Research trends for simulation modeling, parametric optimization of bead geometry and mechanical-metallurgical characteristics of submerged arc weld: Review and future scope

[1]Dr. Saurav Datta and [2]Dr. Asish Bandyopadhyay

[1]Department of Mechanical Engineering, National Institute of Technology, Rourkela, Orissa
[2]Department of Mechanical Engineering, Jadavpur University, Raja S. C. Mallik Road, Kolkata

ABSTRACT

Submerged arc welding (SAW) is a useful metal joining process in fabrication industry. The process is characterized by the use of granular flux blanket that covers the molten weld pool during operation. This arrangement avoids atmospheric contamination to the weld bead, facilitates slower cooling rate and, thereby, enhancing mechanical-metallurgical characteristics of the weldment. It is well-known that several process control parameters influence (directly or indirectly i.e. factorial interaction) various quality features of the weldment. Work, to a far extent, has already been done to study the effects of the parameters (as well as their interactions) like voltage, current, electrode stick-out, wire feed rate, traverse speed etc. on bead geometry, weld quality and performance attributes in terms of mechanical-metallurgical-chemical characteristics of the weld produced by submerged arc welding on structural steel. But the search is still being continued and results thereof are being reported which indicate the necessity of acquiring in depth knowledge in this regard. Control of the above parameters, in a more precise manner, can essentially improve weld quality, enhance the possibility of increased deposition rate and economize the overall process. In consideration of the above, the present reporting outlines the trends of research on various aspects of prediction-modeling, simulation and optimization of submerged arc weld. The application feasibility including relative merits as well as demerits of various modeling-optimization methodologies proposed and adopted by previous investigators in examining the process behavior of SAW has been illustratively highlighted. It is felt that the information provided in this reporting may definitely give an insight to the young researchers especially to identify the root locus of the past research progressed in the said field and, thereby, helping them in selection of proper direction of work towards value added outcome for the benefit of both academic fraternity as well as industry personnel.

Key words: SAW, modeling, simulation, optimization

INTRODUCTION

SAW is one of the major metal fabrication techniques in industry due to its reliability and capability of producing good quality weld. The ability to join thick plates (as thick as 1.5 inch) in a single pass, with high metal deposition rate has made the process useful in large structural applications. In multi-pass welding, much higher than 1.5 inch thick plates can be welded by SAW. Indeed various research works have been explored on various aspects of SAW, but still investigations are being carried on to study the phenomenon that occurs during the process, and many other related maters, so that the process becomes controllable more precisely, and can be monitored well both manually as well as automatically.

In SAW, various process parameters interact in a complicated manner, and the interactions influence bead geometry and mechanical-metallurgical characteristics of the weldment. Precise understanding of the process phenomena is highly required because acceptability of the weld depends on various quality indices that confirm functional requirements of the welded joint in the intended area of application.

In many of the cases, quality of the weld is left dependent on operators past experience and working skill. But, with the advent of automation, it is now possible to design a machine capable of selecting optimal process parameters to provide desired yield. However, this requires reliable data of knowledge.

TRENDS OF RESEARCH

Efforts have been made by previous researchers for modeling, simulation and optimization of submerged arc welding technique. The major trends of research related to the present context of SAW include:

(a) Modeling and simulation of the process behavior; mathematical modeling to establish the effect of various process control parameters on features of bead geometry, mechanical properties of the weldment and metallurgical characteristics and chemical composition of the weld metal as well as heat affected zone (HAZ).

(b) Parametric optimization to achieve desired quality of the weldment.

RESEARCH ON BEAD GEOMETRY, ELECTRODE MELTING RATE

Literature depicts that ample work has been made to study the effect of parameter variation, base metal and flux composition on electrode melting rate during SA welding. Robinson Michael, H. (1961) pointed out that the significant factors controlling SAW electrode melting rate were current, composition used, electrode extension, electrode diameter and flux. Tušek, J. (1999) developed a mathematical model for calculation of the melting rate on the basis of the physical principles of the welding arc and of the wire extension heating due to current conduction and mutual influence of the welding arcs. Tušek, J. and Suban, M. (2003) investigated some aspects of multiple wire Submerged Arc Welding (and cladding) with metal powder addition. They observed that the use of metal powder increased the deposition rate, welding arc efficiency and reduced the shielding-flux consumption. By incorporating the metal powder addition technique, it was possible to alloy a weld or a cladding with optimal chemical elements.

