Alloy. The experiments were conducted based on a two level, three factors factorial design. By using the mathematical models the main and interaction effects of various process parameters on weld quality are studied.

Yildiz and Gur (2011a) studied the abrasive wear behavior of AISI 1030 substrate material whose surface was coated with high Cr in different atmospheres. The effect of wear loss on the lowest wear behavior was optimized with the-lowest-the-best control characteristics of the Taguchi method. Iio et al. (2011b) used grey relational Taguchi method for the optimization of PTA-processing in hardfacing of WC/W_2C-reinforced Ni-based MMC, considering multiple quality characteristics of the microstructure parameters relevant to abrasion resistance. An L_8 orthogonal array with three control factors (welding current, welding speed and oscillating speed) was used to study linear effects and interactions on signal-to-noise ratios of the various quality responses (carbide volume fraction, equivalent diameter, matrix hardness). Based on this study, optimised processing conditions of the hard-particle MMC fabrication were defined. Zhengyi Jiang et al. (2011c) used design of experiments based on RSM while developing a robust plasma transfer arc (PTA) coating process. The relative important parameters with respect to surface at hardness values were identified in the Taguchi design. In addition, they applied three-dimensional graphs in RSM to develop a robust PTA response surface yielding the desired-better area of a treated layer. Quadratic polynomial with a Box-Behnken design is utilized in their study. The results reveal that RSM provides the effective method as compared to the traditional trial-and-error method for exploring the effects of controlled factors on response. Srimanth and Murugan (2011d) used five factor, five level factorial technique for developing mathematical equations for the prediction of geometry of the weld in the deposition of stainless steel SS410L (Cr-Si-Ni) onto carbon seat valve seat rings. The amount of metal deposited has reduced and the mechanical and the metallurgical properties of the hardfaced layers have been enhanced by optimizing the process-parameters. Kondapalli Siva Prasad et al. (2011e) developed mathematical models to predict weld pool geometry of MPAW welded stainless steel 304L sheets. DOE based on full factorial design is employed for the development of a mathematical model correlating the important controlled pulsed MPAW process parameters like peak current, background current, pulse and pulse width with front width, back width, front height and back height. By using the developed mathematical models, effect of pulsed MPAW process parameters on weld pool geometry are studied.

Conclusions

The research work reported so far reveals the following conclusions in establishing DOE.

- Taguchi is interested in finding a "robust" solution to the experimental problem. It seeks an answer that is insensitive to factor variations and noise. It doesn't predict the best combination of factors to achieve desired goals.
- "Factorial", or "Classical DOE," was the first method used with designed experiments; it allows the user to see which factors are most important and helps to identify important interactions among the factors. It doesn't predict the best factor levels to meet the desired goals.
- Response Surface Methodology (RSM) uses model to make contour plots of predicted behavior. Using these plots, the best combination of factors to meet the desired goals can be predicted.
- RSM has an edge over the Taguchi method in terms of significance of interactions and square terms of parameters.
- Taguchi analysis can provide definitive information if there is only one response, but it does not deal with situations where a number of responses are to be optimized. Using RSM, only two control factors may be viewed at a time on a single contour plot although more than about four responses on one graph becomes very difficult to interpret. However, since a response surface is available, an automatic optimizer can be used to help in determining the optimum setting for each response. All the above strategies use DOE. The way DOE is applied will differ depending on the goals of the strategy, but the DOE technique does not change.
- Adaptation of RSM and ANNs to predict and optimize the welding processes are preferred over adaptation of Taguchi method and ANN's because in RSM interaction, effects of multiple variables are available, which are non available in Taguchi method.
- The time required for conducting experiments using RSM is almost twice that needed for the Taguchi methodology. However, one may use any type of optimization methods such as Artificial Neural Networks (ANN), Genetic Algorithms (GA), Fuzzy, Particle Swarm Optimisation (PSO) etc., after selecting appropriate DOE for any method of welding phenomena.
- From the literature review it was understood that most of the works reported were related to PTAW. Most of the researchers discussed about effect of weld input parameters on weld pool

geometry. Very less works are reported related to weld quality characteristics like tensile properties, hardness etc. Another interesting thing is that very few works are reported on usage of DOE techniques in lower current ranges and low thickness applications of PAW.

References

Abhishek Jivrag, Shashikant Pople, 2010b, "Erosion Wear Behavior of Inconel625 Plasma Transferred Arc Weld (PTAW) Deposits Using Air Jet Erosion Tester", Proceedings of the World Congress on Engineering and Computer Science 2010, San Francisco, USA, Vol. II, WCECS 2010, pp. 20-22.

Alagumurthi, N., Palaniradja, K. and Soundararajan, V., 2006a, "Optimization of Grinding Process Through Design of Experiment (DOE) – A Comparative Study", *Materials and Manufacturing Processes*, 21(1), pp. 19-21.

Asiabanpour, B., Khoshnevis, B. and Palmer, K., 2006b, "Development of a rapid prototyping system using response surface methodology", *Journal of Quality and Reliability Engineering International*, 22(8), pp. 919-937.

