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ANGULAR DISTORTION IN BUTT ARC WELDING

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Abstract - The importance of fusion welding technology has been widely recognized in the manufacturing process of various steel structures such as ships, bridges, construction machines, power plants, and automobiles. However, a significant disadvantage of fusion welding is that it often generates unacceptable levels of geometric imperfections such as shrinkage and distortion. Angular distortion is a major problem and most pronounced among different types of distortion in the butt welded plates. This angular distortion is mainly caused by the non-uniform extension and contraction through thickness direction due to the temperature gradient. The principal factors affecting the degree of welding angular distortion are: material properties (the thermal expansion coefficient, the thermal conductivity and the specific heat), weld groove geometry, joint type and welding procedures (welding current, arc voltage, welding speed, shielding gas chemical composition, gas flow rate, welding gun angle, time gap between successive passes and number of passes). All these factors are explained in the paper.

Key Words - Welding, distortion, Angular distortion, Welding parameters

1. Introduction

Welding involves highly localised heating of joint edges to fuse the material, non-uniform stresses are set up in the component because of expansion and contraction of the heated material. The magnitude of thermal stresses induced into the material can be seen by the volume change in the weld area on solidification and subsequent cooling to room temperature. If the stresses generated from thermal contraction exceed the yield strength of the parent metal, localised plastic deformation of the metal occurs. Plastic deformation causes a permanent reduction in the component dimensions and distorts the structure. Distortion occurs in six main forms. One of them is the angular distortion as shown in Figure 1(1).

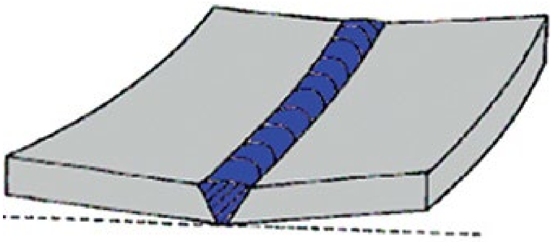

Figure 1. Angular distortion of a butt weld.

The angular distortion consists of the rotation of the structure around the welding line (2). The angular distortion occurs in a butt joint when the transverse shrinkage is not uniform in the thickness direction (3). A research asserted that the elastic contraction on the top is larger than at the bottom and this causes the angular distortion (4). Figure 2 shows an example of a transverse through thickness shrinkage force gradient (5). Bending distortion occurs for the same causes of angular distortion, yet, it is defined by both the longitudinal shrinkages and the base metal's longitudinal cross-section instead of the transversal.

Rotational distortion is an in-plane angular distortion due to the localized thermal expansion and shrinkage.

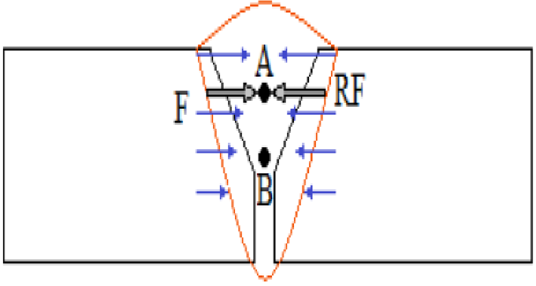

Figure 2. Development of angular distortion in butt welding of a single “V” Groove (5).
A: Centroid of the weld metal, B: Centroid of the transversal cross-section, F:Transverse shrinkage forces and RF: Resultant shrinkage force.

2. Factors Which Affect Angular Distortion

The principal factors affecting the degree of welding angular distortion (6) are: material properties, weld groove geometry, joint type, amount of restraint, and welding procedure. All these factors are explained below.

2.1. Effects of material properties

The mechanical and thermal properties of the base metal are of high importance in which concerns to weld distortion. The most important base metal properties which influence on weld distortion are the yield strength, the Young’s Modulus, the thermal expansion coefficient, the thermal conductivity and the specific heat.

The Young’s Modulus is linked to base material’s rigidity and decreases when increasing the temperature. If at high temperatures the yield strength is too high, there’s an inability of the thermal strains to produce plastic deformations i.e. only elastic strains would be present and zero plastic strains produced. The high-temperature yield strength of a material affectes its angular distortion. Angular distortion increased with high-temperature yield strength. The yield strength of high strength steels are higher than mild steels at high temperatures. Therefore high strength steels have lower distortion resistance compared to mild steels (7). The same trend was found in aluminium alloys (8).

