Journal of Materials Processing Technology 123 (2002) 346–353

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

The effect of pulsed GTA welding on the residual stress of a stainless steel weldment

K.H. Tseng, C.P. Chou*

Department of Mechanical Engineering, National Chiao Tung University, Hsinchu 30049, Taiwan

Received 15 December 2000

Abstract

The objective of this study was to investigate the effect of pulsed GTA welding parameters on the residual stress of the weldment. Autogenous gas tungsten arc welding was applied on SUS 304 and SUS 310 stainless steels to produce a bead-on-plate weld. The residual stress was determined by using the hole-drilling strain-gage method of ASTM standard E837. The experimental results show that a greater pulse frequency, a larger pulse spacing, a greater amplitude ratio, and a greater duration ratio can reduce the magnitude of the residual stress in the austenitic stainless steel weldment. The residual stress of the 310 stainless steel weldment is greater than that of the 304 stainless steel weldment under the same welding conditions because of its lower thermal conductivity and thermal diffusivity. The experimental results also showed that pulsed current welding has a smaller range of the tensile residual stress zone as compared to that of constant current welding because of its lesser amount of heat input. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Welding parameter; Residual stress; Pulsed GTA welding; Tensile residual stress zone

1. Introduction

The pulsed current welding (PCW) process was introduced in the late 1960s as a variant of the constant current welding (CCW) process that is now used in a wide range of applications. Switching between a pre-determined high and low level of welding current can produce pulsed gas tungsten arc welds. Usually, the pulse waves are rectangular in shape (as described in Fig. 1).

The PCW has many specific advantages compared to CCW, such as enhanced arc stability, increased weld depth-to-width ratio, a narrower HAZ range, reduced hot cracking sensitivity, refined grain size, and reduced porosity [1–6].

The parameters used for PCW are shown in Fig. 1. The main pulse parameters of PCW are peak current I_P, base current I_B, peak time t_P, and base time t_B. From combining the above four pulse parameters, the following four characteristic weld parameters can be determined [3,4,7]:

1. pulse frequency, $F = 1/(t_P + t_B)$;
2. pulse spacing, $S = V(t_P + t_B)$, where V is the travel speed;
3. amplitude ratio, $A = I_B/I_P$;
4. duration ratio, $T = t_B/t_P$.

* Corresponding author.
E-mail address: cpchou@cc.nctu.edu.tw (C.P. Chou).

The above weld parameters can actually control the thermal characteristics and weld bead geometry.

During welding, the weldment is heated locally, therefore the temperature distribution in the weldment is not uniform, and the temperature also changes with time. During the welding cycle, thermal strains are induced in both the weld metal and the base metal near to the weld. The thermal strains produced during heating are accompanied by plastic upsetting. The thermal stresses resulting from these strains combine and react to produce internal forces that cause residual stresses. In past studies [8–11], it was found that residual stress existing in a weldment can influence the mechanical and/or corrosion properties of materials in service, such as brittle fracture, fracture toughness, fatigue strength, stress corrosion cracking, and hydrogen cracking, etc.

Previous investigation on pulsed GTA welding were still focusing on the study of pulsed wave shapes [1], the investigation of pulsed GTA welding parameters [3,4,7,12–14], and the effect of GTA welding on the microstructures or mechanical properties of the weldment [2,6,15]. Study of the influence of pulsed GTA welding on the residual stress of weldment was limited.

By means of detailed experiments, the aim of this paper was to explore the effect of pulsed GTA welding on the residual stress in an austenitic stainless steel weldment, and also to try to find a proper explanation of the results.

0924-0136/02/$ – see front matter
PII: S0924-0136(02)00004-3

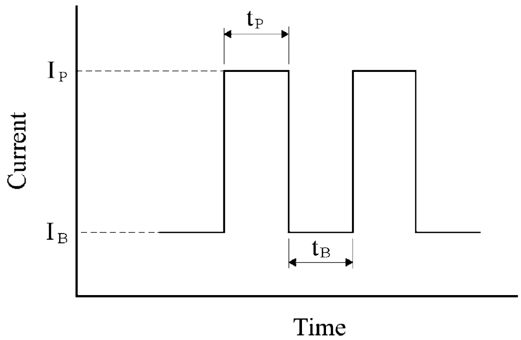

Fig. 1. Parameters used for pulsed GTA welding: I_P, peak current; I_B, base current; t_P, peak time; t_B, base time.

2. Experimental procedure

Types 304 and 310 austenitic stainless steels were used in this study, their chemical compositions and mechanical properties being listed in Tables 1 and 2. In order to obtain the same initial stress-state condition, the test specimens, having the dimensions 130 mm × 130 mm × 138 mm, were annealed at 950 °C for 3 h before testing. The test specimens were roughly polished with 400 grit abrasive paper to remove surface impurities, then they were cleaned with acetone. Autogenous gas tungsten arc welding was conducted using an EWTh-2 electrode.

