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A Review on Parametric Optimization of MIG Welding and SMAW Techniques on Different AISI Steels and Alloys

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Abstract – Metal Inert Gas (MIG) welding and Shielded Metal Arc Welding (SMAW) processes are leading arc welding processes in terms of fine quality and higher productivity. In this review paper, the effect of various process parameters of MIG and SMAW welding techniques on weld bead strength, micro-structure and weld bead depth in AISI carbon steels is studied. These parameters are optimized by various design of experiment techniques and best set of parameters can be obtained for the optimum quality of weld. The variables chosen in the study of SMAW are current, voltage, welding speed, root gap, preheat temperature etc. Similarly, the variables used in the MIG welding are current, voltage, gas flow rate, groove angle, preheat temperature, welding speed etc. In the end, a number of trials have been conducted to confirm the expected values with the experimental values.

Keywords - AISI Carbon Steel, MIG Welding, SMAW, Taguchi technique, Optimization, Preheating.

Nomenclature

NG-GMA	Narrow Gap - Gas Metal Arc
GFR	Gas Flow Rate
AWS	American Welding Society
AISI	American Iron and Steel Institute
TEM	Transmission Electron Microscopy
ARAS	Additive Ratio Assessment
CCPS	Constant Current Power Source
CVPS	Constant Voltage Power Source
RBF-NN	Radial Basis Feed Forward Neural Network
MLP-NN	Multi-Layer Perceptron Neural Network
ANN-GA	Artificial Neural Network-Genetic Algorithm
AHP-MOORA	Analytical Hierarchy Process-Multi-Objective Optimization on the basis of Ratio Analysis

I. INTRODUCTION

Welding can be defined as the joining of two metal pieces by heating them to a very high temperature to cause their melting or softening with or without the use of filler metal and pressure or using pressure alone without using any filler metal. Welding plays a key role in various products and infrastructure.

In automotive industry, AISI carbon steels are generally used to manufacture various components like turbine blades, worms, gears, tool die set, pinions, ratchets, etc. The Society of Automotive Engineers and the AISI have developed a numbering system based on the chemical analysis of steels to identify their different types. The numbering system makes it possible to use the numerals on shop drawings that indicate the type of steel to be used in fabrication. Carbon steels have been classified into three categories namely low, medium and high carbon steels. Out of numerous welding techniques, arc welding is generally used on these steels as per the user requirements. The most frequent arc welding techniques used on AISI carbon steels are MIG and SMAW.

SMAW, also known as Manual Metal Arc Welding (MMAW), uses an electric arc created between a flux coated consumable electrode (metal rod) and the specimen to produce heat for welding. Therefore, it is also called stick electrode welding. Gaseous shield created by electrode combustion and decomposition shields the electrode tip, arc, weld puddle and the highly heated work from contamination by atmospheric gases. For the molten metal in the weld pool additional shielding is provided by a coating of molten flux. Metal core of the consumable electrode supplies the weld metal. The mechanical, chemical, metallurgical and electrical characteristics of the weld are largely controlled by the shielding and filler metal. It is mainly used onsite for establishing structural members and piping systems. Portability and ability to weld without using external gas supplies that are not suitable for welding in open environments make this welding the logical choice for many applications. SMAW equipment is simpler to use and set up. No external gas supplies, gauges, regulators, gas cylinders or peripheral equipment are needed. Motor generator power sources can be transported to work sites on truck beds.

MIG Welding, also called Gas Metal Arc Welding (GMAW), was developed in 1950. The gas here depicts the

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weld area covered by an inert atmosphere of argon, helium, carbon dioxide etc. The consumable solid wire is fed automatically through a nozzle into the weld directly. The filler metal can be deposited on the base metal through open arc, short-circuit and globular transfer. GMAW arc has a high current density. The stream of the GMAW arc is sharp and incisive. The major advantage of MIG welding is the continuous supply of welding electrode which avoids poor penetration, crater cracking and improper fusion. The weld spatter is minimum. Metal can be welded in any positions. Welding can be performed on both light and heavy gauge materials. MIG welding gives a seamless weld surface. These characteristics provide enough cost savings since metal finishing is frequently a costly production item. Weld has no slag. It cannot be used in windy areas as shielding gas can be blown away by slight breeze.

II. LITERATURE REVIEW

Various research papers have been reviewed and divided into sections A and B. In Section A, research papers related to MIG welding and in Section B, various research papers related to SMAW welding have been reviewed thoroughly.