Weld pool size and shape, extent of heat affected zone, microstructure, mode of metal transfer, droplet size, frequency of transfer, arc force, bead geometry and shape relationships, burn off rate and equilibrium in submerged arc welding process are important criteria in determining the weld ability of any metal. Useful predictions about these characteristics can be made if there exists a correlation between the quality parameters of the weld and welding process parameters controlling the same.

Mechanical properties of weld are influenced by the composition of the base metal and to a large extent by the weld bead geometry and shape relationships as well. In turn, the weld bead geometry is influenced by the direct and indirect welding parameters. Therefore, researchers have made extensive study in evaluating the effect of process control parameters on features of bead geometry, which indirectly influence mechanical strength of the weldment. Also in recent years, there has been a significant growth in the use of automatic and robotic welding systems. These systems can be used effectively when mathematical models that correlate welding process parameters to the weld bead geometry and shape relationships are available. Therefore, it becomes important to represent the welding process behavior through mathematical models. The derived models can also be helpful to determine optimal parametric combination to achieve satisfactory quality weld.

Kaae, J. L. (1968) observed that HAZ width was influenced by heat input, thickness, initial temperature and thermal conductivity of the base metal. Renwick, B. G., and Patchett, B. M. (1976) studied the characteristics of the weld bead penetration, melting rate under variable operating current conditions and found that those increased with the increase in current. They also investigated that increase in welding voltage produced flatter and wider bead and increased flux consumption.

Gupta, S. R. and Arora, N. (1993) studied the effect of welding parameters on weld bead geometry as well as HAZ and concluded that welding parameters and flux basicity appreciably influenced the depth of penetration, weld bead dimension and width of HAZ at the centre line and at the toe of the weld bead.

Malin, V. (September 2001) conducted experiments employing modified refractory flux (MRF) welding and studied the effects of welding variables (current, voltage, travel speed, angle of electrode inclination and amount of iron powder in the groove) on formation of root (backside) welds, including the root bead (deposit inside the groove) and root reinforcement (deposit outside the groove). The work also revealed that welding variables produced profound and sometimes conflicting effects on the root weld's shape. In another paper

(Part 2) Malin, V. (September 2001) established relationships between shape of the root weld and variations in joint geometry.

Murray, P. E. (July 2002) established analytical relationships between welding parameters and process variables by regression and dimensional analysis of the experimental data. Non-dimensional variables were used to correlate experimental data to obtain accurate analytical relationships between welding parameters, arc process variables and bead geometry.

RESPONSE SURFACE METHOD (RSM) FOR PROCESS MODELING

Response Surface Methodology (RSM) is a combination of mathematical and statistical techniques, and is useful for modeling and analyzing the problems in which several independent variables influence a dependent variable or the process response. This technique provides a quadratic second order model that represents mathematical relationship among various predictors (factors) and the process response. The RSM offers some advantages while solving optimization problem of a response variable within experimental domain. However, this depends on proper selection of the Design of Experiment (DOE) [Myers, R. and Montgomery, D. C].

The most efficient Design of Experiment capable of modeling as well as simulation of a process is the Central Composite Design (CCD). This technique has been found wide applications, in combination with RSM, to determine optimal factor setting to yield desired result. For full factorial design of experiment, as the number of factors and their levels increases, the number of experimental runs exponentially increases. This results an increase in experimental cost as well as time for conducting experiments. Compared to full factorial design, the Central Composite Design (CCD) is more efficient to establish process behavior by a mathematical model. Moreover, this design reduces experimental run number thereby saving time and cost.

Gunaraj, V. and Murugan, N. (1999) gave a clear idea to show how the relationship between the input process parameters and the features of weld bead geometry would be constructed correctly. In their investigation, mathematical models were developed to study the effects of process variables and heat input on various geometrical aspects, like width of HAZ weld interface and grain growth as well as grain refinement regions of the HAZ.

In another publication, Gunaraj, V. and Murugan, N. (1999) highlighted the use of Response Surface Methodology by designing a four-factor, five-level central composite rotatable design matrix with full replication for planning, conduction, execution and development of mathematical relationships for modeling of the welding phenomena. The models were helpful for predicting weld bead quality and also could be applied for process optimization. Gunaraj, V. and Murugan, N. (October 2000) developed a model using the five level factorial technique to relate the important process control variables welding voltage, wire feed rate, welding speed and nozzle to plate distanceto a few important bead quality parameters penetration, reinforcement, bead width, total volume of the weld bead and dilution. The model thus developed was checked for its adequacy with the F-Test. They highlighted quantitatively as well as graphically the main/direct and interactive effect of the process control variables on important bead geometry parameters.

