Memoirs of Fukui University of Technology, Vol. 28, Part 1, 1998

Penetration of Stainless Steel TIG Weld and a Method to Evaluate It

Kiichi Saito*

[SYNOPSIS]

Penetration of TIG weld has been discussed so far using the ratio of penetration depth (d) to bead width (W), i.e. (d/W), as an index. However, the ratio (d/W) differs according to heat input (Q) and varies widely, and this is disadvantageous in that it is difficult to estimate size of melting (Melting area; S_B) from the ratio (d/W). In the present study, it was attempted to turn the ratio (d/W) and the value (S_B) to specific values based on the relationship between (d) or (W) and (Q) in mathematical expression, and to find a method to evaluate the penetration using the specific values as indices. The present evaluation method was applied to study the influence of the shielding gas on the penetration of stainless steel TIG weld.

I. INTRODUCTION

Penetration of TIG weld is closely related to heat transport property, which is attributed to fluid flow in molten pool. As the causes to induce the fluidity in the molten pool, the factors such as (1) electromagnetic force, (2) buoyancy, (3) surface tension, and (4) plasma stream are taken into consideration[(1)-(6)], and among these factors, surface tension is regarded as the most dominant[(7)]. The same phenomenon is observed in case of stainless steel.

Heiple et al. already reported on penetration of high Cr-Ni stainless steel[(8)] and demonstrated that surface active elements such as oxygen or sulfur exert extensive action on shape of penetration even when these are present in small quantity and give extreme influence on the penetration. However, the ratio (d/W), i.e. the ratio of penetration depth (d) to bead width (W), used as an index in the evaluation of penetration is a function of welding heat input (Q) and hence it varies according to the value of (Q). As in the example shown in Figure 1, the ratio (d/W) is very rarely reported in relation with the value (Q) regardless of the fact that the ratio (d/W) varies widely. Such circumstances make it considerably difficult to hold the data in common or to accurately identify the phenomenon. The use of the ratio (d/W) is also disadvantageous in that the "scale of melting" such as melting area (S_B) in not taken into account. If the index such as the ratio (d/W) could be expressed as a specific value peculiar to the material to be welded or welding enviroment without being influenced by the welding conditions, it would be very meaningful because it is helpful to accurately identify thepenetration and to more clearly identify and

* Department of Mechanical Engineering

understand the penetration phenomenon.

In this respect, we performed welding under various shielding gas conditions, which may exert influence on the values (d) and (W) of stainless steel TIG weld, and performed detailed study on the relationship between (d) and (W) of the weld and also the melting area (S_B) and the value (Q). Further, we have attempted to determine how to express the ratio(d/W), which can be handled as an objective specific value, and have decided to propose a method to evaluete the penetration, whereby the scale of melting is also taken into consideration.

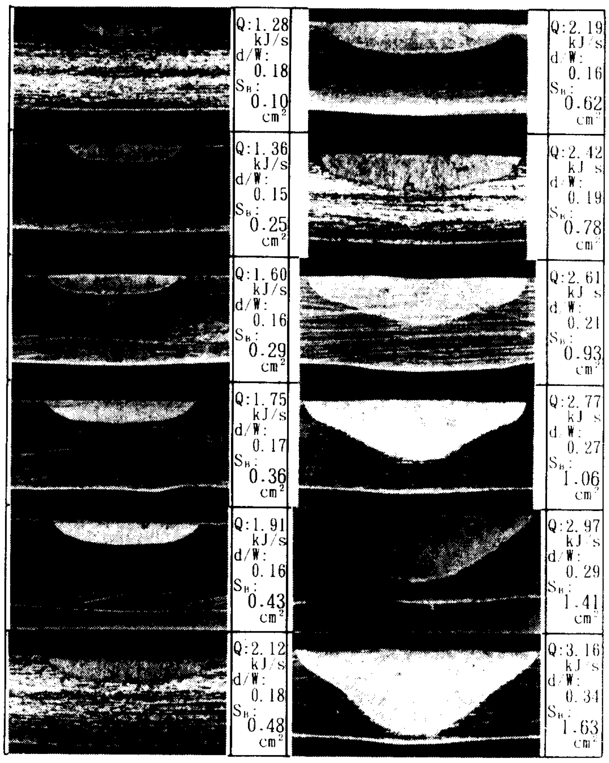

Figure 1 Relation between Heat Input (Q),(d/W) Ratio, Melting Area (S_B) and the Shape of Bead Section of Stainless Steel, welded by TIG Process.

