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A study on welding quality for the automatic vertical-position welding process based on Mahalanobis Distance method

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ABSTRACT

Purpose: The welding quality and reducing production cost could be achieved by developing the automatic on-line welding quality monitoring system. However, investigation of welding fault to quantify the welding quality on the horizontal-position welding has been concentrated. Therefore, MD (Mahalanobis Distance) method on the vertical-position welding process by analysing the transform arc voltage and welding current gained from the on-line monitoring system has been applied.

Design/methodology/approach: The transformed welding current and arc voltage data were taken from the experiment whereby the data number was 2500 data/s. The prediction of Contact Tip to Work Distance (CTWD) to gain best welding quality using the waveform variations were then taken from the experimental results. MD was employed to quantify the welding quality by analysing the transformed arc voltage and welding current. Finally, the optimal CTWD setting has verified the developed algorithms through additional experiments. Two kinds of experiments has been carried out by changing welding parameters artificially to verify the sensitivity and feasibility of WQ (Welding Quality) based on the concepts of MD and normal distribution.

Findings: The results represented that WQ was fully capable of quantifying and qualifying the welding faults for automatic vertical-position welding process.

Research limitations/implications: The arc welding process on the vertical-position compared to a horizontal-position welding is much more difficult because the metal transfer is influenced by the gravity force. To solve the problem, a new algorithm to monitor and control the welding fault during the arc welding process has been developed. Furthermore, optimization of welding parameters for the vertical-position welding process was really difficult to use the developed algorithms because they are only useful in selecting stored data and not for evaluating the effect of the variation of welding parameters on the weld ability.

Practical implications: The developed algorithm could be achieved the highest welding quality at 15mm CTWD setting which the welding quality is 99.50% for the start section and 99.68% at the middle section.

Originality/value: This paper proposed a new algorithm which employed the concepts of MD (Mahalanobis Distance) and normal distribution to describe a good quality welding.

Keywords: Vertical-position welding, Contact Tip to Work Distance (CTWD), Welding quality, Welding fault, On-line monitoring system, Mahalanobis Distance

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Generally the arc welding process is widely employed in many industrial applications which are difficulty replaced by other techniques. For instance, the shipbuilding industry is one of many applications of the arc welding process which is applied in engineering field. So far, the welding method to join the plate of outer ship body still couldn't be modified by other joining method. Another work of the welding process is in large steel structures which required high tensile strength that is influenced by the welding quality. However, the high quality of the weld has the welding strength similar with specification of the desired strength. The auomated welding processes looked for meeting the demands for quality and performance through product improvements and cost reductions. The CTWD has significant effect to production improvement, by decreasing the spatter and maintaining constant welding current. Furthermore, the CTWD in arc welding process could be caused to decrease the heat input, weld defects and the weld reinforcement as the welding quality [1]. Moreover, the welding position has important role to determine the welding quality during the welding process. As the gravity force on the vertical-position welding acts on the metal transfer during the welding process, the horizontal-position welding process generally produces better welding quality that of the vertical-position welding process. As a results, it is much more complicated to control welding quality for the vertical-position welding than the horizontal-position welding. Currently, the welding fault detection has still been based on the off-line detection method which leads to decreasing in productivity and also the welding quality couldn't be controlled during the welding process because the welding fault detection is only carried on since the welding process finished. Consequently, the on-line welding fault detection method is very significant not only to achieve good quality of the weld, but also to increase the productivity. In addition, the welding control system should be required the optimal welding parameters during the welding process as welding quality. The developed system with optimal welding parameters lead to low labor intense, time saving as well as production cost reduction. Due to those advantages, the optimal welding parameters might be applied in a welding automation system. So far, the optimal welding parameters which give rise to high degree welding automation system for the horizontal-position welding process have widely been employed [2-8]. The automated welding system has many challenging issues such as accurate seam tracking, precise pipeline alignment and welding parameters optimizing [9]. The welding quality which pointed to bead geometry is affected by the input energy dissipation and amount of input energy on the workpiece area [10]. Also, the automatic on-line welding quality monitoring system can be accomplished increasing the welding quality and reducing production cost [11]. Consequently, the automatic on-line monitoring system might be developed and by implemented to control the welding process A real-time welding system could be applied to ensure the welding quality and avoid the welding fault on the work surface [12]. To quantify the welding quality, the transformed arc voltage and welding current from on-line monitoring system are employed. Until now, a few studies which examined the transformed arc voltage and welding current from on-line monitoring system to detect welding faults have been done [13,14]. Adolfsson et al. [14] have performed the prediction of welding quality based on arc voltage variance. MD (Mahalanobis Distance), a robust and simple method is widely employed. Many studies on welding quality quantified from the welding faults based on MD theory has been carried out [10-12,15]. To find the welding fault by qualitative quantities analysis in Gas Metal Arc (GMA) welding process, Feng et al. [11] employed MD algorithm. Arc voltage and welding current analyzed to determine the welding quality by quantified the welding fault on overlay pipeline welding process used MD method [10]. Muzaka et al. [16] studied welding quality on the vertical-position welding process by calculating the welding fault. The reviewed literatures [10-15] mostly limited on investigation of welding fault to quantify the welding quality on the horizontal-position welding.