In order to monitor the thermal cycles during the welding process, four thermocouples were separately attached at 2, 10, 30, 50 mm from the fusion line and transverse to the weld bead. The thermal cycle recording equipment included a dynamic temperature measurement system and a chromel/alumel thermocouple and is shown in Fig. 2.

After welding, a three-element strain-gage rosette (Tokyo Sokki Kenkyujo, type TML FRS-2-17) was attached at the center location of the surface of the weld. A hole of 1.6 mm diameter was drilled at the center of the rosette to measure the welding residual stress. The residual stress was determined by using the hole-drilling strain-gage method of ASTM standard E837. The residual stress measuring system is presented in Fig. 3.

An optical microscope was used to measure the weld depth-to-width ratio and HAZ range caused by pulsed GTA welding. All metallographic specimens were prepared by mechanical lapping, grinding, and polishing to a 0.3 μm finish, followed by etching in a solution of 10 g $CuSO_4$ + 50 ml HCl + 50 ml H_2O.

Table 1
Chemical composition of the austenitic stainless steels used (wt.%)

Material	C[a]	Si	Mn	P[a]	S[a]	Cr	Ni	Fe
SUS 304 SS	0.08	0.44	0.95	0.04	0.04	18.7	8.16	Balance
SUS 310 SS	0.20	0.79	1.64	0.04	0.04	23.9	19.61	Balance

[a] Maximum value.

Table 2
Mechanical properties of the austenitic stainless steels used

Material	Yield strength (MPa)	Elasticity modulus (GPa)	Poisson's ratio
SUS 304 SS	290	193	0.25
SUS 310 SS	311	204	0.32

3. Results and discussion

3.1. Initial stress evaluation

In order to evaluate the initial stress in the test specimen, the stress of the specimen was measured using the hole-drilling

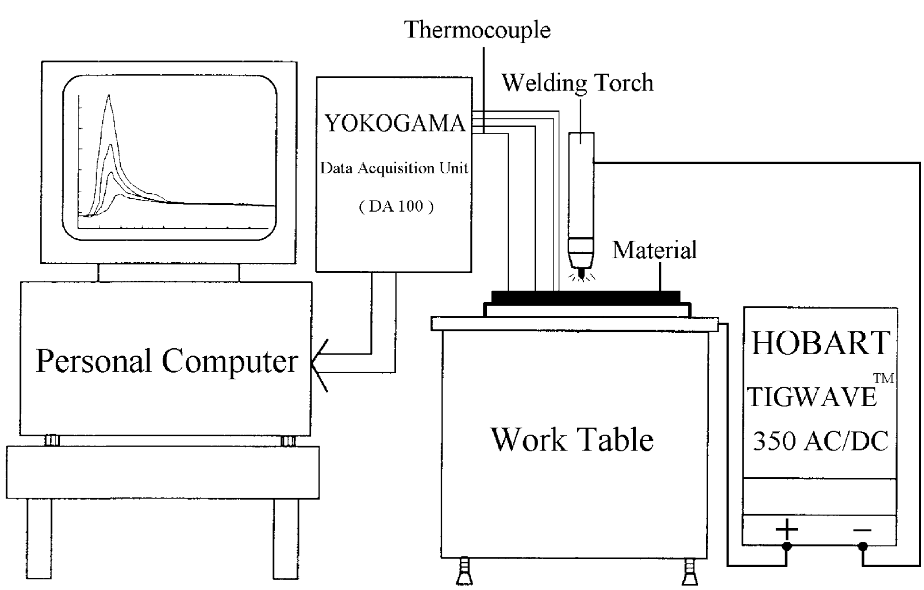

Fig. 2. The thermal cycle recording system used.

