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Modelling the effects of preheating on angular distortions in one sided fillet welds

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Analysis and modelling

ABSTRACT

In all fusion welded joints, residual, transverse, lateral, angular and bowing deformations are observed. In fillet joints the angular distortion is the predominant deformation. The distortions and thermal history of a fillet joint can be measured experimentally which is not economically viable all times. It is time consuming and the deformation can be measured only after the completion of the joining process. So prevention is not possible. In the present work a numerical elasto-plastic thermo mechanical model has been developed for predicting the thermal history and resulting angular distortions of manual metal arc welding in one sided fillet joints.
To create a realistic simulation of the single sided fillet welding, a moving distributed heat source is used in finite element model. The effect of filler metal deposition is simulated by implementing a birth and death process for the elements. The temperature dependent material properties are used for predicting the transient temperature distribution in the material which in turn helps to predict the angular distortion profiles of the fillet joint. The simulated modeling results obtained are found to be in complete agreement with the experimental values.
Keywords: Finite element analysis; Manual Metal arc welding; Transient thermal analysis; Temperature distribution; Element birth and death method; Thermomechanical analysis; Angular distortions

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1. Introduction

The core of any welding process is to supply heat for melting the work piece. The heat transfer has the following consequences:
i) Metallurgical changes takes place in fusion zone, where the metal is liquefied and Subsequently solidified
ii) In the adjacent "Heat affected zone" the metal is heated to a temperatures that are below the melting point, but are sufficiently high to produce changes in the micro structure and mechanical properties.
iii) Vaporization of selective elements due to excessive temperature can also change the composition of the material.
iv) Localized heating and cooling generates plastic deformation and distribution of residual stresses.
v) Also the shrinkage of material in weld metal and heat affected zone induces permanent distortions of the weldment.

Shielded Metal Arc Welding (SMAW) is widely used in structural and fabrication where the metal plates of different thickness are joined. In such welding single sided fillet and double sided fillets are widely used. A fillet weld is the most common weld type used in the fabrication of structural members in automobile, shipbuilding, petrochemical and other industries. Fillet welded joints suffer from various welding distortion patterns, such as angular distortion, transverse shrinkage, longitudinal distortion and buckling. All the above mentioned distortions, especially, angular distortion has significant impact on fabrication accuracy influencing the productivity and quality of the welded structures. Angular distortion can reduce the quality of welded structures because of misalignment in adjacent joints during fabrication, and after fabrication undesirable appearance and change of structure stiffness. It can also increase the cost of fabrication due to rework such as fairing, cutting, attaching, fitting, gap filling, etc. Recently, many industries have been seeking application of light materials, such as aluminum and magnesium alloys, to structural members to reduce the weight of structures, and increase the performance of structures in terms of fuel efficiency and recycling. However, due to higher thermal expansion coefficient, low stiffness/strength ratio, and low softening temperature of aluminum and magnesium alloys, control of welding-induced distortion in these connections becomes a critical issue. These light materials can be applicable in structural frame members and panels consisting of T-plate and T-tubular connections. T-plates and T-tubular connections are built by fillet welds in which angular distortion is one of the major concerns regarding precise prediction and control.

Numerous efforts have been devoted to predict distortion, investigating the characteristics of the generation mechanism of distortion using analytical, experimental, and numerical approaches.

2. Literature review

Hirai and Nakamura [1] investigated angular distortion experimentally for steel fillet welded joints, and provided a graph to predict angular distortion for fillet welded T-joints with different thickness. Taniguchi [2] applied the same method to aluminum alloy fillet welds. In both results, angular distortion was prescribed as a function of plate thickness, and weight of electrode consumed per weld length, which means that angular distortion is related with the rigidity of joints (plate thickness) and welding parameters (weight of electrode deposited). Results also showed that the maximum angular distortion occurred at a certain thickness range, which means if plates were thinner or thicker than this thickness range, less angular distortion would occur.

This implies that angular distortion in fillet welded T-joints is related with not only the temperature gradient along a flange plate thickness, but also rigidity of joints. Watanabe and Satoh proposed a formula predicting angular distortion of fillet welded T-joints including the effect of welding parameters, electrode and plate thickness which is given below as Equation 1.

$$\emptyset = C_1\left(\frac{I}{h\sqrt{vh}}\right)^{1.5} exp\left(\frac{-C_2 I}{h\sqrt{vh}}\right) \tag{1}$$

$$C_1 \propto \left(\frac{\eta V}{D^{0.25}}\right)^{2.5} \tag{2}$$

$$C_2\, \alpha \frac{\eta V}{D^{2.25}} \tag{3}$$

where: h = thickness of plate, D = diameter of an electrode, η = arc efficiency, V = voltage, I = current and v = welding speed.

