Pulsed current and dual pulse gas metal arc welding of grade AISI: 310S austenitic stainless steel

A. MATHIVANAN [a], A. SENTHILKUMAR [b], K. DEVAKUMARAN [c],*

[a] *Mechanical Engineering Department, SRM University, Ramapuram, Chennai 600089, Tamilnadu, India*
[b] *School of Mechanical and Building Sciences (SMBS), VIT University, Vellore 632014, Tamilnadu, India*
[c] *Welding Research Institute, Bharath Heavy Electricals Limited (BHEL), Trichy 620014, Tamilnadu, India*

Abstract

The transverse shrinkage, mechanical and metallurgical properties of AISI: 310S ASS weld joints prepared by P-GMAW and DP-GMAW processes were investigated. It was observed that the use of the DP-GMAW process improves the aforementioned characteristics in comparison to that of the P-GMAW process. The enhanced quality of weld joints obtained with DP-GMAW process is primarily due to the combined effect of pulsed current and thermal pulsation (low frequency pulse). During the thermal pulsation period, there is a fluctuation of wire feed rate, which results in the further increase in welding current and the decrease in arc voltage. Because of this synchronization between welding current and arc voltage during the period of low frequency pulse, the DP-GMAW deposit introduces comparatively more thermal shock compared to the P-GMAW deposit, thereby reducing the heat input and improves the properties of weld joints.

1. Introduction

The gas metal arc welding (GMAW) process has been widely investigated and reported since 1950s [1]. A number of variants of GMAW have been developed in an attempt to improve the performance and productivity of the process [2]. In this regard, John Norrish et al. [2,3] reported the evolution of the GMAW process starting from standard operating modes, such as surface tension, globular and spray, of metal transfer behavior to waveform control technology up to the various hybrid techniques. From these literatures, it is well understood that the conventional GMAW process can be modified to enhance productivity and quality by manipulating the

operating parameters, such as the electrical extension of wire/ polarity, and the improved process control can be achieved by modifying the current waveform. Dual pulse is also introduced in the GMAW process to improve the energy transfer efficiency in comparison to the conventional and pulsed GMAW processes. Praveen et al. [4] reported that the dual pulse GMAW (DP-GMAW) process operates at low heat input. In the DP-GMAW process, the low frequency current pulsation is superimposed on high frequency pulsed current for better control of arc and metal transfer behavior as reported by Anhua Liu et al. [5] in the case of welding of AA5754 aluminum alloy. Celina Leal Mendes da Silva et al. [6] concluded that DP-GMAW technique maintains the capability of porosity minimization in aluminum weldment attributed to the pulsed current GMAW (P-GMAW) technique. The process characteristics of inverter type GMAW process under static and dynamic operating conditions were reported by Devakumaran et al. [7]. It was concluded that the DP-GMAW process operates at low heat input compared to the

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* Corresponding author. Tel.: +91 9443689943.

E-mail addresses: mathivanana@gmail.com (A. MATHIVANAN), asenthilkumar@vit.ac.in (A. SENTHILKUMAR), devakumaran@bheltry.co.in (K. DEVAKUMARAN).

Table 1
Chemical compositions of base and filler materials.

Materials	C	Si	Mn	Cr	Ni	P	S	Fe
Base material AISI: 310S ASS	0.026	1.28	1.49	25.06	19.75	0.025	0.01	Bal.
Filler material E309L	0.05	0.35	1.80	24.51	13.91	0.023	0.01	Bal.

conventional and pulsed GMAW processes, which is in agreement to the earlier work reported by Praveen et al. [4]. From the above literature, it is understood that very little work has been carried out with respect to the process characteristics of DP-GMAW process, but the utilization of DP-GMAW process for various applications is not well known to the users because of the limited understanding of the mechanism of DP-GMAW and its influence on weld joint quality. Hence, it is felt that a systematic understanding of the DP-GMAW process in welding of various ferrous and nonferrous materials are very much important.