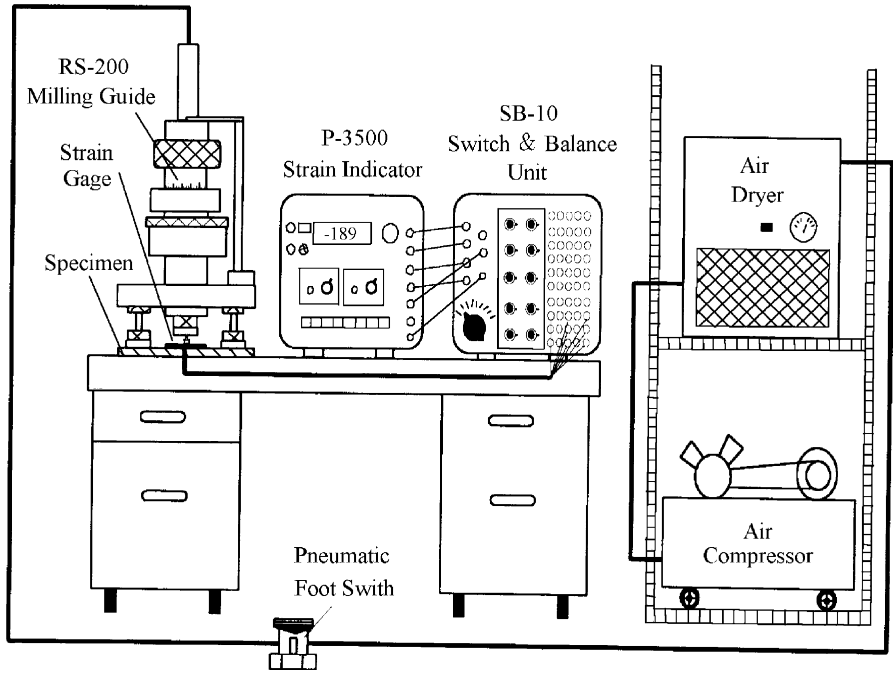

Fig. 3. The residual stress measuring system used.

strain-gage method before welding. Table 3 presents the measured initial principal stress of the materials used. These values are quite small, so that they can be neglected in the investigation of the welding residual stress.

3.2. Effect of the pulse frequency on the residual stress

Fig. 4 shows the effect of the pulse frequency on the residual stress of the weldment. The experimental result shows that the residual stress decreases with the increase of the pulse frequency. The measured geometric shape of the welds shown in Figs. 5 and 6 can be used to explain this result. It is observed that a greater pulse frequency can increase the weld depth-to-width ratio and reduce the HAZ range of the weldment. According to the results of previous investigations [16,17], a greater weld depth-to-width ratio and a narrower HAZ range represent a greater concentration of energy density in the heat source. Based on the experimental results, a greater pulse frequency in the pulsed GTA welding process can enhance the concentration of the energy density in the heat source, therefore the residual stress of an austenitic stainless steel weldment can be reduced.

Table 3
Initial stress evaluation of the austenitic stainless steels used

Material	Yield stress (MPa)	Initial stress (MPa)	Stress ratio[a] (%)
SUS 304 SS	290	5.9	2.0
SUS 310 SS	311	10.6	3.4

[a] Initial stress/yielding stress.

3.3. Effect of the pulse spacing on the residual stress

Fig. 7 presents the residual stress measured for various pulse spacings in pulsed GTA welding. As the pulse spacing increases, the residual stress of the weldment decreases. This result can be explained from the different size of the double fusion zone of welds, as shown in Fig. 8. It was found that a greater pulse spacing can reduce the degree of double fusion

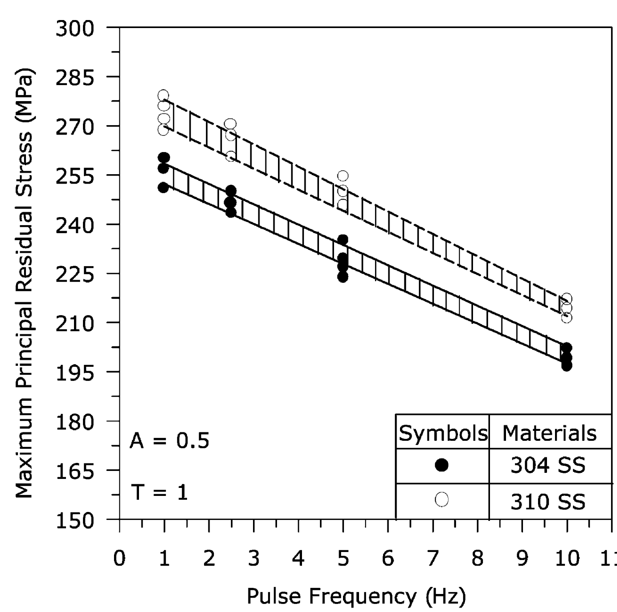

Fig. 4. Residual stress measured for various pulse frequencies during the pulsed GTA welding process.

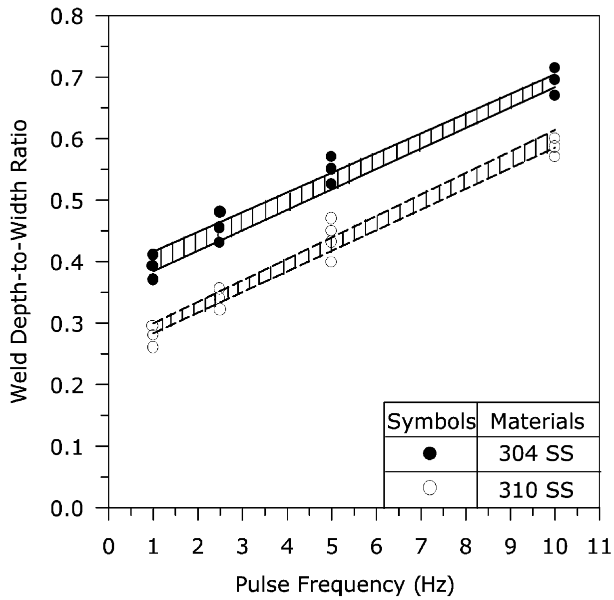

Fig. 5. The effect of pulse frequency on the weld depth-to-width ratio.