Therefore, this study takes into consideration of the development of a new algorithm to select optimal CTWD using MD method on the vertical-position welding process by analyzing the transform arc voltage and welding current gained from the on-line monitoring system. The transformed welding current and arc voltage data were taken from the experiment whereby the data number was 2500 data/s. The prediction of CTWD to gain best welding quality using the waveform variations were taken from the experimental results. MD was employed to quantify the welding quality by analyzing the transformed arc voltage and welding current. Finally, the optimal CTWD setting has verified the developed algorithms through additional experiments.

2. Experimental procedures

In order to calculate welding quality in this study, sequence experiments conducted bead-on-plate GMA welding process with the vertical-position using SS400 steel plates of size 400 x 400 x 10 mm^3. The chemical compositions of base metal and filler wire are presented in Table 1. The shielding gas was used 100% CO_2, and constant current power source has been applied. Sheets of steel were cleaned using steel wire brush continued by acetone swabbing just before to welding, and followed by bead-on-plate GMA welding process [17]. Figure 1 shows setting up the equipment of the experiment, followed by positioned the steel plate vertically which held in fix jig to minimize the welding distortion during the welding process as shown in Figure 2.

Fig. 1. Overview of experimental setup

Table 1.
Chemical compositions for base metal and filler wire

Material	Element weight, %							
	C	Si	Mn	Ti	P	S	Al	Zr
Base metal, %	0.17	0.54	1.40	0.07	0.04	0.04	-	-
Filler wire, %	0.07	0.54	1.18	0.07	-	-	0.08	0.05

The welding inverter was set manually for the arc voltage and welding current which is measured during the automatic welding process using the digital data acquisition system.

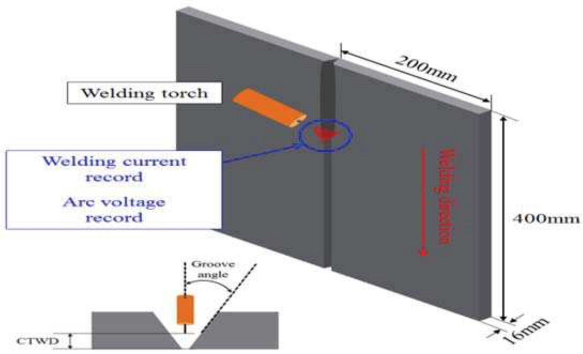


Fig. 2. Welding fixture of base metal and welding torch

The experimental data was recorded using a specifically designed power supply. To establish adequate operating condition during the welding process, it performed initial trials before the experiment. The electrode moved downward direction during GMA welding process which programed the CTWD. The experimental design is shown in Table 2. which used four different setting of CTWD [18].

Table 2.
Experimental design

Parameter	Value	Unit
Contact Tip to Work Distance (CTWD)	11, 13, 15, 17	mm
Electrode angle	75	o
Arc voltage	23	V
Welding current	250	A
Gas Flow rate	18	l/min
Welding Speed	53	cm/min

To get the welding quality, a MD has been used to analyse the transform welding current and arc voltage taken during the arc welding process. Since the welding quality was gained by quantifying the number of welding fault per second, a few steps should be needed to determine the welding fault. First step is setting up the MD threshold value (σ), then the welding fault is determined using threshold value 3σ [10] and calculated the welding fault in every 0.25 s. Finally, the welding quality for the vertical-position welding process could be finded out calculating the welding fault percentage.

3. Results and discussion

3.1. Development of optimal algorithm for CTWD setting

To carry out the experiment, the specimens were prepared in Figure 3 which indicated the measured position to determine the optimal CTWD by quantifying the welding quality. Two sections picked up the specimen (the start section and the middle section) which showed by marked 1 and 2 respectively were chosed for this study. Because welding quality at base metal are generally unstable for the initial and the end section area, the experimental results were recorded 2 seconds after the start for the start section and the middle section at 11 seconds after the start [12,13]. The experimental results from the start position of each CTWD setting whereas the quality quantified in every 0.25 second was designated the reference.