SECTION A

Xinhua Tang et al. studied the effect of preheating in NG-GMA welding. The approach used is statistical analysis of different specimens at predefined parameters. 5083 Al alloy is used as the base material while filler material is ER5183 wire. The parameters used are arc travel speed (mm/s), welding current (A), oscillating frequency (Hz), arc voltage (V) and gas flow rate (L/min.). The experiment concludes that the tensile strength of a proper welded joint can be as high as 90% of the base metal with proper preheating. [1]

I. Bitharas et. al. optimized shielding gas coverage in GMAW. The visualization technique used in the experiment is Schiliren imaging while optimization technique is Finite Element Modelling. The base material used is DH36, higher strength construction steel. The filler materials used are mild steel filler wire with shielding gas composition (80% Argon, 20% Carbon dioxide) and flux cored filler wire with shielding gas (86% argon, 12% carbon dioxide, 2% oxygen). The parameters considered for the study are nozzle standoff, nozzle angle, shielding gas flow rate. The experiment concludes that optimized shielding can be achieved by having shielding gas flow rate as less as 9 L/min. [2]

K. R. Carpenter et. al. investigated the GMAW and optimized the process parameters to study the effect of shielding gas on the formation of fume and distribution of particle size. The experimental technique used is image analysis and TEM. The base material used is mild steel plate of thickness 10 mm and AWS ER70S-6 is used as the filler wire. The process parameters considered are g.f.r. (L/min.), voltage (V), contact tip-work distance (mm), wire feed rate (mm/min.) and weld travel speed (mm/min.). The experiment concludes that average fume particle decreases with decrease in g.f.r. and shielding gas CO_2 content. As CO_2 and O_2 increase, the particle size increases. Current, arc length and voltage decreased during the auto control tests. [3]

Sudipto Chaki et. al. optimized hybrid CO_2 laser-MIG welding. The experimental techniques used are integrated soft computing-based models. The base material used is AA8011 grade Al alloy while ER403 has been used as filler material. The input process parameters considered are wire feed rate (m/min.), laser power (kW) and welding speed (m/min.). The experiment concludes that ANN-GA gives best performance for optimization with 0.09% absolute percentage error which shows the effectiveness of models. [4]

Pavan G. Chaudhari et. al. investigated various process parameters of GMAW. AHP-MOORA and Additive Ratio Assessment method were used to optimize the parameters. The base material used is SS316L and two fluxes Cr_2O_3 and SiO_2 in powdered form are used. The process parameters considered are shielding gas ($Ar+CO_2$), welding speed (mm/min.), arc voltage (V), travel speed (mm/min.) and gas flow rate (L/min.). The experiment concludes that Multi Objective Optimization on the basis of Ratio Analysis method is robust, sound and simpler than ARAS as computational time and mathematical calculations are minimum in MOORA method. [5]

Sujit Ghosal et. al. studied hybrid CO_2 LASER-MIG welding. The ANN optimization hybrid model is used to estimate and optimize penetration depth. The base material used is 5005 Al-Mg alloy. The process parameters considered are torch angle (in degrees), power (W), focal distance from the work piece surface (mm), distance between the laser and the welding torch (mm). The experiment concludes that ANN model is better than regression model to predict the output with minimum error. [6]

Zhao Jiang et. al. studied hybrid laser-MIG welding plus MIG welding. The base material used is Al 5083 alloy and ER5183 is used as filler wire. The laser beam parameters used are wavelength (mm), focal radius (mm), beam parameter product (mm-rad). Groove angle was kept constant during the experiments. The experiment concludes that hybrid laser-MIG welding plus MIG welding process is more efficient than conventional MIG welding. [7]

Sripriyan Karuthapandi et. al. studied GMAW. They conducted experiments to study the impact of using a flat wire electrode. Weldment shape profile is predicted using Simulink fuzzy logic model. The base material used is 6062 Al alloy and ER4043 is used as filler wire. The process parameters considered are welding current (A), welding speed (mm/min.), flat wire electrode orientation (in degrees). The experiment concludes that the use of flat wire

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electrode is a good option to enhance the weldment characteristics. [8]

Rakesh Malviya et. al. studied MIG welding. The Particle Swarm Optimization technique is used to modulate the neural networks for mapping gas metal arc welding process both in back and forth directions. The base material used is AISI 1040 mild steel and ER70S-6 is used as filler wire. The process parameters considered are wire feed rate (m/min.), arc voltage (V), gas flow rate (L/min.), nozzle to plate distance (mm), welding speed (cm/min.), torch angle (in degrees). The experiment concludes that when a function having good number of variables is optimized, permutation problems were found in Particle Swarm Optimization. A back-propagation algorithm can be used to avoid it. [9]

