Research Article

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Effects of welding parameters on the angular distortion of welded steel plates

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Abstract: In a welding process, distortion is inevitable and causes a significant problem. Distortion could be minimized up to a specific limit by controlling the welding parameters. The expansion and contraction of the welding metal and the adjacent base metal during the heating and cooling cycles of the welding process create thermal stresses and angular distortion in a welding joint. The welding parameters determine the geometry of a weld bead. The form of the weld bead is vital in the angular distortion of butt welded plates. This article discusses the influence of some flux-cored arc welding process parameters such as shielding gas flow rate, weaving motion of welding electrodes, and torch angle on bead profile and angular distortion of St 37 steel plates of 10 mm thickness. The angular distortion decreases with the torch angle, but it increases with the gas flow rate. The electrode weaving motion consists of three components: the designed weld width, the vertical motion period in the welding direction, and the lateral motion speed normal to the welding direction. The angular distortion decreases with the weld width and the vertical motion period but decreases with the lateral speed.

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Keywords: FCAW, angular distortion, gas flow rate, torch angle, weaving motion of welding electrodes

1 Introduction

In every welding process, the weld metal and adjacent base metal heterogeneity heat and cool. Meanwhile, heterogeneous expansion and contraction occur in the weld area, producing thermal stresses in the weld zone [1]. The weld metal size is maximum at the solidification temperature. On cooling, the weld metal contracts, but it is restrained from doing by the adjacent base metal. Because of this, stresses develop within the weld and the adjacent base metal. Six types of distortions happen in weldments because of the weld shrinkage stresses [2]. The transverse and longitudinal shrinkage types occur when the shrinkage forces are perpendicular and parallel to the weld bead. The angular distortion occurs when the non-uniform shrinkage forces are produced through the thickness, generating a resultant force in the weld metal's centroid [3]. When this centroid differs from the centroid of the base metal's transverse cross section, a bending moment occurs and warps the plate [4]. Angular distortion is a widespread welding defect that leads to expensive repairs in steel constructions [5].

The weld bead geometry is critical because it determines the shrinkage amount and the created internal shrinkage stresses. The magnitude and the direction of the angular distortion depend on the contraction stresses [6]. Two different full penetration and butt weld joint beads are produced using laser welding [7]. Multiplying the contraction force of each weld metal point and the distance between this point and the centroid of the plate gives the bending moment that occurred at that point. The resultant bending moment of all weld metal points gives the resultant bending moment of the weld. Each weld has a different weld bead so that different contraction stresses and bending moments could be produced after the welding process. When the distance between the centroid of the weld bead and the plate is short, a small resultant bending moment and a tiny angular distortion are obtained. Welding parameters influence the bead geometry. The welding parameters can be classified as primary and secondary parameters [8]. The primary parameters are the welding current, the arc voltage, and the welding speed, which directly determine the profile of the weld pool and the weld form [9]. The secondary parameters indirectly affect the weld bead geometry. They make changes to primary parameters and hence affect the weld form. These parameters are arc distance, torch angle, the chemical composition of the shielding gas, gas flow rate, electrode polarity, etc. [10]. The objective of the present study involves studying the effect of shielding gas flow rate, weaving motion of welding electrodes, and torch angle on bead profile and angular distortion of mild steel plates. These three parameters are all-electric arc welding secondary parameters.

From the gas flow rate effect and the torch angle effect experiments, the researchers got conflicting results. Sudhakaran et al. found that the angular distortion decreased between the 50° and 60° torch angle. They also found that the angular distortion remained constant between 60° and 80° and increased when the torch angle was above 80° [11]. Aggarwal et al. found that the angular distortion increased when the torch angle varied from 50° to 70°. The angular distortion was maximum at 70° and then decreased with the torch angle increase [12]. In his experiments, Pandit determined that the angular distortion decreases linearly when the torch angle is increased from 70° to 100° [13]. Ramani et al. found that the angular distortion increased continuously as the torch angle increased between 70° and 100° [14]. The results of Ramani and Pandit have been entirely opposite to each other. Upreti et al., on the other hand, found that the angular distortion remained constant when the torch angle was between 45° and 55°, and it increased continuously after 55° [15]. Since the researchers' experiments showed contradictory results, exactly how the torch angle affected the angular distortion could not be determined.