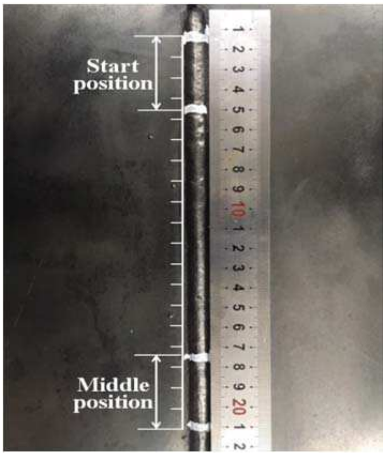
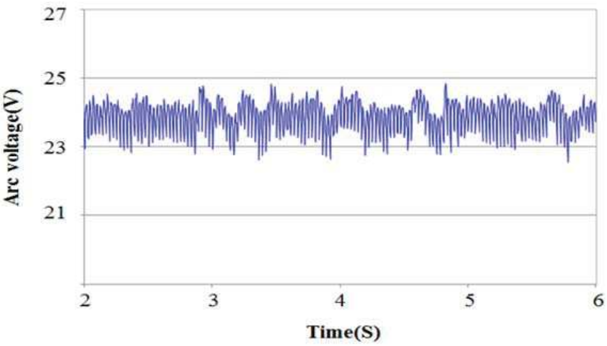


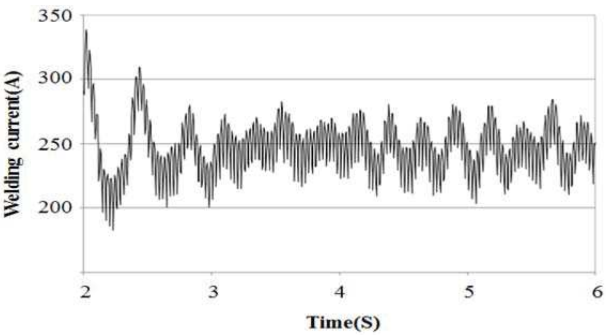
Fig. 3. Measured position on weld base metal during welding process

Figure 4(a) shows the waveform of arc voltage at the start position of CTWD setting at 11 mm has many fluctuations in wave length, the fluctuation occurred mostly around 3 s to 4 s which is the fluctuation in wave length due to decreasing of the arc voltage. From the Figure 4(b), it can be observed that the waveform of welding current also has many fluctuations in wave length from about 2 s to 3 s continued stable up to 6 s. The fluctuations of welding current in wave length happened due to increasing the welding current. Figure 4(c) shows the arc voltage waveform of the middle position of CTWD setting at 11 mm has lesser fluctuations in wave length compared the arc voltage at the start position that showed in Figure 4(a). The fluctuations in wave length mostly occurred from 23 s to 24 s. The waveform of the welding current of the middle position of CTWD setting at 11 mm that showed in Figure 4(d) indicated less fluctuations in wave length which accumulated around 22.4 s to 22.6 s and also much more stable compared to the welding current at the start position shown in Figure 4(b).

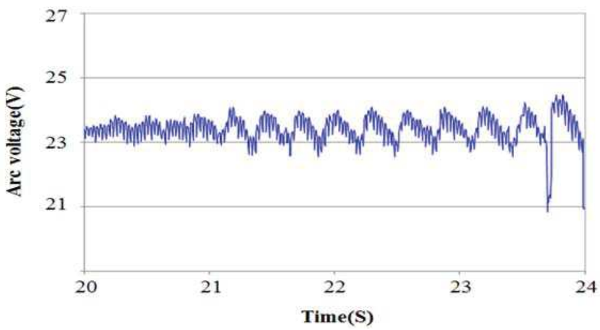
There are many fluctuations in wave length of arc voltage waveform at the start position of CTWD setting at 13 mm shown in Figure 5(a), whereas the most fluctuations happened from 2 s to 3 s and from 4 s to 6 s. In addition, the fluctuation in wave length has tendency to downward direction or decreases in the transformed arc voltage as showed in Figure 5. Figure 5(b) shows waveform of welding current at the start position of CTWD setting at 13 mm which is the highest fluctuation in wave length occurred around 5 s to 6 s and 4 s.