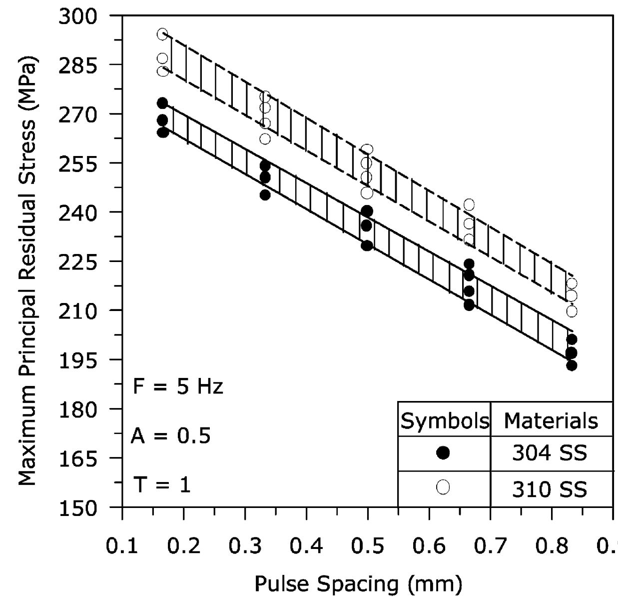

Fig. 7. Residual stress measured for various pulse spacings during the pulsed GTA welding process.

of welds. The extent of double fusion caused by the peak current is related to the amount of the heat input. A larger pulse spacing can induce a lesser heat input, therefore the residual stress of the weldment will be reduced.

3.4. Effect of the amplitude ratio on the residual stress

The peak current was held as a constant value of 150 A, with the base current being set differently for various welding conditions. The effect of the amplitude ratio on the residual stress is shown in Fig. 9. The results indicate that the residual stress decreases as the amplitude ratio increases. This result can be related to the welding thermal cycle during welding process, as shown in Fig. 10. In the pulsed GTA welding process, a greater amplitude ratio will reduce the temperature difference between the fusion zone and the unaffected base metal in the weldment. According to the results of previous study, the magnitude of the shrinkage stresses were reduced by a smaller temperature gradient [18,19]. Based on the above discussion, a greater amplitude ratio can reduce the temperature gradient and therefore the welding residual stresses can be reduced.

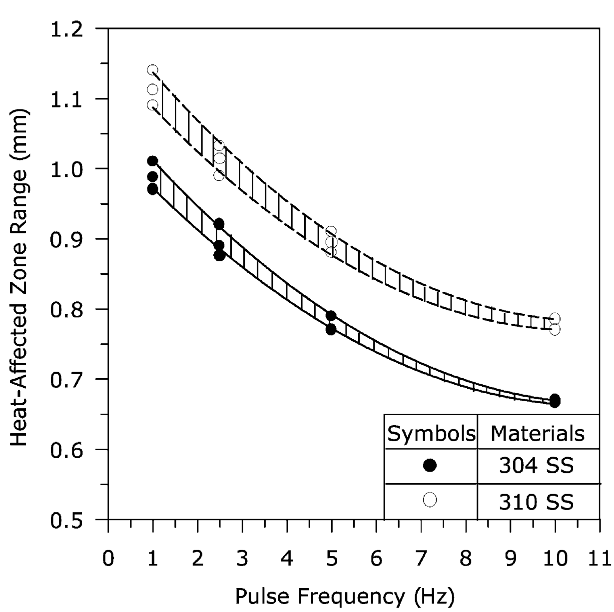

Fig. 6. The effect of pulse frequency on the HAZ range.

3.5. Effect of the duration ratio on the residual stress

Fig. 11 shows the measured residual stress induced by different duration ratios in the pulsed GTA welding. The result indicates that as the duration ratio increases, the residual stress of the weldment decreases. This result is also related to the thermal cycle during the welding process, as shown in Fig. 12. As the magnitude of the duration ratio increases, the peak temperature of the thermal cycle decreases. According to the result of investigations by Lin et al. [19–21], the welding thermal stress increases with the increase of the peak temperature. Therefore, a lesser smaller welding residual stress can be obtained by using a greater duration ratio in the pulsed GTA welding process.