In a study, the effects of shielding gas flow rate on welding angular distortion in Tungsten Inert Gas welding of stainless steels were investigated. It was observed that when the gas flow rate was increased from 5 to 15 L/min, the angular distortion decreased and then distortion increased with higher gas flow rates [11]. Three different researchers found that the angular distortion increases with the torch angle [4,16–18]. Akella's tests indicated that the angular distortion decreased with the torch angle [19]. During the welding process, the electrode weaving movement causes a change in the geometry of the liquid weld pool and thus the center of gravity of the weld, which affects the angular distortion [20]. The electrode weaving movement determines the weld thermal stresses and hence affects the welding distortion [21]. There are not enough articles describing the effect of electrode weaving movement on the welding angular distortion. In these studies, which were examined in the literature, it was seen that contradictory results were obtained with regard to the torch angle, shielding gas flow rate, and electrode weaving motion, which are among the factors affecting the weld distortion. The aim of this study is to conduct an experimental study in order to clarify the contradiction in the relevant factors.

2 Materials and methods

A 10 mm thick mild steel plate-type St 37 with chemical composition listed in Table 1 was used in this study. The C% describes the carbon content of the material which is used in the experiments. The mechanical properties of the plate are shown in Table 2; 100X250 mm test specimens were cut from the plates.

ESAB Aristo Mig U5000i metal inert gas welding machine and ESAB Railtrac B42V welding robot was used in welding operations. ESAB OK Tubrod 15.17 flux-cored arc welding (FCAW) wire of 1.2 mm diameter has been used in welding operations. The welding operations were carried out on a specially prepared table. Before welding, one end of the test piece was tightened with a screw. Bead on plate welding was done on the test piece. The length of each weld was 100 mm. The vertical movement of the plate over the free end of the test piece was measured with a dial indicator. This vertical movement gave the measurement of the angular distortion of the weld. The working table, the workpiece, the weld, and the dial indicator are shown in Figure 1. The dial indicator

Table 1: Chemical analysis of the test plate

C%	Mn%	Cu%	S%	P%	Balance (Fe)%
0.15	1.24	0.36	0.03	0.02	98.2

Table 2: Mechanical properties of the test plate

Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
229	387	18.4

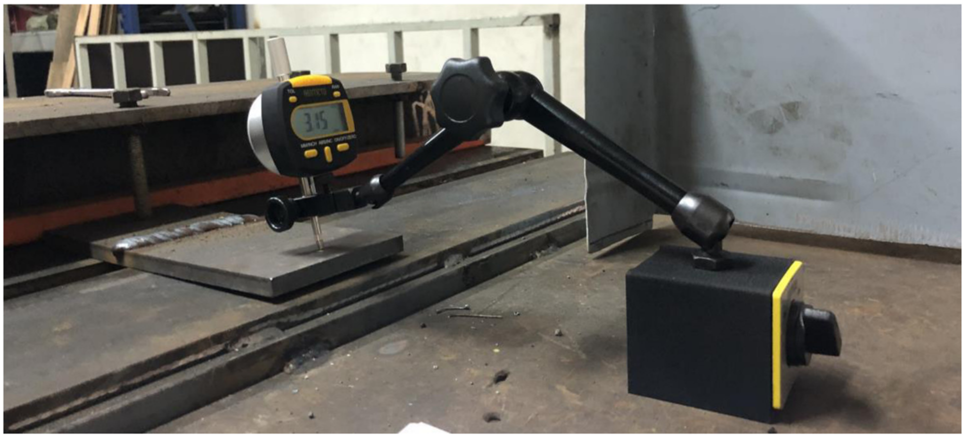

Figure 1: The welded workpiece and the dial indicator.

was protected from welding spatters by placing a sheet metal curtain between the device and the welding torch during welding.

