Influence of Welding Process Parameters on Bead Geometry-A Review

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Abstract
Surfacing techniques are developed to impart desirable properties like corrosion and wear resistance to low cost substrates like low carbon steels. Weld surfacing is capable of processing prefabricated and worn-out components. The various welding parameters influence the heat input, bead geometry and occurrence of weld defects. This paper briefly looks into various methods adapted to model, regulate and control weld surfacing techniques. The knowledge on effects of welding process parameters, percentage of overlap, inter-pass temperature, pulse characteristics, oscillation methods and control techniques is helpful to tailor the properties of the deposits. This review is mainly focused on selected welding techniques that can be readily and economically adopted for surfacing process.

Keywords: *Corrosion, substrates, parameters, welding, overlap*

INTRODUCTION

Weld surfacing techniques were widely used impart corrosion and wear resisting characteristics to the low-carbon steel substrates. The welding techniques adopted for surfacing can be classified into consumable electrode, non-consumable electrode and unconventional processes. The welding parameters of these processes have direct influence on bead geometry, strength, and hardness distribution and corrosion behaviour of the welded joints. Further, the welding parameters can be categorised into primary and secondary based on their influence over heat input and bead geometry. The primary welding parameters are having direct influence over the heat input and geometry like welding current, arc voltage etc. The secondary welding parameters also influence bead geometry but their extent of application was limited like electrode preheat, arc oscillation etc. The composition and corrosion resistance properties are strongly dependent on the bead geometry. The geometry of the weld bead was defined by its width, height, depth and contact angle. The width and height of the weld bead governs number of welding passes required to cover the given surface area. The penetration depth influences the dilution of the filler and composition of the deposits. The bead geometry variables were affected by number of process parameters like welding voltage, welding current, welding speed etc. The objective of this paper is to present comprehensive view on the effect of process parameters on bead geometry and mechanical properties in various welding techniques used for surfacing.

GAS METAL ARC WELDING PROCESS (GMAW)

Kang and Na, 2003, studied the effect of oscillation frequency and magnetic flux density on arc and weld bead characteristics. The arc penetration and arc oscillation width was increased by increasing magnetic flux density in narrow groove GMAW process [1]. S.D. Kore *et al.* 2008, investigated mechanical properties of dissimilar aluminium and stainless steel magnetic impulse welded joints. The microstructural investigation of the welded joints shows continuous weld. It is also observed that increased current density in the coil leads to improved mechanical properties [2].

Węglowski and Zhang, 2013, studied the linear relationship between arc radiation intensity and welding current in GMAW process. The arc radiation intensity monitoring is useful to control the fusion characteristics of the welded joints [3]. C. L. Fan *et al.* 2013, investigated the relationship between welding voltage and arc length in both conventional and ultrasonic wave assisted GMAW (U-GMAW). It was found that arc length in U-GMAW process is considerably shorter than conventional GMAW. The rate of increase in the arc length with welding voltage is low in U-GMAW when compared with conventional GMAW process [4].

Mallya and Srinivas, July 1993, studied the effect of magnetic arc steering in submerged arc strip cladding of austenitic stainless steels. It was found that magnetic steering of arc reduces dilution and corrosion rate in the deposits. The use of magnetic arc steering permitted welding at higher current levels without significantly increasing dilution [5]. X. Yu *et al.* 2014, investigated the influence of magnetic stirring on cracking tendency of the high nickel filler cladding on austenitic stainless steels. The magnetic arc stirring significantly reduced cracking tendency, grain size in the deposits and penetration [6].

