Residual Stress and Deformation of Butt-Welded Joint of Low Carbon Steel to Stainless Steel

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Abstract

This paper investigates and determines residual stress and deformation of butt welded joint between two plates of low carbon steel and stainless steel. Based on the theoretical basis of the virtual force method [1-3], this study has constructed the formulas to calculate the residual stress and deformation in fusion welding of two dissimilar materials for butt joint and single-pass weld. The residual stresses and deformations in the butt-welded joint of two plates of 5 mm thickness, beveled edge, single-pass weld between low carbon steel and stainless steel are determined and compared to show the difference of residual stress and deformation in each plate. These results are also compared with the butt welded joint of two low carbon steel plates.

Keywords: Welding dissimilar materials, residual stress, welding deformation, butt-welded joint, stainless steel welding

1. Introduction

Many welding structures are made from two or more different materials to promote the advantages of each material to suit the required working ability. In particular, welding structures between carbon steel and stainless steel are increasingly used in chemical, petrochemical, nuclear, power generation, and other industries [4]. Stainless steel can be chosen in many applications, but when it comes to heavy fabrication, the cost of constructing large structures entirely from stainless steel can be too great. Constructing structures from a lower costing carbon steel can reduce the overall costs of larger fabrication structures. However, low carbon steel has low chemical corrosion resistance. Therefore, many structures are made from stainless steel and low carbon steel by welding processes to reduce production costs while still ensuring their working requirements.

Welding of dissimilar metals is complex due to the difference in chemical composition, metallurgical processes, mechanical, physical, and chemical properties. The properties of carbon steel and stainless steel vary widely. In particular, the thermal expansion coefficient of stainless steel is much larger than that of carbon steel, so the welding residual stress and deformation are very different in each plate.

This paper will develop formulas to determine residual stress and deformation of butt joint of single-pass weld in welding of low carbon steel to stainless steel. To reduce costs and increase productivity in welding carbon steel with stainless steel, it is most appropriate to use the MIG welding process [5-7]. So, the MIG welding parameters are used in the application part to determine the residual stress and deformation in butt joint of these two materials.

2. Determining welding stress and deformation

2.1. Stress and deformation due to vertical contraction

We consider a butt-welded joint between two different materials with the same thickness (δ), the width of the first plate (made by carbon steel) is h_c and the width of the second plate (made by stainless steel) is h_s. After welding and cooling, in each plate, the active zones (b_{nc} and b_{ns}) are tensile stress and the reactive zones (c and s) are compressive stress (Fig.1).

Using an assumption that the stress is constant in each zone [1-2] and the stress in the active zone is equal to the yield strength of that material (σ_{Tc} for first material, σ_{Ts} for second material) and the reactive stresses in the first plate and second plate are σ_{2c} and σ_{2s}, respectively.

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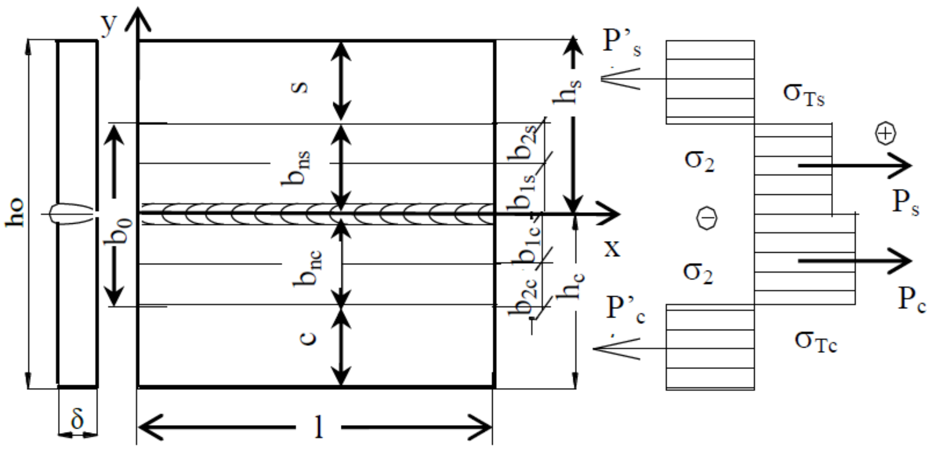