As a continuation of the study, Gunaraj, V. and Murugan, N. (November 2000) proposed a mathematical model to relate the process parameters with the weld bead quality parameters including total volume of the weld bead. They used MATLAB software package to optimize (minimize) the weld bead volume. The mathematical models thus developed were capable for predicting the weld bead quality parameters and setting the process parameters at optimal values to achieve preferable weld quality and at the same time high productivity.

Murugan, N. and Gunaraj, V. (2005) Proposed mathematical models for submerged arc welding of pipes using five level factorial technique to predict three critical dimensions of weld bead geometry and shape relationships: height of penetration, height of reinforcement, width of weld bead, PSF (Penetration Size Factor) and RFF (Reinforcement Form Factor). The significance and adequacy of the developed models were tested by using F-test and t-test respectively. The predictions as given by the models were represented graphically to show direct as well as interactive effects of selected process parameters- (arc voltage, wire feed rate, welding speed and nozzle to plate distance) on important weld bead dimensions and shape relationships.

NEURAL NETWORK (NN) FOR SIMULATION AND PREDICTION

Another approach used for modeling, simulation and prediction in submerged arc welding is the Artificial Neural Network (ANN). ANN creates a mapping between set of inputs and corresponding responses. ANN is very efficient to model and simulate a process behavior, while the nature of response variation, with varying inputs, is very much complicated and not completely known. Depending on huge data set obtained from experiments (combination of inputs and outputs), ANN itself establishes a correlation among inputs and outputs, into its internal architecture, that consists of input, output and hidden layers, connection between the layers (nodes/neuron). ANN then predicts output for a given combination of factor settings (inputs). The perfection of network prediction or network performance depends on the data set used to train the network, and selection of its internal features viz. number of hidden layers, number of nodes in a layer, leaning rate, training algorithm, performance goal and so on, [Widrow, B. and Lehr, M. A. (1990), Chester, D. (1990) and Bebis, G., and Georgio-poulus, M. (1994)]. Adequate data set with optimal network architecture can predict results with minimum error. An important step in building the network is selection of input variables. In the field of welding, some studies have been made with the neurons of the input layer used to receive the input process parameters, while the neurons of the output layer used to send out the features of quality characteristics of the weldment viz. weld bead and HAZ geometry, mechanical properties of the weldment, metallurgical features of the weld metal as well as HAZ.

Vitek, J. M. *et al.* (February 2000) developed an Artificial Neural Network model to predict Ferrite Number (FN) in arc welds as a function of composition. The paper included valuable information for the development of neural a network model, named FNN 1999, which was capable of identifying the optimum network architecture and net work parameters. Results of the model were presented in Part 2 of the paper. It was shown that the accuracy of the FNN-1999 model in predicting Ferrite Number was superior to the accuracy of other available models at that time.

The work done by Ridings, G. E. *et al.* (October 2002) described the application of neural network technique to predict the weld bead shape for three wire, single pass per side, submerged arc line pipe seam welds. The effect of a particular welding process parameter (input relevance) to the variation in the final weld bead shape was also considered. Kim. I. S. *et al.* (November 2003) applied an intelligent system for the determination of welding parameters for each pass and welding position, for pipeline welding, based on database and finite element method, and on two back-propagation neural network models and a corrective neural network model (CNN). Experiments using the predicted welding parameters from the developed system proved the feasibility of interface standards and intelligent control technology to increase productivity, improve quality and reduce the cost of system integration.

Lightfoot, M. P. *et al.* (February 2005) developed a model of ANN and established that the carbon content of the steel plate played a key role in the amount of distortion produced by the welding process. The mechanism of the effect of carbon appeared to be linked to its effect on grain size, trans-formation temperature, mechanical properties and pearlite content, at least. It was established that an increase in carbon content was beneficial in reducing thin plate distortion caused by welding.

RESEARCH ON CHEMICAL ASPECTS OF THE WELDMENT

Remarkable attention has also been employed to study different aspects of weld chemistry. It is quite understandable that compositions of base metal, electrode wire, and flux impose profound effect on mechanical properties of the welded joint, which in turn depends on microstructure of weld metal and HAZ. Literature provides ample scope to review the study in evaluating the effect of compositional variation of base metal, wire electrode as well as welding flux on different aspects of submerged arc weldment. Attempts have also been made by the researchers to understand the nature of chemical reaction and element transfer during Submerged Arc Welding.