II. EXPERIMENTAL PROCEDURE

In the present study, as parameters to give influence on the values (d) and (W) of stainless steel TIG weld, shielding gas was used. As the shielding gas, pure Ar and He or mixture of these gases as well as shielding gas obtained by blending Ar with H_2,N_2,O_2,etc. by 5 to 10 voi.% were used. On the base material of commercially available SUS 304(3.0 mm in thickness) having chemical composition as shown in Table 1, bead-on-plate welding was performed under the welding conditions shown in Table 2. After welding, the values (d) and (W) and melting area (S_B) were obtained from cross-section of bead. Then, the relationship between these values and heat input (Q) was analysed using least square method. Based on empirical formula, which was turned to mathematical expression, study was performed to fined out the method to obtain the ratio (d/W) as a specific value or to identify a practical method to evaluate penetration. Using the method as proposed here, we have attempted to evaluate the influence of the shielding gas on the penetration.

Table 1 Chemical Composition of SUS 304 Stainless Steel Used.

C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N
0.043	0.59	1.22	0.094	0.002	18.26	8.17	0.27	0.24	0.047

Table 2 Details of TIG Welding

Welding Current	80 A ~250 A
Welding Voltage	11.5 V ~ 13.5 V
Heat Input	0.9 kJ/s~ 3.5 kJ/s
Welding Speed	40 cm/min const.
Shielding Gas	Ar,He and their Mixture, $Ar-O_2$,$Ar-H_2$,$Ar-N_2$
Gas Consumption	10 ℓ/min const.
Arc Length	2.0 mm const.
Electrode Dia.	2.4 φmm Thoriated Tungusten
Gas Nozzle Dia.	10.0 φmm
Welding Position	Flat, Bead-on-Plate Welding
Material	3.0 mm thick.SUS 304 (2B)

Ⅲ. RESULTS OF EXPERIMENT AND DISCUSSION

(i) Relationship between (d) or (W) and (Q)

As an example of the results of the determination of the relationship of (d),(W)and (Q) by the method discussed in Ⅱ. above, Figure 2 shows the result of the experiment, in which vertex angle of electrode was welded at 30°, 60°,90° and 120° using pure Ar as the shielding gas. As it is evident from the example shown in Figure 2, the influence of vertex angle on the values (d) and (W) is not specifically clear, while it is apparent that the values of (d) or (W) and the value (Q) are in approximately linear relationship. If it is assumed that the values (d) and (W) indicate temperature distribution of the melting point of the weld due to the moving point heat source, this agrees well with the result of heat transfer analysis by three-dimentional moving point heat sourceas reported by Rosenthal et al [9]. who demonstrated that temperature distribution is proportional to heat input (Q). Then, it was assumed that the relationship between the values (d) or (W) and (Q) shown in Figure 2 can be expressed by linear equation, and data analysis by least square method was performed to obtain empirical formula. As a result, (d) = 0.66(Q) − 0.12 (correlation coefficient; r = 0.924), (W) = 1.91(Q) + 0.12 (correlation coefficient;r=0.980). This agree well with the solution of heat transfer analysis. As shown in Table 3, this trend is expressed by linear equation under the environmental condition of other shielding gas.