The weaving motion is described in Figure 2. The *x* sign describes the movement length of the electrode perpendicular to the welding direction. The letter *y* identifies the electrode movement in the direction of welding progress. The letter *t* defines the moving duration in the *y* direction. Welding was done with only two different values of each of the electrode weaving motion parameters. The *x* value was 10 or 20 mm, the *y* parameter was 0.6 or 0.9 s, and the *t* parameter was 20 or 25 mm/s.

An optical microscope was used to measure the dimensions of the weld bead depth and bead width. All metallographic specimens were obtained by cutting the weldments normal to the welding direction. Then, microscope specimens were prepared by conventional grinding, polishing, and etching technics. The etching reagent was a 2 mL HNO_3 + 98 mL ethyl alcohol solution.

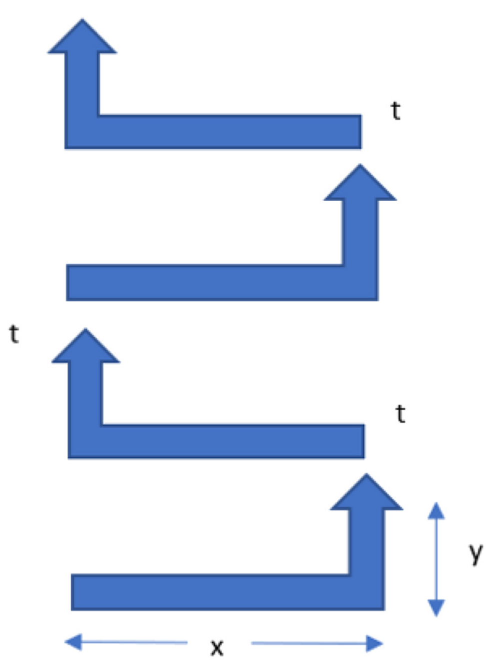

Figure 2: The weaving motion of the welding electrode.

3 Results and discussions

3.1 Effects of torch angle on welding angular distortion

The effect of the welding torch angle on the angular distortion is shown in Figure 3. The welds were produced with a constant 6.5 m/min wire feeding rate, 26 volts arc voltage, 5.5 mm/s welding speed, and 12 L/min gas flow rate. The angular distortion decreased linearly with the torch angle. The cross-sections of weld bead geometries are indicated in Figure 4. The weld on the left belongs to the 70° weld angle welding operation. The other weld was produced with the 110° torch angle. The size of the welds is given in Table 3. At the 70° torch angle, there was

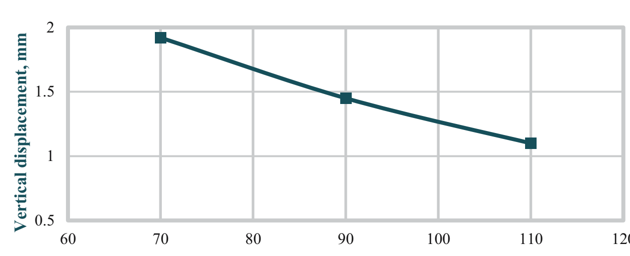

Figure 3: The variation of the angular distortion with the torch angle.

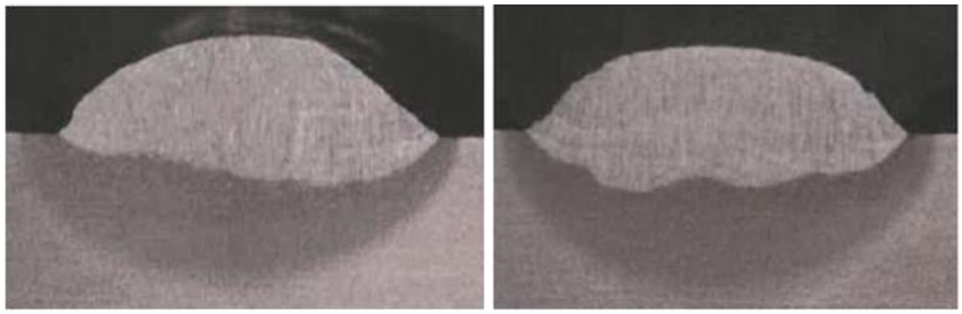

Figure 4: The welds' microstructures were produced with 70° torch angle shown in the picture on the left and 110° torch angle shown in the picture on the right.