Belton, G. R. *et al.* (1963) remarked that the study of slag-metal reactions during SAW of steel was made difficult by the complex temperature cycle, which the metal and slag experienced. The authors reported that higher weld pool temperature was maintained with increase in silica content of the slag whereas bead width to depth of penetration ratio increased significantly with increased FeO content in slag.

The effect of flux composition on weld metal in submerged arc welding of QT35 alloy steel was studied by Bennet, A. P. and Stanley, P. J. (1966). They found that weld metal tensile strength was independent of flux composition and heat input unless alloying elements had been deliberately added to the flux. Weld metal impact properties, however, had been affected remarkably by flux composition as well as heat input. The authors mentioned that SiO_2 and MnO in the flux would influence the levels of Si and Mn in the weld metal, influencing the impact strength of the weldment. They also discussed about transfer of S and P between metal and slag.

Ferrera, K. P. and Olson, D. L. (1975)

found that the basic constituents like CaO, $CaCO_3$, CaF_2 in flux produced shallow penetration whereas MgO led to deep penetration. The similar conclusion came from the work of North, T. H. (1978).

Schwemmer, D.D. and Olson, D.L. (1979) reported about higher penetration due to increase in SiO_2 content of the flux. It was reported that sodium and potassium salts, and other elements, which improved arc stability and reduced cathode spot wandering, generally increased penetration.

Several investigators like Schwemmer, D. D. and Olson, D. L. (1979) and Davis, M. L. E. and Bailey, N., (April 1982) had shown that a flux with higher viscosity would tend to confine the molten weld pool, thus increasing the heat input for a given area and resulting into deeper penetration.

Chai, C. S. and Eagar, T. W. (September 1981) developed a theory for predicting slag-metal equilibrium during submerged arc welding with fused neutral fluxes. The proposed theory was capable of predicting the gain or loss of Mn and Si over a wide range of flux-electrode-base plate compositions. The study represented a significant advancement in the ability to predict and control the extent of the reactions related to Mn and Si transfer in the weld pool.

Chai, C. S. and Eagar, T. W. (July 1982) showed that the stability of metal oxides during submerged arc welding was not directly related to their thermodynamic stability. Some otherwise chemically stable fluxes might decompose into suboxides in the presence of welding arcs, thereby providing higher levels of O_2 in weld metal than those oxides, which did not form suboxides. It was shown that CaF_2 would reduce the amount of oxygen in the weld metal, but the effect might be due to dilution of the metal oxide rather than due to a direct chemical reaction. The effect of CaF_2 in reducing the level of weld metal oxidation was dependent upon the stability of the metal oxide, which was present. Mitra, U. and Eagar, T. W. (January 1984) studied the transfer of Cr, Si, Mn, P, S, C, Ni and Mo between the slag and the weld pool of submerged arc weldment made with calcium silicate and manganese silicate fluxes. They observed a strong interaction between Cr and Si transfer but no interaction with Mn. The manganese silicate flux produced lower residual sulphur whereas the calcium silicate fluxes were more effective for removal of phosphorous.

In another reporting, Mitra, U. *et al.* (1984) gave a quantitative theory which was able to predict weld metal composition on the basis and analysis of slag-metal reactions during submerged arc welding of steel.

Polar, A. *et al.* (January 1991) evaluated the relative effects of thermo-chemical reactions on the transfer of elements, particularly Mn, from the flux to the weld metal in submerged arc welding of steel.

Davis, M. L. E. and Bailey, N. (February 1991) described that the complex change, in composition during submerged arc welding of C-Mn steels were related to flux composition and weld metal inclusions which formed the final reaction products. They analyzed the chemical factors controlling the transfer of elements into the weld pool and also observed that high temperature reactions in the arc plasma were followed by reactions in the slag and the weld pool.

Gupta, S. R. and Arora, N. (July 1991) used five different commercial fluxes in their investigation of submerged arc welding of mild steel, and found that the welding parameters and the flux basicity appreciably affected the depth of penetration and width of the weld bead. The reinforcement was also influenced by welding parameters, but not appreciably by flux basicity. With respect to HAZ width, the authors observed lower values with highly basic fluxes as compared to lower basicity fluxes, at lower welding current range.

Ana Ma. Paniagua-Mercado et al. (2003) conducted a study for chemical and structural characterization of fluxes used in submerged arc welding process, which enabled one to quantify the ions that might be present in the plasma arc during the submerged arc welding process due to the fluxes. Their analysis was capable for prediction of reactions that occur in the weld pool.