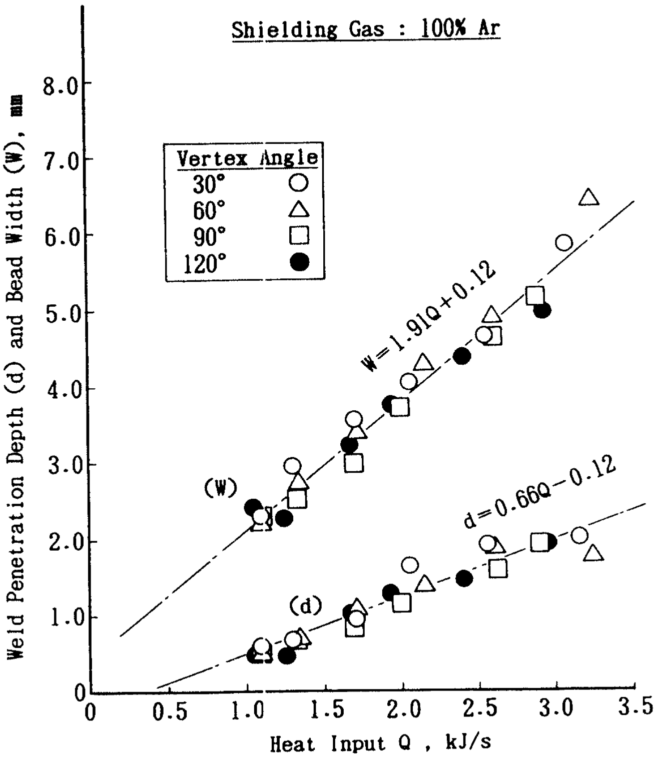

Figure 2 Relationship between Weld Penetration Depth (d) and Bead Width(W) vs. Heat Input (Q) of Stainless Steel, welded in 100% Argon as a Shielding Gas by TIG Process.

Table 3 Empirical Equation of Weld Penetration Depth (d),Bead Width (W) and Melting Area (S_B) on the TIG Welds, welded in Argon, Helium and thier Mixture as Shielding Gas.

Shielding Gas	(d) and (W)	(S_B)
100%Ar	d=0.66Q−0.12 (r=0.924) W=1.91Q+0.12 (r=0.980)	$S_B=Q^{1.86}\times e^{-0.42}$ (r=0.985)
25%He-75%Ar	d=0.32Q−0.076 (r=0.928) W=1.32Q+0.60 (r=0.951)	$S_B=Q^{2.06}\times e^{-0.0064}$ (r=0.994)
50%Ee-50%Ar	d=0.90Q−0.18 (r=0.971) W=2.05Q+0.23 (r=0.986)	$S_B=Q^{2.16}\times e^{-0.048}$ (r=0.983)
75%He-25%Ar	d=0.92Q−0.18 (r=0.951) W=1.80Q+0.71 (r=0.986)	$S_B=Q^{2.19}\times e^{-0.082}$ (r=0.995)
100%He	d=1.16Q−0.33 (r=0.975) W=2.16Q−0.061 (r=0.991)	$S_B=Q^{2.38}\times e^{0.015}$ (r=0.998)

*) r : Coefficient of Correlation

Therefor, the relationship between (d) or (W) and (Q) can be generally expressed by the equation (1) and (2):

$$(d) = a_1(Q) \pm b_1 \quad \cdots(1)$$

$$(W) = a_2(Q) \pm b_2 \quad \cdots(2)$$

Consequently, the ratio (d/W), used as an index for penetration, can be expressed by a rational function such as the equation (3), while the ratio (d/W) is still a function of (Q), and it cannot be treated as a specific value.

$$(d/W) = \{a_1(Q) \pm b_1\}/\{a_2(Q) \pm b_1\} \quad \cdots(3)$$

If, in the equation (1) and (2), the values (d) and (W) are rewritten as value per unit heat input shown as in the equation (4) and (5), a_1 and a_2 of the equation (1) and (2) are turned to asymptotic line of lim(d/Q) and (W/Q) when $Q \to \infty$.

$$(d/Q) = a_1 \pm (b_1/Q) \quad \cdots(4)$$

$$(W/Q) = a_2 \pm (b_2/Q) \quad \cdots(5)$$

$$\lim_{Q\to\infty}(d/Q)/\lim_{Q\to\infty}(W/Q) = (a_1/a_2) = (d/W) \quad \cdots(6)$$

Therefore, $\{\lim(d/Q)\}/\{\lim(W/Q)\} = (a_1/a_2)$. The ratio (d/W) thus obtained is turned to a value specific to the weld and can be treated as a specific value.

(ii) Relationship between (S_B) and (Q)

Similarly to Figure 2, Figure 3 shows the relationship between the melting area (S_B) of the stainless steel weld and (Q),using pure Ar as the shielding gas, and welding was performed with vertex angle of 30° to 120°. As seen in Figure 3, the value (S_B) tends to increase as exponential function with the increase of the value (Q). This trend is also seen on the weld, which is welded under the other shielding gas environment. In this respect, the value of (S_B) and (Q) in Figure 3 were turned to logarithm, and these two values were plotted using logarithmic scale. The results are as shown in Figure 4, and from this, it is evident that the relationship between $\ln(S_B)$ and $\ln(Q)$ can be expressed as approximately linear relation. Assuming that $\ln(S_B)$ and $\ln(Q)$ are in linear relation, analysis was performed by least square method. As a result, it was demonstrated that the result can be expressed by a linear equation:

