ELSEVIER Journal of Materials Processing Technology 48 (1995) 693–698

Journal of
Materials
Processing
Technology

A new technique for reducing the residual stress induced by welding in type 304 stainless steel

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A new Technique named as "parallel heat welding"(PHW) is developed for the reduction of residual stress. It is performed by a pair of parallel heating torches attached to the welding torch on both sides as a movable heat source during welding. Autogenous gas tungsten arc welding process was used in type 304 stainless steel. The experimental results showed that the maximum principal residual stress and parallel welding direction stress can be reduced by 21-32 % when the conventional welding(CW) process is replaced by the parallel heat welding process. The elevation of equilibrium temperature during welding process is a main mechanism for the reduction of residual stress in PHW process.

1. INTRODUCTION

Austenitic stainless steels, such as type 304 are used in various plants including nuclear reactors because of their excellent corrosion resistance, good strength at high temperature and fracture toughness at low temperature. However, the austenitic stainless steels have higher thermal expansion coefficient and lower thermal conductivity than the carbon and alloy steels, therefore, a large amount of shrinkage, distortion, and residual stress can be induced after welding fabrication.

Residual stress due to welding is remains as thermal stress when the material has been cooled to ambient temperature. Thermal stress has been investigated both analytically and experimentally by a number of workers[1-6]. Basic mechanism of residual stress introduced by welding process was proposed by Wells[1] for the description of residual stress formation and the prediction of stress distribution. This model pointed out an important concept of "equilibrium temperature". The uniform temperature distribution in the welded part will be reached due to conduction of heat, before final cooling to the ambient temperature. A plate subjected to a uniform temperature field is free of thermal stress[1].

A schematic explanation of residual stress induction during welding process by modified Wells' model is shown in Fig. 1, which illustrates a typical thermal/stress cycle for an element of material near the fusion zone. When the thermal/stress cycle start from room temperature (position O), to higher temperature (position A), the initial thermal expansion is restrained by the surrounding cold material, thus an elastic compressive stress is generated until the yield strength is reached at position A. With further increases in temperature, plastic strains occur following the material characteristic compressive

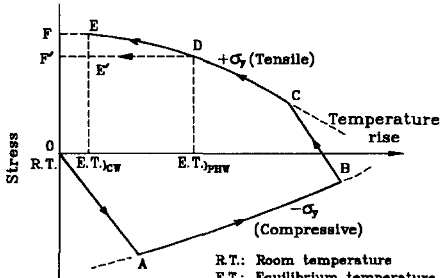

Fig.1 Schematic illustration of origin of residual stress during heating and cooling

0924-0136/95/$09.50
SSDI 0924-0136(94)01710-I

yielding curve, AB. On cooling from B, the initial response in once again elastic, but opposite in sense to the heating cycle (OAB), until the tensile yield strength is achieved at position C. Cooling back to room temperature (position F), it then follows the material characteristic tensile yielding curve, CDE. Thus, a residual stress equal to the magnitude of yield stress at room temperature is generated after the complete cycle. As this cycle reaches the position E, this element may approach to the equilibrium temperature/stress state, because of the uniform temperature distribution by the long time heating. Below this temperature, the magnitude of stress will be maintained at its final value.

According to this mechanism of welding residual stress formation, it is found that the residual stress is dependent on the final equilibrium temperature of thermal/stress cycle. If the equilibrium temperature of cycle can be increased from position E to position D (see Fig. 1), the thermal/stress cycle will be altered to follow CDE'F'curve, thus residual stress introduced by welding can be properly reduced from position F to position F'.

This paper aimed at using this model of welding residual stress formation to develop a new technique named as "parallel heat welding" (PHW) for reduction of residual stress during welding and verify its mechanism.

2. EXPERIMENTAL PROCEDURE

The type 304 stainless steel was used in this study, its chemical compositions and mechanical properties are indicated in Table 1. In order to obtain the same initial stress relief condition, the test specimens of 130 × 130 × 7 m had been annealed at 900°C for 2 hours before testing.

