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A Study on Welding Quality of Robotic Arc Welding Process using Mahalanobis Distance Method

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Abstract: In robotic GMA (Gas Metal Arc) welding process, heat and mass inputs are coupled and transferred by the weld arc and molten base material to the weld pool. The amount and distribution of the input energy are basically controlled by the obvious and careful choices of welding process parameters in order to accomplish the optimal bead geometry and the desired mechanical properties of the quality weldment. To make effective use of automated and robotic GMA welding, it is imperative to predict online faults for bead geometry and welding quality with respect to welding parameters, applicable to all welding positions and covering a wide range of material thickness. To successfully accomplish this objective, two sets of experiment were performed with different welding parameters; the welded samples from SM 490A steel flats adopting the bead-on-plate technique were employed in the experiment. The experimental results of current and voltage waveforms were used to predict the magnitude of bead geometry and welding quality, and to establish the relationships between weld process parameters and online welding faults. MD (Mahalanobis Distance) technique is employed for investigating and modeling of GMA welding process and significance test techniques were applied for the interpretation of the experimental data. Statistical models developed from experimental results which can be used to control the welding process parameters in order to achieve the desired bead geometry based on weld quality criteria.

Introduction

The robotic arc welding is employed to monitor information about weld characteristics and process parameters as well as to modify those parameters to hold weld quality within acceptable limits. Typical characteristics are the residual stresses, composition, microstructure, appearance, and process parameters that govern the quality of the final weld in areas like marine pressure vessel. Bead geometry depends on the amount and distribution of the input energy on the work-piece surface and the dissipation of input energy in the work-piece. The ability to monitor the welding quality automatically is important in order to reduce production cost and to assure an improved weld [1-6]. Due to recent increase in emphasis on assurance welding quality, a real time quality monitoring and controlling welding parameter is critically important to avoid welding faults on the work-piece [5]. If weldments used without determining welding fault and quality could pose a critical risk on the welding product.

There has been myriad statistical method used to determine the welding online faults; however there is very limited literature describing the welding quality with respect to the welding parameter. In previous researches, studies have investigated on welding online faults based on the welding voltage and current. For instants, Shengqiang et al. employed Mahalanobis distance method to perform the qualitative and quantities analysis GMAW welding fault and compared with the reference weld [1]. Wu et al. developed a real-time monitoring system for detecting abnormal conditions in robotic gas metal arc welding on the butt weld. Through the statistical processing, it was found that the correct identification rates for normal and abnormal welding conditions are 100% and 95%, respectively [2]. Adolfsson et al. used statistical method based on the variance of the arc voltage to predict weld quality [3]. Li et al. studied the parametric approach to position fault detection in short arc welding, the electric data from short arc welding were separated into two data sets using independent components [4]. Moreover, Cook et al. applied a kind of statistical tool to execute the welding quality detection through data trending analysis, sequential analysis and tolerance analysis [5].

In this study, the current and voltage obtained from the mentoring system are analyzed using the Mahalanobis distance (MD) and normal distribution method to determine the relationship between the welding quality and welding parameters. Two sets to experiment data were obtained, by changing the welding parameter for each case. During welding process the data obtained consist of transformed current and voltage with rate of 2500 data per seconds. The fault and good welding is determined using the concentration current and voltage during welding process. MD values are being calculated through the obtained data and compared between the fault and good weld.

Development of Mahalanobis Distance Algorithms

The proposed statistical method is to determine the welding quality based on Mahalanobis distance and normal distribution methods. Mahalanobis distance (MD) is a multivariate statistical method which was established by P.C.Mahalanobis in1936, an Indian famous statistician. Mahalanobis distance (MD) is mainly used effectively to calculate the similarity of two unknown samples that may have similar spatial orientation but may be located far part [7-8]. This method is different from Euclidian distance by means: first by maintaining the correlation between data, and second by in dependency from the measurement scale. The calculation of MD is described in the field of statistics, and is commonly used for multivariate outlier detection [9]. MD is superior to other multidimensional distance, because it involves a covariance matrix which takes into account the distribution and size of each point. The MD is define;

$$MD_i = \left((x_i - \mu)^T C^{-1} (x_i - \mu)^{1/2} \right) \tag{1}$$

Where μ is the mean multivariate location and *C* is mean covariance matrix. For normally distribution data, the value of MD_i^2 is approximately chi-square distribution with *p* degree of freedom.