Higher coefficient of thermal expansion means higher amount of expansion, when heated and greater subsequent contraction when cooled. High coefficient of thermal expansion tends to increase the shrinkage of the weld metal and the metal adjacent to the weld. Thus increases distortion(7).

The thermal expansion coefficient, is a property that quantifies the physical expansion of a material when heated up. Higher coefficient of thermal expansion means higher amount of expansion, when heated and greater subsequent contraction when cooled. High coefficient of thermal expansion tends to increase the shrinkage of the weld metal and the metal adjacent to the weld. Thus distortion increases with the thermal expansion(7).

2.2. Weld groove geometry and joint type

The thermal conductivity is a measure of heat flow in the material. Thermal conductivity increases slightly as temperature of the material increases. Higher thermal conductivity results in a uniform heat distribution along the plate’s thickness and width. With that, the thermal gradients responsible for shrinkage stresses are reduced, decreasing the weld distortion (9). The lower thermal conductivity causes a steeper temperature gradient which increases the distortion. Therefore weld distortions were highly sensible to the thermal conductivity (10).

The specific heat of a material is defined as the heat capacity per unit of mass of a certain material. The heat capacity measures the ratio between transferred heat to or from the material and its temperature change. Higher values of specific heat reduce the peak temperature achieved during welding (1). The shrinkage forces are proportional to the peak temperature achieved in the plate (7).

Phase transition effect is proven to affect the residual stresses and distortions on some steel grades. The maximum temperature reached and the metal’s cooling rate produce dissimilar martensitic fractions for different steel grades. The phase transformation has little effect on distortion for low carbon steels while on the other hand, it has a rather significant effect on distortion for mid and high carbon steels. It is known that when cooling rate is fast enough, the austenite transforms to martensite. This transformation increaes the material’s total volume. This increase in volume partially cancels the transverse shrinkage, reducing weld distortion in mid and high carbon steels. The increase in volume creates compressive stresses and reduces the residual stresses for mid and high carbon steels (11).

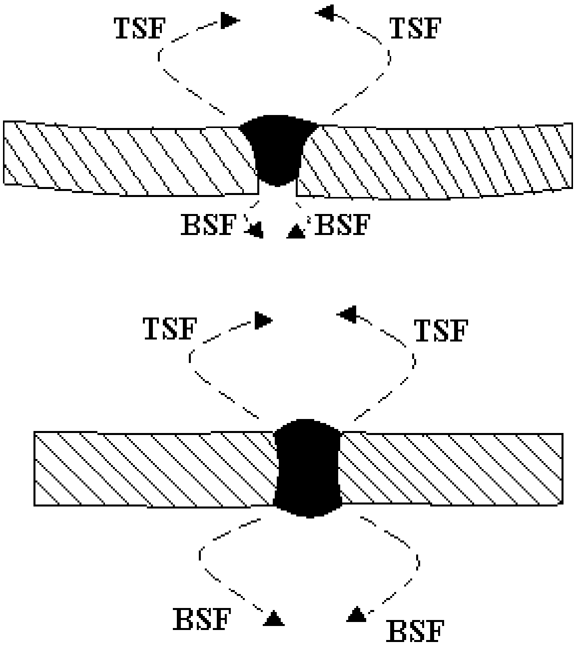

Figure 3. (a) A butt joint with greater top side shrinkage force (TSF) due to greater weld deposition at the top side; (b) A butt joint with near equal top side shrinkage force (TSF) and bottom side shrinkage force (BSF) (12).

Figure 3 shows the effects of the top side shrinkage force (TSF) and bottom side shrinkage force (BSF) on angular distortion of a butt weld(12). The figure shows two weld cross sections schematically. Both plates were 12 mm thick and welded with submerged arc welding (SAW) process. Figure 4a shows that the plates was welded from one side. This weldment indicates greater top side shrinkage force (TSF) due to larger weld deposition at the top side leading to higher angular distortion. The plate shown in Figure 4b was welded from both sides. The topside shrinkage force (TSF) and bottom side shrinkage force (BSF) are nearly equal in this weldment. Therefore less angular distortion occurred in the weld.