Fig. 1. Active zones and reactive zones

The axial active internal force in the first plate is calculated by the following formula:

$$P_c = \sigma_{Tc} \,.\, F_{cc} = \sigma_{Tc} \,.\, b_{nc} \,.\, \delta \qquad (1)$$

In this: F_{cc} - Cross section of the first plate ($F_{cc} = b_{nc}.\delta$). with: $b_{nc} = b_{1c} + b_{2c}$. and:

- b_{1c} is a zone locating near the welding heat source including the weld metal zone and the base metal zone which have undergone plastic deformation during welding [1-3]: $b_{1c} = \dfrac{0{,}484.q}{\sum\delta.v.c_c.\rho_c.T_{\max c}}$.

with: q - Effective power of welding heat source [7]: q = 0,24.U.$I.\eta$. where: I - welding current; U - welding potential; η - efficiency factor of welding arc; v - welding speed; $\Sigma\delta$ - total thickness of heat transfer; In butt weld joint: $\Sigma\delta = 2.\delta$; ρ_c - density of the first material; c_c - specific heat of the first material; T_{maxc} - temperature of changing from plastic to elastic state of the first material.

- b_{2c} is the base metal zone in the first material that has undergone an elastic state during welding [1-3]: $b_{2c}=k_2(h-b_{1c})$. In which: k_2 – The coefficient that depends on q_0 and σ_T. This coefficient is determined by the graph in Fig.2 [2]; q_0 - specific energy of heat source: $q_0 = \dfrac{q}{v\sum\delta}$; h – calculation width of plate.

If k_{21} of steel having a yield strength of σ_{T1} is found, it is easy to determine k_{22} of steel having a yield strength of σ_{T2} with the condition of $q_{01} = q_{02}$:

$$k_{22} = \frac{k_{21}.\sigma_{T1}}{\sigma_{T2}}$$

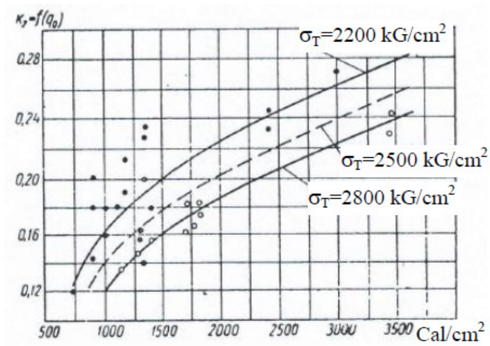

Fig. 2. The graph for determining the coefficient k_2

Similarly, the axial active internal force in the second plate is determined by following equation:

$$P_s = \sigma_{Ts} \,.\, F_{cs} = \sigma_{Ts} \,.\, b_{ns} \,.\, \delta \qquad (2)$$

The reactive internal force in the first plate is expressed by:

$$P'_c = \sigma_{2c} \,.\, c \,.\, \delta \qquad (3)$$

The reactive internal force in the second plate is following:

$$P'_s = \sigma_{2s} \,.\, s \,.\, \delta \qquad (4)$$

Based on the condition of internal force balance, we have:

$$P_c + P_s = P'_c + P'_s \qquad (5)$$

Combining equations (1) to (5) with an assumption that the reaction stresses in the two plates are the same (= σ_2), it leads to:

$$\sigma_{2c} = \sigma_{2s} = \sigma_2 = \frac{\sigma_{Tc}.b_{nc} + \sigma_{Ts}.b_{ns}}{c+s} \qquad (6)$$

Then, the amount of shrinkage along a weld line will be:

$$\Delta l = \frac{\sigma_2}{E}.l \quad (7)$$

where: E – Average Young modulus of the first material (E_c) and the second material (E_s): $E=(E_c+E_s)/2$.