In this context, the present investigation describes the superiority of DP-GMAW process in welding of AISI: 310S austenitic stainless steel in comparison to the conventional P-GMAW process. The grade AISI: 310S austenitic stainless steel (ASS) is designed for high temperature service due to excellent high temperature properties and good ductility [8]. It resists oxidation in continuous service at the temperatures up to 1000 °C [9]. However, it is reported that the welding of high chromium grade AISI: 310S material is critical since it is susceptible to Intergranular corrosion attack because of chromium depletion near the fusion line of HAZ [10]. It is generally known that the increase of heat input enhances the chromium depletion. Thus, special attention should be taken in welding of grade AISI: 310S ASS material. From the literature review, it is well understood that there is limited published literatures about welding of grade AISI: 310S ASS [11]. Hence, it is felt that the dual pulse GMAW process is one of the welding techniques which may improve the weld joint characteristics of grade AISI: 310S ASS material.

2. Experimental

2.1. Welding

10 mm-thick AISI: 310S austenitic stainless steel (ASS) plate having a chemical composition in Table 1 were used in this investigation. The plate was butt-welded using single V-groove with included angle of 60°. The plates were welded by using 1.2 mm-diameter filler wire in P-GMAW and DP-GMAW processes. The chemical compositions of the filler wires used for AISI: 310S ASS materials are also given in Table 1. The shielding gas used for present investigation is
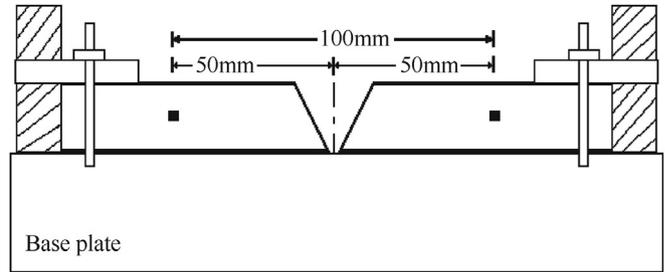
Fig. 1. Schematic diagram showing the technique of measurement of transverse shrinkage.

commercial pure argon (99.97%) with a gas flow rate of 15 lpm, and the distance between the contact tip and work piece was maintained at 14—16 mm. The welding of the plates was carried out using mechanized torch travel at direct current electrode positive (DCEP) (Kemppi-ProMIG-530). The welding parameters used in the welding of AISI: 310S ASS plate are shown in Table 2. In order to ensure the quality of the weld joints, studies were carried out by keeping the different welding parameters with respect to the wire feed speed, mean current and arc voltage. To maintain the reliability in the study, three weld joints were made for each welding process.

2.2. Studies on the weld joints

During welding the transverse shrinkage of the weld joint per weld pass was measured using a Vernier caliper having least count of 0.01 mm at a given distance (straining length) of 100 mm from weld centerline (Fig. 1), which was referred to the center of the weld groove. After each pass of welding at a given heat input, the transverse shrinkage of the plate at its initial position was measured.

The metallurgical characteristics of weld joints prepared by P-GMAW and DP-GMAW processes were studied under optical microscope with respect to the microstructure of weld and heat affected zone (HAZ) as revealed in its metallographic polished and etched transverse section. The mechanical properties such as tensile, Cv impact toughness and hardness of both welds were studied as per ASTM: E8M, ASTM: E23 and ASTM: E384 standards, respectively.

3. Results

The present section describes the advantage of DP-GMAW process over the P-GMAW process in welding of AISI 310S ASS in reference to the improved mechanical and metallurgical properties of the weld joint.

Table 2
Welding parameters used for preparation of weld joints.

Welding processes	Heat input/(kJ · cm^{-1})	Welding parameters			
		Wire feed rate/(m · min^{-1})	Mean current I_m/A	Arc voltage/V	Travel speed S/(cm · min^{-1})
P-GMAW	5.06—6.05	4—5	174—196	19.4—20.6	40
DP-GMAW	4.92—6.23	6—6.5	170—188	19.3—22.1	40

(a)