In the PHW process, a pair of parallel heating torches were attached on both sides of welding torch as a heat source supplied with natural gas. The diameter of the nozzle of the heating torch is 1 in. (2.54 cm) and the distance between two heating torches is 8.5 cm, the schematic illustration of this torch system is shown in Fig. 2.

In order to study the effect of welding conditions on the residual stress of the conventional welding(CW) and PHW, six different welding conditions were employed. Autogenous gas tungsten arc welding process was used in this study. The welding parameters used in this study are listed in Table 2. After welding, three-element strain-gage rosettes (Tokyo Sokki Kenkyujo Co., type TML FRS-2-17) were applied at 7, 17, 27, 37, 47 mm from the fusion line. A hole of 1.6 mm diameter was drilled by the hole-drilling machine (Measurements Group, Inc.) in the center of the rosette to measure the residual stresses. The residual stresses were determined by using the hole-drilling strain-gage method of ASTM standard E837.

In order to measure the thermal cycles, four thermocouples were separately applied at 1, 13, 33, and 45 mm from the fusion line and transverse to

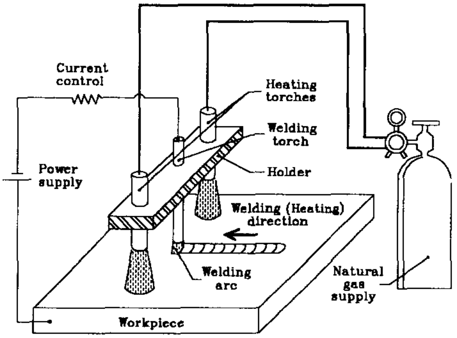

Fig.2 Schematic illustration of the parallel heat welding process

Table 1 Chemical compositions,wt% and mechanical properties

Cr	Ni	C	Si	Mn	P	S	Fe	Yield stress(MPa)	Young's modulus(GPa)	Poision's ratio
18.07	8.65	0.069	0.483	1.203	0.022	0.015	Bal.	262	193	0.28

Table 2 Welding parameters used

Welding conditions	Current(A)	Voltage(V)	Travel speed(cm/min)	Gas flow rate(ℓ/min)	Heat input(kj/cm)
A	200	16.0	12.8	15	15.0
B	180	15.0	12.0	15	13.5
C	160	14.0	11.2	15	12.0
D	140	13.2	10.6	15	10.5
E	130	12.8	10.0	15	10.0
F	120	12.5	9.5	15	9.5

the weld bead. The thermocouples were inserted in a tiny hole drilled from the backside of specimen at 3 mm below the surface to avoid the error induced from the radiation heat of welding arc.

3. RESULTS AND DISCUSSION

3.1. Residual stress evaluation

Fig. 3 shows the measured maximum principal residual stress distribution from the CW sample and PHW sample with welding condition C. The magnitude of measured residual stress from PHW process is always lower than that measured from CW process. Fig. 4 shows the measured minimum principal residual stress distribution with the same condition. The magnitude of measured residual stress from PHW process is always lower than that measured from CW process, except below 35 mm from the fusion line.

The effect of welding heat input of maximum principal residual stress in CW process and PHW process is plotted in Fig. 5. The result shows that the difference of residual stress between the CW and PHW increases with the decrease in the welding heat input. It is observed that the using of the lower heat input is more efficient than the using of higher heat input to reduce the welding residual stress.

