Arc Behavior Study Using Welding Current Module and its Impact on Residual Stress and Weld Bead in Anti-Phase Synchronized Twin-Wire Gas Metal Arc Welding

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ABSTRACT

The importance of twin-wire welding in increasing the deposition rate is known for a long, but its application in gas metal arc welding is limited due to the arc-stability related issues. An unstable welding arc causes irregular weld bead and material loss in the form of spatters. Previous investigations indicate that the problem can be addressed through arc-stability induced by dissimilar twin-arcs as the electromagnetic field concentrates around the arc with higher current. The present study is intended to reduce the twin-arcs' interactions and to improve the arc stability in twin-wire gas metal arc welding by evaluating different conditions at lead and trail wires. Further, their influence on the residual stresses and weld bead geometry is studied. Bead-on-plate-welds are carried out. A data acquisition system is used to capture the electrical signals during welding. The results indicate that the unequal currents at trail and lead wires provide stability to the arc that also results in a shift in residual stresses from compressive to tensile along the weld transverse direction. In addition, the maximum residual stress is located at the weld toe. When the current difference between the trail and lead wire is more, the arc produces stable metal transfer with uniform heating and cooling that results in reduction in stresses and improvement in weld quality.

Keywords: Twin-wire GMAW; heat input; residual stresses; weld bead geometry.

1.0 INTRODUCTION

Gas metal arc welding (GMAW) is a commonly used process in industries owing to its wide range of applications and economic efficiency. GMAW process involves a filler wire that melts and transfers into the weld pool- a dynamic behavior wherein energy is drawn from the power source for melting of the wire and work-pieces followed by cooling. Despite several advantages, residual stress in GMAW weldments is inevitable. Tekriwal et al. [1] was among the firsts to report on residual stress in GMAW process. The non-uniform heating and cooling of metal during and after welding procedures causes non-uniform thermal expansion and contraction causing a plastic deformation in the weld neighborhood, resulting in residual stresses and permanent distortion of the weldment. High tensile residual stresses are known to generate fatigue, corrosion cracking, and fracture in a welded structure. On the contrary, compressive residual stress decreases the buckling strength. Results suggest that maximum transverse residual stress is observed in the heat affected zone (HAZ) boundary and that is tensile in nature and acts as a crack initiation point. Several investigations on assessment of residual stress in different process variants of GMAW are available in the literature. The work of Choi et al. [2] analyzes, numerically and experimentally, the residual stress and solidification in AISI 304 stainless steel using the GMAW process. Davoud et al. [3] predicted and compared the evolution and formation of residual stresses using the GMAW process. A two-dimensional and three-dimensional model is developed for prediction of residual stress along the longitudinal and transverse direction. The longitudinal stress remains maximum near the weld line than the transverse stress in the HAZ and weld. However, both the stresses in the HAZ region can promote cracking in the weldment. In work of Gosh et al. [4], the residual stress is controlled to improve the fatigue life of high-strength aluminum alloy using pulsed GMAW process. The influence of pulse parameter is expressed in a dimensionless factor Φ. The increase in Φ reduces the transverse and longitudinal stresses in the weld joint. Similarly, Bajpei et al. [5] utilizes three different heat sink models in the GMAW process to minimize the residual stress and distortion in aluminum alloy plates. Further, finite element simulation of transient temperature and residual stresses in thin dissimilar aluminum alloy plates has been carried out using Goldak's double-ellipsoid heat flux distribution [6]. Armentani et al. [7] determines the influence of preheating and thermal properties both on residual stress and on temperature distribution in GMAW process. A two-dimensional model is developed using ANSYS to measure the temperature distribution. Results suggest that longitudinal stresses are maximum near the weld bead. In addition, residual stresses decrease with increase in preheating temperature. Further, an investigation in post heat treatment on residual stress using the GMAW process shows that more than 35% reduction in longitudinal residual stresses is possible by post heating [8]. Anis et al. [9] studied the effect of the position of a weld and thickness on residual stress and distortion of welded structural steel. Results show that the highest tensile residual stress observed in vertical welding position (3G) measure along weld longitudinal direction. Dixneit et al. [10] restrains stress development in multi-run welding using lower transformation temperature (LTT) fillers. Results suggest that on surface the longitudinal residual stress distribution are vastly affected by the phase transformation temperature, whereas transverse residual stress distribution are greatly affected by quenching effects. A similar study carried out by Schroepfer et al. [11] shows that over matching filler materials are beneficial for global reaction stress and residual stress in the HAZ. Further, Costa et al. [12] used a cold wire in the GMAW process to reduce the heat input to the base metal, thereby reducing residual stresses.