(b)
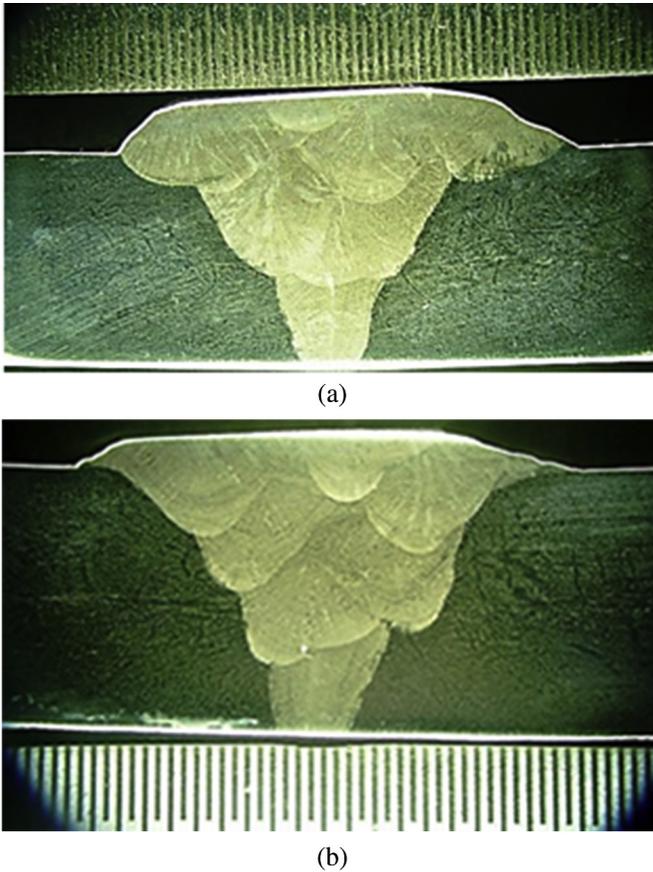
Fig. 2. Typical macrographs of weld joints. (a) P-GMAW and (b) DP-GMAW.

3.1. Macrograph of weld joint

The typical macrographs of the weld as revealed in a transverse section of P-GMAW and DP-GMAW joints are shown in Fig. 2(a) and (b), respectively which depicts the typical multi-pass deposition and desired sidewall fusion with respect to the absence of defect. In addition, it is also observed that the weld pool size per pass by DP-GMAW shows relatively smaller than that by P-GMAW. This may be considered as the advantage of DP-GMAW in reference to the reduction in stress generation of the weld joint.

3.2. Transverse shrinkage of weld joint

The effects of P-GMAW and DP-GMAW processes on transverse shrinkage of weld joint observed during welding are shown in Table 3. It can be seen from Table 3 that DP-GMAW process instead of P-GMAW process is used to minimize the transverse shrinkage of weld joint by 40% during welding.

Table 3
Effects of welding processes on transverse shrinkage generated in weld joint.

Welding process	Transverse shrinkage/mm
P-GMAW	2.8 ± 0.4
DP-GMAW	1.7 ± 0.3
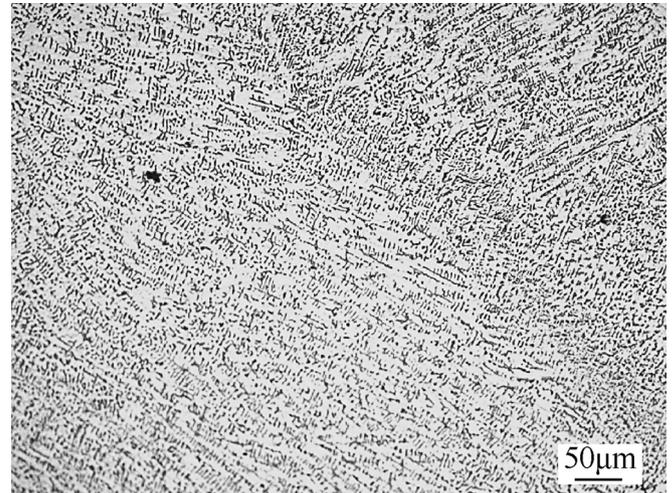
Fig. 3. Typical microstructure of multi-pass P-GMA weld deposition.