The bending moments in the first plate and the second plate are, respectively:

$$M_c = P_c \frac{c+b_0}{2}; \quad M_s = P_s \frac{s+b_0}{2} \quad (8)$$

in which: $b_0 = b_{nc} + b_{ns}$

The total bending moment is given by:

$$M = M_c - M_s = P_c \frac{c+b_0}{2} - P_s \frac{s+b_0}{2} \quad (9)$$

The bending stress being created by the bending moment is calculated by the next equation:

$$\sigma_M = \frac{M}{J}.y \quad => \quad \sigma_{M\max} = \frac{6.M}{\delta.h_0^2} \quad (10)$$

where: J – moment of inertia of the cross-section of two plates around the x-axis; y – distance between the neutral axis of the total cross-section and the considered point in y-direction.

The maximum deflection at the middle of a welding line is calculated by the formula:

$$f_{\max} = \frac{M.l^2}{8.E.J} \quad (11)$$

with: l – length of each plate.

We find that the formulas of bending moment established above (equations 8 and 9) are similar to that in butt weld of two plates, the same material but different widths [2]. By the same manner to establish the formula of horizontal stress created by the vertical contraction in butt weld of two plates same material but with different widths [2], we obtain the formula of horizontal stress in butt weld of two plates with same widths but different materials:

$$\sigma_x = \frac{32}{\delta.l^2}(M_c - M_s)\left[\frac{6x.(l-x)}{l^2} - 1\right] \quad (12)$$

2.2. Stress and deformation due to horizontal contraction

In the butt weld of two beveled plates (Fig.3), the total deformation (Δy_t) due to horizontal contraction of each metal layer at z thickness in butt weld consists of 2 parts:

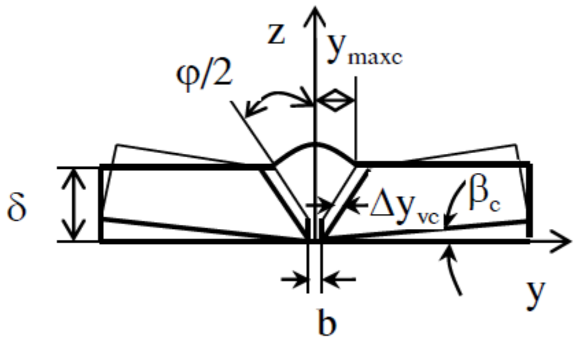

Fig. 3. Beveled butt weld

- The unchanged part (Δy_0) is a horizontal deformation of base metal at the heat-affected zone:

$$\Delta y_0 = \Delta y_{0c} + \Delta y_{0s} \quad (13)$$

where: Δy_{0c} - Unchanged part of horizontal deformation in the first plate; Δy_{0s} - Unchanged part of horizontal deformation in the second plate.

$$\Delta y_{0c} = \int_0^\infty \varepsilon_t.dy = \int_0^\infty \alpha_c.T(y,x).dy \quad (14)$$

with: ε_T is the elastic deformation of "dy" element until complete cooling; α_c - coefficient of thermal expansion of the first plate. $T(y,x)$ is the temperature of points on a cross section [2-3]:

$$T(y,x) = \frac{q}{\delta.\sqrt{4\pi\lambda.c\rho.v.x}}.e^{-\frac{vy^2}{4.a.x}} \quad (15)$$

in which: λ - thermal conductivity; $\lambda = a.\rho.c$ with: a - thermal diffusivity.

The equations (14) and (15) leads to:

$$\Delta y_{0c} = \frac{\alpha_c.q}{2.c_c.\rho_c.v.\delta} \quad (16)$$

Similarly, we can deduce the unchanged part of horizontal deformation in the second plate:

$$\Delta y_{0s} = \frac{\alpha_s.q}{2.c_s.\rho_s.v.\delta} \quad (17)$$

- The changed part (Δy_v) is a horizontal contraction deformation of each deposit metal layer:

$$\Delta y_v = \Delta y_{vc} + \Delta y_{vs} \quad (18)$$

In which: Δy_{vc} - changed part of horizontal contraction deformation in the first plate; Δy_{vs} - changed part of horizontal contraction deformation in the second plate.

$$\Delta y_{vc} = \alpha_c.T_{tbc}.y \quad (19)$$

where: T_{tbc} - average temperature of deposit metal before the transition of the highest heated points, from plastic state to elastic state of the first plate; y - the width of the deposit metal layer: $y = z.tg.\frac{\varphi}{2}$.