Kanjilal, P. *et al.* (2004) developed a prediction model for submerged arc weld metal chemical composition in terms of flux ingredients with the help of statistical experiments for mixture (extreme vertices design). Experiments were performed to obtain bead-on-plate weld deposits at some specific process parameters (current, voltage, speed, electrode extension) using CaO_2 MgO-CaF_2-Al_2O_3 flux system. They reported that some of the individual flux ingredients and their binary mixtures had predominant effects on weld metal oxygen, manganese, silicon, sulphur, nickel and carbon contents. The predicted results showed a good agreement with the experimental results.

Mohan, N. and Pandey, S. (2005) analyzed the effect of welding parameters on the Mn, Si, C and Cr content of the weld metal through quadratic response surface modeling.

It was observed that the welding parameters and basicity index affected the Mn, Si and C content of the weld metal. Cr content of the weld metal was influenced by the basicity index of the flux used.

RESEARCH ON METALLURGICAL-MECHANICAL PROPERTIES OF THE WELD

Metallurgical characteristics of the weld metal as well as HAZ are very important because this directly influence on the weld mechanical properties and joint performances. It is known that weld microstructures, however, are somewhat different with respect to distributions of pearlite and ferrite, their amounts, grain sizes etc., depending upon the welding conditions adopted.

In a pass of the welding torch, material is rapidly heated to the maximum temperature and allowed to cool more slowly by conduction of heat into the bulk of the parent metal. Phase chance can occur depending on the temperature reached. Sufficiently far from the weld pool, the material remains unaffected.

The region next to the fusion zone (weld pool) where micro-structural changes have occurred but no melting of base metal has effected is known as heat-affected zone or HAZ. Such micro-structural changes may affect the mechanical properties of the weld and need to be controlled.

The weld metal microstructure is controlled mainly by the cooling cycle. At lower energy input (i.e. with low level of current) the time for solidification is less. This rapid cooling promotes smaller grains. With higher energy input, the time required for solidification decreases, and, therefore, cooling rate slows down-which yields coarser grains. Courser grains in the microstructure generally indicate lower hardness and low tensile strength.

Mechanical properties are the important characteristics of the weldment that must conform to the application feasibility as well as functional requirements of the welded joint. These include hardness, impact strength (toughness), yield strength, ultimate tensile strength, percentage elongation, resistance to wear and corrosion, etc. These mechanical properties greatly depend on weld microstructure, which in turn is related to cooling condition, compo-sition of base metal, wire electrode as well as flux. Moreover, welding process parameters also impose direct/indirect influence on weld mechanical properties and microstructure.

Fleck, N. A. *et al.* (1986) found that filler material and flux composition in SAW would influence the growth of austenite considerably.

Tandon, S. *et al.* (1988) observed that heat input and cooling rate played major roles in deciding the extent of HAZ, the microstructure and the hardness. They pointed out that higher cooling rate led to smaller HAZ width.

Smith, N. J. *et al.* (1989) demonstrated that the notch toughness of the coarse grained HAZ decreased with increase in energy input. They also found that stress relieving reduced the notch toughness of both the weld metal and HAZ as a result of embitterment caused by carbide precipitation.

Reddy, G. M. *et al.* (July 1991) investigated the effect of electrode polarity and welding current on mechanical properties in multi pass submerged arc welding. They studied on the influence of welding current with two polarities over mechanical properties of the weldment. They also found that the hardness value increased in coarse microstructure region than the reheat-refined region of the weld deposit.

Joarder, A. *et al.* (1991) made an extensive study on the microstructure of weld metal and heat affected zone of plain carbon steel plate in SAW. They noticed that depending on the number, size and distribution of inclusions, the weld metal microstructure varied. Bhadeshia, H. K. D. H. (1997) gave quantitative relationships between microstructure and mechanical properties so that the variety of models could be consolidated and used directly in the design process.

Eroğlu, M. *et al.* (1999) investigated the effects of coarse initial grain size with varying heat inputs on microstructure and mechanical properties of weld metal and heat affected zone (HAZ). It was concluded that the coarse initial grain size had a great influence on the microstructure, hardness and toughness of HAZ of low carbon steel. The investigators recommended a higher heat input to obtain maximum toughness of the HAZ in the welding of grain-coarsened low carbon steels, taking into consideration of the plate thickness.

Surian, E. S. and Vedia, L. A. de (1999) made experiments with all-weld metal, deposited with various types of electrodes, and reported the role of different alloying elements such as manganese, carbon and chromium on the tensile properties, hardness as well as on the microstructure of the submerged arc weldment. They suggested criteria for selecting the weld metal composition leading to optimal combination of tensile strength and toughness. It was concluded that an increase in Mn, C or Cr individually produced an increase of tensile and yield strengths and hardness.