According to the concept of MD, multivariate outlier can simply be defined as observation having a large MD. In other word, a longer MD space illustrates the existence of an outlier. In quality control, a longer MD elucidates worse quality. Meanwhile, the magnitude of the compared values of MD is an indicator of a welding faults when large distance between points.

The welding quality whether it is fault or good could be determined by the observations MD space of the multivariate outliers. In order to provide reliable measures for recognition of outliers current and voltage for welding quality, the above equation is being transformed by means of robust procedure complied in matlab software, the transformed equation is define below;

$$M_d = \frac{V_i^{'2} - 2rV_i^{'} + C_i^{'2}}{1 - r^2} \tag{2}$$

Where $V_i^{'}$ and $C_i^{'}$ indicate the normalized *ith* value of welding current and voltage. Firstly the mean and standard deviations for voltage *V* and current *C* are calculate by following equations.

$$\bar{V} = \frac{1}{n}\sum_{i=1}^{n} V_i \,, \quad \bar{C} = \frac{1}{n}\sum_{i=1}^{n} C_i \tag{3}$$

$$\sigma_V = \sqrt{\frac{\sum_{i=1}^{n}\left(V_i - \bar{V}\right)^2}{n}} \,, \quad \sigma_C = \sqrt{\frac{\sum_{i=1}^{n}\left(C_i - \bar{C}\right)^2}{n}} \tag{4}$$

The value of voltage and current are normalized using equation below,

$$V'_n = \frac{V_n - \bar{V}}{\sigma_V}, \qquad C'_n = \frac{C_n - \bar{C}}{\sigma_C} \tag{5}$$

The values of voltage and current tend to be zero, and the standard deviation of voltage and current tend to one after normalization process. However, the dimension of the data does not the MD, since the dimensions of current and voltage are different. Therefore, the normalization of voltage and current is crucial. The correlation coefficient *r* also is normalized with equation below;

$$r = \sum_{i=1}^{n} \frac{V'_i * C'_i}{n} \tag{6}$$

It is important to normalize the value of *r*, since it relies on the distribution of the data and indicates the relationships of the two parameters [1].

The normal distribution is important concept beside MD to quantify the welding quality. The normal distribution is described by the density function;

$$f(x) = \frac{1}{\sqrt{2\pi^2}} e^{-\frac{(x-\mu)}{2\sigma^2}} \tag{7}$$

According to general quality control (QC) and the theory of the normal distribution, the threshold for considering a point to belong to the distribution is commonly set to ±3σ. That is, if results are within the range of ±3σ this shows predicted results good in outliers. In this study, MD values distribution is assumed to obey normal distribution rule. However, MD values are always positive, therefore, the range of MD is acceptable from 0 to ±3σ. This indicates that if the calculated MD from welding voltage and current lie in the range from 0 to ±3σ, welding quality is considered to be good weld. Conversely, if the values of MD lie outside this range welding quality regards as fault.

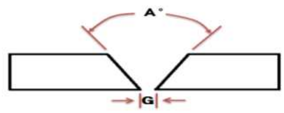
Experiment procedures

In order to quantify the welding quality in robotic arc welding, two sets of experiments were performed using different welding parameter. Fig 1 below shows analytical algorithm procedure and overview of robotic arc welding is performed.

Fig. 1 Analytical algorithm procedure for robotic arc welding

To perform GMA robotic welding on SM490A steel which is mainly used in marine pressure vessel requires specification on the manual welding condition. Table I represents welding details based on standard Welding Specification Procedure (WPS) and manual welding conditions based on preliminary experiments to drive a stable bead area.

Table I. Robotic GMAW details through WPS.

	Details
Joint Type	
Groove Angle	60°
Base Metal Grade	SM490A
Thickness	12mm
Welding Wire	AWS ER70S-3
Shielding Gas	CO2 99%
Root Gap	1mm
Welding Length	400mm
Evaluation Item	Welding Condition (Amp/Volt/Speed/Weaving)

Two different set experiment parameters selected as shown in table II. In each case the parameter such as arc voltage, and welding speed are different, but the gap between two plates and welding current is the same in both cases.

