Transactions of the Japan Welding Society, Vol. 22, No. 1, April 1991

The Effect of Pressure on Mechanical Properties of Welded Joints*
—On Gravity Arc Welding under High Pressure Atmosphere—

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Abstract

The effect of ambient pressure on mechanical properties of mild steel welded joints obtained by the gravity arc welding process was investigated. Welding was executed by low hydrogen type electrode of 4 *mm in diameter under pressure range from* 0.1 *to* 5.1 *MPa(abs.). As base metals, SM41A steel plates of* 6 *and* 9 *mm in thickness were used.*

Main results obtained are summarized as follows:

1) *Charpy impact value of weld metal decreases considerably with an increasing pressure. The tensile strength and the elongation decrease somewhat and the average hardness increases slightly with it.*
2) *As the pressure increases, volume of pearlite in weld metal increases and the structure tends to be bainitic. The grain size of dendrite tends to decrease.*
3) *As the pressure increases, the content of diffusible hydrogen in deposited metal (H_D) increases up to about* 1 *MPa, but it tends to decrease over that pressure.*
4) *As the pressure increases, the contents of Si and Mn in weld metal decrease, but the contents of C and O increase considerably. The contents of P and S are approximately constant regardless of pressure.*
5) *As the ambient pressure increases, mechanical properties of weld metal deteriorate, because the contents of C, O and H in weld metal increase.*

Key Words: *High pressure, Gravity arc welding, Mechanical properties of welds, Low hydrogen type electrode, Chemical composition of weld metal, Diffusible hydrogen*

1. Introduction

As underwater "dry" welding process up to about 1.1 MPa, flux shield metal arc welding process (SMAW) has been often used for the construction or the repair of pipelines under the sea[1,2]. Authors have been trying application of the gravity arc welding process to the welding under the high pressure atmosphere up to 5.1 MPa, and already reported on the applicability of the welding process to the hyperbaric welding and the effect of pressure on the welding arc phenomena[3]. However, as pointed out by Christensen et al.[4,5], mechanical properties of welded joints have a tendency to decrease with an increasing pressure. Therefore effects of ambient pressure on mechanical properties of welded joints of mild steel plates were investigated, and besides the reason why the properties of welds change with the pressure was discussed.

2. Experimental Equipment and Materials

Welding was done in a pressure chamber. The pressure chamber has inner volume of 4000 cm^3 (4l) and can be pressurized up to 5.1 MPa (500 m depth under water). A small gravity arc welding equipment is situated in it. The D.C. electrical source of drooping characteristic was used and the polarity was electrode negative (DCEN). Welding was executed as follows. At first the chamber was evacuated up to 133 Pa (1 torr), and then was pressurized by argon gas up to a preset pressure. Then an arc was started by means of high frequency electrical source.

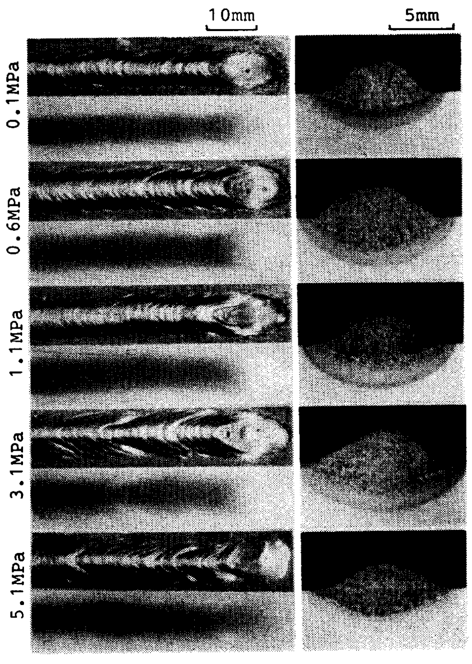

Fig. 1 Appearances, macro-structures and X-ray inspections of welds (D4316, I=150A)

As the electrode, low hydrogen type (D4316) electrodes of 4 mm in diameter were used. Before welding, the electrodes were dried in a furnace of 300°C for 1 hr.