Ghosh, P. K. and Ahmed, M. (October 1999) built up an analytical model for quantitative analysis of micro structural constituents of a multi-pass weld. The authors experimented with multi-pass submerged arc welding of C-Mn steel blocks, and developed PC based software to carry out the complex analysis of microstructure of the weld along with execution of database, for estimation of mechanical properties-using their empirical relationships with the matrix microstructure.

Kostrivas, A. and Lippold, J. C. (January 2000) developed a technique that would allow the nature and evolution of the fusion boundary to be studied under controlled thermal conditions. In their reporting, non-dendrite equiaxed grain microstructures were simulated in Li-bearing Alloy 2195.

Wojnowski, D. *et al.* (May 2000) worked for metallurgical assessment of the softened HAZ region during multi-pass submerged arc welding of Cr-Mo-V steels. Their study focused on the effect of multiple thermal cycles on the development of the softened zone. Peng, Y. *et al.* (2001) studied the variations of elements between wire and weld metal, and discussed the effects of Mo, B and Ti on the microstructure and mechanical properties. The study concluded that fine and uniformly distributed inclusion particles in the weld metal could promote the formation of acicular ferrite. TiN particles could pin the prior austenite grain boundaries of the heat affected zone (HAZ) and inhibit the growth of austenite grains. Boron was found to segregate in the prior austenite grain boundaries and suppress the growth of pro eutectoid ferrite.

Basu, B. and Raman, R. (November 2002) experimented to obtain bead-in-groove weld under isoheat input conditions by submerged arc welding using quenched and tempered (Q & T) HSLA steel, a suitable welding wire and an agglomerated basic flux (Basicity index 3.1). Utilizing multiple regression analysis, a correlation between acicular ferrite content and the different welding parameters was established with 90% correlation coefficient. That correlation could be utilized in selecting the trial welding parameters for similar grades of steel substrates and consumables with the aim to maximize the acicular ferrite content.

In course of the investigation performed by Gülenç, B. and Kahraman, N. (2003), worn parts were welded using submerged arc welding process with various wires and fluxes. These welded parts were subjected to pin-on-disk wear tests under different loads to examine the changes in the hardness and microstructures. They concluded that weld hardness and wear resistance were dependent on the chemical composition of the weld wire and flux.

Ana Ma. Paniagua-Mercado *et al.* (2005) focused on the effect of flux composition for the microstructure and tensile properties of submerged welded AISI 1025 steel. In their study, three flux compositions were used with a low-carbon electrode. The study revealed that the presence of acicular ferrite was detected for welds of fluxes with the highest content of titanium oxide. The presence of acicular ferrite was found to influence the yield and ultimate tensile strength of the weldment. The elongation and percentage of reduction of cross sectional area were affected by the inclusion volume percentage. Predicted values obtained from computer Programme, for tensile properties and microstructure were compared with that obtained through experiments.

Kolhe, Kishor P. and Datta, C. K. (2005) conducted a detailed study on the microstructure, phase analysis and mechanical properties and HAZ width of submerged arc weld in multi-pass joint and heat affected zone of 16 mm thick mild steel plate. The bulk hardness, impact energy and micro hardness of the multi-pass welded joint were tested by Rockwell hardness testing machine, Charpy V Notch testing machine and Vickers micro hardness tester. The various sub zones in the microstructure observed in the HAZ were spheroidized, partially transformed, grain refined and grain coarsened. The variation in hardness of weld metal, fractured surface and base metal were compared. The authors made an attempt to establish correlation between hardness and microstructures as observed in the weld and HAZ.

Kanjilal, P. et al. (2006) adopted rotatable design based on statistical design of experiments to predict the combined effect of flux mixture and welding parameters on submerged arc weld metal chemical composition and mechanical properties. The results showed that variables related to flux mixtures- based on individual flux ingredients and welding parameters-had individual as well as interaction effects on responses, viz. weld metal chemical composition and mechanical properties.

PARAMETRIC OPTIMIZATION OF SUBMERGED ARC WELDING

Several process control parameters influence bead geometry, weld quality and joint performance in submerged arc welding. So these parameters should be selected in a judicious manner so as to reach the desired target or objective dictated by the area of application of the weidment. This can be achieved by optimization of welding phenomena.