3.6. Study on the residual stress in an austenitic stainless steel weldment

In this study, the experimental results clearly indicate that the residual stress of a 310 stainless steel weldment is greater than that of a 304 stainless steel weldment under the same

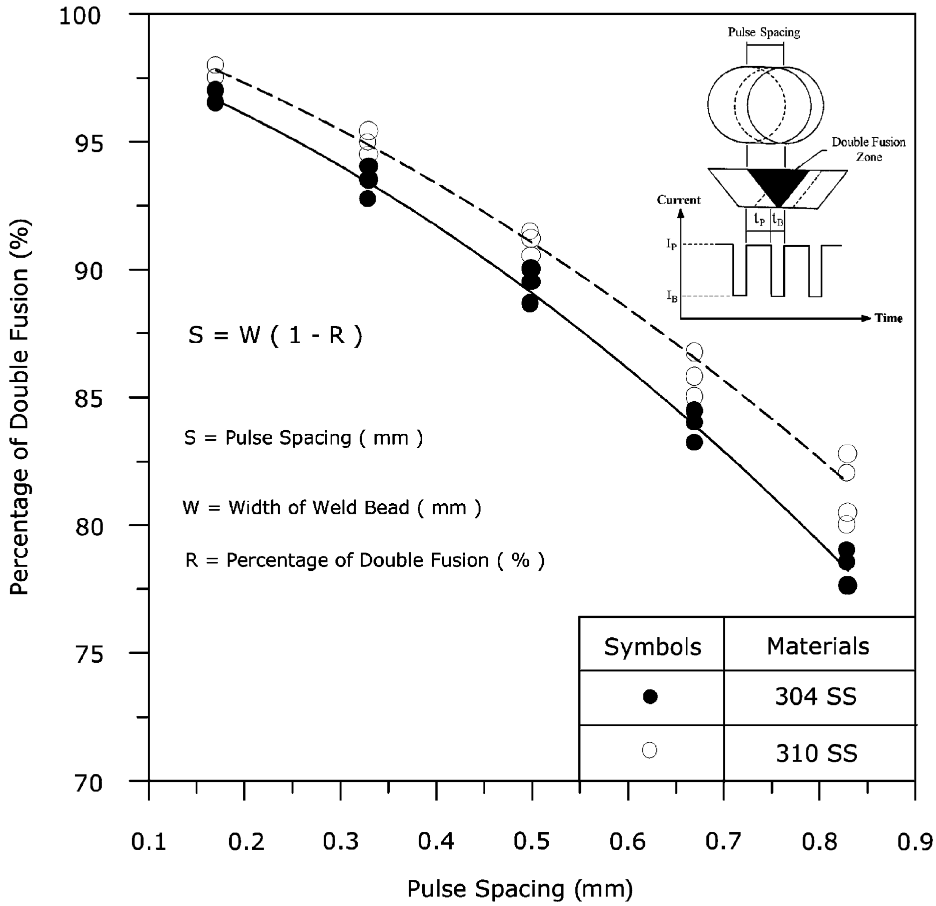

Fig. 8. The effect of pulse spacing on the double fusion zone of the weld.

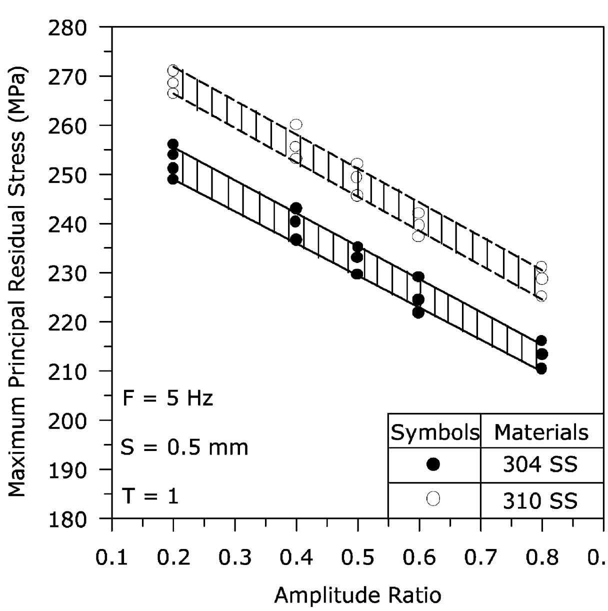

Fig. 9. Residual stress measured for various amplitude ratios during the pulsed GTA welding process.