The process characteristics that are required to be considered are: [1] a moving heat source, [2] arc travel speed, [3] current and voltage, [4] temperature dependent material properties, and [5] deposition of the filler material. In 1993, Kamala and Goldak (1993) [3] opined that a two-dimensional approximation of a three-dimensional problem is not appropriate to predict temperature distribution, residual stresses, and distortion patterns. Brown and Song [4] were in favour of three-dimensional thermomechanical coupled solutions to predict distortion patterns. Tsai and Cheng [5] investigated distortion mechanisms and the effects of welding sequence on panel distortion using finite element analysis. Tsai and Jung [6] modelled the angular distortion of T-joints using plasticity-based distortion analysis. Teng et al. [7] investigated the residual stresses and distortion of fillet joints using two-dimensional finite element analysis.

Since the welding process involves very complex physical and metallurgical changes in the parent metal, it becomes practically impossible to establish an exact mathematical model of a welding process. The nonlinear and temperature-dependent physical parameters make the problem even more complex.

3. Composition and material properties of mild steel

The composition of the mild steel used in the experiment is shown in Table 1.

The temperature dependent properties of the mild steel used for modeling temperature distribution and distortions is shown in Table 2.

Table 1.
Composition of mild steel used in the experiment

C (%)	Si (%)	Mn (%)	P (%)	S (%)	Ni (%)	Cr (%)	Fe (%)
0.15584	0.17774	0.45330	0.17975	0.06918	0.1324	0.01567	98.8413

Table 2.
Thermal and mechanical properties of steel

Temp, °C	Thermal Conductivity (W/m K)	Specific Heat (J/kg K)	Enthalpy (J/m^3)	Poisson's Ratio	Yield Stress (MPa)	Young's Modulus (GPa)	Thermal Expansion Coefficient
0	51.9	450	1×10^9	0.2786	290	200	10
100	51.1	499.2	2×10^9	0.3095	260	200	11
300	46.1	565.5	2.65×10^9	0.331	200	200	12
450	41.05	630.5	3.8×10^9	0.338	150	150	13
550	37.5	705.5	4.1×10^9	0.3575	120	110	14
600	35.6	773.3	4.55×10^9	0.3738	110	88	14
720	30.64	1080.4	5×10^9	0.3738	9.8	20	14
800	26	931	5.23×10^9	0.4238	9.8	20	15
1450	29.45	437.93	9×10^9	0.4738	-	2	-
1510	29.7	400	1.1×10^9	0.499	-	0.2	-
1580	29.7	735.25	1.1×10^9	0.499	0.0098	0.00002	-
5000	42.2	400	1.25×10^9	0.499	0.0098	0.00002	15.5

4. Methodology adopted for modelling

In developing a general purpose model for the welding process, it is important to consider the moving heat source, heat loss, temperature-dependent material properties and metal deposition.

A moving heat source is modelled by setting a heat flux distribution that varies with time applied to the top surface of the weld pool zone. The moving heat load applied in the finite element model was taken as a distributed heat flux.

A schematic diagram and the photograph of the weld specimen of a one-sided fillet joint is shown in Fig. 1. Meshing and modelling of the one-sided fillet joints are shown in Fig. 2.

a) b)

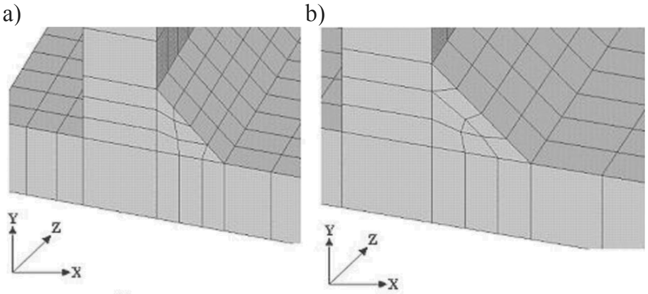

Fig. 1. Modelling and meshing of: (a) 6.5 mm thick one-sided fillet welds (jobs 4 and 5) and (b) 6.5 mm thick one-sided fillet welds (jobs 18 and 19) adopting leg lengths obtained from the experiments

The moving heat load was applied on the area bounded by the points 22 to 25 as shown as shown in Figure 2, and except for this area other areas of the plate are subjected to heat loss due to convection.

As far as possible the actual welding conditions were considered in the thermal model. However, the following assumptions were still required.