From the above literature, it is evident that most of the investigators have modeled and validated the residual stresses using single wire conventional or pulsed GMAW process wherein increase in heat input for higher productivity may lead to residual stress and distortion. To overcome these limitations, twin-wire is a potential solution because of higher deposition possible at higher speeds with controlled residual stress. A major concern in twin-wire GMAW process is arc instability. A preliminary investigation suggested that instability can be reduced with the help of unalike currents at trail and lead wires [13]. These currents are anti-phase synchronized pulsed (i.e. lead wire remains in peak current while trail wire in the base current, and conversely) to avoid mutual interaction between the arcs and thereby increase the stability of the process. There are very few investigations that depict residual stress in twin-wire welding. Meng et al. [14] analyzes the stress and temperature field in Aluminium alloy using twin-wire GMAW process. Results show that the maximum transverse residual stress occurs at the fusion line, whereas the longitudinal residual stress is only 10% higher than the single wire welding though the deposition rate almost doubles. In addition, the HAZ remains narrow compared to single wire welding. Lu et al. [15] demonstrates an ultrasonic stress measurement system to evaluate the transverse and longitudinal residual stresses in twin-wire welded plates and compared to the simulated results. Estefen et al. [16] evaluates residual stress on surface for double-wire butt-welded steel plates. Yang et al. [17] studied the effect of residual stress with a variation in spacing between the wires in twin-wire submerged arc welding. Results show that the spacing between two-wire ranges from 20-100 mm reduces the residual stress in joints. Paradowska et al. [18] correlates the residual stress and hardness in pulse tandem GMAW (PT-GMAW) process. From the literature, it is evident that no investigation is carried out residual stresses in anti-phased synchronized twin-wire GMAW process. To fill the gap, the preliminary work has been carried out to satisfy the need. The present work aims to understand the effect of current on residual stress and weld bead in anti-phase synchronized pulsed GMAW. This study investigates the development of stresses build up when similar currents and dissimilar current are used. Also, the interrelation between the bead shape and residual stresses on different current modules is presented. The following section briefs about the experimental procedure followed by a discussion on the results.

2.0 EXPERIMENTAL PROCEDURE

Experiments were conducted on IS 2062:2011 grade A mild steel plate of 10 mm thickness with a dimension of 75 X 300 mm^2. ER70S-6 was used as a filler material. The yield strength

Table 1 : Chemical composition of filler and base material

Element (%)	**S**	**C**	**Mn**	**Si**	**P**	**Fe**
ER70S-6 (AWS A5.18)	0.035 max	0.07-0.15	1.85 max	0.80-1.15	0.025 max	balance
Base material	0.018	0.211	0.7	0.201	0.015	balance

of the filler and base material was 517MPa and 600MPa respectively. Chemical compositions of filler and base material are shown in **Table 1**. The base plate was clamped at four locations to arrest distortion during welding. Before welding, the base plate is subjected to residual stress measurement using X-ray diffraction (XRD). The average residual stress of base metal was 300MPa, which was compressive in nature. To improve the stability of the process, the trailing arc was anti-phased by 1ms.