As base metals, SM41A steel plates of 6 and 9 mm in thickness were used. Chemical compositions of base metals are shown in Table 1.

* Received 19 November 1990
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Table 1 Chemical compositions of base metals (%)

Thickness of base metal	C	Si	Mn	P	S	Ceq*
6 mm	0.12	0.22	0.73	0.012	0.004	0.25
9 mm	0.09	0.22	0.91	0.014	0.007	0.25

* Ceq = C + Mn/6 + Si/24 (%)

3. Experimental Results

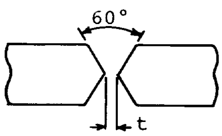
3.1 *Effect of pressure on welding result*

Fig. 1 shows the effect of ambient pressure on appearances, macro-structures and X-ray inspections of bead-on-plate welds obtained by low hydrogen type electrodes. Welding current was 150A. From the photographs, it is seen that sound welds without porosity or pits are obtained under the pressure up to 5.1 MPa.

Moreover, butt welding was executed in order to investigate the effect of pressure on mechanical properties of welded joints. As base metal, SM41A steel plates of 6 mm in thickness were used. Welding conditions for butt welding under several argon pressures are shown in Table 2. All butt welded joints in this report are obtained using the conditions shown in the table.

Table 2 Example of butt welding conditions

Ambient pressure (MPa)	Welding current (A)	Arc voltage (V)	Welding speed (cm/min)	Root gap t(mm)
0.1	160-170	27-32	20-23	1
0.5	165-180	26-30	20-24	1
1.1	180-190	26-30	20-24	1
2.1	180-200	28-32	21-24	1
3.1	190-210	26-33	22-24	1
4.1	195-210	27-35	23-24	1
5.1	195-210	26-35	23-25	1



Edge preparation

(A) 0.1MPa

(B) 3.1MPa

(C) 5.1MPa

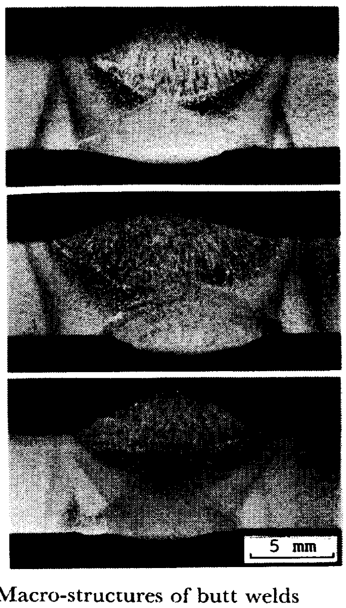


Fig. 2 Macro-structures of butt welds

Fig. 2 shows cross sectional macro-structures of butt welds obtained under 0.1, 3.1 and 5.1 MPa. From the figure, it is seen that sound welds without defects of undercut or lack of fusion were obtained under the pressure up to 5.1 MPa.

3.2 *Mechanical properties of welds*

Mechanical properties of butt welded joints of SM-41A mild steel plates obtained in the pressure range up to 5.1 MPa were investigated. Fig. 3 shows the results of tensile test with as-welded specimens. From the figure, it is seen that all specimens were fractured at base metal, and it is confirmed that the welded joints have adequate tensile strength.

Moreover, in order to investigate the effect of ambient pressure on mechanical properties of weld metal, V-notched tensile test specimens illustrated in Fig. 4 were made, and submitted to tensile test. Fig. 4 shows the result of the tensile test in log-log scale. From the figure, it is seen that all specimens have tensile strength of more than that of base metal of 525 MPa, and accordingly the welded joints have no problems for practical use. However, both tensile strength and elongation tend to decrease with an increasing pressure. For example, the tensile strength of weld metal at 0.1 MPa is 610 MPa, and on the contrary, that at 5.1 MPa is 565 MPa. The latter is

