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CAUSE OF POROSITY IN WELD METAL BY A LOW-HYDROGEN ELECTRODE

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Abstract

This study aims to clarify the reason why a low-hydrogen lime type electrode is sensitive to hydrogen porosity of weld metal in spite of its low diffusible hydrogen content. Metal transfer, viscosity of molten slag, and the difference of features of hydrogen bubbles through molten slag are studied by various kinds of electrode fluxes dried or moistened. As a result, it is deduced that oversaturated gaseous bubbles form more easily and continuously in molten metal under molten low-hydrogen slag than under molten ilmenite slag and, in the latter cases, a large amount of oversaturated gas is generated just after solidification of molten metal.

1. Introduction

In the author's previous reports[1,2] it has been clarified that the main cause of porosity in weld metal by a dried low-hydrogen lime type electrode can be ascribed to insufficient protective action of this type of flux.

Therefore, a moistened low-hydrogen lime type electrode was apt to produce porosity due to hydrogen in weld metal, even though its diffusible hydrogen content was much lower than that of other types of electrodes, as described in the previous reports.[3,4] Many studies were reported concerning weld metal porosity. These studies were mainly related to the chemical behavior of molten pool and slag; however, porosity in weld metal should be influenced by not only chemical behavior but also the physical properties of molten slag, for instance the difficulty of gas rising through molten slag. In addition, the difference of features of hydrogen bubbles through molten slags was studied by various electrode fluxes, mainly ilmenite and low-hydrogen types. Metal transfer was observed by high speed camera, and the viscosity of the molten slags was measured.

2. Experimental method

2. 1. *Materials and equipment*

Mild steel of 6 or 12mm thick plate was used as the base metal. There were six kinds of covered electrodes (4mm diameter) used in this experiment for mild steel i.e. ilmenite (D 4301), lime-titania (D 4303), high cellulose (D 4311), high titanium oxide (D 4313), low-hydrogen (D 4316) and iron-powder iron oxide (D 4327). Immediately after these covered electrodes were dried, they were moistened in a box saturated with water vapor. The amount of water absorbed by the covered electrode was calculated by the following equation.

$$\text{Absorbed water content of covered electrode} = [(w_m - w_d)/(w_d - w_c)] \times 100\,[\text{wt.}\%]$$

where, w_m : weight of the covered electrode after being moistened
w_d : weight of the covered electrode after being dried
w_c : weight of the core wire

An A.C. arc welding transformer of 500A capacity was used as the power source, and welding was performed by a gravity welding device. The core wire and fluxes of the covered electrode were melted in a tammann crucible by a high frequency furnace in a hydrogen atmosphere and gaseous bubbling and solidification features were observed. The experimental set up is shown in Fig. 1. The bucket of flux at the upper part of this figure is used to add flux after the melting down of the core wire. The chemical analyses of the base metals and core wire were given in Table 1.

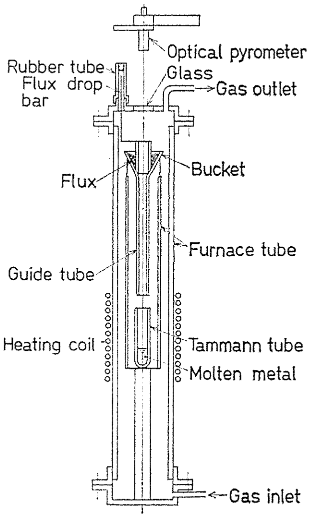


Fig. 1. Design of the furnace used in the experiment.

Table 1. Chemical compositions of base metals and core wire.

Materials		Thickness of plate or diameter of core wire, mm	Elements, wt. %				
			C	Si	Mn	P	S
Base metals (SS 41)	A	6	0.17	0.04	0.86	0.012	0.029
	B	12	0.14	0.20	0.61	0.019	0.020
Core wire of low-hydrogen electrode for mild steel		4	0.08	0.004	0.46	0.004	0.013

2. 2. *Observation of molten pool and measurement of viscosity of molten slag*

A mild steel specimen of 6×50×150mm, whose chemical composition is shown as the symbol A in Table 1, was used as the base metal. When bead welding was made by the above mentioned six kinds of moistened and dried covered electrodes under conditions of 135～185A welding current and 200～260mm/min welding speed, features of molten pool were observed in detail by high speed camera with 2160 frames/sec.

Next, solidified slags were transferred to measure the viscosity of the molten slag. The measurement of viscosity was carried out by using a balance as shown in Fig. 2, in which a platinum ball was suspended by platinum wire in the molten slag. The velocity of the platinum ball in the molten slag was measured by loading additional weight on the balance and the viscosity of the molten slag was calculated by Endell-Wagenmann's equation.[5]

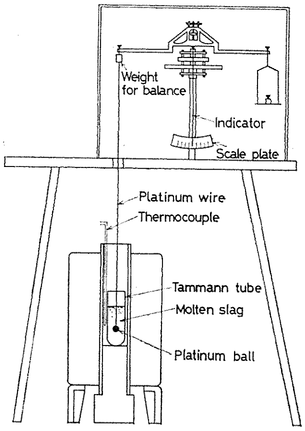


Fig. 2. Measuring apparatus for viscosity of molten slag.

$$\text{Viscosity } \eta = p \cdot 981/v[6\pi r(1+2.4r/R_2)(1+3.1r/l) + 2\pi L\ \mathrm{l_n}(R_2/R_1)]\ [\text{poise}]$$

where, p : weight of loading (g)
r : radius of platinum ball (cm)
R_1 : radius of platinum wire (cm)
R_2 : radius of tammann crucible (cm)
l : height of molten slag (cm)
L : length of platinum wire in molten slag (cm)
v : transferred velocity in molten slag of platinum ball (cm/sec)