Table II. GMA welding process parameters for two different cases

Symbol	Process parameter	Cases	
		1	2
V	Arc Voltage (V)	24	26
I	Welding Current (A)	220	220
S	Welding Speed (cm/min)	20	30
G	Gap (mm)	1	1

The welding plate's dimensions and the direction for butt GMA welding process on a test work-piece is shown below in fig. 2.

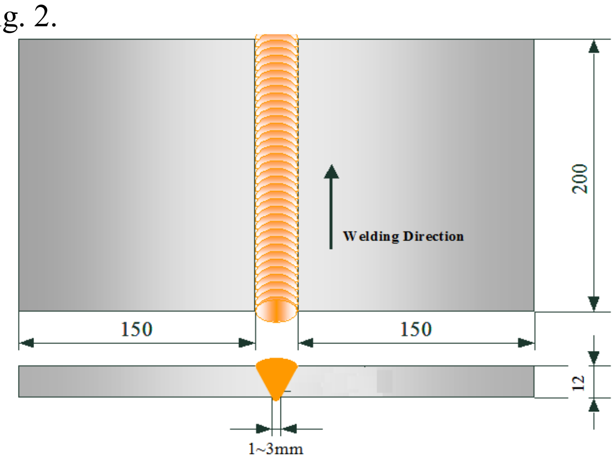


Fig. 2 Overview of GMA butt weld specimen

For quantifying welding quality, the result data of arc voltage and welding current from the online monitoring system were obtained and changed from analog to digital. Through the defined formulas above, mean and standard deviations and with that MD are calculated for conducted experiment data. Using the calculated MD, normal distributions methods the quantified welding quality is obtained. There are three steps in determining the welding faults, first the weld fault is determined by concentration of transformed current and voltage which is set as reference for quality weld. Second determine the behavior of MD with respect to time during welding process and lastly determine welding quality percentage using normal distribution.

Results and Discussion

The transformed welding voltage and current obtained during the welding process from the online monitoring system with its bead geometry is shown in fig 3. From the results it can be observed the input variables that have the greatest impact factor on weldability are welding current, arc voltage, welding speed whereas the output variables that occur on the plate are bead width and bead width. In case 1, it can be observed that bead geometry obtain is good compared to the bead geometry in case 2. Fig. 3 below also shows that during initial welding state the welding regarded as welding reference because at the beginning and end part of the welding, the process is unstable and welding quality is regarded as fault compared with other part of welding.

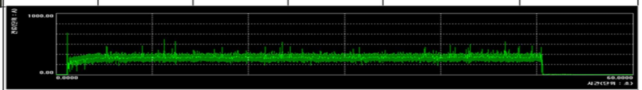
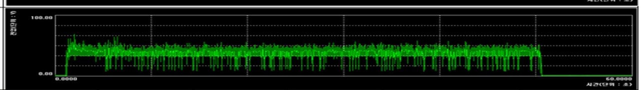
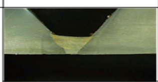
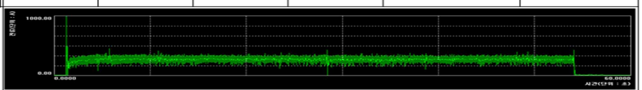
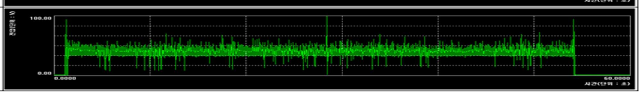
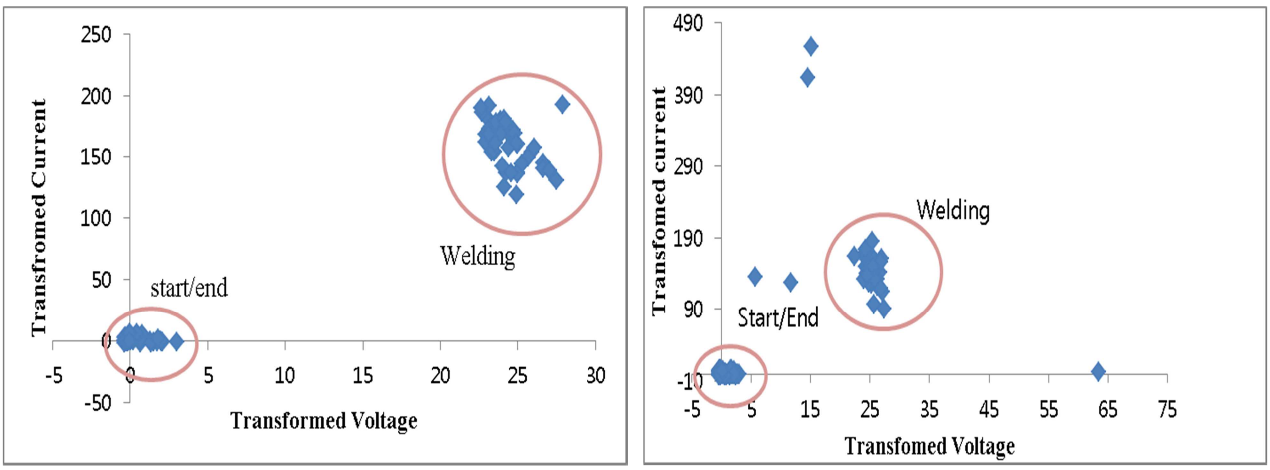
Number	Bead Geometry	Arc Voltage	Welding Current	Welding Speed	Gap	Back-bead Width	Back-bead Height
1		220	24	20	1	13.0	1.8
	Current waveform						
	Voltage waveform						
2		220	26	30	1	4.1	0.4
	Current waveform						
	Voltage waveform						