3.3. Microstructures of weld and HAZ

The microstructure of the multi-pass P-GMAW deposit has been found to consist of a mixture of dendrite and fine grain reheat-refined regions in the matrix, as shown in Fig. 3. This may happen due to partial heat treatment of matrix by multi-pass deposition. The typical morphology of dendrite observed in the central part of the weld is shown in Fig. 4. It is observed that the cast structure of P-GMAW deposit is found to be finer primarily due to the variation in thermal shock during solidification through interruption in metal deposition imparted by the pulsed current. However, it is further observed that the microstructure of the weld consists of a primary dendritic phase (brighter area) and secondary inter-dendritic phase (darker area) that is formed during the terminal stage of solidification.

The typical microstructure of the heat affected zone (HAZ) of the weld joint prepared using P-GMAW process is shown in Fig. 5. The microstructure of HAZ adjacent to the fusion line
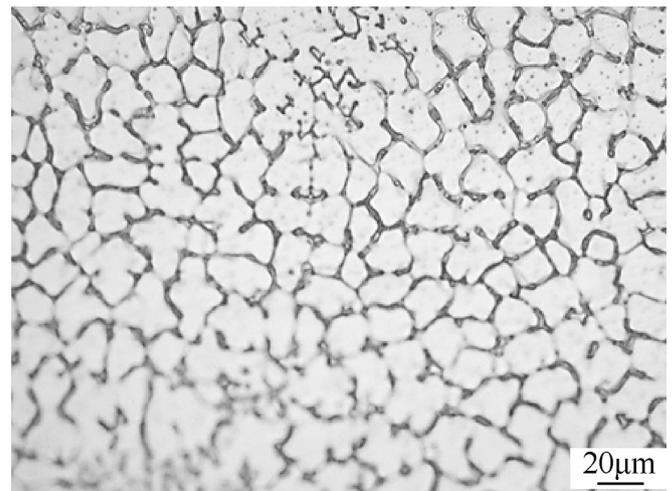
Fig. 4. Typical microstructure showing morphology of dendrite in P-GMA weld.
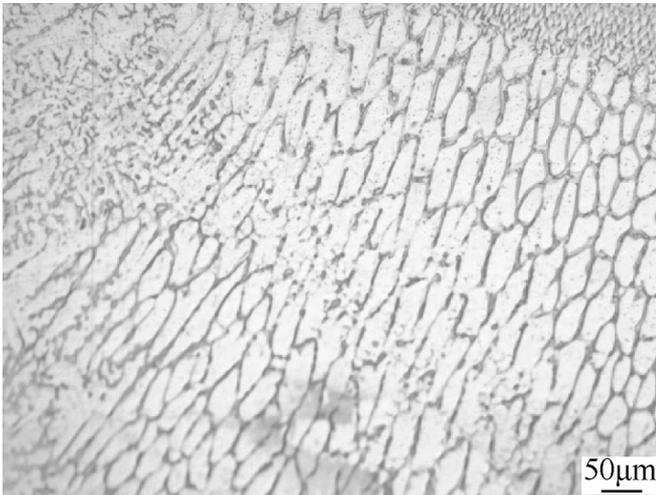
Fig. 5. Typical microstructure of HAZ near to fusion line in P-GMA weld.
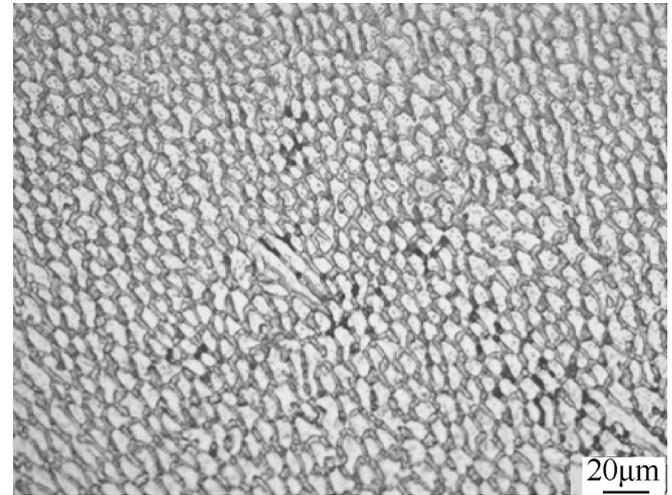
Fig. 7. Typical microstructure showing morphology of dendrite in DP-GMA weld.

of the P-GMAW weld shows a certain extent of grain coarsening near to fusion line. This may happen primarily due to the considerable effect of weld isotherm arising out of the heat of weld deposition adjacent to the groove wall.