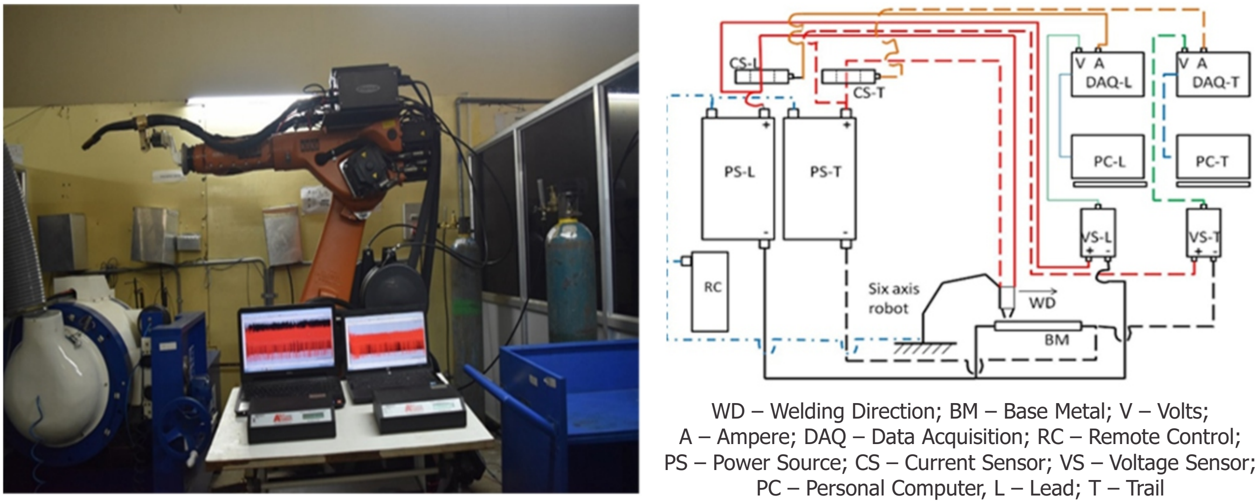
Experiments were conducted as per conditions mentioned in **Table 2**, with a six-axis robotic twin-wire GMAW experimental set-up as shown in **Fig. 1(a)**. A data acquisition system (Arc-client 3000p) was connected to the welding machine to measure and monitor the welding current and voltage signals. This data acquisition system consists of a Hall Effect non-contact current sensor and a voltage sensor that can measure up to ± 1000 A and ± 100 V respectively. The data acquisition system is integrated with a computer to monitor the real-time welding signals data as shown in **Fig. 3.1**, and its connections are shown in a schematic diagram in **Fig. 1(b)**.

After each welding experiment, the specimens were subjected to residual stress measurement using XRD method in the transverse direction at three locations– at the centre of weld length, left to the centre and right to the centre. Subsequently, the specimens were cut into small samples, polished and etched with 4% Nital (HNO_3+Ethanol) solution. Images of etched samples were captured, and reinforcement height, penetration depth, and weld width were measured.

3.0 RESULTS AND DISCUSSION

3.1 Effect of Welding Parameters on Heat Input and Residual Stress

The **Fig. 2(a)**, shows the instantaneous heat input of different welding conditions. The product of welding current and voltage dividing by travel speed results instantaneous heat input per unit length. It is evident that total heat input increase with an increase in total current (i.e. currents at trail and lead wires). However, the heat consumption at the lead is always greater than the trail for all conditions, even though the current at lead



WD – Welding Direction; BM – Base Metal; V – Volts;
A – Ampere; DAQ – Data Acquisition; RC – Remote Control;
PS – Power Source; CS – Current Sensor; VS – Voltage Sensor;
PC – Personal Computer, L – Lead; T – Trail

(a) (b)