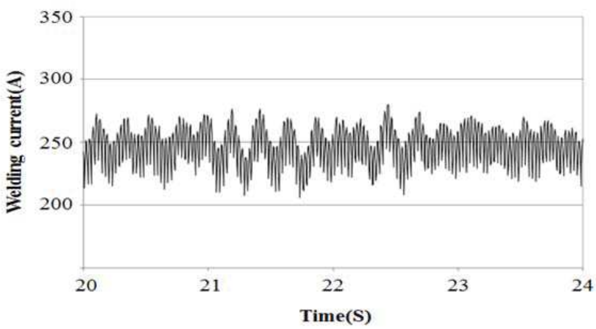
a) Arc voltage at start position



b) Welding current at start position

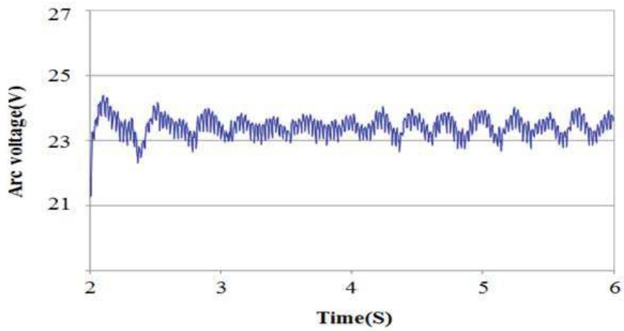


c) Arc voltage at middle position

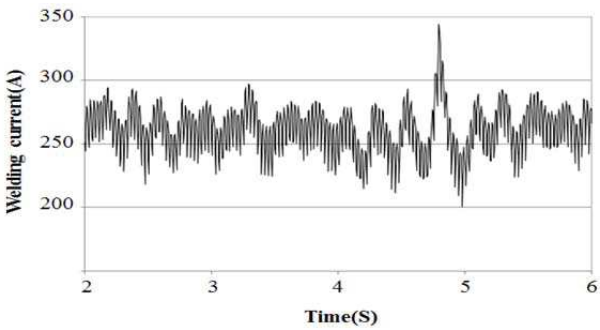


d) Welding current at middle position

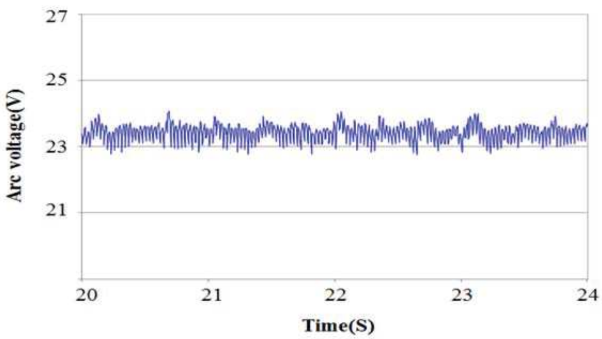
Fig. 4. Arc voltage and welding current waveform of CTWD setting at 11 mm



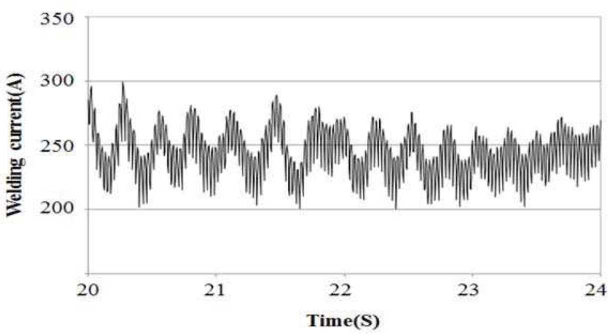
a) Arc voltage at start position



b) Welding current at start position



c) Arc voltage at middle position



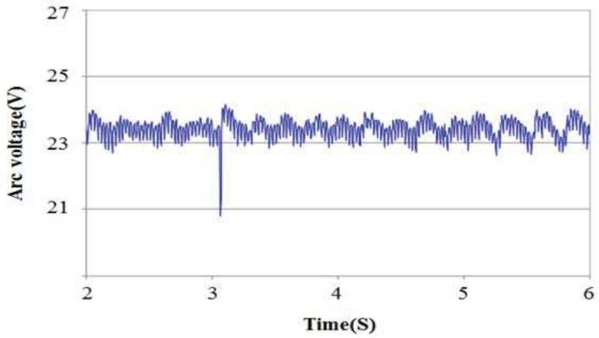
d) Welding current at middle position

Fig. 5. Arc voltage and welding current waveform of CTWD setting at 13 mm

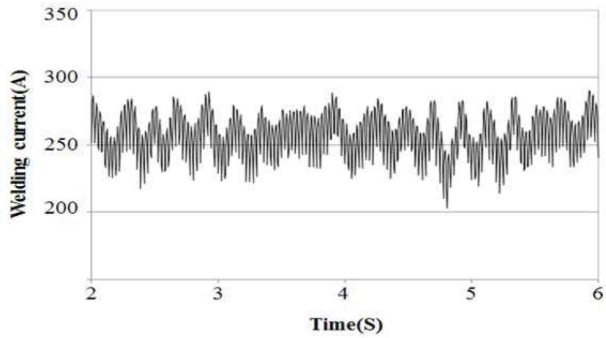
Figure 5(c) indicates the arc voltage waveform of the middle position of CTWD setting at 13 mm confirmed much more stable compared to arc voltage at the start position (Fig. 5(a)) with little fluctuations in wave length spread during the welding process. Figure 5(d) represents welding current waveform at the middle position of CTWD setting at 13 mm had few fluctuations in wave length which is more stable compare to welding current waveform at the start position in Figure 5(b).