Table 3: Weld bead geometry sizes and distortion of the welds as shown in Figure 6

Torch angle (°)	Weld depth (mm)	Weld width (mm)	Height of reinforcement (mm)	Vertical displacement (mm)
70	0.78	11.07	2.64	1.92
110	0.89	10.67	1.82	1.11

less weld depth, but bigger weld width, higher reinforcement height, and more distortion were obtained. The increment of the torch angle caused a change in the weld geometry and the distortion magnitude as shown in Table 3. The weld depth increased, and the reinforcement and the width decreased. The distance between the weld metal centroid and the plate center decreased. The increase in the torch angle changed the weld geometry, which caused a drastic decrease in distortion, as shown in Figure 3.

The torch angle is effective in the transfer of welding energy to the workpiece. Larger torch angles have been reported to introduce an entire arc on the weld zone resulting in a higher penetration in the base metal [22]. The photographs in Figure 4 and the results in Table 4 are compatible with the published literature. In the 70° torch angle, a wide weld bead caused higher shrinkage stress in the weld [6]. The distance between the centroid of the weld metal and the center of the plate was considerable because the reinforcement was high. The long distance caused a high bending moment and a significant distortion in the weld [11]. The bending moment produced in the 70° torch angle was huge. The high reinforcement was the main reason for the high bending moment. The high bending moment resulted in high distortion. The variations in the weld bead geometry of the 100° torch angle produced a smaller bending moment and hence a more minor distortion than the 70° torch angle.

3.2 Effects of shielding gas flow rate on welding angular distortion

In the welding process, the amount of gas flowing per unit time is known as the gas flow rate. The gas flow rate will determine the amount of depth of melting, and thus, it will affect the dilution. The effect of shielding gas flow rate on angular distortion is shown in Figure 5. In this test, all welds were produced with a constant 6.5 m/min wire feeding rate, 26 volts arc voltage, 5.5 mm/s welding speed, and 90° torch angle. The angular distortion increased with the gas flow rate. It has been determined that in electric arc welding operations, the net weld energy increases with the gas flow rate, regardless of the chemical composition of the shielding gas [23].

Table 4: Weld bead geometry sizes and distortion of the welds as shown in Figure 6

Shielding gas flow rate (L/min)	Weld depth (mm)	Weld width (mm)	Height of reinforcement (mm)	Vertical displacement (mm)
9	1.32	12.51	2.81	0.80
18	1.01	13.00	3.17	2.04

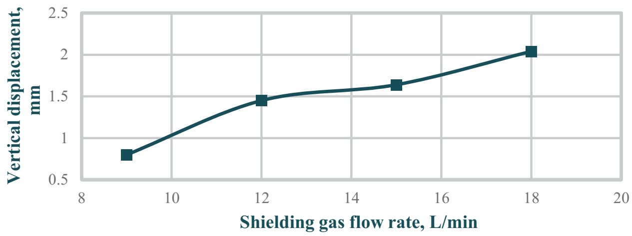

Figure 5: The variation of the angular distortion with the shielding gas flow rate.

It has been experimentally proven that when CO_2 is used as a shielding gas, the disintegrated carbon and oxygen atoms in the arc region recombine and increase the number of CO_2 molecules in the arc [23]. As the gas flow rate increases, this event occurs more. The combination of these atoms causes more energy input in the weld pool [24]. The increase in the energy transfer to the workpiece leads to the pool's high amount of metal deposition. As a consequence of higher metal deposition in the weld pool, more shrinkage and shrinkage stress occurs. Therefore, the angular distortion increases with the gas flow rate.