From Fig. 5, it is further analyzed that the inter-granular attack with respect to grain boundary thickening in HAZ away from the fusion line (0.5 mm) is present in the case of P-GMA weld joint. The measured value of thickness is around 5 ± 2 µm which is lesser than those of conventional ASS weld joints reported by Ghosh et al. [12].

The typical microstructure of the multi-pass DP-GMAW deposit is shown in Fig. 6. As in the case of P-GMAW deposit (Fig. 3) here also it is found to consist of a mixture of dendrite and fine grain reheat-refined regions in the matrix. However, the morphology of DP-GMAW weld is different from that of P-GMAW multi-pass weld deposit. The DP-GMAW deposit primarily shows a considerable refinement of microstructure along with scarcely distributed dendritic structure, whereas the P-GMAW weld (Fig. 3) shows the conventional pulsed behavior of multi-pass weld that significantly consists of both

dendritic and reheat refined regions. Such variation of microstructure in DP-GMAW welds is primarily due to the variation in thermal shock during solidification through interruption in metal deposition imparted by the high frequency pulse current and low frequency thermal pulsation along with the usual reheat refinement by the subsequent weld pass. Thus, it is inferred that the use of DP-GMAW significantly reduces the dendritic region in the weld with respect to that observed in P-GMAW.

The typical morphology of dendrite observed in central part of the weld deposit produced by DP-GMAW process is shown in Fig. 7. From Fig. 4, here also it is observed that the cast structure of DP-GMAW deposit is found to be finer primarily due to the combined effect of pulse current and thermal pulsation. However, it is further noticed that, because of thermal pulsation, the cast structure of DP-GMAW deposit is finer than that of the P-GMAW deposit.

The typical microstructure of the HAZ of the weld joint prepared using DP-GMAW process is shown in Fig. 8. The
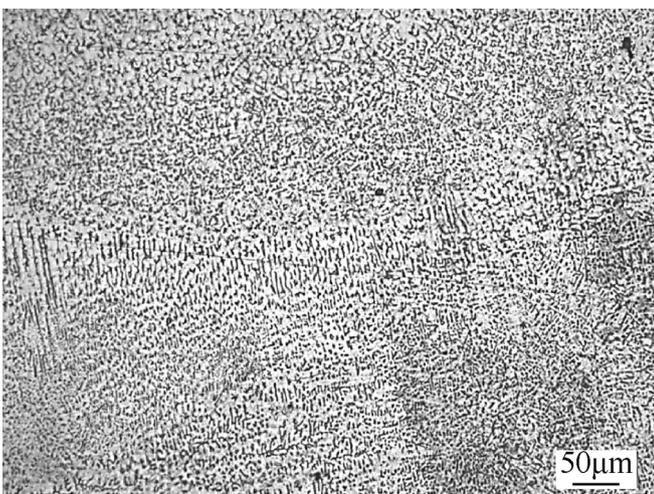
Fig. 6. Typical microstructure of multi-pass DP-GMA weld deposition.
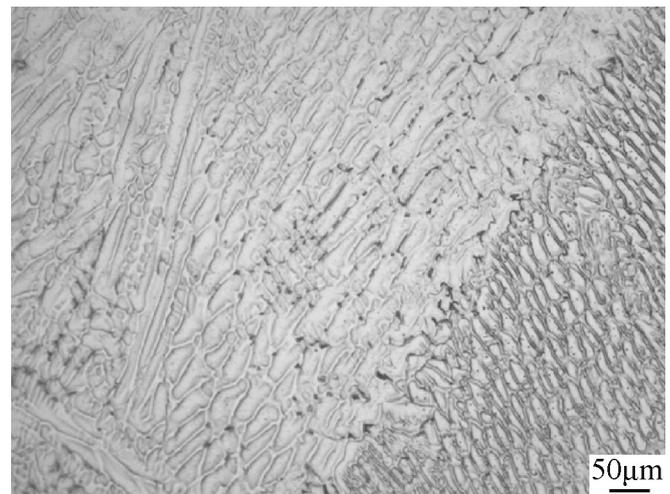
Fig. 8. Typical microstructure of HAZ near to the fusion line in DP-GMAW.