Torres *et al.* 2013, investigated influence of GMAW process parameters and metal transfer modes on bead geometry. The authors used mathematical models to study about the interaction effects of welding process parameters on the responses. The metal transfer modes for the solid wire and cored wire were different because of the changes in resistivity [7]. Grujicic M. *et al.*, 2013, developed multi-physics GMAW model composed of modules like welding gun, metal transfer, thermo mechanical, microstructure evolution and relationship between microstructure and weld properties. The model can be used predict the evolution of microstructural at the fusion and heat affected zone [8]. Janez *et al.*, 2012, developed a GMAW quality monitoring system by measuring arc voltage, welding current, light intensity and sound pressure. The important findings from work was sensing the welding current is particularly useful to determine the arc stability, droplet size, number of short circuits per unit time in case short circuit mode. Measurement of light intensity indicates the amount of heat energy released. The sound intensity shows the type of transfer mode, arc oscillations and arc stability. The authors recommended sound pressure technique is useful welding process monitoring [9].

Ladislav *et al.* 2012, evaluated the suitability of intelligent arc control in overhead and vertical welding positions. The control system improved the arc behaviour, metal transfer and arc stability. In addition to these spatter was suppressed and small heat affected zone in the base metal were realized [10]. Bai *et al.* 2013, studied the effect of electromagnetic confinement of the welding arc. The authors were successfully deposited weld metal at larger tilt angle using the magnetically confined arc. The proposed technique overcomes the flow down problems associated with welding of overhanging structures [11]. Kolahan and Heidari 2010, compared the linear, curvilinear and logarithmic models for their predictability. The authors optimized the GMAW process using simulated annealing algorithm. The developed models were then used to investigate the direct and interaction effect of process parameters on the responses. The objective function is defined in the form error function which is composed of desired and predicted values of the bead geometry [12].

M Boselli *et al.* 2013, investigated the fume formation and nanoparticle transportation characteristics around the arc in pulsed GMAW process. The developed models predicted the maximum fume formation during peak current in pulsed current GMAW process. These results can be used to minimize the exposure of the welder to the harmful fumes [13]. Vipin Kumar *et al*. 2013, modelled GMAW cladding process using response surface methodology. The parameters controlling the heat input plays a significant role in determining the dilution of the filler at the base metal. The parameters were arranged on the order influence they exert on dilution was current, welding voltage and nozzle to plate distance [14].

Guo N. *et al.* 2014, studied the effect of rotating arc on heat distribution in horizontal narrow groove GMAW process. The rotating arc has increased side wall penetration along with reduced tendency of molten pool sagging [15]. Kah P *et al*. 2012, studied the new welding techniques developed with aim of reducing heat input, spatter and increasing flexibility. The authors compared different droplet detachment techniques particularly useful in welding thin sheets and stainless steel like heat sensitive materials [16].

Karadeniz *et al.* 2007, investigated the effect of welding parameters like welding current, arc voltage and welding speed on penetration in robotic GMAW process. Welding current exerts significant influence over penetration than arc voltage and welding speed [17]. Iordachescu and Quintino 2008, reviewed various modes of metal transfer in GMAW. The metal transfer modes influence arc stability, bead appearance and bead quality. The authors related different transfer modes with respect to current, voltage and shielding gas composition [18]. Cayo and Alfaro, 2011, established relationship between bead geometry and optical and acoustic arc emissions from the GMAW process. The authors concluded that there is strong relationship exists between bead geometry and arc emissions. The acoustic emissions exhibit a definite relationship with the bead geometry parameters. The infrared emissions were indicative of arc power and depth of penetration [19].

Curiel *et al.* 2011, investigated the effect of axially applied magnetic field on sensitization and corrosion properties in the weld as well as HAZ of austenitic stainless steel welds. The tendency to form complex carbides decreased with increasing intensity of the applied magnetic field [20]. Hsuan-Liang Lin, 2012, combined Taguchi, grey relational analysis and neural network to model and optimization of the bead geometry in GMAW process. It is carried out in two stages in the first stage Taguchi method used to create database for the neural network. In the second stage grey relational grade is generated for the each combination of Taguchi experimental results. Further back-propagation neural network is used to search for the optimal parameter combinations [21]. Chakrabart *et al*. 2013, studied the effect of GMAW process parameters on weld deposit microstructure, low temperature impact toughness and resistance to pitting corrosion on duplex weld metal. The multi pass deposits on the base plate with 40% overlap and inter-pass temperature was maintained at 125°C. The results show that heat input influence the nitrogen absorption and delta ferrite content in the weld metal. The nitrogen content in the weld metal affected the low temperature toughness of the welds. The shielding gas composition and heat input together affects the pitting corrosion resistance of the welds [22].