The effect of gas flow rate on weld bead formation is shown in Figure 6. The welds were produced with a constant 6.5 m/min wire feeding rate, 26 volts arc voltage, 5.5 mm/s welding speed, and 90° torch angle. The gas flow rate was 9 L/min on the left weld and 18 L/min on the proper weld. The weld bead parameter sizes of these two welds are given in Table 4. The increase in the gas flow rate increased the cross-sectional area of the weld. The weld produced with 18 L/min gas flow has a bigger weld width and a reinforcement height than the other weld. The weld depth decreased as the gas flow rate increased, while the weld width and reinforcement height increased [25]. The increase in the width increased the amount of shrinkage during solidification and, accordingly, the shrinkage stress. The changes in weld bead geometry also made a difference in the location of the weld center point. As the gas flow rate increases, the center of gravity of the weld shifts upward and the distance between the centroid of gravity of the workpiece increases. As the shrinkage force and the distance between the center of gravity increased, the bending moment in the welded part increased. The amount of angular distortion grew with the bending moment. Figure 6 shows that the angular distortion increases almost linearly with the gas flow rate.

3.3 Effects of electrode weaving motion on welding angular distortion

Table 5 shows the varying parameters used in the weaving motion experiments and the obtained angular distortion values. In these experiments, the wire feed speed was 6 m/min, the arc voltage was 25 volts, the welding speed was 6 mm/s, the gas flow rate was 12 L/min, and the torch angle was kept constant 90°. In the experiments, the weld width was either 10 mm or 20 mm, the *x*-axis welding speed was 20 or 25 mm/s, and the travel time on the *y*-axis was changed to 0.6–0.9 s. The obtained angular distortion test results are shown in Table 5. Figures 7–9 are drawn by using the results of Table 5.

The angular distortion increased when the weld bead width was increased from 10 to 20 mm under all test conditions (Table 5). As the weld bead width increased, the amount of shrinkage and the shrinkage force grew, increasing the angular distortion. This situation tells us that the weld should not be wider than the optimum size.

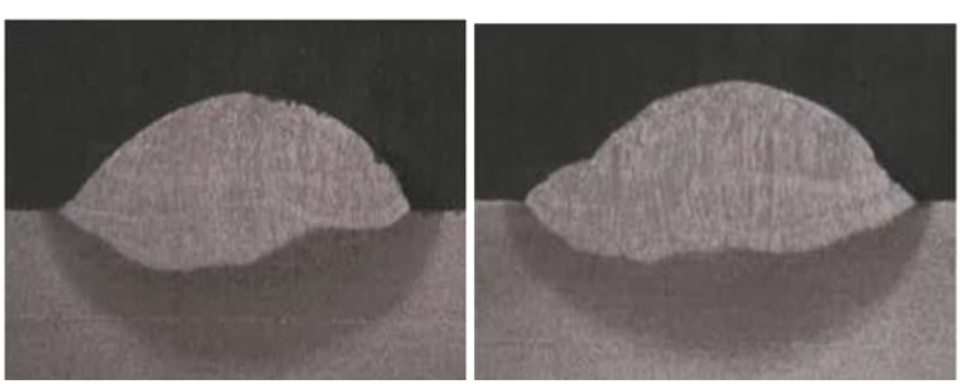

Figure 6: The welds' microstructures were produced by 9 L/min gas flow rate shown in the picture on the left and 18 L/min gas flow rate shown in the picture on the right.

Table 5: Electrode weaving movement parameters and angular distortions

Weld width (x) (mm)	Movement duration in y-axis (s)	Movement speed in x-axis (mm/s)	Vertical displacement (mm)
10	0.6	20	1.41
10	0.9	20	1.58
20	0.6	20	1.77
20	0.9	20	1.98
10	0.6	25	1.12
10	0.9	25	1.45
20	0.6	25	1.51
20	0.9	25	1.63

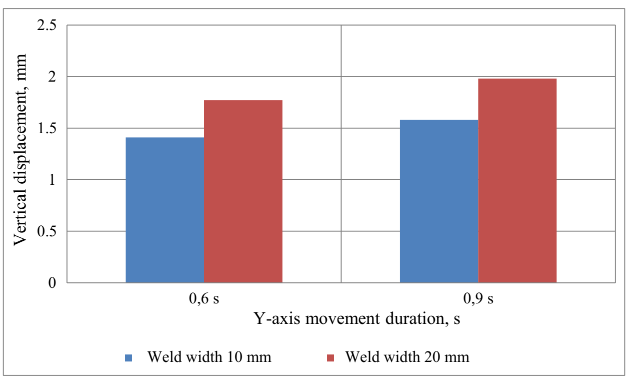

Figure 7: The effect of weld width and y-axis movement duration on the angular distortion of plates welded with 20 mm/s x-axis welding speed.

