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RESIDUAL STRESS AND DEFORMATION OF WELDED T-JOINT BETWEEN LOW CARBON STEEL AND STAINLESS STEEL

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Abstract. The welded structures between carbon steel and stainless steel are widely used in many sectors such as pedestrian bridges, food industry, chemical industry, petroleum, and thermal power plants, . . . These composite structures take advantages of each material for different parts of structure. In the welded structures between carbon steel and stainless steel, the structure is made by T-joint that is the most common. The calculation of residual stress and welding strain of the T-joint between low-carbon and stainless steel materials is the basis to evaluate the working ability of this structure. In this study, the residual stress and welding deformation of the T-joint are determined by the imaginary force method. The double-sided weld of T-joint between low carbon steel and stainless steel is welded simultaneously by MIG welding process. The obtained results of residual stress and welding deformation in this case are compared with the case of single-sided weld so that we can find the difference between residual stress and welding deformation in two cases.

Keywords: dissimilar materials, double-sided welding, residual stress, T-joint, welding deformation.

1. INTRODUCTION

Stainless steel has the advantage of corrosion resistance, but it is very expensive. Low-carbon steel is easy to process and is very cheap. The corrosion resistance of this material is poor, especially in chemical environments. So, low carbon steel and stainless steel are combined in a structure in order to ensure chemical resistance and low costs. Today, the welded structures between carbon steel and stainless steel are widely used in many sectors such as food industry, chemical industry, petroleum, and thermal power plants,... The welded joints of these two materials are used to fabricate structures such as pressure vessels, tanks, heat exchangers,... The most common welding joint of low carbon steel and stainless steel is the T joint. In which, the stainless steel is used as a flange plate. Its surface contacts with the corrosive environment. The carbon steel is used as a web plate that increases the stiffness of the structure. In this case, the stainless steel plate that has small thickness is used to reduce the cost while the stiffness of the structure was ensured by a low cost carbon steel plate.

To weld two different metal materials together in general, welding carbon steel with stainless steel in particular, there are many different welding processes that can be used such as explosive welding, friction welding, resistance welding, arc welding, and laser welding,... However, for welding T-joint, the most reasonable and most commonly, an arc welding process is used. In which, the MIG welding process is used to weld low carbon steel with stainless steel. This welding process is most appropriate in order to increase productivity, reduce costs and still ensure quality. Normally in T-joint with two-sided welds, two welds will be performed simultaneously to improve the productivity of manufacturing.

There are many studies on the welding of carbon steel with stainless steel [1,2] but mainly on the technological process to weld these materials. However, there are very few studies that mention the residual stress and welding strain of these materials [3]. Especially, the welding residual stress and strain of T-joint between carbon steel and stainless steel, it is even less. The calculation and determination of residual stress and welding strain of the T-joint between low carbon steel with stainless steel is very important. It permits to evaluation of the working ability of welded structures. In addition, it also helps to take reasonable measures to reduce the welding residual stress and strain, thereby improving accuracy, load capacity as well as the lifetime of structures.

2. WELDING STRESS AND STRAIN OF T-JOINT DUE TO VERTICAL CONTRACTION

A T-joint is welded on two sides (Fig. 1). The web is made by low carbon steel and the flange is made by stainless steel. Based on the imaginary force method [4], the following formulas are developed to determine the welding residual stress and strain of this T-joint between two dissimilar materials.