Zhijiang *et al.* 2012, developed control system based on the interaction between welding voltage and weld pool surface during peak current period. The depth of penetration can be expressed as a function of welding voltage during the pulse period with reasonable accuracy in GMAW-P process [23]. Izaatul Aini Ibrahim *et al.* 2012, investigate the effect of welding parameters like welding current and welding speed on penetration depth in robotic GMAW process. Increasing welding current and welding speed has positively influenced the penetration depth. Hardness distribution and grain size in the weld metal were also affected by these welding parameters [24].

Suraj Joshi *et al*. 2013, simulated the shape of the reinforcement, penetration profile and heat affect zone in GMAW welds with 40 to 80% overlap. The authors found good agreement between the results of Goldak’s double ellipsoidal heat source model and experimental results [25]. Xiong Jun *et al*. 2013, developed mathematical and neural network models to predict the bead geometry in robotic GMAW process. The models were statistically and experimentally validated. The neural network model has the better performance than the non-linear mathematical models [26].

Xiong Jun *et al.* 2014, developed the closed loop control system for robotic GMAW process. The forward and reverse models used to predict responses and levels of the process parameters. The proposed system regulates the process parameters effectively so as to maintain the bead geometry within acceptable levels [27]. Ning Guo *et al.* 2014, studied the pool behaviour under mechanically rotated arc with varying welding voltage, wire feed speed, arc rotation frequency and arc rotation radius in narrow grove GMAW process. The causes for the typical weld defects are categorized into three are excessive heat input; unstable welding process and mismatch between fusion area and filler metal. Rotating arc regulates the weld pool characteristics that effectively reduce the tendency to form defects in the weld metal [28].

V. Villaret *et al.* 2013, investigated the influence of filler metal composition on the thermal fatigue properties AISI 444 ferritic stainless steels by GMAW process. The number of cycles to failure in the welds was less than the base metal specimens. Titanium content promoted oxidation which can be reduced by the addition of niobium [29]. DM Arya *et al.* 2013, modelled the MIG using wire diameter, welding current, arc voltage, welding speed and gas flow rate. The grey relational analysis performed to optimize the bead geometry with smaller the better criteria. The parameter welding current has the largest contribution to the bead geometry [30].

Kwame *et al.* 2013, compared the high cycle fatigue behaviour of dual phase steel welded using GMAW and PAW process. The PAW specimens showed increased fatigue life than the specimens welded with GMA process. The characteristic is attributed to the bead geometry and lower stress levels at the welds. The double lap joint performs better than single lap joints due to the introduction of new load paths within the material [31].

P. Sreeraj *et al.* 2012, optimised GMAW process parameters using particle swarm optimization (PSO). RSM models developed using central composite rotatable design with full replication technique. The optimised values can be used increase the quality of the austenitic stainless steel cladding [32]. Reis, Ruham Pablo *et al.* 2012, investigated the effect of dynamically applied magnetic field on arc behaviour in GMAW-P process. The constant current GTAW process is used to mimic the tandem pulsed GMAW process. It was found that welding current has positive influence on the resistance arc extinction. Arc deflection exerts minor influence on the arc extinction also back deflection increased the arc extinction resistance [33].

İÇ *et al.* 2012, identified the critical variables by combining design of experiments and goal programming techniques. Both FEA and DOE-GP techniques yielded similar results. The proposed methodology has reduced cost, time and number of experimental runs [34].