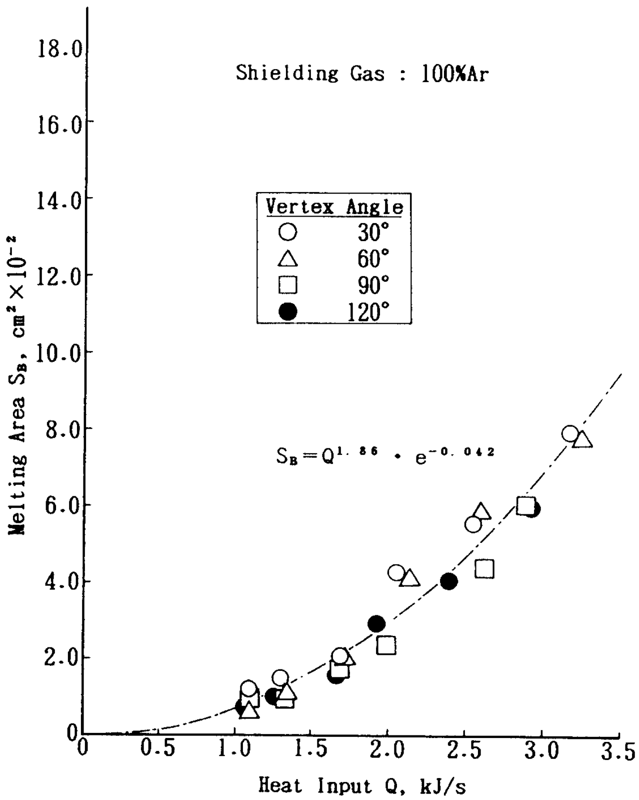

Figure 3 Relationship between Melting Area (S_B) and Heat Input (Q) of SUS 304 Stainless Steel, welded in 100% Argon as a Shielding Gas by TIG Process.

$$\ln(S_B) = 1.86\ln(Q) - 0.42$$

(correlation coefficient $r=0.985$)

The relationship between (S_B) and (Q) of Figure 3 can be expressed by exponential function:

$$(S_B) = (Q)^{1.86} \times e^{-0.42}.$$

Such results were also observed under the other shielding gas condition in very good correlation as shown in Table 3. Therefore, it can be generally said that the relationship between (S_B) and (Q) is expressed by the the equation (7) or (8).

$$(S_B) = (Q)^n \times e^{\pm c} \quad \cdots(7)$$

$$\ln(S_B) = n\ \ln(Q) \pm c \quad \cdots(8)$$

If the equation (8) is rewritten as the equation (9) in the same manner as in the equations (4) and (5), and if the value of $\lim \ln(S_B/Q)$ when $(Q)\to\infty$ is obtained, it is an asymptotic line (n) as given in the equation (10). The value (n) is a value specific to the penetration of the welding, and it can be handled as a specific value.

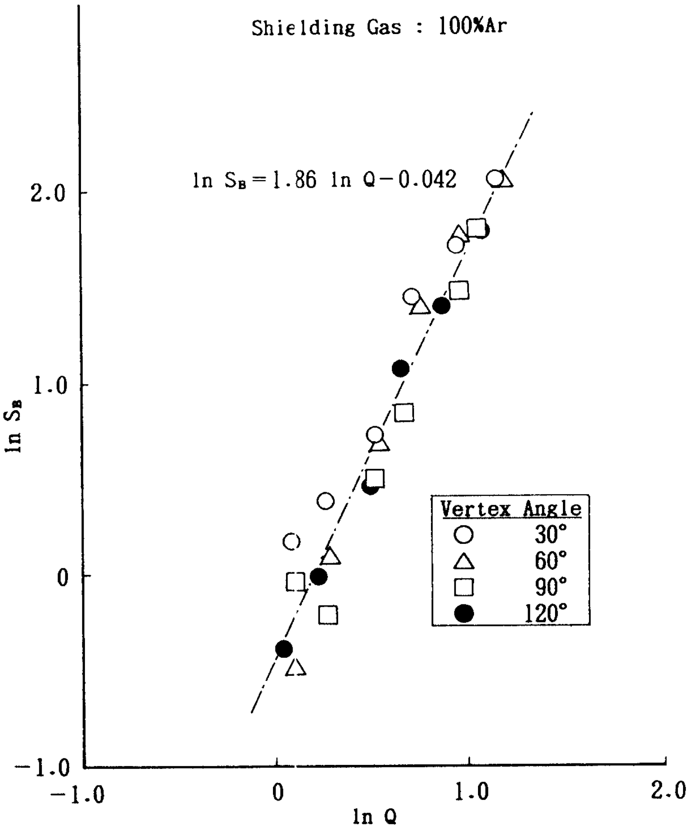

Figure 4 Logarithmic Plot of Relation between Melting Area (S_B) and Heat Input (Q) of Stainless Steel, welded by TIG Process using 100% Argon as a Shielding Gas.