Weld groove geometry has a significant influence on weld distortion as the amount of weld metal varies with groove angle and weld penetration depth. The distance of the weld metal's centroid to the cross-section neutral axis also changes according to the groove geometry used, affecting the final distortion. Therefore, different shrinkage values can be obtained for different groove geometries. Experiments and numerical simulations concluded that the weld groove shape has an important influence on the residual stresses distribution in thicker plates. Plates welded with a X groove shape have nearly equal amount of weld metal on both sides. The contraction forces are also similiar. They also possess higher tensile residual stresses in the weld metal and higher compressive residual stresses in the HAZ. Therefore a X weld show less distortion than a V shaped groove weld (13). The use of a narrow weld groove instead of a conventional V-groove also decreases the angular distortion (14). Plates welded with a U shaped groove require more weld metal than plates welded with a V shaped groove, however, a U shaped groove approaches the centroid of the weld from the neutral axis of the plate, diminishing the weld distortion (15).

Another weld groove characteristic is the groove angle. The angular distortion was proved to increases with the V groove angle due to the increase in the shrinkage force as a wider weld pool is formed during welding. Figure 4 shows the angular distortion results obtained by welding three different aluminium plates, each with four different V weld groove angles (5). Experimental data showed that the 60º V shaped groove angle displays the lower angular distortion. Similar results were oıbtained for steel plates(16). The result of an another research is shown in Figure 5 (17). The angular distortion in single V-groove butt welded joints decreased with the increase in included angle, which was due the change in transverse shrinkage along the thickness of the specimen. The findings of these investigations and the obtained graphics are in conflict as shown in Figure 4 and 5.

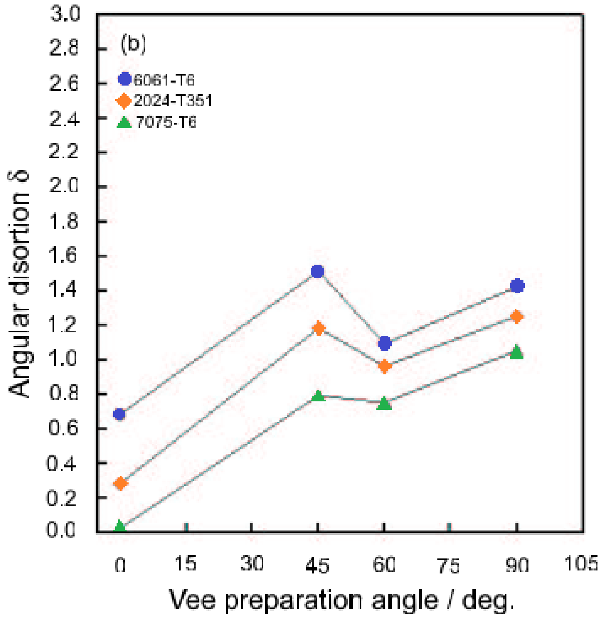

Figure 4. Angular distortion of three aluminium alloys for four different weld groove angles(5).

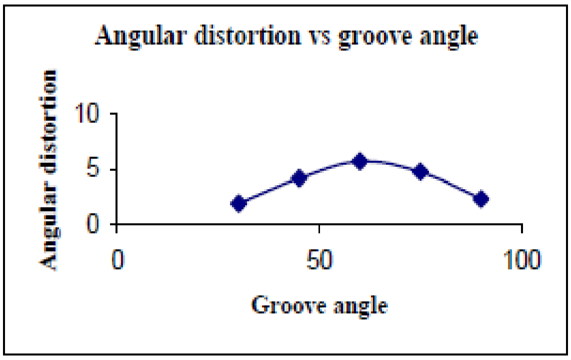

Figure 5. Effect of groove angle on angular distortion(17).

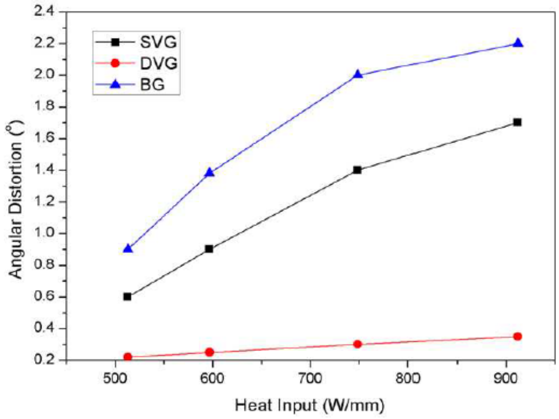

Figure 6. The effect of heat input on angular distortion for single V-groove (SVG), bevel groove (BG) and double V Groove or X groove(DVG) butt joints(18).