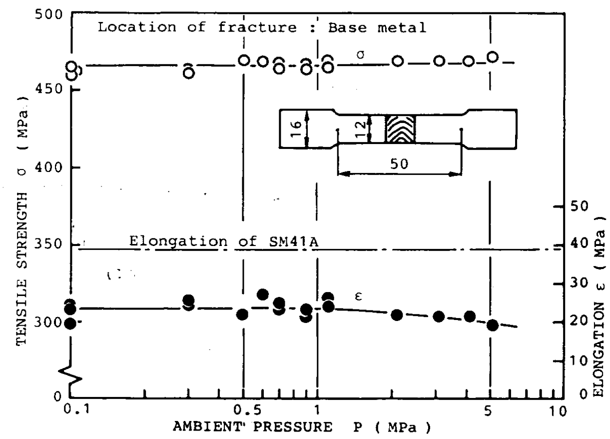


Fig. 3 Result of tensile test of welded joints

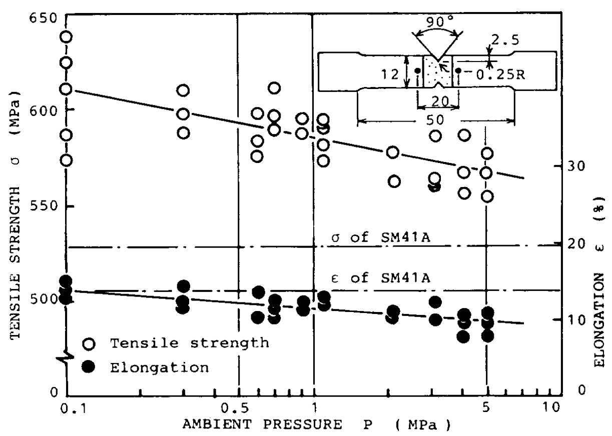


Fig. 4 Effect of ambient pressure on result of tensile test of weld metal

lower by 9% than the former. Moreover, the elongation also decreases from 12.5% to 9%.

Fig. 5 shows the effect of pressure on the result of Charpy impact test of weld metal. As the specimen, V-notched specimens illustrated in Fig. 5 were used. The impact value Ev is shown by the absorbed energy per unit cross-section. Although the impact value is 185 J/cm^2 under atmospheric pressure, it decreases linearly in log-log scale with an increasing pressure. At 5.1 MPa it is about 85 J/cm^2. The latter is about 46% of the former.