Fig. 3 Experiment results from the performed experiment with bead geometry

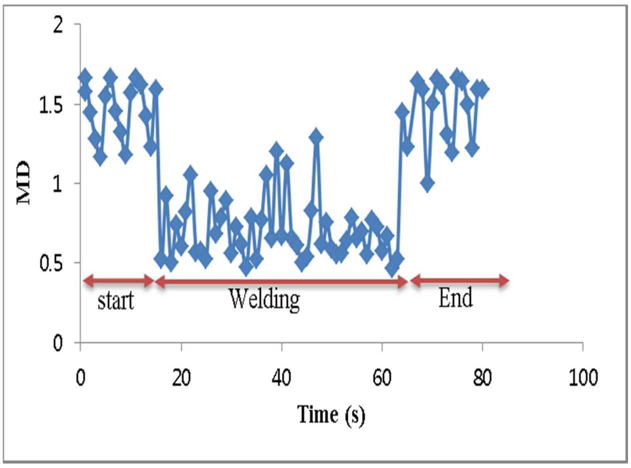
Fig. 4 shows typical transformed averaged arc voltage and welding current graphs for two different cases of welding process. The data shown in Fig. 1(a) is obtained from the case 1 which shows that the distribution of data is more concentrated during welding process compared to the fig. 1 (b) where data is more distributed outward to each other.

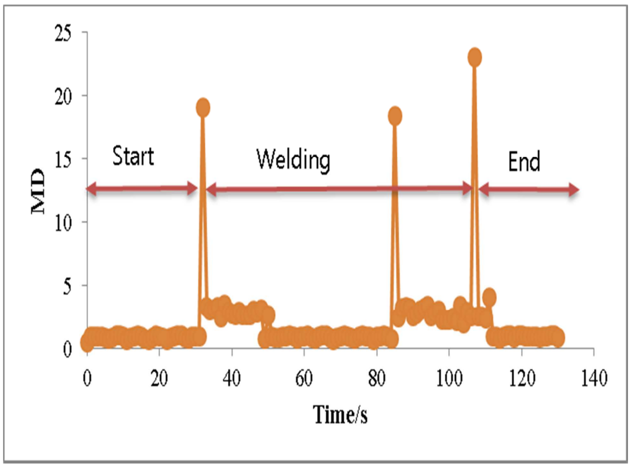


(a) Good weld (b) Fault weld

Fig. 4 Typical transformed welding current and arc voltage

This preliminary analysis determines fault weld and good weld and this analysis also set as a reference to determine the fault welding quality percentage. According to MD concept, a longer data space existence between each other indicates the fault weld. Therefore, fig. 4(a) is found to be faultless weld, whereas fig. 4(b) is found to a fault weld. The start and end welding current and arc voltage was also recorded on the online monitoring system, and present on transformed current verse transformed voltage. The result shows that current and voltage are very low and unstable during start and end welding process. Fig. 5 shows the MD distribution with respect welding process time. The fig. 5(a) shows good weld quality, it is clearly observed that at start and end welding the normalized MD is unstable but as it move along process, it get stable. Fig. 5 (b) shows unstable normalized MD results through welding process. The MD values are big during the welding process results to fault weld quality, which is also the results of artificial increase of arc length.