The active stress zone (crossed area in Fig. 1) is determined by following formula

$$F_c = F_{c1} + F_{c2} + F_w,$$

where F_{c1} is the active stress zone in the flange: $F_{c1} = (2b_{n1} + \delta_2)\delta_1$; F_{c2} is the active stress zone in the web: $F_{c2} = b_{n2}\delta_2$; F_w is the active stress zone in two welds: $F_w = K^2$

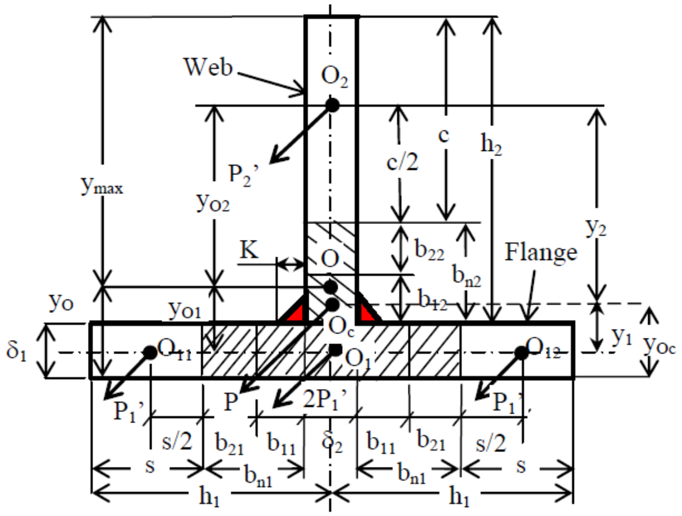

Fig. 1. Cross section and active stress zone of T-joint

(K is the throat thickness of fillet weld); b_{n1} is the active stress zone in each half flange: $b_{n1} = b_{11} + b_{21}$; b_{n2} is the active stress zone in the web: $b_{n2} = b_{12} + b_{22}$; b_{11} and b_{12} are the regions which have undergone the plastic deformation during welding. They are generally denoted b_1 [4]

$$b_1 = \frac{0.484q}{\sum \delta v c \rho T_m},$$

where T_m is the temperature of changing from plastic to elastic state of the material (called change temperature); $\Sigma\delta$ is the total thickness of heat transfer. In T-joint, it is

$$\Sigma\delta = 2\delta_1 + \delta_2,$$

b_{21} and b_{22} are the regions which have undergone the elastic state during welding. They are generally denoted b_2 [4]

$$b_2 = k_2(h_{tt} - b_1),$$

in which h_{tt} is the calculation width, its value depends on the welding process; k_2 is the coefficient which is determined by the graph [4]. This coefficient depends on the specific energy of the heat source (q_0) and the yield strength of the material (σ_T). The specific energy of the heat source (q_0) is determined by [4]

$$q_0 = q\,(v\Sigma\delta)^{-1},$$

with v is the welding speed and q is the net power of welding heat source [5]

$$q = 0.24UI\eta,$$

where U is the welding potential; I is the welding current; η is the efficiency factor of welding arc.

The total active internal force putting at the centroid (point O_c) of the active stress zone is given by

$$P = P_1 + P_2 + P_w,$$

where P_1 is the active internal force in the flange, $P_1 = \sigma_{T1} F_{c1}$; P_2 is the active internal force in the web, $P_2 = \sigma_{T2} F_{c2}$; P_w is the active internal force in two welds,

$$P_w = \sigma_{Tw} F_w,$$

here σ_{Tw} is the yield strength of weld metal. It is calculated by the average of the yield strength of two materials

$$\sigma_{Tw} = (\sigma_{T1} + \sigma_{T2})/2.$$

The total reactive internal force is determined by

$$P' = \sigma_2 F_{re},$$

where σ_2 is the reaction stress; F_{re} is the reaction zone area

$$F_{re} = 2s\delta_1 + c\delta_2,$$

with s is the width of the reaction zone at each half flange

$$s = h_{1t} - b_{n1},$$

here c is the width of the reaction zone at the web

$$c = h_{2t} - b_{n2},$$

in which h_{1t} and h_{2t} are the calculation width of each half flange and of the web, respectively.

If $h_{1tt} > (h_1 - \delta_2/2)$ then it takes: $h_{1tt} = (h_1 - \delta_2/2)$.

If $h_{2tt} > h_2$ then it takes: $h_{2tt} = h_2$.