Figure 6(a) presents the stable waveform of arc voltage at the start position with small amount of fluctuations in wave length whereas spread during welding process about 4 s to 6 s. The waveform of welding current at the start position of CTWD setting at 15 mm has the uniformed shape with 2 fluctuations in wave length which happened around 3.2s and 4s, as shown in Figure 6b that the waveform is very stable. Figure 6c indicates the arc voltage waveform at the middle position of CTWD setting at 15 mm fluctuated in wave length during the welding process and more fluctuations compared to the arc voltage waveform at the start position in Figure 6(a). The welding current waveform at the middle position of welding CTWD setting at 15 mm has many fluctuations which spread around 23 s to 24 s shown in Figure 6(d). The welding current waveform at the middle position in Figure 6(d) has much more fluctuation in wave length compared to the waveform of the welding current at the start position in Figure 6(b). According to Figures 4-6, it could be encountered that both arc voltage and welding current waveform at the start position has more stable than those of the arc voltage and welding current at the middle position. It could be noted that the arc voltage waveform fluctuations in wave length occurred due decreasing of the transformed arc voltage, and in converse, the welding current waveform fluctuations in wave length due to increasing the transformed welding current.

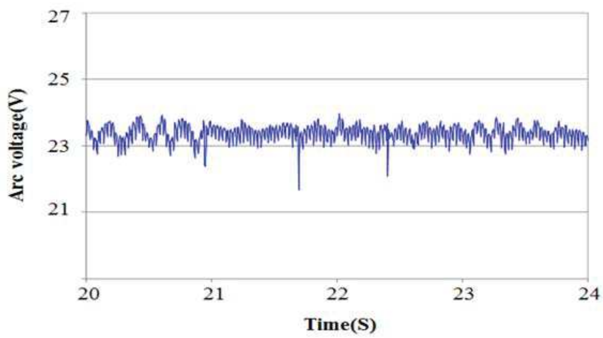
Figure 7(a) shows the waveform of arc voltage at the start position of CTWD setting at 17 mm has many fluctuations in wave length, the fluctuation occurred mostly around 3 s to 5 s which is the fluctuation in wave length due to decreasing of the arc voltage. From the Figure 7(b), it can be observed that the waveform of welding current also has many fluctuations in wave length from about 2.5 s to 3.5 s continued stable up to 5 s. The fluctuations of welding current in wave length happened due to increasing the welding current. Figure 7(c) shows the arc voltage waveform of the middle position of CTWD setting at 17 mm has lesser fluctuations in wave length compared the arc voltage at the start position that showed in Figure 7(a). The fluctuations in wave length mostly occurred from 21.5 s to 22.5 s.