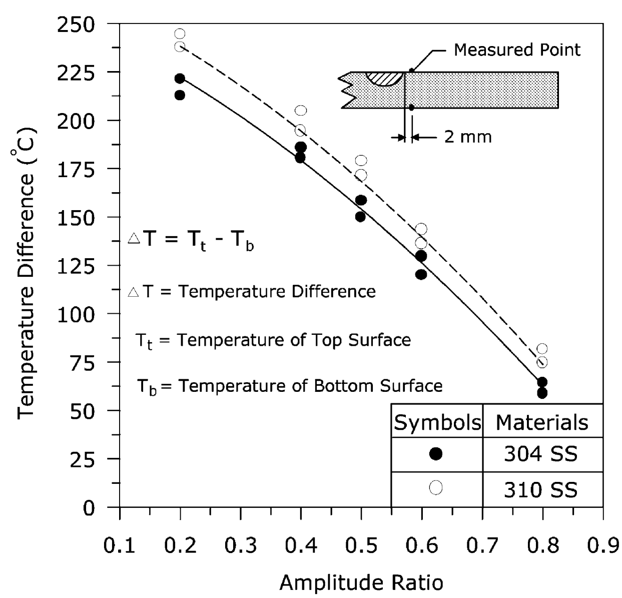

Fig. 10. Effect of the amplitude ratio on the temperature difference of the weldment.

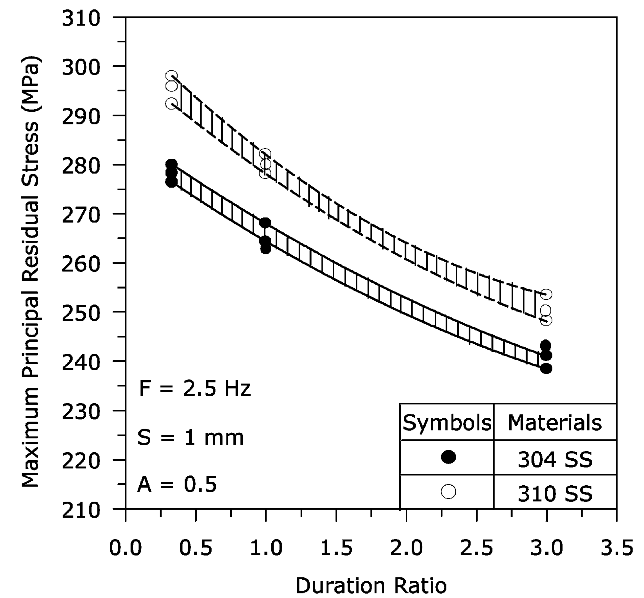

Fig. 11. Residual stress measured for various duration ratios during the pulsed GTA welding process.

welding conditions. The results can be analyzed from the thermophysical properties of the materials used.

3.6.1. Coefficient of thermal expansion

Table 4 shows that types 304 and 310 stainless steels have almost the same coefficient of thermal expansion. Thus, the effect of the coefficient of thermal expansion on the welding residual stress can be neglected.

3.6.2. Thermal conductivity

Table 4 shows that 310 stainless steel has a lower thermal conductivity than that of 304 stainless steel. The thermal conductivity usually can be considered as the ability of heat transfer of material. In general, a lower thermal conductivity will increase the temperature difference between the fusion zone and the unaffected base metal in the weldment, therefore, the welding residual stress will be increased.

Table 4
Thermophysical properties of austenitic stainless steels used

Material	Coefficient of expansion (μm/mm °C)	Thermal conductivity (W/m K)	Thermal diffusivity[a] (m^2/s)
SUS 304 SS	17.0	16.3	4.14×10^{-6}
SUS 310 SS	16.1	14.1	3.63×10^{-6}

[a] $\lambda = K/\rho C_P$, where λ is the thermal diffusivity, K the thermal conductivity, ρ the density, and C_P the specific heat.

3.6.3. Thermal diffusivity

Table 4 also shows that 310 stainless steel has a lower thermal diffusivity. The thermal diffusivity can be considered as, the capacity of the material for heat storage. Usually, a lower thermal diffusivity relates to a high capacity for heat storage and a consequent increase in the peak temperature of the thermal cycle in welding process, thus the residual stress of the weldment can be increased.

Since 310 stainless steel has a lower thermal conductivity and thermal diffusivity, a greater temperature gradient and a higher peak temperature of thermal cycle can be obtained during the welding process as compared to that for 304 stainless steel. Therefore, the residual stress of the 310 stainless steel weldment is greater than that of the 304 stainless steel weldment.

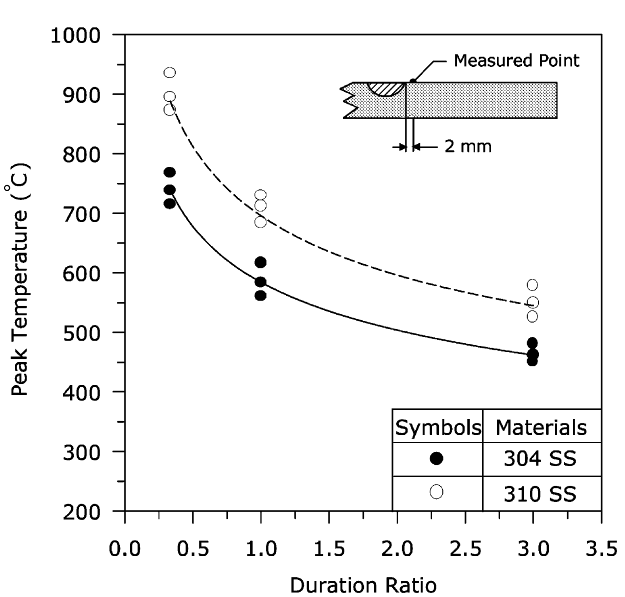

Fig. 12. Effect of the duration ratio on the peak temperature of the weldment.