$$\ln\{(S_B)/(Q)\} = (n) \pm \{c/\ln(Q)\} \quad \cdots(9)$$

$$\lim_{Q\to\infty} \ln\{(S_B)/(Q)\} = (n) \quad \cdots(10)$$

(iii) Method to evaluate penetration

When the ratio (d/W) and the melting area (S_B) are turned to specific values by the asymptotic line of the relational expression, the value (d/W) and the value (S_B) can be objectively handled, and the following evaluation method can be introduced using these values as indices for penetration.

1) Penetration : (P) value

As described above, the ratio (a_1/a_2) represents the ratio (d/W) and (n) represents the value (S_B). Accordingly, the product $(a_1/a_2) \times (n)$ can be used as an index (P) for penetration as given in the equation (11), in which the scale of penetration is taken into consideration.

$$(P) = (d/W) \times (S_B) = (a_1/a_2) \times (n) \quad \cdots(11)$$

2) Critical Heat Input : $(Q)_C$

Because the value (d) can be expressed by the equation (1), the critical heat input $(Q)_C$, by which complete penetration can be obtained up to plate thickness (t) by a single pass of welding, can be given by the equation (12). Because this value $(Q)_C$ is a value specific to the weld, it can be used as an index to evaluate the penetration.

$$(Q)_C = (t \pm b_1)/a_1 \quad \cdots(12)$$

3) Critical Melting Area : $(S_B)_C$

If the value (Q) obtained by the equation (12) is used as the value (Q) of the equation (7), the critical melting area $(S_B)_C$ of the equation (13) when the value $(Q)_C$ is given is turned to a value specific to the weld, and it can be used as an index to evaluate the penetration in the same manner as the value $(Q)_C$ of 2) above.

$$(S_B)_C = (Q)^n{}_C \times e^{\pm C} \quad \cdots(13)$$

(iv) Influence of shielding gas on penetration of stainless steel

Table 4 shows the result of evaluation, in which penetration of SUS 304 stainless steel is turned to specific value using various evaluation methods as described in III above when bead-on-plate welding is performed under various shielding gas conditions as given in II above. Figure 5 shows the result when the value (P) was expressed in bar graph as an example to explain the penetration. In any of these cases, the influence of shielding gas is very clearly evaluated despite of the fact that it could be compared only ambiguously because of very slight difference as the penetration in the past. It was confirmed that He gas is effective as shielding gas from the viewpoint of penetration. Even Ar gas blended with oxygen, which has beenemphasized as having good effect to improve the penetration is considerably inferior if compared with Ar gas blended with He gas.

Table 4 Proposals of the Method to evaluate TIG Weld Penetration of Stainless Steel Sheet and some Examples of the Result evaluated the Effect of various Shielding Gases.

Shielding Gas	d/W ($\fallingdotseq a_1/a_2$)	$\ln(S_B/Q)$ ($\fallingdotseq n$)	d/W × n	Heat Input required to penetrate 3.0mm thick. SUS 304 sheet, [$Q=(d\pm b_1)/a_1$], d=3.0mm, kJ/s	Melting Area estimated when penetration depth reached 3.0mm of sheet thickness, mm^2 [$S_B = Q^n \cdot e^c$]	Defference between Actual Melting Area and Melting Area*) estimated from thermal conduction theory for penetration depth of 3.0mm, mm^2
100%He	0.53	2.38	1.26	2.87	12.48	−1.66
75%He - 25%Ar	0.51	2.19	1.12	3.46	14.24	0.10
50%He - 50%Ar	0.44	2.16	0.95	3.53	14.53	0.39
25%He - 75%Ar	0.45	2.05	0.92	3.75	14.93	0.79
100%Ar	0.35	1.86	0.65	4.73	17.26	3.12
Ar - 5%H_2	0.31	1.61	0.50	3.44	18.16	4.02
Ar - 10%H_2	0.43	1.77	0.76	2.92	17.76	3.62
Ar - 5%O_2	0.47	1.56	0.73	5.04	19.95	5.81
Ar - 10%O_2	0.52	1.70	0.88	4.66	18.47	4.33
Ar - 5%N_2	0.22	2.04	0.45	4.59	31.15	17.01
Ar - 10%N_2	0.17	1.90	0.32	5.56	39.63	25.49