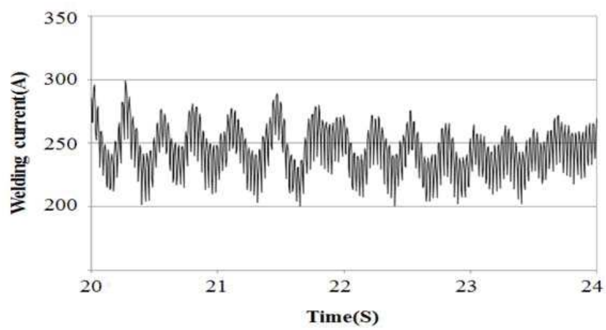
a) Arc voltage at start position



b) Welding current at start position

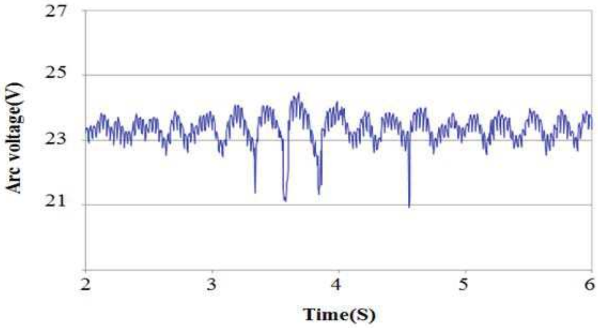


c) Arc voltage at middle position

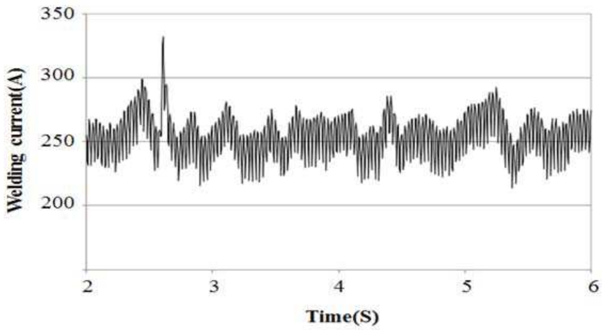


d) Welding current at middle position

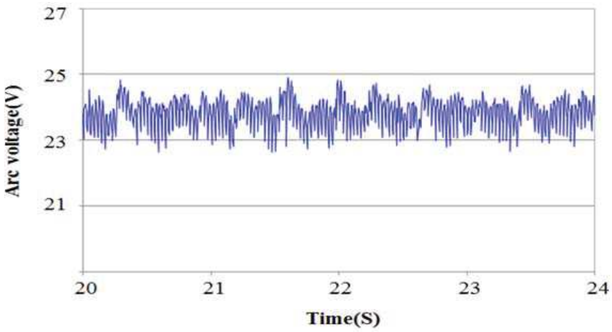
Fig. 6. Arc voltage and welding current waveform of CTWD setting at 15 mm



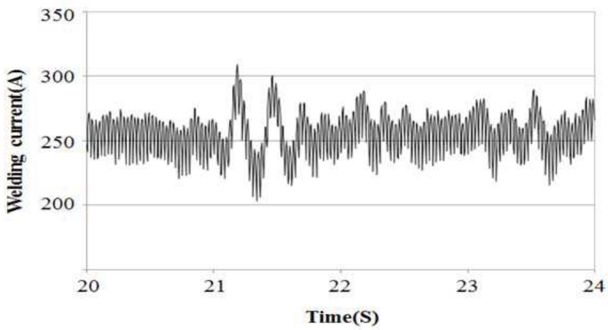
a) Arc voltage at start position



b) Welding current at start position

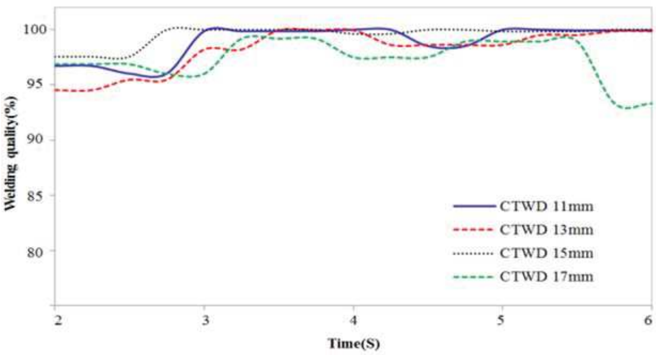


c) Arc voltage at middle position

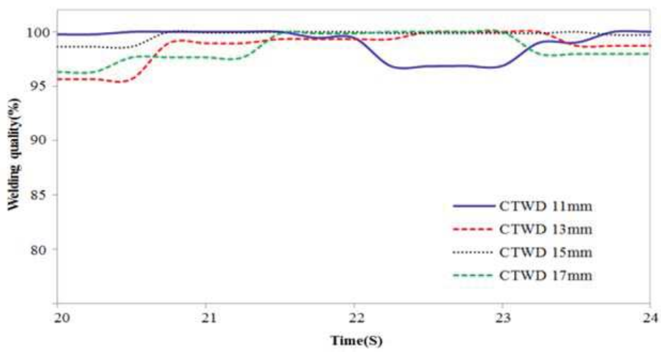


d) Welding current at middle position

Fig. 7. Arc voltage and welding current waveform of CTWD setting at 17 mm



a) Start position



b) Middle position

Fig. 8. The comparison of welding quality among CTWD at 11, 13, 15, 17 mm

The waveform of the welding current of the middle position of CTWD setting at 17 mm that showed in Figure 7(d) indicated less fluctuations in wave length which accumulated around 21.1 s to 21.7 s and also much more stable compared to the welding current at the start position shown in Figure 7(b).