From the balance condition of internal force ($P = P'$), it gives: σ_2. F_{re} =P.

So, it leads to

$$\sigma_2 = P/F_{re}.$$

The shrinkage along a weld line will be [4]

$$\Delta l = \frac{\sigma_2}{E} l,$$

where E is the average Young modulus of the first material (E_1) and the second material (E_2)

$$E = (E_1 + E_2)/2.$$

The reactive internal force at each half flange is calculated by

$$P_1' = \sigma_2 s \delta_1.$$

The reactive internal force at the web is determined by

$$P_2' = \sigma_2 c \delta_2.$$

The reactive internal force at the left flange (P_1') is put at the centroid of the reactive zone of this half flange (point O_{11}). The reactive internal force at the right flange (P_1') is situated at the centroid of the reactive zone of this half flange (point O_{12}). These two forces are replaced by the concentrated force $2P_1'$ that is put at the centroid of the flange (point O_1). The reactive internal force at the web (P_2') is located at the centroid of the reactive zone of the web (point O_2) (Fig. 1). At that time, there are two pairs of forces ($2P_1'$ and P_2') that create two bending moments acting in opposite directions in the joint ($2P_1'y_1$ and $P_2'y_2$). In which: y_1 and y_2 are the distance from point O_1 and point O_2 to point O_c, respectively.

The reactive internal force of the weld will produce a bending moment M acting in the plane of the web

$$M = P_2'y_2 - 2P_1'y_1.$$

The bending moment M creates bending stress

$$\sigma_M = \frac{M}{J} y,$$

with y is the distance from the considered point to the centroid of the T-joint (point O); J is the moment of inertia of T-joint.

The maximum residual deflection at the middle of T-joint is calculated by the formula

$$f_{\max} = \frac{Ml^2}{8EJ},$$

where l is the length of T-joint.

3. WELDING STRESS AND STRAIN OF T-JOINT DUE TO HORIZONTAL CONTRACTION

In the case of two fillet welds in T-joint are welded alternately. After welding the first fillet weld, due to the horizontal contraction of this weld, the web will rotate at an angle

β compared to the original position. This angle is determined by the formula [4]

$$\beta = 2\alpha T_{ev},$$

where α is the coefficient of thermal expansion of material; T_{ev} is the average temperature of deposit metal when changing from plastic state to elastic state.

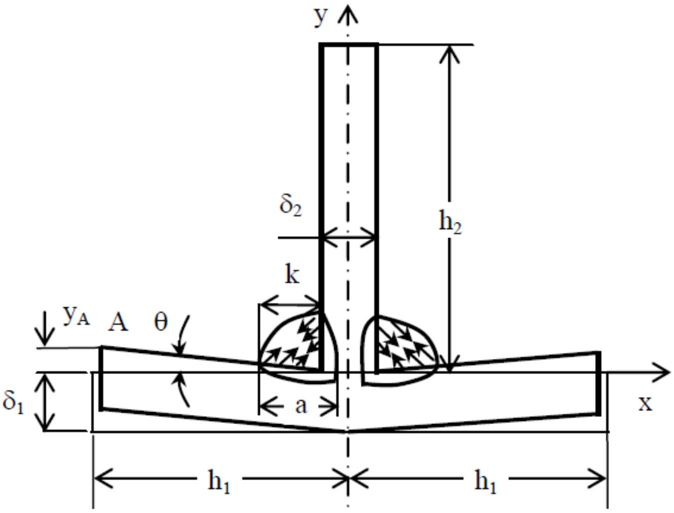

Fig. 2. Angular deformation of T-joint welded on both sides simultaneously

When welding the second weld, its contraction is restrained by the first weld. Therefore, it will appear the horizontal stresses in the filler metal of the second weld. The horizontal stresses also occur in the first weld because it resists the free rotation of the second weld. If two welds are the same, due to the equal internal force, horizontal tensile stresses are the same, then the web situates in the original position and two wings of the flange are rotated at an angle θ (Fig. 2) due to the horizontal tensile stress [4]