Literature depicts that work has been explored on various aspects of modeling, simulation and process optimization in submerged arc welding. The common approaches to tackle optimization problem in welding include multiple regression analysis, Response Surface Methodology (RSM), Artificial Neural Network (ANN) modeling and Taguchi method, [Unal, R. and Dean, Edwin B., (1991), Rowlands, H., *et al.* 2000, Antony, J. and Antony, F., (2001), Maghsoodloo, S. *et al.* (2004)]. In most of the cases the optimization has been performed using single objective function. For a multi-response process, while applying the optimal setting of control factors, it can be observed that, an increase/improvement of one response may cause change in another response, beyond the acceptable limit. Thus for solving multi-criteria optimization problem, it is convenient to convert all the objectives into an equivalent single objective function. This equivalent objective function, which is the representative of all the quality characteristics of the product, is to be optimized (maximized).

OPTIMIZATION TECHNIQUES

Optimization using desirability function (DF) approach is very helpful in this context. Asiabanpour, B. *et al.* (2004), Ful-Chiang, Wu. (2005) used this approach in their research work. This approach converts each of the responses (objectives) into their individual desirability value. Corresponding to each objective, these individual desirability values are then accumulated to compute the overall/composite desirability function, which is to be optimized (maximized) next [Datta, S. *et al.* (2006)].

Taguchi's philosophy is an efficient tool for the design of high quality manufacturing system. Dr. Genichi Taguchi, a Japanese quality management consultant, developed a method based on Orthogonal Array (OA) experiments, which provide much-reduced variance for the experiment with optimum setting of process control parameters. Thus the integration of Design of Experiments (DOE) with parametric optimization of process is achieved in the Taguchi method. Taguchi method uses a statistical measure of performance called signal-to-noise ratio. The S/N ratio developed by Dr. Taguchi is a performance measure to select control levels in order to set minimum noise. S/N ratio takes both the mean and the variability into account. It is the ratio of the mean (Signal) to the standard deviation (Noise). The ratio depends on the quality characteristics of the product/ process to be optimized.

However, general Taguchi method cannot solve multi-objective optimization problem Jeyapaul, R. *et al.* (2005). Therefore, Taguchi method coupled with grey relational analysis is the appropriate option. Grey relational analysis is more or less similar to the desirability function approach.

Previous researchers, in various fields of production engineering, have adopted Taguchi method coupled with grey relational analysis. In this method, a multiple response process optimization problem is converted to a single response optimization problem where overall grey relational grade serves as the single objective function or response function to be optimized (maximized).

Tarng, Y. S. *et al.* (2002) applied grey-based Taguchi methods for optimization of Submerged Arc Welding process parameters in hardfacing. They considered multiple weld qualities and determined optimal process parameters based on grey relational grade from grey relational analysis proposed by Taguchi method.

Apart from desirability function and grey-based Taguchi approach, Genetic Algorithm (GA) and Fuzzy Logic are also found to be useful techniques to solve optimization problem in the field of welding. GA was essentially developed in 1980s to emulate the "survival for fittest" principle introduced by Charles Darwin in his theory of evolution. From this perspective and since optimization is analogous to fitness or the ability to survive real-world conditions, it makes good sense to apply GA approach for system improvement and process /product optimization-as mentioned by Al-Aomar, Reid (2002).

Apart from Genetic Algorithm, fuzzy logic also comes into the scenario of solving optimization problems in material processing technology. Fuzzy logic allows degrees of truthfulness that measures to what extent a given object is included in a fuzzy set. Fuzzy sets correspond to linguistic variables used in a human language, [Wang, Jen-Ting and Jean, Ming-Der (2006)]. Xue, Y. *et al.* (2005) reported the possibilities of the fuzzy regression method in modeling the bead width in the robotic arc-welding process. In their paper, they developed a model for proper prediction of the process variables for obtaining the optimal bead width.

Desirability Function (DF) approach coupled with Taguchi method has been used by some researchers to investigate conditions leading to process optimization. In this context, application of other hybrid techniques deserves mention. These techniques are: - (i) Taguchi method coupled with fuzzy logic, (ii) Genetic Algorithm and fuzzy logic, (iii) desirability function approach coupled with fuzzy logic, (iv) Genetic Algorithm in combination with Response Surface Methodology, and (v) Taguchi-Genetic Algorithm [Tsai, Jinn-Tsong (August 2004)].