Fig. 1 : Robotic twin-wire GMAW (a) set-up (b) connections

Table 2 : Experimental conditions

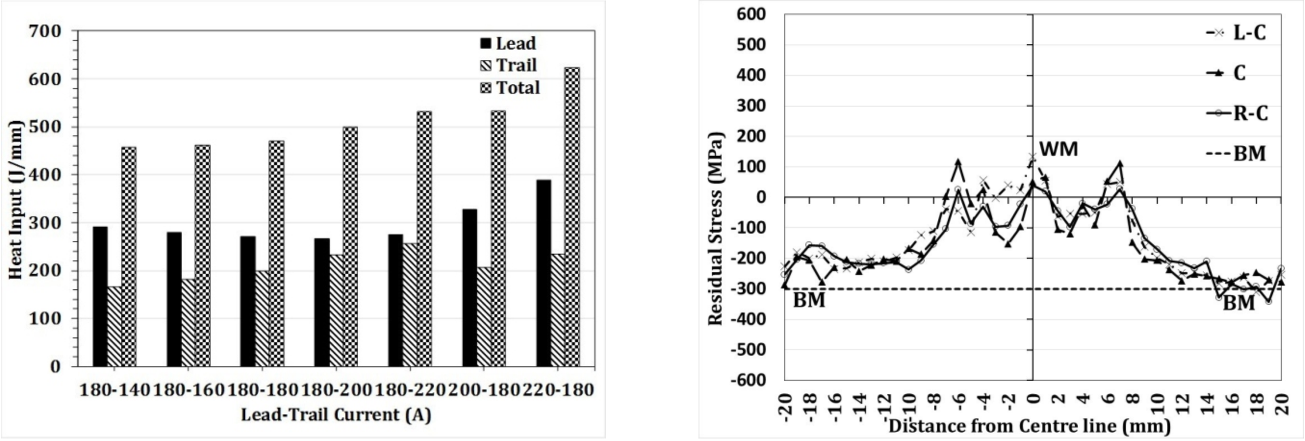
Sl. No.	**Lead**		**Trail**		**Constant parameters**
	(A)	**(V)**	**(A)**	**(V)**	
1	180	25.9	140	23.9	Synergic Pulse-Pulse mode Wire diameters : Ø0.8- Ø0.8 mm Contact tip to workpiece distance- 20 mm Travel speed- 0.9m/min 82%Ar- 8%CO$_2$ Gas flow rate- 16lpm
2	180	25.9	160	24.8	
3	180	25.9	180	25.9	
4	180	25.9	200	27.4	
5	180	25.9	220	28.5	
6	200	27.4	180	25.9	
7	220	28.5	180	25.9	

is set lower than the trail. The lead wire acts on the fresh material and draws more energy, whereas trail wire acts on the molten pool and draws less energy [19].

From **Fig. 2(b–h)**, it is noted that as the total heat input increases, the residual stress in transverse direction increases and the maximum is found at the weld toe region that is in good agreement with the literature [17]. The change in transverse residual stresses of base metal is caused due to the heat conduction while clamping and unclamping after cooling to the room temperature. The residual stresses in the base metal remain compressive in nature for all welding conditions before and after welding as shown in **Fig. 2**. The change in residual stresses from compressive to tensile in weld zone may be due to shrinkage of material because of the heat treatment followed by fast cooling. Shrinkage of material leads to the dislocations of initial grain structure and phase transformations.

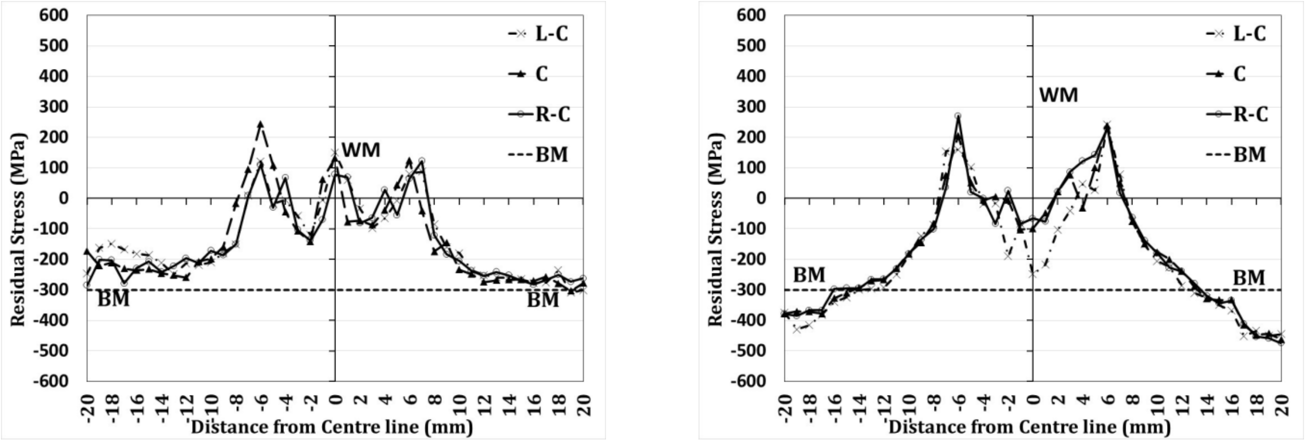
The transverse residual stresses as shown in **Fig. 2(b-h)** are higher on both sides of the weldment. On comparing **Fig. 2(e-f)** with **Fig. 2(g)** and **Fig. 2(h)** respectively, wherein the total current is the same but the residual stress patterns are different. Higher current at lead wire (**Fig. 2(g-h)**) results in uniform residual stress at three locations (i.e., centre, left to centre, and right to centre) compared to cases of higher current at trail wire (**Fig. 2(e-f)**), respectively.