$$\tan\theta = \frac{0.075\,(a+\delta_1)}{a\,(0.075a+\delta_1)+3\dfrac{k\delta_1}{a^3}}$$

in which a is the width of fillet weld; If two welds penetrate through web thickness then

$$a = k + \delta_2/2.$$

The displacement of the endpoint A at the top edge of the flange is defined by

$$y_A = h_1 \tan(\theta).$$

4. RESULTS AND DISCUSSION

A T-joint between the web plate made by SS400 low-carbon steel and the flange plate made by SUS304 stainless steel is welded simultaneously on both sides by using MIG welding with welding parameters [6]: $I = 140$ A, $U = 24$ V, $V = 0.486$ cm/s, arc efficiency $\eta = 0.8$. The throat thickness of the fillet weld is $K = 4$ mm [6]. The material properties and dimensions of the plates are given in Table 1.

Table 1. Material properties and plate dimensions [7]

Parameter	Flange (SUS304)	Web (SS400)
*Material properties		
- Yield strength (kG/cm^2)	$\sigma_{T1} = 2100$	$\sigma_{T2} = 2500$
- Young modulus (kG/cm^2)	$E_1 = 199 \times 10^4$	$E_2 = 210 \times 10^4$
- Coefficient of thermal expansion (1/°C)	$\alpha_1 = 1.66 \times 10^5$	$\alpha_2 = 1.2 \times 10^5$
- Change temperature (°C)	$T_{m1} = 600$	$T_{m2} = 600$
- Product of density and specific heat (cal/cm^3.°C)	$\rho_1 c_1 = 0.96$	$\rho_2 c_2 = 1.248$
*Plate dimensions		
- Length (cm)	$l_1 = 500$	$l_2 = 500$
- Width (cm)	$2h_1 = 50$	$h_2 = 25$
- Thickness (cm)	$\delta_1 = 1$	$\delta_2 = 1$

Obtained results are presented in Table 2.

Table 2. Calculation results for internal force, deformations and residual stresses

Parameter	Unit	Double-side	Single-side	Difference (%)
b_n	cm	$b_{n1} = 4.48$; $b_{n2} = 3.63$	$b_{n1} = 3.4$; $b_{n2} = 2.9$	23.9; 20.1
F_c	cm^2	13.74	9.79	28.7
P	kG	30334.1	21724.7	28.4
σ_2	kG/cm^2	-493.87	-335.3	32.1
Δl	mm	1.21	0.82	32.1
M	kG.cm	137636.1	94549.4	31.3
$\sigma_{M\max}$	kG/cm^2	706.6	485.4	31.3
$f_{\max}$	mm	5.1	3.5	31.3
$2\theta/\beta$	Degree	0.64	1.14	78.1
y_A	mm	1.4	4.3	207

From the results in Table 2, for the case of double-sided weld of T-joint, we find that:

- The stress in the reaction area is quite high (σ_2 = 493.87 kG/cm^2). This stress is equal to 23.5% of the yield limit of low carbon steel. The largest bending stress achieved on a web plate of carbon steel is 706.6 (kG/cm^2) that is equal to 33.6% of its yield limit.

- The permissible vertical shrinkage of fillet weld is 0.1 mm/m of welding length [8]. In this case, the welding length is 5 m, hence the permissible vertical shrinkage is 0.5 mm. Thus the amount of vertical contraction (1.21 mm) is greater than 2.4 times the value of vertical shrinkage allowed. The deformation due to vertical contraction here does not affect the working ability of the structure very much, because we can completely compensate this shortage before welding by workpiece fabrication.

- The maximum deflection is 5.1 mm, we have the ratio: $f/l = 0.00102 \approx 1/980$.