Tarng, Y. S. *et al.* (July 2000) applied fuzzy logic in the Taguchi method to optimize the submerged arc welding process with multiple performance characteristics. An orthogonal array, the signal-to-noise ratio, multi-response performance index and Analysis of Variance (ANOVA) were employed to study the performance characteristics in the submerged arc welding process. The process parameters, namely arc current, arc voltage, welding speed, electrode protrusion and preheat temperature were optimized with considerations of the performance characteristics, including deposition rate and dilution. Experimental results were provided to confirm the effectiveness of this approach.

Another approach for optimization is the Controlled Random Search Algorithm (CRS), developed by Price, W. L. (1977). In this algorithm, the new trial point in search space (parameter) is generated on the basis of a randomly chosen subset of previously generated points. At each iteration, a simplex is formed from a sample and a new trial point is generated as a reflection of one point in the centroid of the other points in this simplex. If the worst point in the initially generated set is worse than the new one, it is replaced by the later. After some repetition of this technique the solution clusters around the global minima. The advantage of this algorithm is that, the objective function needs not be differentiable. It only counts the objective function value, obtained through experiments; mathematical modeling of the process is not required. Moreover, optimization can be achieved within a limited number of experimental runs. This technique can also be applied for optimization in submerged arc welding, Datta, S. *et al.* (2007).

LIMITATIONS OF OPTIMIZATION TECHNIQUES AND HOW TO GET RID OF THAT

Many methodologies have been proposed in the past research to address optimization of submerged arc weld. However, a good number of past works seek to optimize SAW process parameters with one response only. In practical situations, it is felt necessary to optimize more than one response simultaneously. The common trend in order to solve a multi-response optimization problem is the derivation of a mathematical model (Linear/ Quadratic Response Surface or non-linear exponential model) repressing overall quality index of the weld as a function of process control parameters. Prior to this modeling, it is essential to accumulate individual quality indices into an overall quality index. The concept behind this is to convert a multi-response problem to a single response optimization problem. The derived mathematical model for overall quality index is then optimized using various optimization algorithms viz. evolutionary Genetic Algorithm (GA), Controlled Random Search (CRS) algorithm, Swarm intelligence i.e. Particle Swarm Optimization (PSO) and many others. The major limitation of these methods is the requirement of enormous databank for developing an adequate and best-fit regression model. This results in an increase of experimentation cost and loss of considerable time. Furthermore, while applying these algorithms, the outcome i.e. the optimal setting of parameter may not be adjusted in the equip-ment/setup because the aforesaid algorithms usually search the optimal point within a continuous domain. But the equipment or set up generally have provision for adjusting various process control factors at some discrete levels.

Another disadvantage of this approach is the unrealistic assumption of non-existence of correlation among the responses and they are treated as equally important. But, no specific guideline is available on assignment of priority weights to individual responses reflecting their relative importance.

To overcome these shortcomings, Principal Component Analysis (PCA) was recommended to convert correlated response values (output features) into uncorrelated quality indices called principal components, [Johnson, Richard, A. and Wichern, Dean, W.]. Past research showed that individual principal components could be accumulated to calculate the composite principal component for optimizing finally. Application of PCA based Taguchi method could be applied for optimization of SAW process. In order to prioritize the responses, individual response weights (priority weightage) can be calculated by entropy measurement analysis [Wen, Chang and You (1998), Wen *et al.* (1998)]. Few work reported in literature verified the so-called robustness and flexibility of PCA based optimization methodology for solving correlated multi-criteria optimization problem emphasizing off-line quality control in different process, [Su, C. T. and Tong, L. I. (1997)]. But in SAW process optimization this approach was not considered yet. Therefore, ample scope is there to initiate research in this particular direction.

CONCLUSION

In the foregoing sections, the recent trends of research in the field of submerged arc welding have been thoroughly reviewed and thrust arrears have been highlighted in which research can be extended further. Several aspects of modeling, simulation and prediction of process behavior including process responses have also been highlighted. Different optimization techniques with relative merits and demerits have been discussed with the ease of their application feasibility in the field of submerged arc welding. Apart from traditional optimization techniques, the resent tend of investigation directs towards some hybrid methods, evolutionary algorithm based soft computing techniques so as to reduce experimentation time and cost. However, this requires reliable data bank and exploration of parametric setting in a continuous domain which may not be feasible in practice. Moreover response correlation is required to be eliminated prior to applying traditional optimization methodologies. It is understood that several process control parameters in SAW influence bead geometry, micro structure as well as weld chemistry. Their combined effect is reflected on the mechanical properties of the weld in terms of weld quality as well as joint performance. Defect free high quality weld is the prime objective or target and deviation from the target is called quality loss. Every research has been aimed to understand the process behavior in order to control the weld quality within acceptable limit.

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