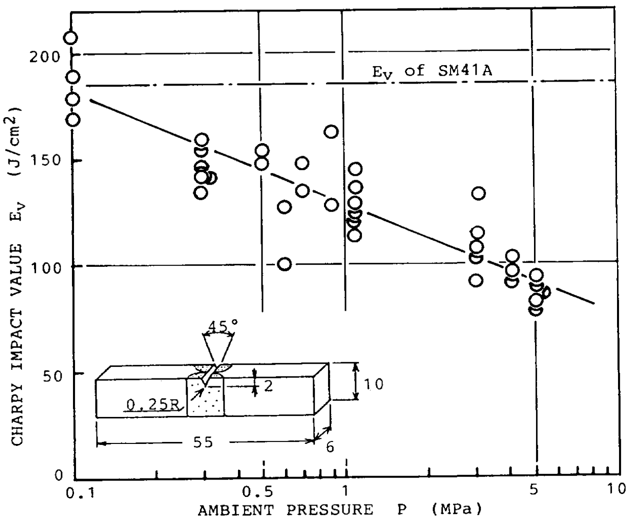


Fig. 5 Effect of ambient pressure on result of Charpy impact test

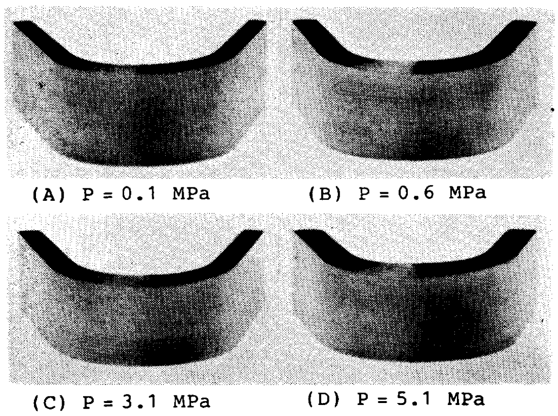


Fig. 6 Results of bending tests

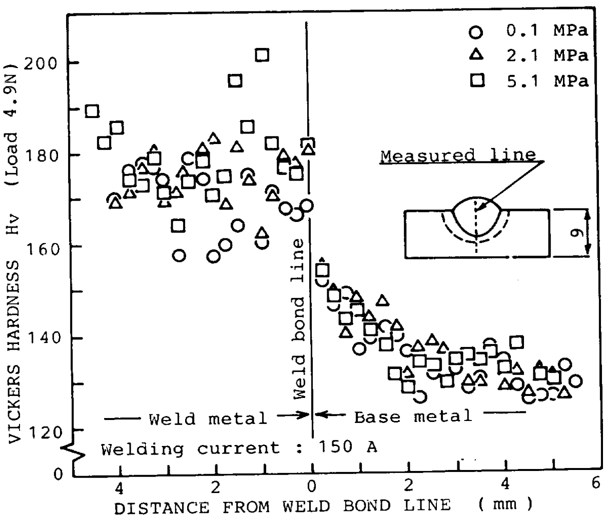


Fig. 7 Effect of ambient pressure on hardness distribution of weld

Fig. 6 shows appearances of specimens just after the bending tests. In the photographs, no cracks are observed on the surface of weld, and accordingly it is seen that the weld has adequate bending ductility.

Fig. 7 shows the effect of pressure on the micro-Vickers hardness (load: 4.9N) distributions on the cross-section of bead-on-plate welds obtained under pressures of 0.1, 2.1 and 5.1 MPa. As base metal, SM41A steel plate of 9 mm in thickness is used. The hardness of weld metal has a tendency to increase somewhat with an increasing pressure. For example, calculating the average hardness of weld metal, Hv 167, Hv 175 and Hv 182 are obtained for each specimen.

3.3 *Micro-structures of weld metal*

Fig. 8(A)-(D) show micro-structures of bead-on-plate weld metal obtained under 0.1, 0.6, 3.1 and 5.1 MPa in 150 A. As the etchant, 2%Nital was used. From the photographs, it is seen that the pearlite structure and lath structure increase and the structure becomes bainitic with an increasing pressure. The change of the structure agrees with the increasing tendency of hardness of weld metal. Moreover, the grain size of the structure seems to decrease with the pressure. The reason is not yet made clear, but the same result is already reported in hyperbaric CO_2 welding[6].

3.4 *Fractography*

Fracture surfaces of V-notched tensile test specimens and Charpy impact test specimens are observed under