If the permissible deflection is $[f/l] \geq 1/980$ then the deflection of this structure locates in the allowable range. Usually, the permissible deflection situates in the range from 1/1000 to 1/250. It means that, if $[f/l] = 1/1000$ then this structure is not satisfactory.

Furthermore, the length of this joint is only 5 meters. In the case of 10 meters of joint length, the maximum deflection at the middle of the joint created by welding is 20.4 mm, corresponding to the ratio $f/l = 0.00204 \approx 1/490$. At that time, if the allowed deflection $[f/l] \leq 1/500$, then the structure is not satisfied.

It should be noted that this is only the deflection created by welding, the structure has not been subjected to an external load yet. Only the internal force created by the welding produces a deformation (deflection) that reaches to the limit, so the structure is not able to bring external loads. Therefore, it is need to find a way to eliminate or reduce the deformation after welding.

- The displacement of the endpoint A at the top edge of the flange is y_A = 1.4 mm (Fig. 2). This displacement causes the flange plate to bend with an angle deformation $2\theta = 0.64^\circ$. This angle deformation changes the shape of the structure. Therefore, after welding, this angular deformation usually has to be treated to increase the accuracy as well as increase the workability of the structure. We can use methods of heat treatment or mechanical treatment to eliminate this angular deformation. The most effective method of heat treatment in this case is the heat treatment by an oxygen-acetylene gas flame. The flame heats along the length (line heating) at the back of the flange plate. After cooling, the flange plate will deform in the opposite direction, we can obtain the desired shape. The mechanical treatment method is normally beam rolling. However, this method is only applicable for T-joints of small thickness and they must have space to perform.

Application for the case of single-sided weld of T-joint (Fig. 3) with the same welding parameters and the same throat thickness of fillet weld, obtained results are given in Table 2.

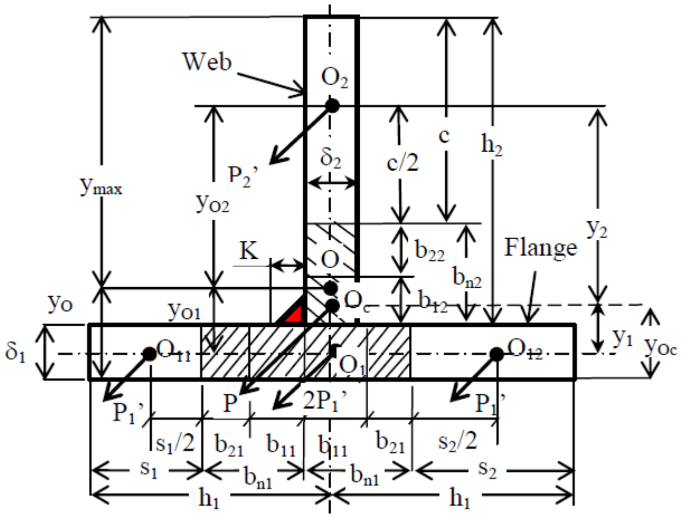

Fig. 3. Single-sided weld of T-joint

The longitudinal stress diagrams due to vertical contraction in two cases (double-sided weld and single-sided weld) on the web and the flange of the T-joint are presented in Figs. 4 and 5, respectively.