1. All the thermal properties were considered to be a function of the temperature.
2. Linear Newtonian convection cooling was considered on all the surfaces.
3. The heat loss due to radiation, conduction through the electrode, and heat consumed by burning of the flux and melting of the electrode were accounted for by the arc energy transfer efficiency parameter η.
4. A constant convection coefficient of 15 W/m^2K was considered.
5. Heat flux was considered as a load.
6. A birth-and-death technique was used in this model to simulate the formation of a weld bead through metal deposition. The proposed method does not remove elements to achieve the "death" effect. Instead, themethod deactivates an element by multiplying its stiffness by a large reduction factor. The mass and energy of deactivated elements are excluded from the summations of model. An element's strain is also set to zero as soon as that element is killed. Similarly, when elements are "born", they are not actually added to the model, but are simply reactivated. When an element is reactivated, its stiffness, mass, element loads, etc. return to their full original values.

5. Experimental details

Single fillet T-joints were made on medium carbon steel plates (170×110×6.5 mm) and (110×100×6.5 mm) using SMAW process.

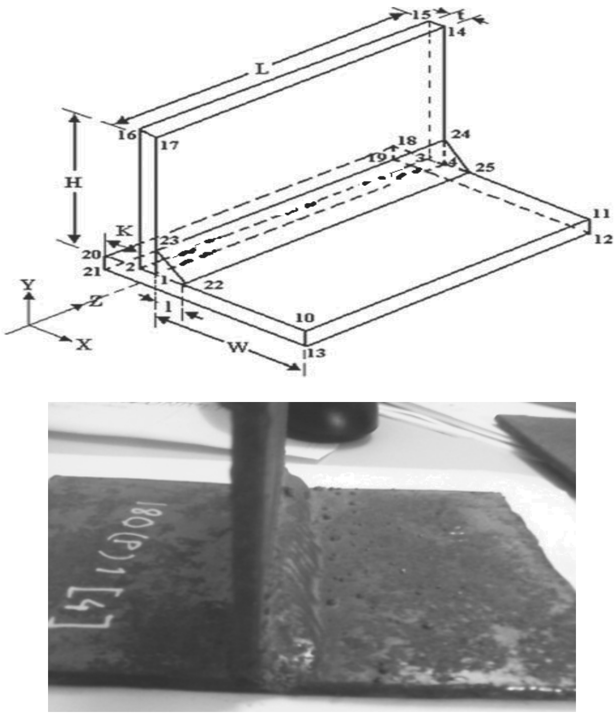

Fig. 2. Schematic Diagram and photo of a one sided fillet join. The fillet to be modeled is numbered from 22 to 24 in the schematic diagram

During the experimentation the parameters varied were as follows: electrode diameter size (2.5 mm, 3.15 mm and 4 mm) (ii) Current (80 amps, 100 amps, 120 amps, 140 amps, 160 amps, 180 amps) (iii) State of preheating. To minimize the number of experiments needed to arrive at any positive conclusion, the principle of fractional factorial design was adopted. Angular distortion was obtained by calculating the angle between the normal at any point on the members prior to and after welding by using a vernier bevel protractor with least count of 0.01 degree. The length and width of the plates were considered appropriate for finite element modeling purpose taking into account the moving distributed heat source. Though semi infinite heat source based modeling was not adopted in the present work the dimensions of the joints were considered to be large enough to be adequate. For the preheating the specimen plates are kept in well insulated electric oven maintained at 300°C. The plates are kept in the oven for three hours so that uniform heat penetration into the material takes place. The plates are brought to the welding table in a portable oven so as to maintain the plate at constant temperature

6. Results and discussion

To study the microstructure of different zones the welded joints were sectioned and metallographic samples were prepared and examined under an optical microscope. The photo of samples obtained is shown in Figure 3.

Table 3.
Angular distortion of preheated plates of 6.5 mm thickness for increasing power input

Job Number	Plate Thickness in mm.	Input Power in kW	Angular Distortion in degrees	
			Base Plate	Vertical Plate
1	6.5	1.35	0.25	0.10
2	6.5	1.46	0.59	0.18
3	6.5	1.92	0.69	0.25
4	6.5	2.20	0.83	0.35
5	6.5	2.33	0.93	0.42
6	6.5	2.47	1.05	0.40
7	6.5	2.60	1.08	0.45

Table 4.
Angular distortion of plates of 6.5 mm thickness for increasing power input

Job Number	Plate Thickness in mm.	Input Power in kW	Angular Distortion in degrees	
			Base Plate	Vertical Plate
14	6.5	1.35	0.35	0.14
15	6.5	1.46	0.70	0.24
16	6.5	1.92	0.80	0.35
17	6.5	2.20	0.88	0.42
18	6.5	2.33	0.93	0.48
19	6.5	2.47	1.18	0.51
20	6.5	2.60	1.25	0.55