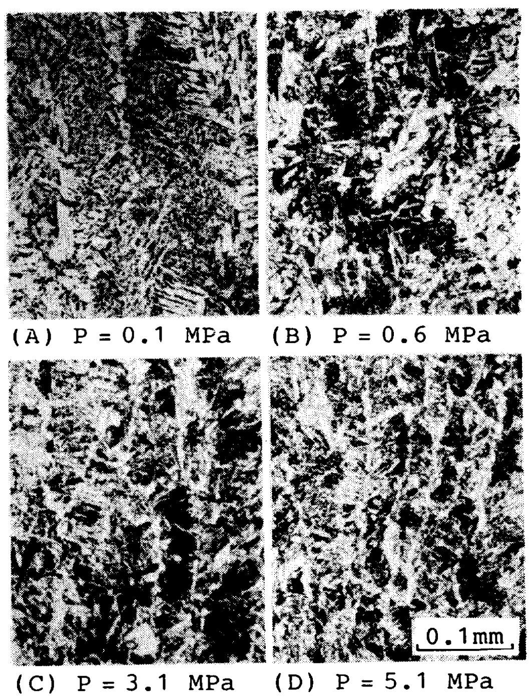


Fig. 8 Micro-structures of weld metals

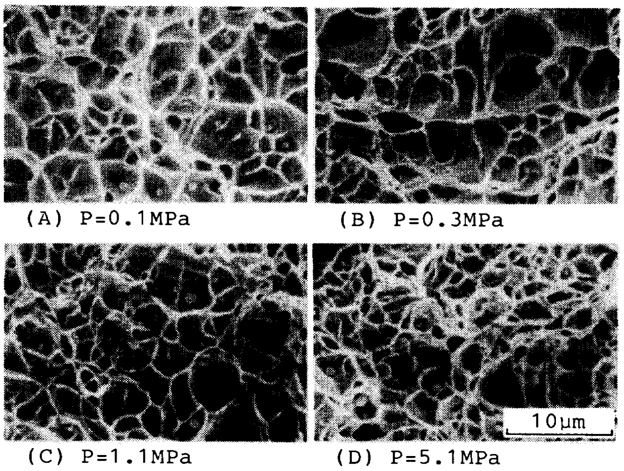


Fig. 9 Scanning electron micrographs of fractured surface (tensile test specimen)

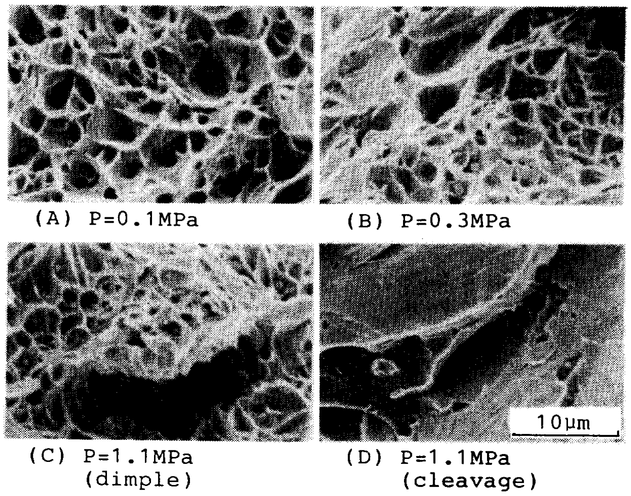


Fig. 10 Scanning electron micrographs of fractured surface (Charpy impact test specimen)

a scanning electron microscope. Fig. 9 (A)-(D) show tensile fracture surfaces and Fig. 10 (A)-(D) impact fracture surfaces. In tensile test specimens, every fracture surface shows a dimple pattern, and the diameter of the dimple decreases somewhat with an increasing pressure due to a decrease of size in non-metallic compounds. In impact test specimens, the fracture surface shows almost dimple pattern, but under the pressure over 1.1 MPa cleavage fracture was sometimes observed.

3.5 *Diffusible hydrogen*

The effect of pressure on diffusible hydrogen content of weld was measured. The measurement was done as follows: Welding was executed in the pressure tank. After the welding, the specimen was taken out and thrown into iced water at 60s after the welding. The specimen cooled was washed with alchohol and acetone, and was dried. Then it was set in the measuring apparatus. It took about 150s after the welding. Measurement was done by the mercury method (IIW method). The trap time is 500 hr and the content of hydrogen is shown by volume of hydrogen per 100 g

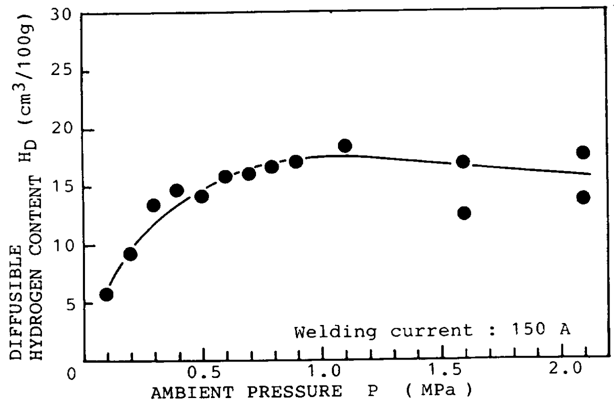


Fig. 11 Effect of ambient pressure on diffusible hydrogen content in weld metal

weld metal in NTP condition, H_D. Fig. 11 shows the effect of pressure on diffusible hydrogen content. At 0.1 MPa, the content is about 6 $cm^3/100$ g. But it increases with an increasing pressure and amounts to about 18 $cm^3/100$ g at 1.1 MPa. Under the pressure higher than 1.1 MPa, the diffusible hydrogen content tends to decrease somewhat.