The heat consumed at the trail and lead wires is different as shown in **Fig. 2(a)**. The maximum transverse residual stresses found at the weld toe region is about 550MPa (Fig.2 (g): 200A-180A) that matches the yield strength of the base material. It is important to note that further increase in the current tends to a reduction in residual stress (Fig. 2(h): 220A-180A). This is perhaps due to arc stability that is induced by dissimilar currents, particularly in the case when lead current is considerably higher than the trail current. The betterment in



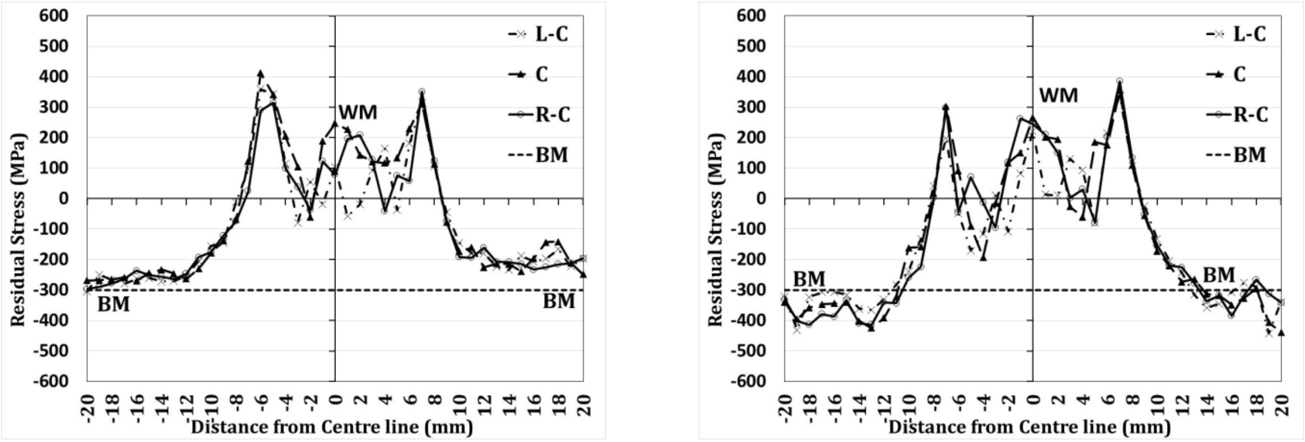
(a) Heat input for different welding conditions