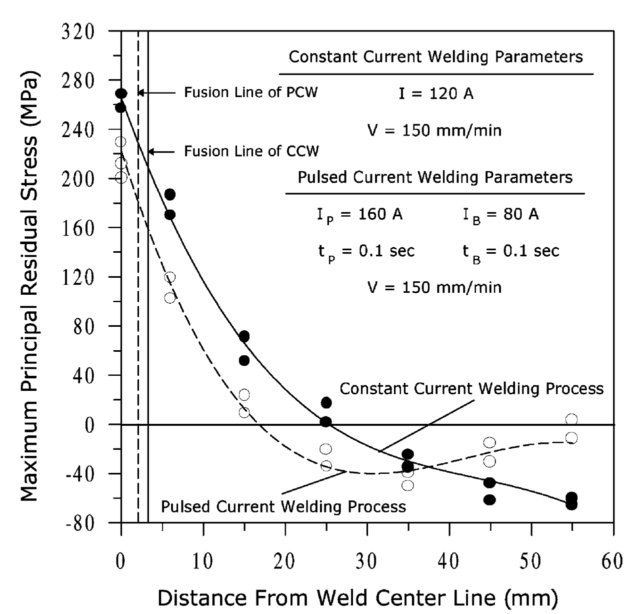

Fig. 13. Distribution of the residual stresses in a weldment of 304 stainless steel for various GTA welding processes.

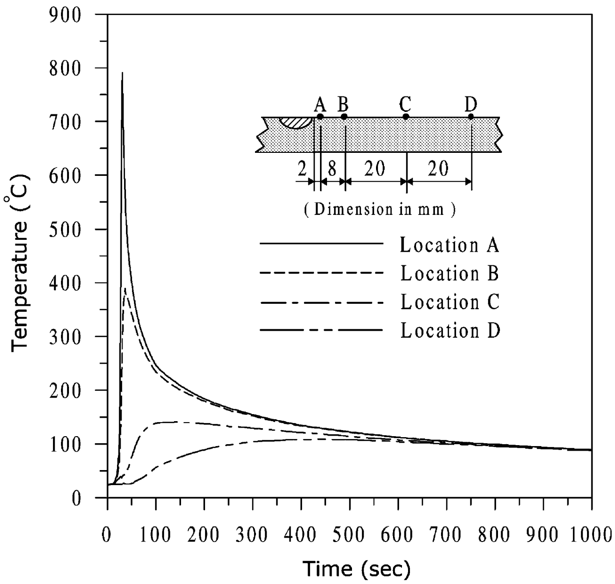

Fig. 14. Thermal cycles at various locations for CCW.

3.7. Study on the tensile residual stress zone in the weldment

Fig. 13 shows the distribution of residual stresses in a weldment of 304 stainless steel during various GTA welding processes. The experimental result shows that the CCW process has a greater range of the tensile residual stress zone as compared to that of the PCW process. The welding thermal cycle during the GTA welding process was recorded to analyze the results in this study. The thermal cycles at various locations for the CCW and PCW processes are shown in Figs. 14 and 15, respectively. Comparing the thermal cycles between the CCW and PCW processes, it is found that the thermal cycle of the CCW process has a greater peak temperature and temperature-history area than that of the PCW process. In other words, the CCW provides a greater amount of heat input into the weldment than that of PCW. According to the studies by Masubuchi [18], a linear heat input is the most significant factor affecting the range of the tensile residual stress zone, which increases with an increasing amount of heat input. Therefore, a smaller range of the tensile residual stress zone in the weldment can be obtained by using the pulsed GTA welding process.