An experimental work was carried out by welding mild steel plates using CO_2 arc welding process to reveal the effect of heat input and the weld groove with respect to angular distortion(18). The bevel angle was 22.5º and the groove angle was 45º in single V-groove (SVG) and double V

Groove or X groove(DVG) in the experiments. The effect of heat input on angular distortion is displayed in Figure 6. DVG has the lowest distortion at every energy input. Bevel groove caused higher angular distortions. It is seen that angular distortion is maximum in bevel groove welded joints as compared with the single V-groove and double V-groove welded joints, and it is minimum for double V-groove welded joint [19]. Angular distortion in bevel-groove butt welded joints decreases with increase in bevel angle similar to the single v- groove butt joints(20).

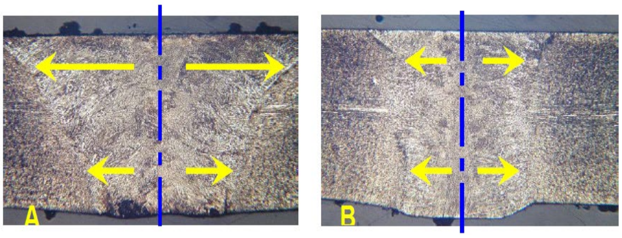

Figure 7. The profile and contracting stresses which develop during the solidification in (A) TIG and (B) A-TIG welded joint of austenitic stainless steel welds (21)

Figure 7 shows the cross-sections of TIG and A-TIG welds of 5 mm thick stainless steel 304 plates(21). The plates were welded from side. The width on the welding side (Top side) is larger than the bottom part. There is a significant variation in bead width of the welds. The top width of the A-TIG weld is narrow than the TIG weld. In the upper part of the TIG weld greater contraction stress was formed than the the bottom part. Therefore a big angular distortion angle was obtained in this weld. The difference between upper and bottom part width was small. Therefore the generated stresses on both sides are nearly equal. Hence, less distortion occurred in this weld (21). This example proved that the weld profile was very important on angular distortion.). The value of angular distortion of the weldment depends on several factors, including (a) the the shape and dimensions of weld bead and (b) the plate thickness (22). The ratio of weld depth(D) to plate thickness(T) determines the angular distortion angle(22). If D/T is 0.5 it causes maximum angular distortion. The angular distortion angle decreases as the D/T ratio change from the critical value. Each welding process has a characteristic weld profile. Proper welding process must be chosen to eliminate big angular distortions. A-TIG welding causes less distortion than than the TIG process(23). Friction stir welding is superior than gas metal arc welding and submerged arc welding(24).

With the increase in joint gap, the angular distortion increases (6). It is due to the fact that for a sound welding joint, as the joint gap increases, the number of passes has to be increased which results in more amount of metal deposited in the V-groove. As the number of passes increases the heat input per unit length increases. The distortion increases(6) because of the increased heat input.

2.3. Welding Parameters

The primary welding parameters (welding current, welding speed and arc voltage) directly determine the welding heat input and weld bead geometry(25) and thus determine the angular distortion. The other welding parameters affect the primary welding parameters and affect the angular distortion indirectly(6). The effective welding parameters are listed below:

- Welding current
- Arc voltage
- Welding speed
- Gas flow rate
- Shielding gas chemical composition
- Welding gun angle
- Time gap between successive passes
- Number of passes

2.3.1. Welding current

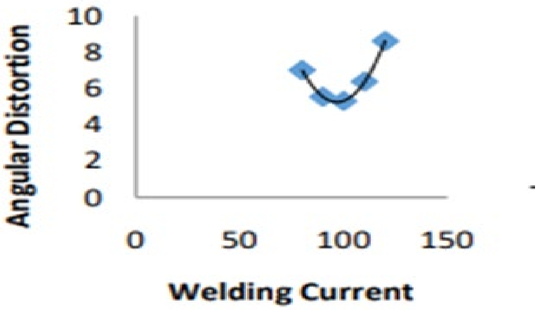

Figure 8. Effect of welding current in TIG welding(26)