The changed part of horizontal contraction deformation at upper layer ($z = \delta$) in the first plate is:

$$\Delta y_{vcmax} = \alpha_c.T_{tbc}.y_{maxc} = \alpha_c.T_{tbc}.\delta.\ tg\varphi/2 \quad (20)$$

The changed part of horizontal contraction deformation at upper layer ($z = \delta$) in the second plate is:

$$\Delta y_{vsmax} = \alpha_s.T_{tbs}.y_{maxs} = \alpha_s.T_{tbs}.\delta.\ tg\varphi/2 \quad (21)$$

The rotation angle β_c due to horizontal contraction of the first plate is determined by:

$$tg\beta_c = \frac{\Delta y_{vc\max}}{\delta} = \alpha_c.T_{tbc}.tg\frac{\varphi}{2}$$

Since angle β_c is usually very small, it can be considered $tg\beta_c \approx \beta_c$. So, we have:

$$\beta_c = \alpha_c.T_{tbc}.\text{tg}\frac{\varphi}{2} \quad (22)$$

Similarly, the angle deformation in the second plate is obtained:

$$\beta_s = \alpha_s.T_{tbc}.\text{tg}\frac{\varphi}{2} \quad (23)$$

The total angle deformation in butt weld is that:

$$\beta = \beta_c + \beta_s \quad (24)$$

In addition, in welding of two beveled plates with the gap (b), there is a horizontal contraction of the welding gap:

$$\Delta y_g = \alpha T_{tb} b \quad (25)$$

Hence, the total deformation due to horizontal contraction is:

$$\Delta y_t = \Delta y_0 + \Delta y_v + \Delta y_g \quad (26)$$

3. Results and discussion

A butt joint of two plates of CT38 low-carbon steel and SUS304 stainless steel is welded by the MIG welding process. Two plates have the same dimensions with a thickness of 5 mm, a width of 60mm, and a length of 200 mm. The welding gap is 2mm. Each plate has beveled an angle of 20^0 (φ = 40^o). The welding parameters are: $U = 21V$; $I = 160\ A$; V = 25 cm/min; η=0,75. The properties of the two materials are given in Table 1.

Table 1. Material properties of CT38 and SUS304 [8]

Parameter	Unit	CT38	SUS304
$\rho.c$	cal/cm^3.^{o}C	1.248	1.248
α	1/^{o}C	12x10^{-6}	17x10^{-6}
a	mm^2/s	8	4
σ_T	kG/cm^2	2500	2050
E	kG/cm^2	2.1x10^6	1.97x10^6

Table 2. Calculation results for welding CT38 to SUS304

	Unit	Plate CT38	Plate SUS304	Error (%)
b_n	mm	18.3	20.4	11.5
P	kG	2284.4	2096.7	8.2
P'	kG	2247.9	2133.2	5.1
σ_2	kG/cm^2	-1052		-
Δl	mm	0.104		-
M	kG.cm	9303.6	8310.6	10.7
σ_{Mmax}	kG/cm^2	80		-
f_{max}	mm	0.0033		-
Δy_0	mm	0.1395	0.1975	41.6
$\Delta y_{v\ (z=\delta)}$	mm	0.0131	0.0185	41.2
Δy_{t1}	mm	0.1526	0.216	41.6
β	^{0}	0.15	0.2127	41.8

The obtained results are shown in Table 2. The results in Table 2 indicate that:

- The width of the active stress zone (bn) in the carbon steel plate is smaller than that in stainless steel plate about 11.5%.