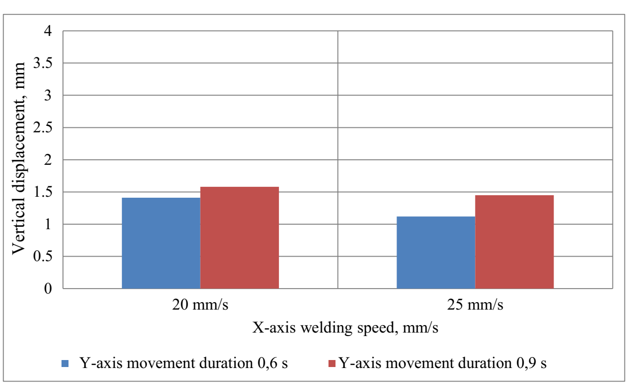

Figure 8: The effect of y-axis movement duration and x-axis welding speed on the angular distortion of 10 mm wide weld plates.

Another point that draws our attention in Table 5 is that the angular distortion enlarged in each experimental group as the electrode movement duration in the y-axis increased. For example, when the travel time in the y-axis is increased from 0.6 to 0.9 s at the moving speed of 20 mm/s with the 10 mm weld width, the amount of angular distortion enlarged from 1.41 to 1.58 mm. Because high welding time causes an increase in the amount of metal deposited in the weld and the shrinkage force increased in the weld. This situation occurred in each experimental group, as indicated in Figure 7. The distortion is more significant in the 20 mm wide weld than the 10 mm wide weld. Increasing the weld time caused a significant growth in distortion in 20 mm wide welds. The enlargement of distortion in 10 mm weld is much smaller.

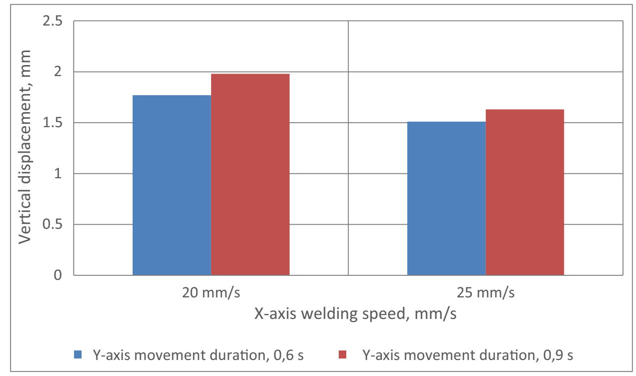

Figure 9: The effect of y-axis movement duration and x-axis welding speed on the angular distortion of 20 mm wide weld plates.

The angular distortion decreased when the x-axis movement speed was increased from 20 to 25 mm/s (Figures 8 and 9). For example, in the 10 mm wide welds, the plate displaced 1.41 mm at the moving speed of 20 mm/s, but the plate displaced 1.12 mm at the 25 mm/s speed (Figure 8). Figure 9 indicates similar results for 20 mm wide welds.

4 Conclusions

The following results were obtained from the FCAW process on-plate welding of St 37 steel plate tests:

1. The angular distortion increases with the shielding gas flow rate.
2. The angular distortion decreases with increase in the torch angle.
3. The weaving motion of electrodes affects the angular distortion.

In this study, it is found that the lowest angular distortion was obtained with a 100^{o} torch angle of 1.11 mm. With a 9 L/min shielding gas flow rate, the minimum vertical displacement was acquired.

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Conflict of interest: The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval: The conducted research is not related to either human or animal use.

Data availability statement: The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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