3.6 *Chemical compositions of weld metal*

Fig. 12 and Fig. 13 show the effect of pressure on chemical compositions of weld metal obtained by bead-on-plate welding with the current of 150 A. From these figures, although the pressure has no effect on the contents of S and P, the contents of Mn and Si are seen to decrease with the pressure. On the other hand, the contents of C and O increase remarkably with an increasing pressure.

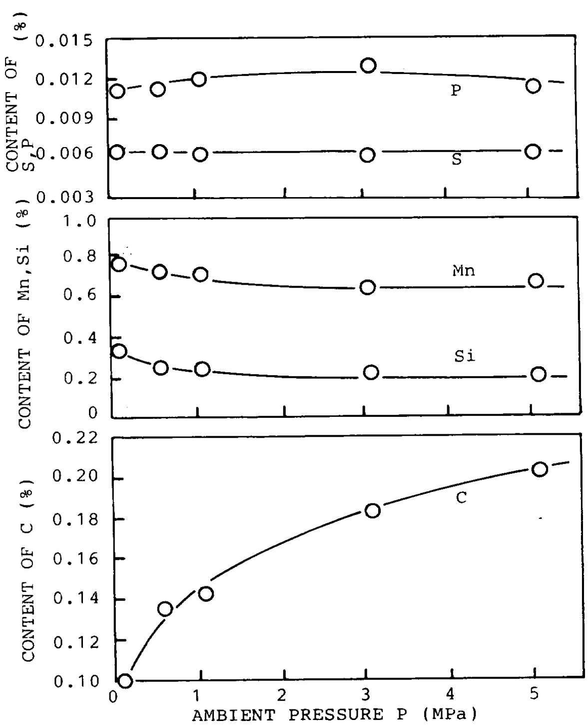


Fig. 12 Effect of ambient pressure on chemical composition of weld metal

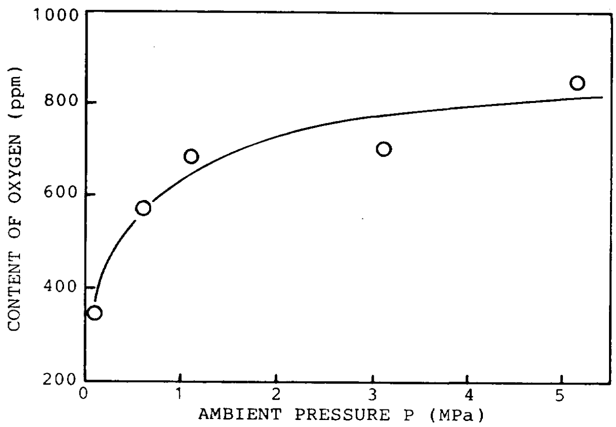


Fig. 13 Effect of ambient pressure on content of oxygen in weld metal

4. Discussion

As stated above, it was made clear that the tensile strength and impact value of weld metal decrease and hardness increases somewhat with the pressure. And the structure of weld metal turns bainitic somewhat with the pressure and diffusible hydrogen content increases remarkably up to 1.1 MPa. Moreover, Si and Mn decrease somewhat and C and O increase with the pressure. Summarizing these results obtained, it is surmised that the behaviors of C, O and H in hyperbaric welding have important effects on the properties of weld metals.

The arc atmosphere consists of O_2, O, CO_2, CO, H_2, H and so on which are generated mainly from flux coating or surrounding gas. A part of them dissolves into the melting metal directly from the surface of weld pool or indirectly from droplet of fused electrode. The gases dissolved diffuse in the melting metal and react with some elements or slag. Generally, it is known that the quantity of gas dissolving into metal increases with an increasing partial pressure. Accordingly, assuming that the gas composition in arc atmosphere is constant, the quantity of gas dissolved should increase. However, because Ar gas was used as the atmosphere, the supply sources of O, CO, H and so on were limited to electrodes, base metal, moisture or contamination on the surface of base metal. Accordingly the volume of these gases may decrease with the pressure, and Ar gas flowing into arc atmosphere increases with the pressure. Therefore an increase of the partial pressure of those gases will be prevented. Moreover, as shown by the Le chatorie law, dissociation of gas becomes more difficult under higher pressure, and accordingly dissolution of gas into the melting metal may be prevented somewhat. Consequently, the increasing rate of dissolution or quantity of dissolution might decrease with an increasing pressure. For example, although the diffusible hydrogen increases with the pressure up to 1.1 MPa, it decreases somewhat over that pressure. The phenomenon may be explained by means of this discussion. However, it might occur by means of an increase of O in weld metal. Regarding this phenomenon, precise discussion should be made further.