Figure 8 represents the direct effect of the welding current on distortion(26). From the figure it is found that, when current is low the distortion is also low. This may be due to low bead width and low D/T ratio resulting from the low current (27). The distortion increases with the increase in current. This is attributed to increase in bead width and D/T ratio with the heat input. The increase in the bead width results in an increase in the distortion due to higher shrinkage on the weld bead upper side. Further increase in the current results in an increase in the heat input and a decrease in bead width and D/T ratio. These variations decreased the distortion angle as shown in Figure 8. In a conventional electric arc welding process increasing the weld current to improve the penetration capability causes the weld shape to become excessively wide with a relatively minor increase in depth. This weld bead geometry results a greater angular distortion angle(28).

Pulsed current welding technology has been widely used in fabrication of structures such as aircraft, vehicles, ships, bridges, and pressure vessels or pipes. The parameters used for pulsed welding are pulse frequency, pulse spacing, amplitude ratio and duration ratio(29). The pulse parameters can actually control the thermal characteristics and the weld bead geometry(30). Therefore, the distortion is affected by pulsed welding parameters. During pulsed GTAW, higher pulse frequency or smaller pulse spacing can enhance the energy density of the welding heat source, thereby reducing the angular distortion of austenitic stainless steel weldments. Greater pulse amplitude ratio and duration ratio can reduce the temperature difference between the fusion zone and unaffected base metal zone in the weldment, and thus decreases the angular distortion(31). Figure 9 shows the effect of pulse frequency on angular distortion and residual stress of 316L stainless steel pulsed TIG weldment(32). The results indicated that the angular distortion and residual stress decrease with the increase of the pulse frequency.

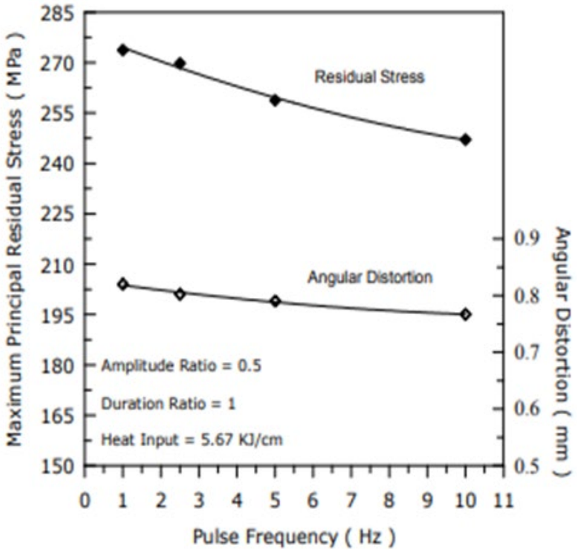

Figure 9. Effect of pulse frequency on angular distortion and residual stress of pulsed TIG weldment(32).

2.3.2. Arc voltage

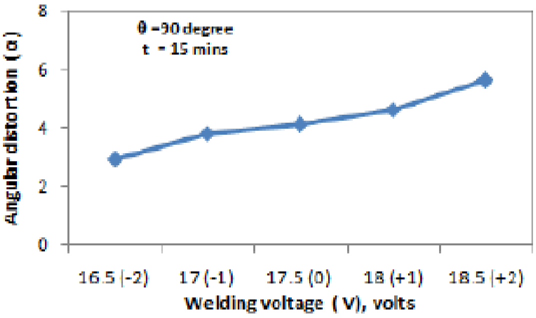

Figure 10. Effect of welding voltage on angular distortion(33).

Figure 10 shows the effect of arc voltage on angular distortion(33). The upper weld width enlarges with the voltage(25). The amount of weld metal increases with the voltage and the distortion increases as its sequence. In electric arc welds the arc voltage increases with the arc length(25). Therefore, welders must avoid to weld with an unnecessary weld arc length.

2.3.3. Welding speed

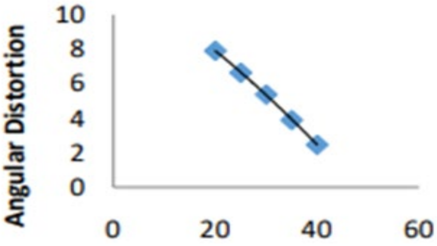

Figure 11. Effect of welding speed on distortion(26).