Jose L. Meseguer Valdenebro et. al. studied MIG welding and optimized electrical parameters of welding geometry. Taguchi method is used for the experimental analysis. The base material used is 6063-T5 Al alloy and ER5356 is used as filler material. The electrical parameters considered are welding speed (mm/s), power (W) and separation between edges (mm). The experiment concludes that welding speed is the most influential factor among all the factors considered followed by power and separation between edges. [10]

P. J. Modenesi et. al. studied the GMAW. They conducted experiments to study the effect of changes in wire characteristics on GMAW process stability. Factorial analysis and statistical methods are used for the experimental analysis. The base material used is AISI 1010 and AWS ER70S-6 is used as filler wire. The process parameters considered are filler wire diameter (mm), cast (mm), mechanical strength of filler wire (MPa), helix. The experiment concludes that spatter can be decreased by increasing the wire diameter. The relation between short-circuit factor and welding voltage was found to be sigmoidal. [11]

Sukhomay Pal et. al. studied pulsed MIG welding process and optimized the quality characteristics parameters. Grey based Taguchi technique is employed for the experimental analysis. The process parameters considered are pulse frequency (Hz), pulse duty factor, pulse voltage (V), background voltage (V), wire feed rate (m/min.) and table feed rate (mm/s). The base material used is AISI 1010 mild steel and AWS ER70S-6 is used as filler wire. The experiment concludes that weld quality is affected by pulse voltage and pulse frequency the most. [12]

Kamal Pal et. al. studied pulsed GMAW. Neuro Elitist Non-Dominated Sorting Genetic Algorithm (Neuro NSGA-II) is used for the experimental analysis. The base material used is AISI 1010 mild carbon steel and filler electrode wire is copper coated ESAB S-6 mild steel. The process parameters considered for the design of experiment are torch angle (in degrees), wire feed rate (m/min.), welding speed (mm/s), peak voltage, pulse frequency (Hz) and pulse on-time (ms). The experiment concludes that for different service requirements, Neuro NSGA-II technique can provide a greater number of solutions without much computation time. Also, at higher joint efficiency, transverse shrinkage reduces significantly. [13]

P. Srinivasa Rao et. al. studied pulsed GMAW. They conducted experiments to study the influence of various process variables and developed a mathematical model for predicting the geometry of weld bead. Taguchi method is used as the design of experiment. The base material used is AISI 1020 mild steel and ER70S-6 is used filler wire. The process parameters considered are plate thickness (mm), wire feed rate (m/min.), pulse frequency (Hz), pulse current magnitude (A) and travel speed (m/min.). The experiment concludes that wire feed rate, ratio of wire feed rate and travel speed affect the weld bead geometry significantly. Also, at high peak current, penetration is more due to high arc force. [14]

Mainak Sen et. al. studied double pulsed GMAW. They conducted experiments to investigate the impact of various process parameters on hardness and microstructure of weld joints. Microscopic analysis is used for studying microstructural changes. The base material used is AISI 1010 mild carbon steel and ER80S-G is used as filler wire. The parameters considered are pulse frequency (Hz), thermal pulse frequency (Hz) and heat input (kJ/mm). The experiment concludes that grain size increases on increasing the heat input. It has been observed also that at low heat input condition, greater hardness of weld metal and heat affected zone can be achieved. [15]

Shih Jing-Shiang et. al. studied MIG welding process. They conducted experiments to optimize multiple quality characteristics of MIG welding. The techniques used for the experimental analysis are Taguchi method and Principal Component Analysis. The base material used is aluminium foam plates and two filler materials type no. 4047 and 5356. The process parameters considered are welding speed (mm/min.), g.f.r. (L/min.), welding arcing angle (in degrees), welding current (A), groove angle (in degrees), workpiece gap (mm) and electrode extension length (mm). The experiment concludes that welding speed, current and workpiece gap are the most influential parameters affecting the various performance characteristics of metal inert gas welding process. [16]

Shekhar Srivastava et. al. optimized the process parameters of GMAW. Box Behnken design technique of Response Surface Methodology is used for the experimental analysis. The base material used is AISI 2062 mild steel and filler wire used is copper coated mild steel wire. The process parameters considered are voltage (V), g.f.r.