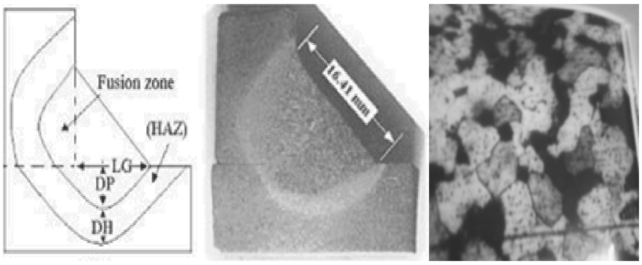

Fig. 3. Different Zones, metallographic photo and the microstructure of Fillet weld

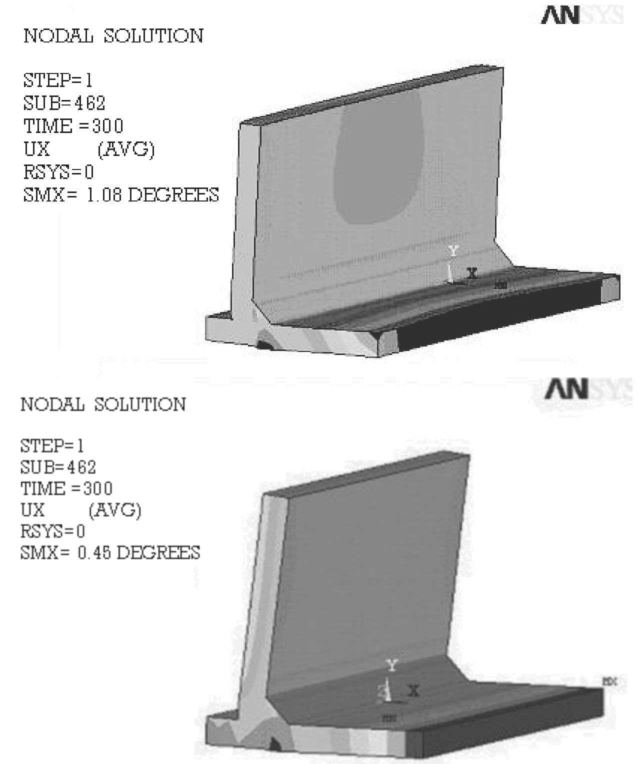

Fig. 4. The deflection of the vertical plate and horizontal plate as obtained by finite element modelling

The maximum angular distortion obtained from the experiments and the finite element modelling was compared. It was found that the data obtained for the horizontal plates and vertical plates. The maximum deflection obtained from the modelling is represented as SMX of the vertical plate and for the horizontal plates are shown in Figure 4 for the job 7.

It is observed from experimental results in Tables 3 and 4, as well as from finite element modeling that the distortion in vertical plates is more than the horizontal plates.

By preheating the plates the distortion in vertical plates and the horizontal plates is reduced which can be observed by comparing the data given in the Tables 3 and 4.

As the diameter of the electrode is increased then the amount of current supplied also increase which leads to increase in input power. As we have observed that with the increase of power input the distortion also increases.

From the Figure 5 it can be observed that at the centre of the weld line the metal attains a temperature of 2500°C, whereas the maximum temperature at a small distance of 7 mm from the weld line it is about 1100°C. As we go further away from the weld centre line there is drastic drop in temperature. The large variation of temperature within a small span of distance can be considered as the major cause for distortion in the fillet welds.

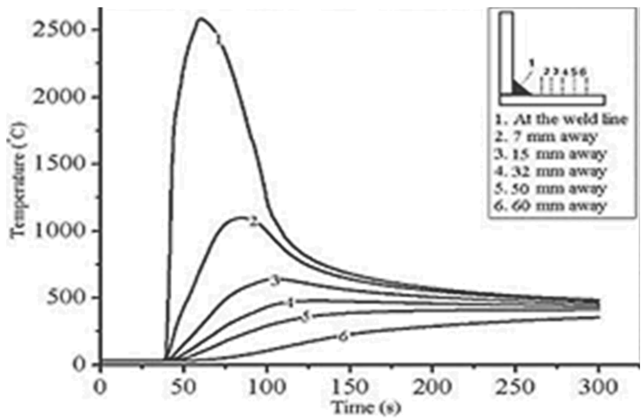

Fig. 5. Predicted surface temperature distribution on the top of the plate

7. Conclusions

The following conclusions can be derived from the present investigation.

1. From the modeling and experiment it was observed as the thickness of the plate increases the distortion decreases.
2. From the experiment and modeling it was also observed that with the increase of power input the distortion also increases.
3. The distortion pattern obtain through finite element modeling and experimental observed patterns matching perfectly.
4. The temperature profile obtained from the finite element modeling compared fairly with the experimental ones

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