Avanish, K.D. and Vinod, Y., 2007a "Laser Beam Machining – A Review", *International Journal of Machine Tools & Manufacture*, 48, pp. 609-628.

Balasubramanian, V., Lakshminarayanan, A.K., Varahamoorthy, R. and Babu, S., 2009a, "Application of Response Surface Methodolody to Prediction of Dilution in Plasma Transferred Arc Hardfacing of Stainless Steel on Carbon Steel", *Science Direct*, 16(1), pp. 44-53.

Bauer, W.K., Parnell, S.G. and Meyers, A.D., 1999a, "Response Surface Methodology as a SensitivityAnalysis Tool in Decision Analysis", *Journal of Multi-Criteria decision Analysis*, 8, pp. 162-168.

Fung, C.P., 2003b, "Manufacturing process optimization for wear property of fiber-reinforced polybutylene terephthalate composites with grey relational analysis", *Science direct*, Wear, 254, pp. 298-306.

Huang, J.T., Liao, Y.S., 2003c, "Optimization of machining parameters of Wire-EDM based on grey relational and statistical analyses", *International J. Production Research*, 41(8), pp. 1707-1720.

De Mast. J., 2004c, "A mathematical comparision of three stratigies for quality improvement", *Int. J. Qual. Reliab. Manage*, 21, pp. 198-213.

Lakshinarayana, A.K., Balasubramanian, V., Varahamoorthy, R. and Babu, S., 2008c, "Predicted the Dilution of Plasma Transferred Arc Hardfacing of Stellite on Carbon Steel using Response Surface Methodology", *Metals and Materials International*, 14(6), pp. 779-789.

Fraley, S., Oom, M., Terrien, B. and Date, J.Z., 2006c, Design of Experiments via Taguchi Methods: Orthogonal Arrays, The Michigan Chemical Process Dynamic and Controls Open Text Book, USA.

Deng, J., 1989, "Introduction to grey system". *J. Grey System*, 1(1), pp. 1-24.

Hsiao, Y.F., Tarng, Y.S. and Huang, W.J., 2007e, "Optimization of Plasma Arc Welding Parameters by Using the Taguchi Method with the Grey Relational Analysis", *Journal of Materials and Manufacturing Processes*, 23, pp. 51-58.

Iio, S., Just, Ch., Xhiku, F., 2011b, "Optimisation of multiple quality characteristics of hardfacing using grey-based Taguchi method", *Materials & Design*, In Press, Corrected Proof, Available online 5 May 2011.

Juang, S.C., Tarng, Y.S., 2002c, "Process parameter selection for optimizing the weld pool geometry in the tungsten inert gas welding of stainless steel", *J. Materials Processing Technology*, 122, pp. 33-37.

Julie Z. Zhang, Joseph C. Chen, E. Daniel Kirby, 2007d, "Surface roughness optimization in an end-milling operation using the Taguchi design method", *Journal of Materials Processing Technology*, 184, pp. 233-239.

Kechagias, J., 2007c, "An experiment investigation of the surface roughness of parts produced by LOM process", *Rapid Prototyping Journal*, 13(1), pp. 17-22.

Kueng-Hueng Tseng , Min Jou , Yun Chang , Her-Yueh Huang , 2008a, "Influence of process parameters on joining strength in microplasma arc welding", *International Journal of Manufacturing Technology and Management*, 13(2/3/4), pp. 265-279.

Kondapalli Siva Prasad, Ch. Srinivasa Rao, D. Nageswara Rao, 2011e, "Prediction of Weld Pool Geometry in Pulsed Current Micro Plasma Arc Welding of SS304L Stainless Steel Sheets", *International Transaction Journal of Engineering, Management Science & Technology*, 2(3), pp. 325-336.

Lin, C.L, 2003d, "Use of the taguchi method and grey relational analysis to optimize turning operations with multiple performance characteristics", *Materials and Manufacturing Processes*, 19, pp. 209-220.

Lin, T.R., Chiu, H.C., Huang, M.F., 2004b, "Optimising removal rate and reliability of polishing of ceramic blocks using a combination of Taguchi and grey methods", *Materials Science and Technology*, 20(12), pp. 1649-1654.

Lin, Z.C., Ho, C.Y., 2003a, "Analysis and application of grey relation and ANOVA in chemical-mechanical polishing process parameters", *International J. Advanced Manufacturing Technology*, 21, pp. 10-14.

Marimuthtu K., Murugan, N., 2003e, "Prediction and optimisation of weld bead geometry of plasma transferred arc hardfaced valve seat rings", *Surface Engineering*, 19(2), pp. 143-149.

Mc Clurkin, J.E. and Rosen, D.W., 2002b, "Computer-aided build style decision support for stereo lithography", *Rapid Prototyping Journal*, 4(1), pp. 4-9.

Ming-Der Jean, Chyuan-Du Liu, Jen-Ting Wang, 2005, "Design and development of artificial neural networks for depositing powders in coating treatment", *Applied Surface Science*, 245(1-4), pp. 290-303.

Mohan, K. and Muragan, N., 2009e, "Effects of Plasma Transferred Arc Welding Parameters on Bead Geometry in Tungsten Carbide Hardfacing", *Journal for Manufacturing Science and Production*, Vol. 10, No. 3-4, pp. 155-168.