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(L/min.), travel speed (mm/min.) and wire feed rate (m/min.). The experiment concludes that wire feed rate is the most and gas flow rate is the least effective parameter among all the parameters considered. [17]

Yanling Xu et. al. studied GMAW and tracked welding seam. The base material used is Q235 steel and welding seam is butt joint type. The process parameters considered are pulse frequency (Hz), welding current (A), welding voltage (V), feed speed (mm/s), weld frequency (Hz), welding speed (mm/s), wire diameter (mm), shielding gas, gas flow rate (L/min.). The experiment concludes that for most welding tasks, welding seam tracking system is precise. [18]

Gang Zhang et. al. studied arc characteristics in narrow gap GMAW. The arc climbing up process is thoroughly studied with metal transfer behavior by using minimum arc voltage technique. The base material used is Q235 steel and ER506 wire used as filler wire. CVPS and CCPS are used to record arc dynamics and droplet transfer. The experiment concludes that in case of CVPS, arc climbing up phenomenon is observed owing to minimal arc voltage combined with arc built-in self-regulation. While in case of CCPS, owing to weak arc built-in self-regulation the arc climbing up phenomenon barely occurs thereby providing a stable welding process. [19]

S. Zielinska et. al. studied microstructure of anode in GMAW. Scanning electron microscopy along with energy dispersive X-ray spectroscopy analysis is employed to examine the microstructures. The base material used is AISI 1010 mild steel and ER70S-6 is used as filler wire. The process parameter used is gas density (kg/m^3). The experiment concludes that at high temperature, the transition of spray-arc to globular transfer mode is guided by the chemical reactions such as redox reactions between shielding gas and molten metal. [20]

J. V. Subrahmanyam et. al. optimized the design parameters of MIG welding. The design of experiment is based on the Taguchi method. 65032 Al alloy is used as the base material. The process parameters considered for the experiment are gas flow rate (kg/hr), current (A), groove angle (in degrees), preheat temperature (^{0}C). The experiment concludes that preheating temperature plays a key role in improving the weld strength. [21]

P. G. Ahire et. al. optimized various process parameters of GMAW. The technique used for the experimental analysis is genetic algorithm. The base material used is SS 304 and AISI 1018 mild steel while the filler electrode is stainless steel 309L. The parameters considered for the experiment are current (A), welding speed (mm/s), root gap distance (mm), weld deposition rate (mm), electrode angle (in degrees). The experiment suggests that genetic algorithm can be an effective way to achieve optimized parameters. [22]

SECTION B

Ali N. Ahmed et. al. studied SMAW to predict weld bead geometry. AI techniques like RBF-NN and MLP-NN have been employed to estimate the weld bead geometry. ABS marine grade-A mild steel AISI 1018 is used as base material. The parameters considered for the experiment are arc length (mm), welding speed (mm/min.), electrode diameter (mm), current (A), joint gap (mm). The experimental analysis concludes that a good degree of accuracy is achieved in the simulation of weld bead geometry and parameters can be predicted satisfactorily by using RBF-NN than by using MLP-NN. [23]

Aman Gupta et. al. studied SMAW. The experiments were conducted to investigate the effects of heat input on microstructure and corrosion behavior using Scanning and Optical Electron Microscopy. The base material used is UNS S32750 super duplex stainless steel and E2595 is used as filler electrode. The process parameters considered are welding current (A), voltage (V), welding speed (mm/s), heat input (kJ/mm), filler electrode diameter (mm) and polarity. The experiment concludes that weld behavior is affected negligibly by heat input, therefore low heat can be used to weld the UNS S32750 super duplex stainless steel. [24]

A. A. Shukla et. al. studied SMAW. They conducted experiments to study the effect of various process parameters on depth of penetration. The Response Surface Methodology is used for the experimental analysis. The base material used is AISI 1020 steel plates. The parameters considered are polarity, current (A) and electrode angle (in degrees). The experiment concludes that direct current electrode negative is the best polarity to achieve maximum depth of penetration. Also, electrode angle 90^0 along with current at 120 A is most preferable for maximum depth of penetration. [25]

Cleiton Carvalho Silva et. al. studied SMAW. They conducted experiments to study variations of residual stress profiles in butt-welded pipes. Mini-diffractometer X-ray is used to measure the residual stress. The base material used is ASTM A106 grade B steel pipe and AWS ER70S-3 is used as filler electrode. The process parameters used are current (A), voltage (V), welding speed (cm/min.) and heat input (kJ/cm). The experiment concludes that there were marked variations in the profiles of residual stresses thereby causing non-uniformity. Under similar conditions, the maximum residual stress can be as high as yield strength. Also, it is not possible to conclude which variables affect the residual stress significantly. [26]