Oxygen dissolved into melting metal reacts with Fe by

$$Fe + O \rightleftharpoons FeO \quad (1)$$

and with Mn and Si by

$$FeO + Mn \rightleftharpoons Fe + MnO \quad (2)$$

$$2FeO + Si \rightleftharpoons 2Fe + SiO_2 \quad (3)$$

and some oxides are produced.

As the pressure increases, quantity of O increases and Mn and Si tend to react easily with O. Accordingly the reaction to the right in equations of (2) and (3) will be promoted and then the resultant oxides will be excluded out of melting metal as slag. Therefore Mn and Si contents in weld metal decrease with the pressure.

Oxygen in the melting metal reacts also with carbon and generates CO by

$$FeO + C \rightleftharpoons Fe + CO \quad (4)$$

However, as the pressure increases, standard generation free energy of CO, dG, increases, and accordingly the reaction to the right in equation (4) is prevented. That is to say, generation of CO gas in molten metal may be prevented. Moreover, under higher pressure, the reaction to the left in equation (4) might occur as follows. That is to say, CO gas generated from $CaCO_3$ and so on involved in flux coating dissolves into the molten metal, and a part of CO reacts with Fe and generates FeO and C. As the result, C and O contents in weld metal increase with an increasing pressure. For example, the fact that C content in weld metal obtained at 5.1 MPa is much higher than that of base metal can be explained by means of the process stated above.

As discussed above, C and O contents increase with the pressure. As C increases, the micro-structure in weld metal changes and carbon equivalent for hardness C_{eq} increases. As the result, hardness and brittleness of weld metal increase. On the other hand, it is reported that O content in weld metal affects the impact value[7], and accordingly an increase of O with the pressure results in an decrease of the impact value as in Fig. 5. On the other hand, the diffusible hydrogen increases with the pressure, and accordingly it may result in a decrease of tensile strength[8]. Consequently, the change in mechanical properties of the weld metal with an increasing pressure occurs due to an increase of carbon, oxygen and hydrogen. The individual effects of C, O and H on the mechanical properties are not yet made clear.

5. Conclusions

The effect of ambient pressure on mechanical properties of mild steel welded joints obtained by the gravity arc welding process was investigated. Welding was executed with low hydrogen type electrode of 4 mm in diameter in pressure range from 0.1 to 5.1 MPa (abs.). As base metals, SM41A steel plates of 6 and 9 mm in thickness were used.

Main results obtained are summarized as follows:
1) Charpy impact value of weld metal decreases considerably with an increasing pressure. The tensile strength and the elongation decrease somewhat and the average hardness increases slightly with it.
2) As the pressure increases, volume of pearlite in weld metal increases and the structure tends to be bainitic. The grain size of dendrite tends to decrease.
3) As the pressure increases, the content of diffusible hydrogen in deposited metal (H_D) increases up to about 1 MPa, but it tends to decrease over that pressure.
4) As the pressure increases, the contents of Si and Mn in weld metal decrease, but the contents of C and O increase considerably. The contents of P and S are approximately constant regardless of pressure.
5) As the ambient pressure increases, mechanical properties of weld metal decrease, because the contents of C, O and H in weld metal increase.

The authors wish to express their thanks to Mr. T. Ashizawa (Keio Univ., now at Sin Caterpillar Mitsubishi Ltd.), T. Kikuchi (Keio Univ. now at Kao Corp.) and Mr. M. Miki (Keio Univ., now at Nichimen Co.) for their assistance in experimental works.

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