It has been observed from the Figure 11 that there has been a decrease in angular distortion degrees with an increase in welding speed. The reason for this can be attributed to the fact that at high welding speed, heat input will be low resulting in a decrease in angular distortion(34). The interaction effects are negligible in case of welding speed.

2.3.4. The shielding gas

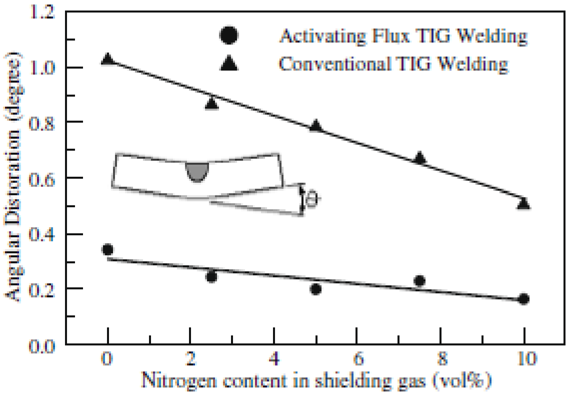

Figure 12. Effect of nitrogen in shielding gas on the angular distortion of TIG and A-TIG welds(38).

The shielding gas chemical composition ant flow rate of it in gas metal arc welding(35-37), TIG(38,39) and FCAW(40) effect the weld bead geometry and angular distortion forming. The effect of nitrogen content of the shielding gas on the angular distortion of austenitic stainless steel TIG and A-TIG welding is given in Figure 12. Nitrogen added to the argon-base shielding gas decreased the angular distortion of the weldment. A-TIG welds are superior than TIG welds due to the weld bead geometry obtained in this process. Figure 13 shows the variation in the amount of weld distortion with weld pass for types of shielding gases and different combinations of TIG welding shielding gases supply(39). Argon shows the highest heat input, and thus highest welding distortion occurred with this gas. The Ar + 67% He gives welding distortion similar to Argon shielding at 13 liter/minute gas flow rate. When the gas flow rate decreased to 9 liter/minute in this gas mixture less distortion happened. This result is in harmonious relationship with other research findings(26,34).

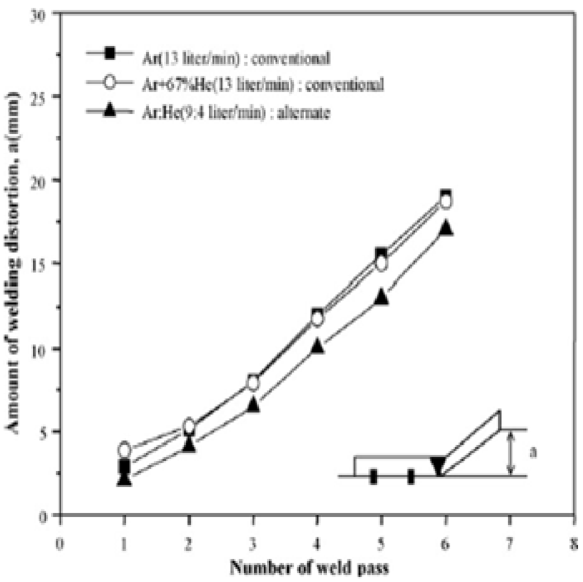

Figure 13. Comparisons of angular distortion of butt weld with the type of gas and type of gas supply in TIG welds(39).

2.3.5. Welding gun angle

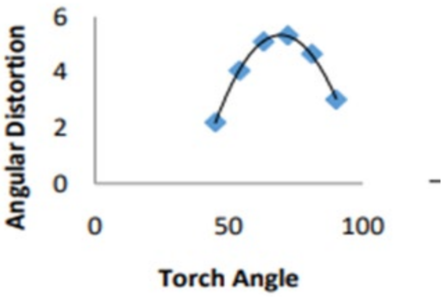

Figure 14. The effect of torch angle on angular distortion(27).

It has been observed from the Figure 14 that there has been an increase in angular distortion from 2.2 degrees to 3.02 degrees with an increase in torch angle from 45 to 90 degrees(27). The reason for this can be attributed to the fact that for steeper torch angle, the depth of penetration in the plate is slightly greater than that for a shallow angled torch. Thus, the heat amount input in the weld bead, giving non-uniform distribution leads to distortion which is more in steeper torch angle positions and less in shallow torch angle positions. There however existed a region between minimum and maximum value of currents in which the angular distortion was found to be first increased and then decreased. The reason might be interaction effects of other welding parameters(27).