- The active internal force (P), reactive internal force (P'), and bending moment (M) in carbon steel plate are about 10% larger than that in the stainless steel plate.

- The angle deformation (β) and the horizontal contraction (Δy_{t1}) including the unchanged part (Δy_0) and the changed part (Δy_{vmax}) in stainless steel plate are much larger ($\approx$ 41.6%) than that in carbon steel plate. This is explained by the fact that the thermal expansion coefficient of stainless steel (α_s=17x10^{-6})

is greater than 41.6% of the thermal expansion coefficient of low carbon steel (α_c=12x10^{-6}).

- The horizontal stress at two welding-line ends is -157.3 kG/cm^2 and the horizontal stress at the middle of the welding line is 78.65 kG/cm^2.

In comparing the stress and deformation in butt weld joint of carbon steel and stainless steel with the results in welding of two carbon steel plates [1] (Table 3), we find that:

Table 3. Comparison of residual stresses and strains in welding of CT38 to SUS304 with CT38 to CT38

	Unit	CT38-SUS304	CT38-CT38 [1]	Error (%)
b_n *in 2 plates*	mm	38.7	36.6	5.7
σ_2	kG/cm^2	-1052	-1069	1.6
Δl	mm	0.104	0.1	4
M	kG.cm	993	0	-
σ_{Mmax}	kG/cm^2	80	0	-
f_{max}	mm	0.0033	0	-
Δy_0	mm	0.337	0.279	20.8
Δy_v $(z=\delta/2)$	mm	0.0158	0.013	21.5
Δy_g	mm	0.174	0.144	20.8
Δy_t	mm	0.526	0.436	20.6
β	^{0}	0.363	0.298	21.8

- The width of active stress zone (b_n), the reactive stress (σ_2), and the vertical contraction (Δl) in welding low carbon steel to stainless steel are not much different (<6%) from that in welding low carbon steel to low carbon steel.

- The angle deformation (β) and the horizontal contraction (Δy_t) include the unchanged part (Δy_0), the changed part (Δy_v) and the horizontal contraction of welding gap (Δy_g) in welding of low carbon steel with stainless steel are much larger (> 20%) than that in welding of low carbon steel with low carbon steel. This difference is caused by the coefficient of thermal expansion of stainless steel being 1.4 times greater than that of low carbon steel.

- The bending moment, the bending stress, and the deflection are equal to zero in the butt-weld joint of two plates of the same material and the same width [2]. However, in welding low carbon steel to stainless steel of the same width, it still has a bending moment, bending stress, and deflection. In this case, the largest deflection at the middle of weld line is quite small (f_{max}=0.0033 mm) due to the small sample length (l=200 mm). If the length of the structure is high then the maximum deflection is very high (e.g. f_{max}=8.1 mm if l=10 m). Similarly, the shrinkage here is small (Δl=0.0104 mm), but if the length of the structure increases then the shrinkage is large (e.g. Δl = 5.2mm if l=10 m).

4. Conclusion

- This paper developed formulas to determine stress and deformation in butt weld joint of two different materials. The formulas constructed above can be applied not only to the butt-weld joint of carbon steel with stainless steel but also applied to any butt-weld joint of two different materials.

- In the butt-weld joint of two plates of the same material and the same width, the bending moment, the bending stress and the deflection are equal to zero. However, in welding of two plates with the same width but different materials, it appears bending moment, bending stress and deflection. We find that the mechanical behavior of the butt-weld joint of two plates with the same width and different materials is similar to the butt-weld joint of two plates of the same material and different widths.

- In the butt-weld joint of low carbon steel with stainless steel, the horizontal contraction and angle deformation are much larger than that in the butt-weld joint of low carbon steel with low carbon steel because the thermal expansion coefficient of stainless steel is larger than that of low carbon steel.

- Due to a large amount of horizontal contraction and angle deformation in the butt-weld joint of low carbon steel with stainless steel, it is necessary to have technological and structural measures before, during, and after welding to limit this amount of deformation.

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