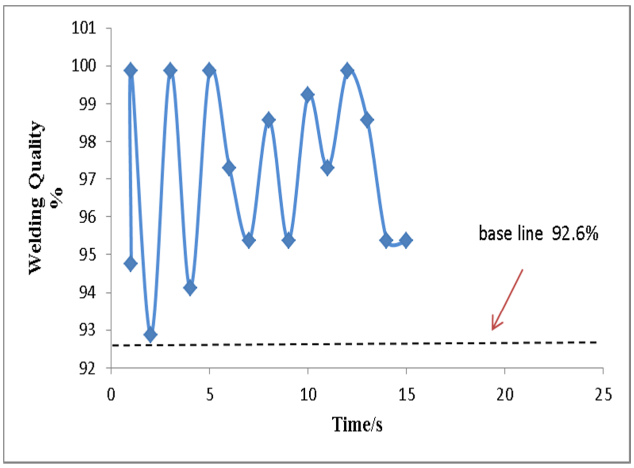


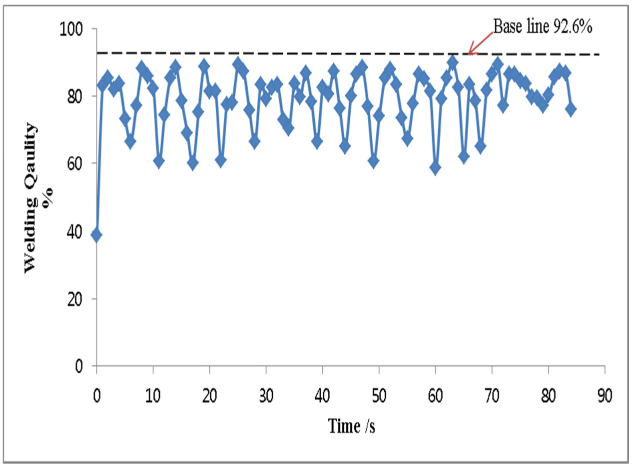


(a) Good quality welding (b) Fault quality welding

Fig. 5 Mahalanobis Distance (MD) distribution with respect to time

Fig. 6 shows the quanitified welding quality percentage obtained from MD analysis of two different experiments. For both the experiments the thresold values of the welding quality is defined by 92.6 %, which is represented in dash lines in fig. 6. This means that, if the quantified welding quality obtained from the experiment is above threshold value, the welding quality could be considered good weld quality, instead if the value of the quantified welding quantified welding quality are below threshold value, the welding quality is regraded as fault. Fig. 6(a) shows the quantified good welding quality for experiment case 1, since the welding quality percentage is above the threshold values compared to Fig. 6(b) experiment case 2 which has fault welding quality. From the MD analysis steps the case 1 tend show a good quality weld compared to case 2.





(a) Quantified welding quality for good weld (b) Quantified welding quality for fault weld

Fig, 6 Welding quality of optimal process parameter

This clearly shows that welding process parameter has a great influence on welding quality such arc voltage, welding current and welding speed.

Conclusion

This study investigates the application of a statistical method for quantifying the welding quality and determines the relationship between welding process parameter and welding quality in robotic GMA welding.

The proposed method employs the Mahalanobis Distance (MD) and normal distribution to evaluate the welding quality. The transformed arc voltage and welding current data obtained from the two different sets of experiment were analyzed using MD and normal distribution. Typical transformed arc voltage and welding current graphs describes as reference for determining welding quality percentage. The results obtained clearly predict that welding parameters has a large impact on welding quality. The bead geometry from the two experiments also indicated the effect of welding parameter on the weld joint quality. Controlling the welding parameters such as arc voltage, welding current and welding torch speed could help in controlling welding quality. These results also suggest that statistical such as Mahalanobios distance (MD) and normal distribution method could be used to determine the online welding quality to avoid joint failure.

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