2.3.6. Time gap between successive passes

Angular distortion decreases with the increase in time gap between successive passes as indicated in Figure 15(41). It is clear that distortion decreases with increase in time gap between the passes. When time is longer more heat is lost by the plate and the plate temperature is lower as compared to that when time is less. So some of the heat applied to the plate during the next pass will be utilize in preheating the plate. Hence the net heat added to the plate is less compared to when the plate temperature is high. When time is longer, a large amount of heat is lost by the plate and the temperature is lower compared to when time gap is shorter. So, the heat applied to the plate during the next pass will result in a marginal rise in temperature of the plate, and hence, angular distortion is less(6).

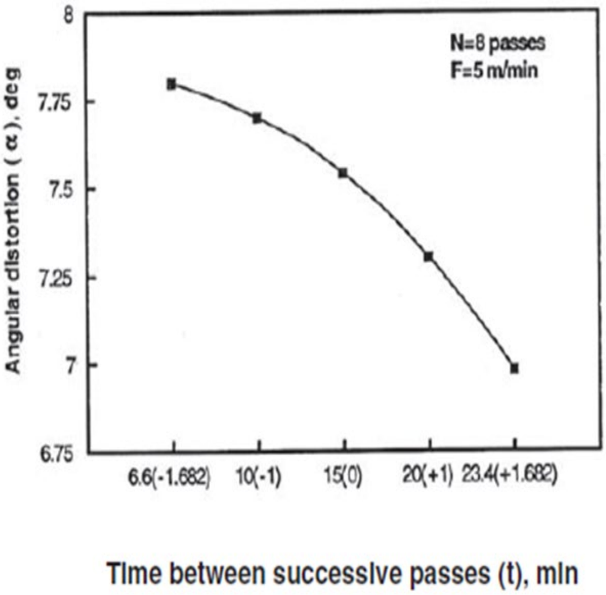

Figure 15. Effects of time gap between successive passes on angular distortion(41).

2.3.7. Number of passes

Specimens of ASTM A36 structural steel were welded using V-groove butt-joints. During the welding process, the angular distortion was measured after each welding operation. Four constant heat inputs were employed in the experiments by adjusting the current, voltage and wire feed speed. The number of passes needed to complete the weld decreased with increasing the the heat input. The cumulative angular distortion of each experiment was shown in Figure 16(42). The welding operation finished with 14 passes in E1(0.7 kJ/mm heat input) group. The distortion increased with the number of the pass. In E4 group the weld completed in 5 passes. The angular distortion produced in a given weld pass was roughly same for all experiments of group, regardless of heat input used in each group. For example equal distortion was obtained in 5 passes for each test group. Figure 16 indicates that angular distortion increases with the number of welding passes. Welding with high energy input and less number of passes causes smaller distortion. Kumar’s findings(6) reinforces this result.

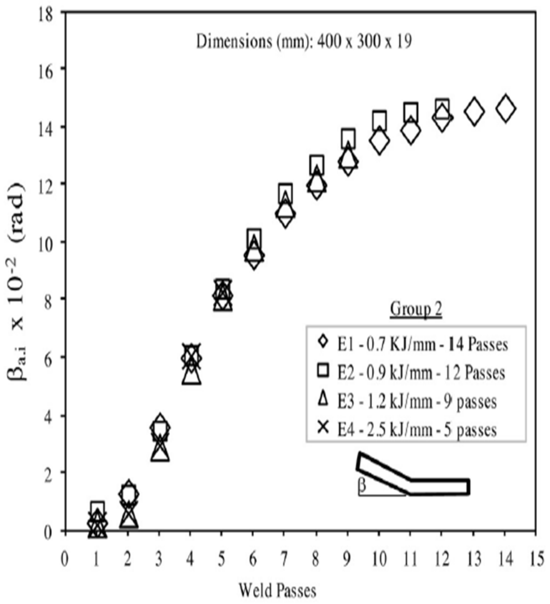

Figure 16. Relation between the angular distortion and the weld passes sequence for all
heat inputs group and and the cumulative angular distortion of groups (42).

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