Table 4
Mechanical properties of P-GMAW and DP-GMAW joints.

Process	Tensile property			C_V − impact toughness/J	Hardness/VHN
	YS/MPa	UTS/MPa	Elongation/%		
P-GMAW	399−406	494−504	45−53	44−47	195 ± 7
DP-GMAW	427−435	534−547	49−57	53−58	208 ± 6

microstructure of HAZ adjacent to the fusion line of the DP-GMAW weld shows a certain extent of grain coarsening. However, it is observed that DP-GMAW joint has comparatively less grain coarsening compared to P-GMA weld joint. This is due to thermal pulsation by DP-GMAW process as explained earlier.

As in the case of P-GMA weldment, here also the inter-granular attack with respect to grain boundary thickening in HAZ away from the fusion line (0.5 mm) of DP-GMAW joint was analyzed. The grain boundary thickening is not clearly visible from Fig. 8. Thus, it is understood that the severity of weld thermal cycle produced by DP-GMAW process is less due to dual pulse effect caused by superimposition of thermal pulse in comparison to that of the P-GMAW process.

3.4. Mechanical properties

The transverse tensile test of the weld joints prepared by P-GMAW and DP-GMAW procedure is given in Table 4. The Cv-impact toughness and hardness of weld metal are also given in Table 4. It is observed that the mechanical properties of DP-GMA weld joint is higher than those of P-GMA weld joint due to thermal pulsation.

4. Discussion

In view of the results discussed above, it is clearly understood that the DP-GMAW process is used to improve the mechanical and metallurgical properties and minimize the transverse shrinkage of AISI: 310 ASS weld joints in comparison to the P-GMAW process. Further, it is noticed that, in the case of AISI: 310S ASS weld joint prepared by DP-GMAW process, the severity of inter-granular attack in the grain boundary of HAZ region of the weld joint is reduced. Such an improved property obtained by using DP-GMAW is largely due to the combined effect of pulsed current and thermal pulsation of the process. The thermal pulsation effect primarily obtained in the DP-GMAW by varying wire feed rate (WFR) is shown in Fig. 9. It is observed that DP-GMAW shows the variation of WFR from the given WFR setting in the power source, but such variation is not observed in P-GMAW process. The variation of

(a) Current (Scale: 1V=100A)

(b) Voltage (Scale: 1V=10V)

Fig. 10. At a given WFR of 4 m/min, typical waveform of DP-GMAW process.
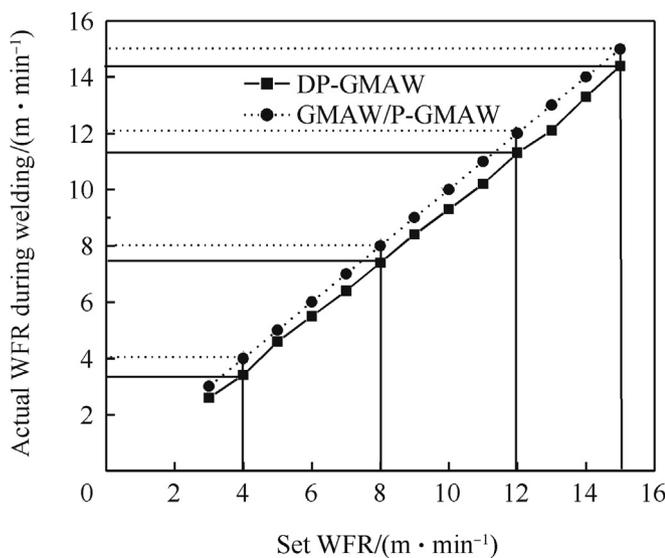
Fig. 9. Comparison of WFR between actual and variation observed during DP-GMAW.