*) Melting Area estimated from thermal conduction theory: 14.14 mm^2

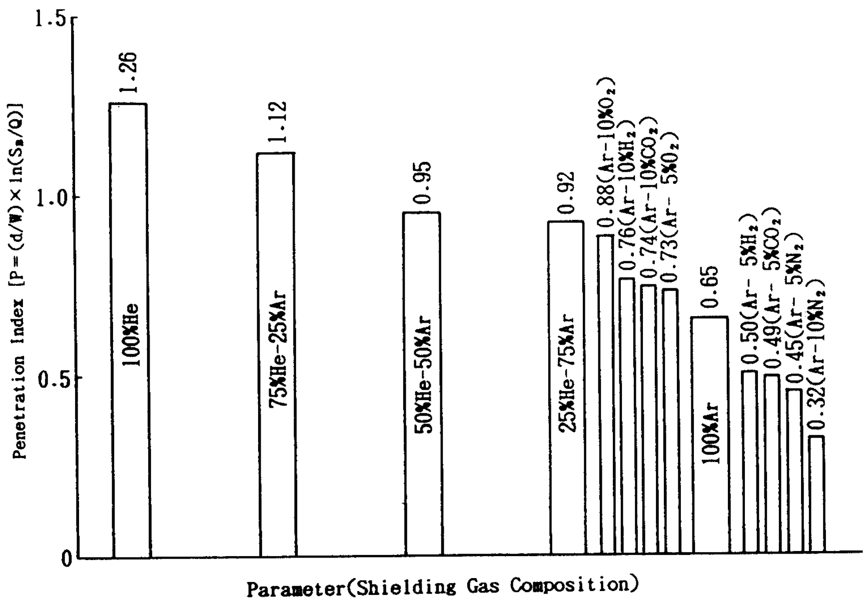

Figure 5 Examples expressed the Weld Penetration in Penetration Index (P) of SUS 304 Stainless Steel Sheet, welded by TIG Process using various Shielding Gases.

V CONCLUSION

To find out an objective method to obtain the ratio (d/W), i.e. the ratio of penetration depth(d) to bead width(W), which is an index for penetration of a weld, and also to identify a method to evaluate penetration, study was performed on TIG weld of SUS 304 stainless steel under various shielding gas conditions. As a result, it was found that clearly linear relationship exists between the values (d) or (W),and (Q), and also there is overt exponential relationship between the melting area (S_R) and (Q), and it was noted that the ratio (d/W) and the value (n) can be obtained as the values specific to the weld respectively. The results of the present study reveal that the method to evaluate penetration using these specific values provides good index in evaluating the penetration of weld.

REFERENCES

(1) W.F.Savage, E.F.Nippes, G.M.Goodwin;"Effect of Minor Elements on Fusion Zone Dimensions in Inconel 600", Welding J.,56(1977), 126s-132s.

(2) H.C.Ludwig ; "Current Density and Anode Spot Size in the Gas Tungsten Arc",Welding J., 47(1968),234s-240s.

(3) J.C.Metcalfe,M.B.C.Quigley ; "Arc and Pool Instability in GTA Welding",Welding J., 56(1977),133s-139s.

(4) S.S.Glickstein, W.Yeniscavich ; "A Review of Minor Element Effect on the Welding Arc and Weld Penetration",Welding Research Council Bulletin 226,May 1977.

(5) T.F.Chase, Jr. and W.F.Savage ; "Effect of Anode Composition on Tungsten Arc Characteristics",Welding J.,50(1971),467s-473s.

(6) S.S.Glickstein ; "Arc Modeling for Welding Analysis" Vol.1, ppl-16 in Arc Physics and Weld Pool Behavior, The Welding Institute, Cambridge,U.K.,1980.

(7) P.Burgardt,R.D.Campbell ; "Chemistry Effects on Stainless Steel Weld Penetration",Ferrous Alloy Weldment,Trans.Tech.Publications, Swizerland, 1992, 379-415.

(8) C.R.Heiple,P.Burgardt ; "Fluid Flow Phenomena during Welding", AMS Handbook, Vol.6 (1993),19-24.

(9) D.Rosenthal ; Mathematical Theory of Heat Distribution during Welding and Cutting,Welding J.,20(1941),22s-234s.

(Received December 2, 1997)