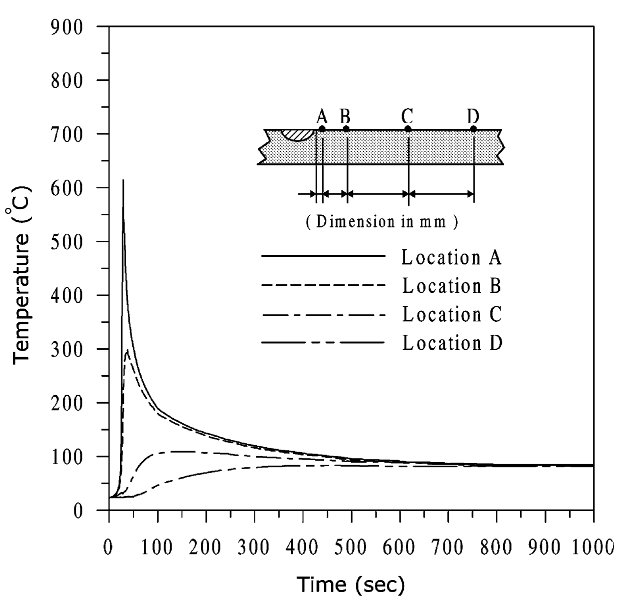

Fig. 15. Thermal cycles at various locations for PCW.

Further, based on experimental observations (as shown in Fig. 13), it was found that the welding residual stresses were tensile near to the weld and compressive away from the weld. In stainless steel weldments, the maximum tensile residual stress usually approaches the yield stress of the base metal.

4. Conclusions

1. In pulsed GTA welding, the greater pulse frequency can enhance the concentration of energy density on the heat source. Therefore, the residual stress of an austenitic stainless steel weldment can be reduced.
2. A larger pulse spacing can induce less heat input, therefore the residual stress of the weldment can be reduced.
3. A greater amplitude ratio can reduce the temperature difference between the fusion zone and the unaffected base metal in the weldment and therefore the welding residual stress can be reduced.
4. A smaller welding residual stress can be obtained by using a greater duration ratio in the pulsed GTA welding process.
5. Since 310 stainless steel has a lower thermal conductivity and thermal diffusivity, a greater temperature gradient and a higher peak temperature of the thermal cycle can be obtained during the welding process, as compared to that for 304 stainless steel. Therefore, the residual stress of a 310 stainless steel weldment is greater than that of a 304 stainless steel weldment.
6. The PCW condition has a smaller range of the tensile residual stress zone as compared to that for the CCW condition because of its lesser amount of heat input.

References

[1] W. Troyer, M. Tomsic, R. Barhorst, Weld. J. 56 (1) (1977) 26–32.
[2] D.W. Becker, C.M. Adams, Weld. J. 58 (5) (1979) 143s–152s.
[3] D.W. Becker, C.M. Adams, Weld. J. 57 (5) (1978) 134s–138s.
[4] A.A. Omar, C.D. Lundin, Weld. J. 58 (4) (1979) 97s–104s.
[5] C.F. Tseng, W.F. Savage, Weld. J. 50 (11) (1971) 777–786.
[6] Y. Sharir, J. Pelleg, A. Grill, Met. Technol. 5 (6) (1978) 190–196.
[7] C.L. Tsai, C.A. Hou, J. Heat Transfer 110 (1988) 160–165.
[8] H. Kihara, K. Masubuchi, Weld. J. 38 (4) (1959) 159s–168s.
[9] K. Masubuchi, D.C. Martin, Weld. J. 40 (12) (1961) 553s–563s.
[10] R. Robelotto, J.M. Lambase, A. Toy, Weld. J. 47 (7) (1968) 289s–298s.

[11] T. Toyooka, T. Tsunenari, R. Ide, T. Tange, Weld. J. 64 (1) (1985) 29s–36s.

[12] S. Rajasekaran, S.D. Kulkarni, U.D. Mallya, R.C. Chaturvedi, Weld. J. 77 (6) (1998) 254s–269s.

[13] A.J.R. Aendenroomer, G. den Ouden, Weld. J. 77 (5) (1998) 181s–187s.

[14] R.E. Leitner, G.H. McElhinney, E.L. Pruitt, Weld. J. 52 (9) (1973) 405s–410s.

[15] G.M. Reddy, A.A. Gokhale, K. Prasad Rao, Mater. Sci. Technol. 14 (1) (1998) 61–66.

[16] D.E. Powers, R.F. Duhamel, P. Anthony, D.A. Belforte, K.W. Carlson, L.S. Derose, D. Elza, D. Gustaferri, A. Lingenfelter, R.W. Walker, in: R.L. O'Brien (Ed.), Welding Handbook, Vol. 2, 8th Edition, American Welding Society, Miami, 1991, pp. 714–738.

[17] H.B. Cary, Modern Welding Technology, 4th Edition, Prentice-Hall, Englewood Cliffs, NJ, 1998, pp. 237–264.

[18] K. Masubuchi, Analysis of Welded Structures, 1st Edition, Pergamon Press, Oxford, 1980, pp. 60–87.

[19] Y.C. Lin, K.H. Lee, J. Mater. Process. Technol. 63 (1997) 797–801.

[20] Y.C. Lin, J.Y. Perng, Sci. Technol. Weld. Joining 2 (3) (1997) 129–132.

[21] Y.C. Lin, K.H. Lee, Int. J. Pres. Ves. Piping 71 (1997) 197–202.