Montgomery, D.C, 1991, "Design and Analysis of Experiments", 3rd Ed., Wiley: New York.

Myers, R. and Montgomery, D., 2002a, "Response Surface Methodology", 2nd ed. Wiley: New York.

Nair, V.N, 1992, "Taguchi's parameter design: A panel discussion", *Technometrices*, 34, pp. 127-161.

Parks, J.M, 2001a, "On stochastic optimization: Taguchi methods demystified, its limitations and fallacy clarified", proab. Engg .Mech, 16, pp. 87-101.

Ramachandran, C.S., Balasubràmanian, V., Varahamoorthy, R., 2009b, "Evaluation of Dry Sliding Wear Behavior of Plasma Transferred Arc Hardfaced Stainless Steel", *Journal of Iron and Steel Research*, International, 16(4), pp. 49-54.

Ross, P.J., 1988, "Taguchi Technique for Quality Engineering", McGraw-Hill: New York.

Roy, R.K., 1990, "A Primer on the Taguchi Method", Van Nostrand Reinhold: New York.

Siva, K., Muragan, N., Logesh, R., 2008b, "Optimization of weld bead geometry in Plasma transferred arc hardfacing austenitic stainless steel plates using genetic algorithm", *Int. J. Adv. Manuf. Technol.*, 41(1-2), pp. 24-30.

Sheng-Chai Chi, LI-Chang Hsu, 2001b, "A fuzzy Radial Basis Function Neural Network for Predicting Multiple Quality characteristics of Plasma Arc Welding", IEEE, 0-7803-7078-3/01, pp. 2807-2812.

Siva, K., Murugan, N. and Logesh, R., 2009c, "Optimization of weld bead geometry in plasma transferred arc hardfaced austenitic stainless steel plates using genetic algorithm", *Int. J. Adv. Manuf. Technol.*, 41, pp. 24-30.

Siva, K., Murugan, N. and Raghupathy, V.P., 2009d, "Modelling, analysis and optimisation of weld bead parameters of nickel based overlay deposited by plasma transferred arc surfacing", *Archives of Computational Materials Science and Surface Engineering*, 1(3), pp. 174-182.

Siva Prasad K., Srinivasa Rao Ch,, Nageswara Rao D., 2010d, "Prediction of Weld Quality in Plasma Arc Welding using Statistical Approach", AIJSTPME, 3(4), pp. 29-35.

Sivarao, Shukor, Anand, T.J.S. and Ammar, 2010a, "DOE Based Statistical Approaches in Modeling of Laser Processing-Review & Suggestion", *International Journal of Engineering & Technology IJET-IJENS*, 10(4).

Srimanth, N. and Murugan, N., 2011d, "Prediction and Optimisation of Weld Bead Geometry of Plasma Transferred Arc Hardfaced Valve Seat Rings", *European Journal of Scientific Research*, 51(2), pp. 285-298.

Tarng, Y.S., Juang, S.C., Chang, C.H., 2002d, "The use of grey-base Taguchi methods to determine submerged arc welding process parameters in hardfacing", *J. Materials Processing Technology*, 128, pp. 1-6.

Unitek Miyachi Group, 1999b, "Welding Material Control", Technical Application Brief, 2, pp. 1-5.

Wang, C.C, Lin. T.W & Hu, S.S, 2007b, Optimizing the rapid prototyping process by integrating the taguchi method with the Gray relational analysis, Rapid Prototyping Journal, 13(5), pp: 304-315.

Wu, D.H., Chang, M.S., 2004a, "Use of Taguchi method to develop a robust design for the magnesium alloy die casting process", *Materials Science and Engineering*, 379, pp. 366-371.

Wurikaixi Aiyiti, Zhao Wanhua, Lu Bingheng, 2006d, "Optimization of Process Parameters for Micro-Plasma Arc Welding-Based Rapid Prototyping", *Journal of Xi'an Jiaotong University* DOI：cnki:ISSN:0253-987X.0.2006-05-017.

Yan BAI, Hong-ming GAO, Lin WU, Zhao-hui MA, Neng CAO, 2010c, “Influence of plasma-MIG welding parameters on aluminum weld porosity by orthogonal test”, *Transactions of Nonferrous Metals Society of China*, 20(8), pp. 1392-1396.

Yildiz. and Gur.A.K, 2011a, “The Optimization of Abrasive Wear Behavior of FeCrC Coating Composite with Taguchi Method”, 6th International Advanced Technologies Symposium (IATS’11), Elazig, Turkey, pp. 16-18.

Zhang, D.K. and Niu, J.T., 2000, “Application of Artificial Neural Network modeling to Plasma Arc Welding of Aluminum alloys”, *Journal of Advanced Metallurgical Sciences*, Vol. 13, No. 1, pp. 194-200 .

Zhengyi Jiang, Shanqing Li, Jianmin Zeng, Xiaoping Liao and Daoguo Yang, 2011c, “On the Hardfacing Performance Optimization after Plasma Transfer Arc Experiments”, *Advanced Materials Research*, 189-193, pp. 3640-3646.