(a) Current (Scale: 1V=100A)

(b) Voltage (Scale: 1V=10V)
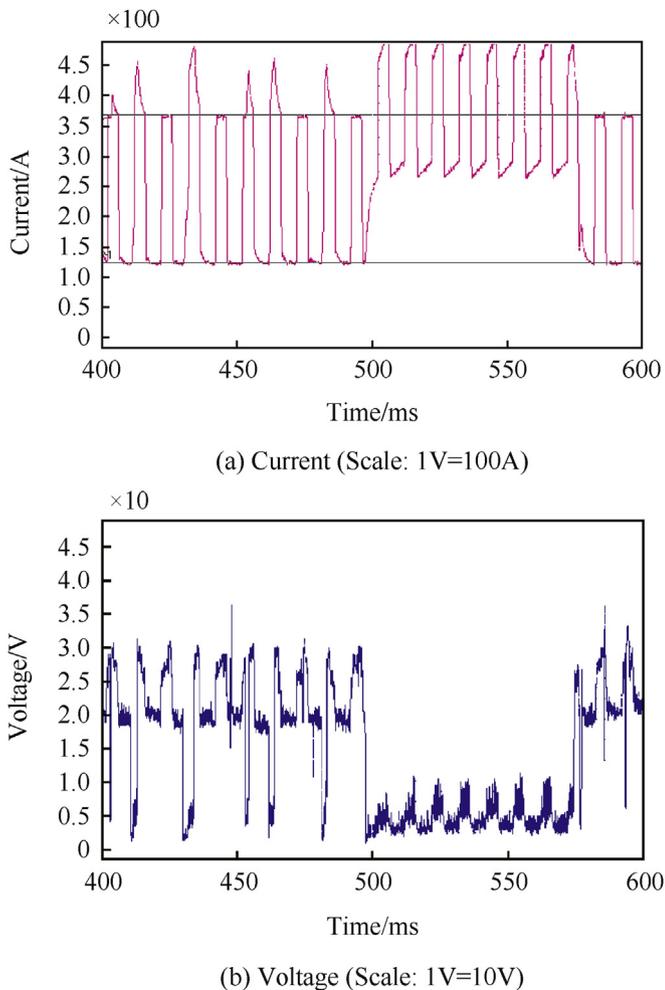
Fig. 11. At a given WFR of 9 m/min, typical waveform of DP-GMAW process.

WFR in DP-GMAW is to maintain a constant arc length because there is a chance to vary the arc length at a given WFR during the thermal pulsation period. This behavior reflects in the current and voltage waveforms (Figs. 10 and 11). The variation of WFR also confirms the synchronization between high frequency pulse and thermal pulse. This synchronization of pulses stirs the weld pool, reduces the heat input of DP-GMAW process accordingly and improves the properties of weld joints.

In order to confirm the variation of WFR during DP-GMAW under dynamic operating conditions, the waveforms of welding current and arc voltage were studied. The typical current and voltage waveforms at relatively low and high WFR of 4 and 9 m/min during DP-GMAW are shown in Figs. 10 and 11, respectively. From the figures it is observed that the arc voltage decreases during the thermal pulsation period, but the welding current increases due to the variation of WFR. These behaviors indicate that the DP-GMAW process introduces comparatively more thermal shock in the weld pool in comparison to the P-GMAW process. This is a beneficial effect to improve the characteristics of weld joints.

5. Conclusions

This study highlights the superiority of DP-GMAW in place of P-GMAW in welding of grade AISI: 310S ASS material. Some of the key observations of the study are as follows.

1) The transverse shrinkage of AISI: 310S ASS weld joints prepared by DP-GMAW process is comparatively lower than that prepared by P-GMAW process.
2) The DP-GMAW process improves the mechanical and metallurgical properties of AISI: 310S ASS weld joints.
3) In the case of AISI: 310S ASS, the use of the DP-GMAW process reduces the susceptibility of inter-granular attack in HAZ.
4) Superior weld joint properties obtained by DP-GMAW process is primarily due to the fluctuation of WFR during the thermal pulsation period, which reduces the overall heat input and improves the properties of the weld joints accordingly.

Acknowledgment

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