Figure 8(a) shows comparison of welding quality among four different setting of CTWD at the start position. It could be observed that the lowest quality value of CTWD setting at 11 mm is 96.45% at 2.6 s with the average quality is 98.93%. The lowest quality of the CTWD setting at 13 mm is 94.55% at 2 s where by the average quality is 98.21%. The lowest quality of the CTWD setting at 15 mm is 94.72% at 3 s where by the average quality is 99.50%. And then the CTWD setting at 17 mm has the lowest quality 92.52% at 5.8 s and for the average quality is 97.36%. The welding quality of four different CTWD at the middle position is shown in Figure 8(b). It was clearly indicated that the quality of CTWD setting at 11 mm has lowest quality 96.42% at 22.25 s which average quality is 99.05%. The quality of CTWD setting at 13 mm has lowest quality 95.15% at 20.6 s whereas the average quality is 98.67%. The quality of CTWD setting at 15 mm has lowest quality 98.21% at 20.7 s whereas the average quality is 99.68%. And then lowest quality of CTWD 17 mm setting is 96.22% at 20.2 s with the average quality is 98.51%.

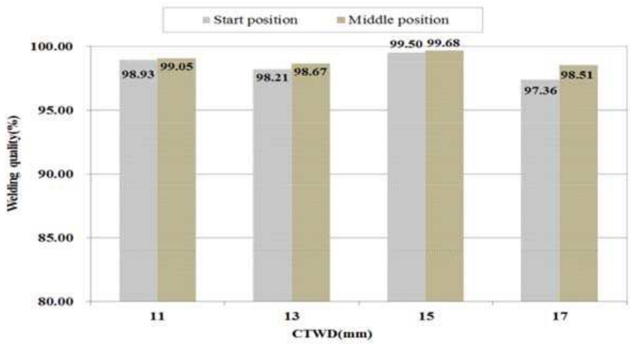


Fig. 9. Welding quality comparison of CTWD at 11, 13, 15, 17 mm

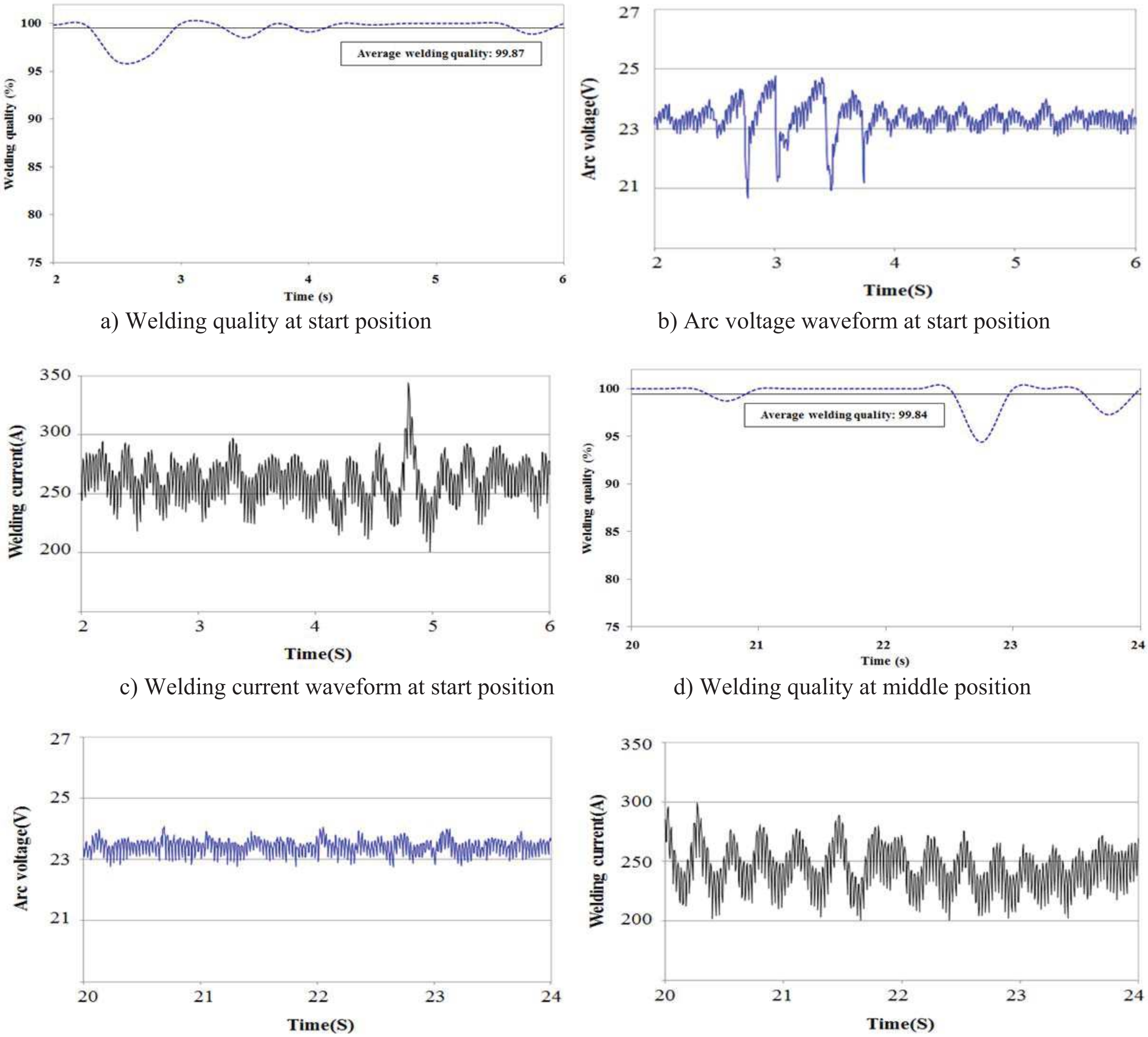
Figure 9 shows the comparison of welding quality of four different CTWD setting at the start and middle positions. It could be observed that the average welding qualities of the start and middle positions of CTWD at 11 mm are 98.93% and 99.05% respectively. It also can be observed that average of welding qualities of the start and middle positions of CTWD at 13mm are 98.21% and 98.67% in series. And then the average of welding qualities of the start and middle position of CTWD setting at 15 mm are 99.50% and 99.68%. Finally, the average of welding qualities of the start and middle position of CTWD setting at 17 mm are 97.36% and 98.51%. From the Figure 9, it is confirmed that the CTWD at 15 mm has increased the welding qualities from the start to the middle positions, and it also has higher quality compared to those three others even though the quality of the start position is below the CTWD setting at 17 mm.