GAS TUNGSTEN ARC WELDING PROCESS (GTAW)

Aendenroomer, A. J. R. and G. Den Ouden, 1998, studied the effect of oscillation frequency on penetration in pulsed GTA welding process. The penetration can be simulated as a function of pulsed current peaks in the frequency distribution [35]. Y. H. Kang and S. J. Na, 2002, developed mathematical models to predict arc deflection in GTAW process. Magnetic arc oscillation resulted variation of arc length producing significant voltage fluctuations. Magnetic flux density decreased with increasing arc oscillation frequency [36].

Cicero M.D. *et al.* 1993, developed statistical models with input process parameters like welding current, travel speed, gap width and arc deflection current in narrow groove GTAW process. The arc oscillation has reduced influence on axial fusion and no effect on lateral fusion characteristics. It is found that bead concavity increased with increasing oscillation amplitude [37]. Y. S. Tarng and W. H. Yang, 1998 used the Taguchi experimental design to optimize the bead geometry in GTAW welding of aluminium plates. The optimization criteria adopted in this work was smaller the better. The experimental results and subsequent statistical analysis shows that bead geometry was strongly influenced by the welding speed, welding current and polarity ratio [38].

Xue Wu Wang and Rui Rui Li, 2013, developed neural network model to predict the penetration characteristics like back side bead width and height in GTAW process. The authors proposed use of these soft sensing models in manufacturing environment reduces the need for expensive destructive testing methods [39]. M. Yousefieh *et al.* 2010, optimised the pitting corrosion resistance of super duplex stainless steel welded by pulsed GTAW process using Taguchi design of experiments. The process parameters influences heat input and bead geometry like peak current, back ground current and percentage on time were regulated to maximize the pitting potential of the material [40].

Mahajan S. *et al.* 2012, studied the effect of arc oscillation on the tensile strength, microstructure and hardness distribution GTA welding of low carbon structural steel plates. The transverse arc oscillation shows marked improvement in the mechanical properties. The hardness measurements at heat affected zone slightly higher than the welds without arc oscillation as a result of increased cooling rate [41]. Na Lv *et al.* 2013, monitored the arc length and sag depression using sound signals. The adaptive PID controller was reasonably predicted the arc length in real time pulsed GTAW process [42].

SUBMERGED ARC WELDING (SAW)

Vinod Kumar, Oct 2011 used response surface methodology to model the bead geometry and shape relationships in submerged arc welding process. Welding current has strong positive influence over bead geometry. At the same time welding speed has the reduced bead dimensions. Open circuit voltage found to have negative influence over penetration and reinforcement dimensions. The effect interaction between welding voltage and current is significant on reinforcement dimensions [43]. S. Shen *et al.* 2011, studied the effect of increased heat input in submerged arc welding on bead geometry, area of HAZ and electrode melting efficiency. Heat input has positive influence on bead geometry, HAZ area and efficiency of electrode melting rate. The plate melting efficiency remains unchanged along with decreased contact angle [44]. Singh *et al.* 2011, developed fuzzy rule model the optimization of bead geometry in submerged arc welding process. The fuzzy approach eliminates the weight assignment to the individual responses in multi-objective optimization. Conversion of numerical responses into linguistic avoids the correlation between responses [45].

FLUX CORED ARC WELDING (FCAW)

J.H.F. Gomes *et al.* 2013, used the weighted multivariate mean square error (WMMSE) to optimize the responses governing bead geometry, productivity and quality in FCAW process. Correlation analysis performed between the responses was found to be significant. The confirmation experiments conducted at the optimum levels shows good agreement between predicted and actual values [46]. Vasantha Kumar and N. Murugan, 2011, modelled influence of FCAW process parameters on the responses governing bead geometry and dilution. The multi pass deposits were made with 40% overlap and inter-pass temperature was 150°C. The dilution increased with welding current, welding speed and open circuit voltage [47].