Jagesvar Verma et. al. used Optical and Scanning Electron Microscopy to represent the microstructures and studied mechanical as well as inter-granular corrosion behavior of welds in SMAW. The base material used are dissimilar duplex stainless steel 2025 and austenitic stainless steel

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316L. The filler electrode used is E2209. The process parameters considered are current (A), welding speed (mm/s), voltage (V), heat input (kJ/mm) and electrode diameter (mm). The experiment concludes that higher hardness and ultimate strength can be obtained for low heat input in comparison to higher one owing to faster cooling rate and higher ferrite content. [27]

A. A. Hassan et. al. optimized the various parameters of SMAW. The design of experiment is based on Taguchi method and ANOVA. The base material used is St 37-2, St 44-2, St 52-3 steel and consumable electrode is AWS E6013. The various parameters considered are groove angle (in degrees), carbon equivalent, heat input and preheat temperature. The experiment concludes that both carbon equivalent and groove angle are significant factors in improving tensile strength collectively. [28]

R. P. Singh et. al. studied the effect of various process parameters of SMAW welding on depth of weld bead using synthetic neural network. The experimental approach used is creation of a model by collating the data in multi-layer feed forward synthetic neural network with back propagation algorithm. The base material used is mild steel and consumable electrode used is AWS E6012. The parameters considered are welding current (A), arc voltage (V) and welding speed (mm/s). It has been observed that by increasing the welding current, depth of weld bead increases. On increasing the welding speed, the depth of bead weld decreases. [29]

B. S. Praveen Kumar et. al. optimized the parameters of SMAW. The experiment is conducted to make sure that no leak occurs during the process. The design of experiment is based on Taguchi method. The base material used is Apollo steel tube and consumable electrode is AWS E6013. The various input parameters used in the experiment are welding current (A), welding speed (mm/s), root gap (mm) and position of electrode. The experiment concludes that welding current is the most influential parameter for better strength of leak proof joints. [30]

III. DESIGN OF EXPERIMENT (DoE)

Design of Experiments, given by Ronald A. Fisher during the 1920s, is a very useful and well-built statistical technique to study the effect of numerous variables at the same time. By designing the experiments using Taguchi approach, one can fulfil the requirements of a problem and optimize the process or product design projects. Using this technique scientists, engineers and researchers can be time-efficient in experimental investigations. In an experiment, DoE technique involves describing and exploring all the possible combinations to find out the best combination. For this, various factors along with their levels are pinpointed. This technique is also helpful in making combinations of different factors at suitable levels having an admissible range so as to yield best results and show little divergence around the optimal results.

Hence, the main objective of a well-planned and designed experiment is to know in a process which combination of variables affect the performance most so that one can find out the best level for that combination of those variables to get desired practical output in products.

In the research papers considered for above literature review, following DoE techniques have been mostly used to study and optimize the effects of process parameters in welding:

a.) Taguchi Orthogonal Array

b.) Full Factorial technique

c.) Response Surface Methodology

d.) Fractional Factorial technique

ANOVA stands for Analysis of Variance. It is used to study the share of effect of each process variable on the response parameter. “Design Expert” and “MINITAB” are the software mostly used for ANOVA and DoE. The interconnection between input and output variables in the welding process is established through a mathematical model.

IV. CONCLUSION

From the above literature review, it can be seen that on AISI 1018 carbon steel, very few researches have been conducted although it is very crucial for and frequently used in the automotive industry to manufacture different types of components. Current, voltage, gas flow rate, welding speed, wire feed rate, type of shielding gas and diameter of electrode are the important control factors that have been used by different researchers for the analysis and optimization of MIG welding to improve mechanical properties of weld bead. Similarly, voltage, current, torch angle, wire feed rate, bevel velocity etc. have been considered by the researchers for the analysis and optimization of SMAW welding to improve mechanical properties of weld bead. Taguchi method has been used by most researchers as it is based on **“**Orthogonal Array**”** experiments which provide optimal setting of control variables with minimal variance for experiments and ANOVA is used to find out which design variables affect the prediction of optimum results and the quality characteristics remarkably.

It has also been seen that preheating is an important process to control the rate of expansion and contraction in a structure during the welding operation. Preheating is done on cast iron, cast aluminium, carbon steels etc. Though very few researches have been carried out in this area in India, preheating for welding has enormous potential for further

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exploration.

Following points have been summarized from this review:

1.) The most influential process parameters for MIG welding are voltage, current, gas flow rate and for SMAW are current, welding speed, wire feed rate.

2.) Taguchi method is the widely used technique selected as DoE method to improve the output.

3.) Preheating factor can play a pivotal role in determining the strength and micro-structure of the weld joint.

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