3.2. Verification of the developed algorithm for optimal CTWD

To verify the developed MD algorithm, the optimal CTWD at 15 mm was employed to quantify the welding quality on the vertical-position welding process. The welding position for analysis is shown in Figure 10, and the experimental data were taken 4 second in every position (point 1 as the start position and point 2 as the middle position) which is 2 second before and after. To define the welding fault, the developed algorithm was employed for analysing the transformed welding current and arc voltage. Then the welding quality quantification was calculated in every 0.25 s. The average welding qualities were showed by dash line in Figures 11(a) and (d) which welding quality values are 99.87% for the start position and 99.84% for the middle position. The welding current and arc voltage has significant effect on the welding quality as can be seen in Figure 11 whereas the fluctuations of welding current and arc voltage waveforms in Figures 11(a) and (b) at around 2.5 s to 3.2 s lead to the welding quality declined. It can be demonstrated that more fluctuation in wave length of welding current and arc voltage waveforms will create the welding quality more decreased. Not only the welding fault will take place as the fluctuations in wave length occurred, but also the welding quality decreased.

Fig. 10. The positioned of data selection for analysis

As the welding current and arc voltage waveform are affected by the CTWD as input parameter, it should be controlled the CTWD using on-line monitoring system in order to obtain the desired welding quality. Therefore, a new algorithm for detection of welding fault on the on-line monitoring system involved the welding current and arc voltage waveform should be devdeloped and applied for GMA welding process. However, the developed algorithm offers a solution that could analyse both the welding current and arc voltage waveform at once which is proved to define the welding quality since welding quality depends on both output parameters. The output parameters from the developed algorithm can be employed as a feedback to control CTWD to accomplish the desired welding quality during vertical-position welding process. It can be surmised from the studies that the developed algorithm has significant for controlling the welding quality during the GMA welding process which is given by the verification results.



a) Welding quality at start position
b) Arc voltage waveform at start position
c) Welding current waveform at start position
d) Welding quality at middle position
e) Arc voltage waveform at middle position
f) Welding current waveform at middle position

Fig. 11. CTWD setting at 15 mm

4. Conclusions

The intelligent algorithm for optimizing the CTWD as welding paramerter to achieve the welding quality during a GMA vertical-position welding process has been developed in this research and the following conclusions have been pointed out:

1) The best welding quality was achieved 99.50% for the start position and 99.68% for the middle position with the optimal CTWD at 15 mm. The welding quality of the CTWD of the start and middle position at 11 mm, 13 mm and 17 mm are 98.93%, 99.05%, 98.21%, 98.67% and 97.36%, 98.51% in sequence.
2) The verification of MD using optimal CTWD setting was gained the welding quality 99.87% for the start position and 99.84% for the middle position. For GMA vertical welding application, the developed algorithm is a novel method that could be applied as a core of welding control to achieve the expected welding quality by manipulating the CTWD.

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