The results of the measured thermal cycles at various locations in the weldment with welding condition A in CW process and PHW process are shown in Fig. 6. In CW process, the temperature reaches to the peak value as the welding arc has just

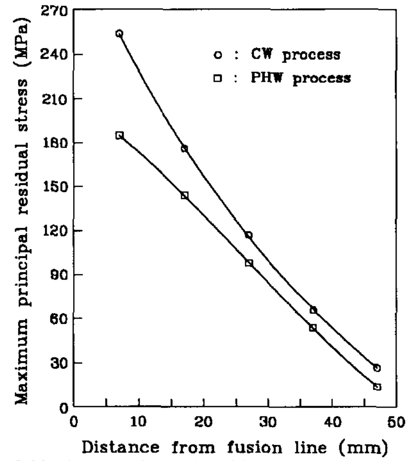

Fig.3 Maximum principal residual stress measured from CW and PHW.with welding condition C

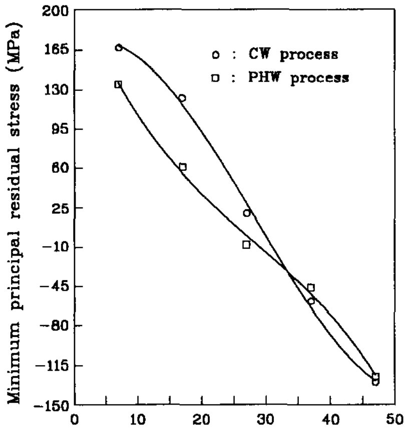

Fig.4 Minimum principal residual stress measured from CW and PHW with welding condition C

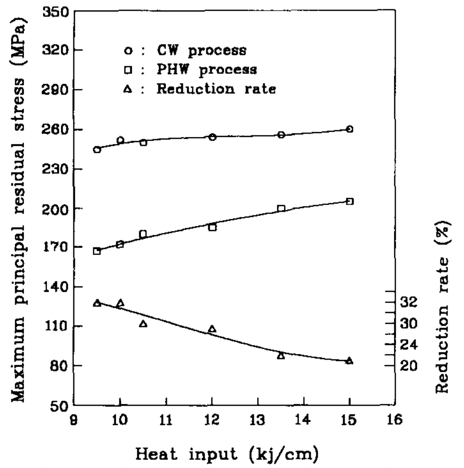

Fig.5 Effect of the heat input on reduction of maximum principle residual stress

passed. The temperature histories at various locations of weldment are different. After reaching the peak temperature, all locations of weldment can reach the equilibrium temperature with different cooling rates. Fig. 6(a) shows that the equilibrium temperature is round 50°C. In the PHW process as shown in Fig. 6(b), the behavior of thermal cycles is similar to the CW process at the beginning. But, as the welding arc and heaters passed, the temperature gradient of weldment is rapidly decreased and the thermal cycles are balanced at about equilibrium temperature of 240°C.

Base on the thermal cycles recorded during welding(see Fig. 6(a) and Fig. 6(b)), the exposure time at temperature in range between 600 and 850 °C during CW and PHW is 9.6 and 9.8 seconds(the time value was obtain from the thermal cycle of the weld metal closest the fusion line). The difference of exposure time is only 0.2 second. According to the previous study[7] showed that the parallel heating torches of PHW will not effect the metallurgical structure of weld metal.

3.2. Verification of mechanism of PHW process

The concept of "equilibrium temperature" proposed by Wells was used to explain the reduction of residual stress with PHW process. The process of verification included the analysis of the theoretical residual stress and the comparison of theoretical and experimental results. The material properties used in elevated temperature are obtained in type 304 stainless steel from literatures[8,9] and are shown in Fig. 7.