PLASMA TRANSFERRED ARC (PTA)

Lakshminarayanan *et al.* 2008, studied the effect of PTA parameters on dilution in hardfacing of cobalt base alloy on carbon steel substrate. It was found that arc current plays a significant role in determining the dilution of the deposits. Powder feed rate has least contribution towards the dilution but it exerts significant influence on reinforcement dimensions [48].

Siva *et al.* 2009, used response surface methodology to study the effect of PTA variables on weld bead dimension and dilution. Welding current plays positive role with responses like penetration, dilution and total area of the weld bead. The preheat temperature increased the penetration and dilution. Powder feed rate influences the reinforcement dimensions positively [49].

LASER WELDING

Jun Zhou and Hai-Lung Tsai, 2007, modelled the influence of electromagnetic force on formation of porosity in pulsed laser welding. The authors compared the effect of small, medium and large electromagnetic force on the weld pool. The medium electromagnetic force can be considered to be the optimum for producing defect free joints [50]. S. Saqib *et al.* 2014, compared fitness characteristics models of ANOVA and ANN for bead geometry in additive manufacturing using laser cladding process. The authors used central composite design with 96 experiments. The ANN models exhibited better prediction characteristics than the regression models [51].

Turichin Gleb *et al.* 2014, developed optical sensor based monitoring system for laser and laser-arc welding. The sensors were used to collect data from coaxial and non-coaxial locations. The use of signal processing algorithms like FFT, wavelet improved the sensitivity of the system. It is also found that sensitivity of different sensors for a particular defect is different [52].

Table 1: *Influence of Welding Parameters and its Applicability.*

Variable	**Feature**	**Process**
Welding Voltage	Arc length	GTAW, GMAW, FCAW and SAW.
Arc Current	Heat input and metal transfer	GTAW, GMAW, FCAW, SAW and PTA
Electrode Feed Rate	Electrode melting rate	GMAW, FCAW and SAW
Welding Speed	Electrode deposition rate	GTAW, GMAW, FCAW, SAW and PTA.
Stand-Off Distance	Resistance heating of the electrode	GTAW, GMAW, FCAW and PTA.
Shielding Gas Type, Composition and Flow Rate	Penetration profile	GTAW, GMAW, FCAW and PTA.
Electrode Preheat	Penetration and dilution	GMAW
Polarity	Penetration and dilution – Straight and reverse polarity	GTAW, GMAW, FCAW and SAW.
Electrode Angle	Arc pressure on the weld pool – push or pull	GTAW, GMAW and FCAW
Electrode Diameter	Heat input and electrode melting rate	GMAW, FCAW and SAW
Pulse Parameters	Metal transfer and heat input	GTAW and GMAW
Oscillation Frequency	Reinforcement dimension and penetration	GTAW, GMAW and PTA
Powder Feed Rate	Reinforcement dimensions and dilution	PTA and Laser welding

CONCLUSION

The study focused on various welding techniques widely used for surfacing process. In consumable electrode process were welding current is a function of electrode feed rate to maintain stable arc between the electrode and the base metal. Electrode feed rate has to be increased to increase the bead dimensions. The reinforcement dimensions were largely influenced by the rate at which filler metal is melted and deposited. As a consequence of this welding current, heat input and arc pressure also increases. This leads to deep penetrating arc with increased dilution of the filler, area of the heat affected zone and formation undesirable phases in the deposits. In non-consumable electrode and laser welding processes were filler feed rate can be controlled independent of heat input. The deposition rate is less in the case of non-consumable than consumable electrode process. The selection of the process is based on the filler material, type of substrate, positional and automation capabilities. The quality of the deposits was controlled by regulating the welding voltage and current by monitoring optical and acoustic emissions from the arc. The use of response surface and neural network models enables to identify suitable combination of process parameters that yield desirable results. Magnetic arc deflection techniques were gaining ground to deflect arc without the use of mechanical torch oscillation techniques. The occurrences of welding defects were dependent on the type of metal transfer modes. The corrosion and wear characteristics were also influenced by the heat input to the surfacing process.

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