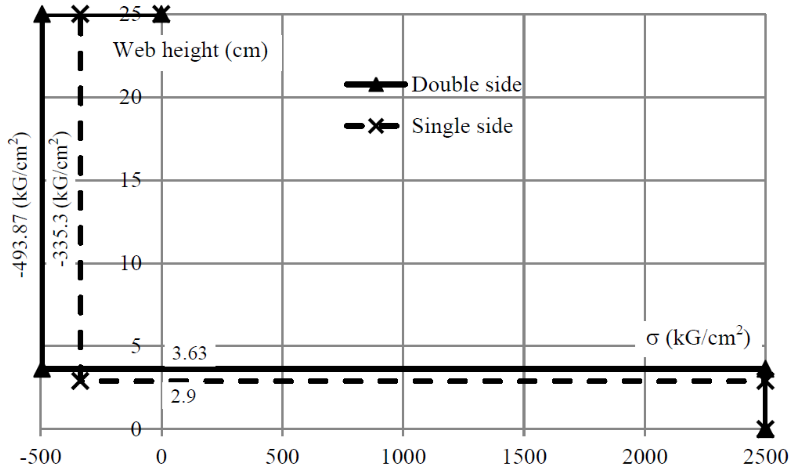

Fig. 4. Longitudinal stress diagram due to vertical contraction on the web

By compare the welding residual stress and strain between the two cases, it indicates that the residual stresses (including reaction stress and bending stress) and welding strain (including shrinkage and maximum deflection) in the case of double-sided weld are greater about 30% than that in the case of single-sided weld. So if the T-joint does not require special, then this joint will be welded from one side to reduce residual stress.

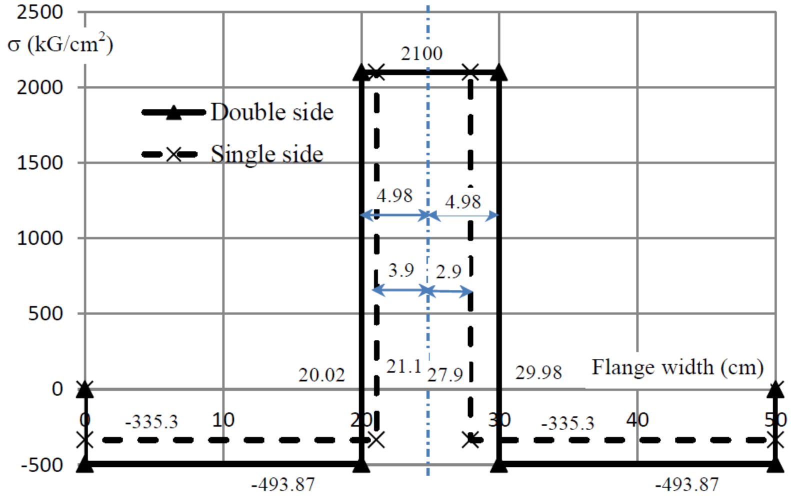

Fig. 5. Longitudinal stress diagram due to vertical contraction on the flange

5. CONCLUSION

Based on the imaginary force method, this paper established the formulas to determine the welding residual stress and strain in the T-joint of dissimilar base metals. These formulas are applied to calculate the welding residual stress and strain of T-joint between the web plate made by SS400 low-carbon steel and the flange plate made by SUS304 stainless steel. In fact, the flange plate is often the shell of structures, so the width of the flange is much larger than that of the web. So, in the applicable of this study, the flange width is taken twice the web width.

The obtained results indicate that the vertical shrinkage and the deflection created by welding are very high. It may be reach to the limit value. Hence, after welding, it is necessary to use the methods to eliminate or reduce these deformations.

In T-joint, if two welds are performed simultaneously with the same welding parameters, then there is no angle deformation of the web plate. However, the flange plate is bent at an angle of 2θ. This deformation may be eliminated by heat treatment or mechanical treatment methods.

The residual stresses are very high, especially bending stress. We can increase the web width to reduce residual bending stress and deflection of the structure.

Due to the durability of welding joints or structures working under dynamic loads, in many cases T-joint welds require two-sided welding. However, if there is no high durability requirement (for example: a small load bearing weld), it is possible to use a one-sided weld. So that, if the double-sided weld is not required, single-sided weld is recommended to reduce residual stress as well as to reduce fabrication costs. However, if the single-sided weld is used then the web plate will be deformed. The web plate will be inclined an angle towards the weld. Therefore, it is necessary to take measures to eliminate this angular deformation after welding.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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