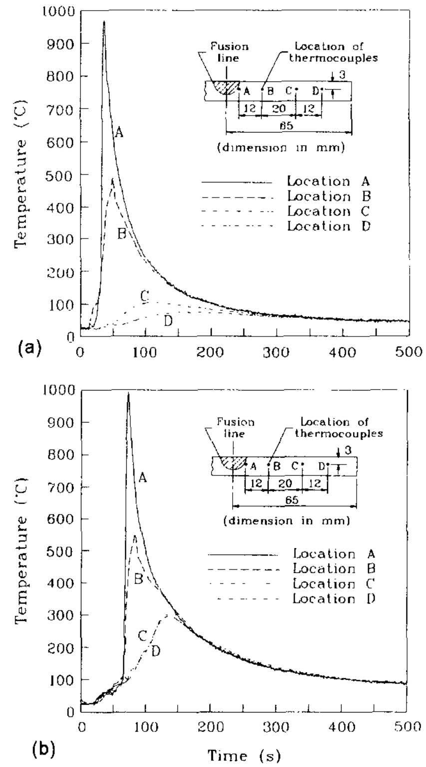

Fig.6 Thermal cycles of (a)CW and (b)PHW processes at various locations of weldment with welding condition A

The analytic and experimental results of relationship between longitudinal residual stress and equilibrium temperature are shown in Fig. 8. The solid line represents the theoretical curve predicted by the modified Wells' model(see Fig.1 and Fig.7), the symbol represents the experimental results obtained under various weldings and heating conditions. It is shown that the experimental results measured are in agreement with the theoretical curve predicted in various welding conditions.

In this investigation of residual stress due to welding, two factors need to be considered: (1)

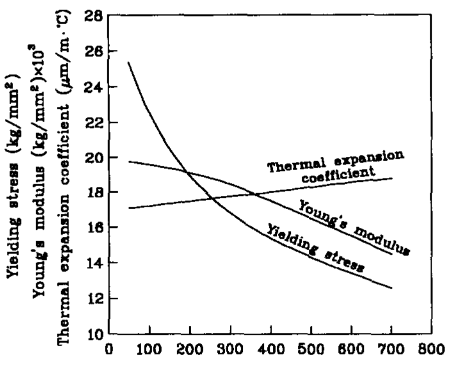

Fig.7 Material properties at elevated temperature [Reference 8,9].

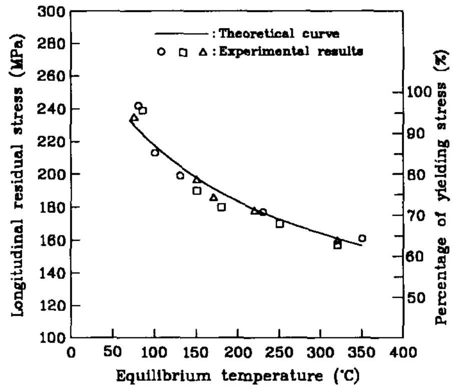

Fig.8 Comparison between theoretical and experimental results in the relation of longitudinal residual stress and equilibrium temperature

initial residual stresses of specimens before welding testing, (2) residual stresses formation by phase transformation during welding process. The initial residual stresses of specimen before welding have been measured accurately by hole-drilling method and the magnitude of longitudinal and transverse stresses equals to 1 MPa and -3 MPa respectively. Because of these values are quite small, they can be neglected during residual stress investigation. In addition, phase changes can have a significant effect on the residual stresses generated by the welding of some steels. Jones[10] studied the residual stresses owing to phase transformation in several materials, and found that phase transformation has no influence on the residual stress in austenitic stainless steels because of their phase transformation (δ ferrite⇔ austenite) occur at very high temperature. Since the type 304 austenitic steel was used in this study, the effect of phase transformation during welding can be neglected in the investigation.

4. CONCLUSIONS

(1) The maximum principal residual stress induced by the CW process can be reduced by 21-32 % by the new PHW process in small specimens in type 304 stainless steel.

(2) The effect of stress relief with lower heat input condition is more efficient than that with higher heat input condition.

(3) The predicted results of longitudinal residual stress by modified Wells' model are agree with the experimental measurement. Thus, the increase of equilibrium temperature during welding process is a major mechanism of stress relief with PHW process.

ACKNOWLEDGMENT

The authors acknowledge the financial support of this research by the National Science Council, Republic of China under grant no. NSC 82-0405-E009-118.

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