(b) 180A – 140A



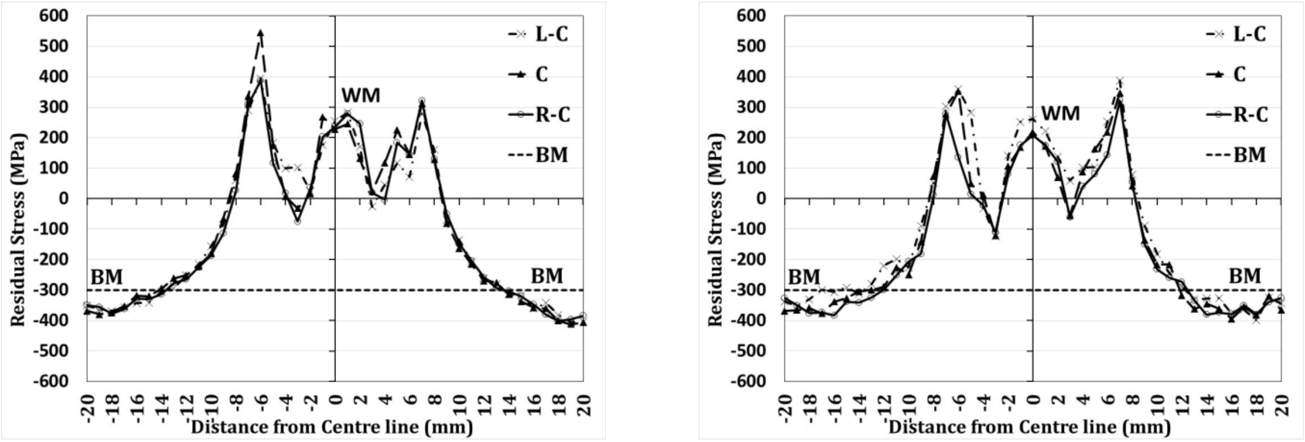
c) 180A – 160A

(d) 180A – 180A



(e) 180A – 200A

(f) 180A – 220A



(g) 200A – 180A

(h) 220A – 180A

Fig. 2 : Heat input and residual stress for different welding condition [C – Center; L-C – Left to the center; R-C – Right to the center; BM – Base Metal]

the residual stress is also related to the size of weld bead shape as explained next.

3.2 Relation between Residual Stress and Weld Bead Geometry

The welding currents at the trail and lead wires affect the weld bead geometry as shown in **Fig. 3**. The proportionality relation in between depth of penetration and welding current - as observed in single wire welding– does not hold good in case of twin-wire welding with dissimilar currents. Similar current of 180A-180A leads to unstable arcs that limit the weld penetration; however, increased arc interaction increases the reinforcement height and weld width **(Fig. 3)**.

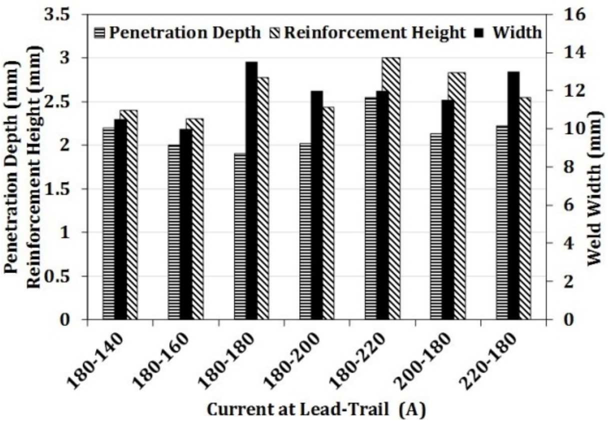


Fig. 3 : Penetration depth, reinforcement height and weld width for different welding conditions

Induced arc stability with dissimilar current improves the penetration as seen in **Fig. 3**. Larger difference of 40A in between the leads and trail wires (i.e., 180A- 140A and 180A-220A) provides deeper penetration compared to a difference of 20 A (i.e., 180 A- 160A and 180A-200A) and similar currents (180A-180A). When the total current is higher and at the same time lead current is greater than the trail (i.e., 200A-180A and 220A-180A) a reduction in penetration is observed. This is because the higher current at lead improves the melting rate, in turn, the molten excess metal is available beneath the trailing arc that hampers the penetration. However, the molten metal spreads and leads to wider weld width. Though, 220A-180A combination consumes maximum heat (Fig. 2(a)) but wider width reduces the heat intensity and thus helps in reducing the overall residual stress in case of 220A-180A.

4.0 CONCLUSIONS

The present investigation related process parameter of twin-wire anti-phase synchronized GMAW process with residual stresses using X-Ray Diffraction (XRD) method and weld bead shape. The maximum transverse residual stress is found at weld toe region and at HAZ that are tensile in nature. As the heat input increases, the residual stress increases at weld zones. When currents at trail and lead wires are equal, arc interactions are high that limits the arc penetration depth and produces inconsistent residual stresses. The current difference between the trail and the lead wire produces stable metal transfer results in a reduction in stresses and deeper welds. Higher welding current at lead wire may reduce the penetration as the trailing wire acts on molten metal provided by the lead wire that limits the contribution of trail wire in total penetration.

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