2. 3. *Effect of types of flux on generating hydrogen from molten metal*

The difference of features of hydrogen bubbles through molten slag was studied by mainly two types of electrode fluxes, i.e. ilmenite and low-hydrogen lime types. The core wire of the covered electrode was melted in a hydrogen atmosphere in a tammann crucible by a high frequency induction furnace. Immediately after it was completely melted down, each flux was added to the molten metal saturated with hydrogen. The molten slag surface, through which hydrogen bubbles of molten metal were rising, was continuously photographed by cinecamera during the solidification period. The solidified metal under each slag was quenched in water immediately after solidification, and its diffusible hydrogen content was determined. Relative porosity of solidified metal was determined by the following equation:

$$\text{Relative porosity} = (1-\rho/\rho_0)\times 100\ [\%]$$

where, ρ_0 : specific gravity of core wire $=7.849$
ρ : specific gravity of solidified metal

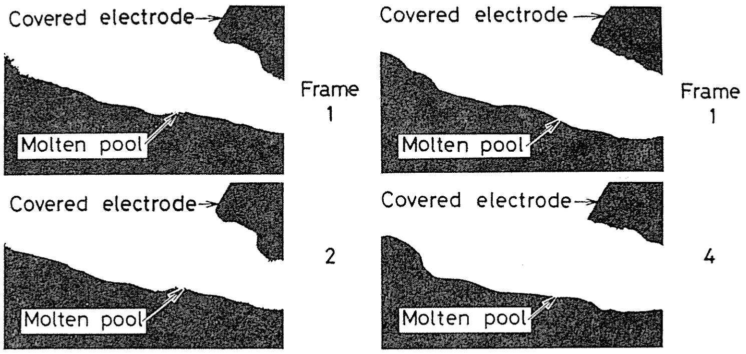
2. 4. Effect of amount of flux on the escape of hydrogen from molten metal

A mild steel specimen of 12×50×150mm of which the chemical composition is shown as symbol B in Table 1, was used in this experiment, and a U groove (6 mm depth with a root radius of 5mm) was prepared. 1~6 g of ilmenite or low-hydrogen flux was put in the groove per 13cm length of bead, and bead welding was done with the same type of covered electrode as the added flux under the following conditions: 170A welding current and 150~200mm/min welding speed. Solidified slags were observed in detail, and an X-ray photograph of the weld was taken.

3. **Experimental results**

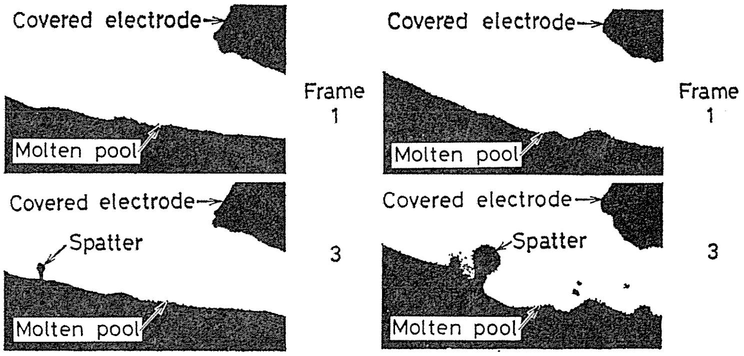
3. 1. Observation of molten pool

Photos 1 and 2 show high speed photographs of molten pools by low-hydrogen and iron-powder iron oxide electrodes, respectively. (a) of both photos is by dried



(a) Dried (b) Absorbed water content: 7.0%

Photo. 1. Molten pools by dried and moistened low-hydrogen electrode (2160 frames/sec).



(a) Dried (b) Absorbed water content: 3.0%

Photo. 2. Molten pools by dried and moistened iron-powder iron oxide electrode (2160 frames/sec).

electrode and (b) is by moistened electrode. The feature of molten pool by low-hydrogen electrode was quite different from that of iron-powder iron oxide. The surface of the former molten pool always had quiet waves, whereas rippling waves were observed in the case of the moistened low-hydrogen electrode. While, in the case of the other covered electrodes, blisters and explosive spatterings on the surface of the molten pool, as shown in Photo. 2, were often observed regardless of the dry or moist condition of the electrode. These blisters and spatterings were larger and more frequent with the moistened electrode than with the dried one. It was considered that the explosive spatterings with the release of gases from the molten metal was due to the high gaseous pressure between the molten metal and molten slag.

Furthermore, influence of the absorbed water content on the droplet transfer was hardly recognized in all cases of covered electrodes, and droplet transfer by significantly moistened covered electrodes was almost the same as that of the dried covered electrodes. Droplet transfer by low-hydrogen type electrodes was a globular one; the other types of electrodes were a mixture of both spray and globular transfer.

3. 2. Measurement of viscosity of molten slag

Fig. 3 shows the results of the measurement of the viscosity of molten slag with various covered electrodes, (a) were dried and (b) were moistened covered electrodes. The influence of absorbed water content on the viscosity of molten slag was hardly recognized for all types of covered electrodes. In addition, the viscosity of molten slag by dried and moistened types of covered electrodes at 1400°C was the smallest with the low-hydrogen electrode (4.1~4.3 poise). Ilmenite and lime-titania electrodes were next. The viscosity was largest with high cellulose, high titanium oxide and iron-powder iron oxide electrodes (7.2~8.4 poise). Furthermore, the rate of increase of viscosity of molten slag for a decrease in temperature was the smallest with the low-hydrogen electrode.

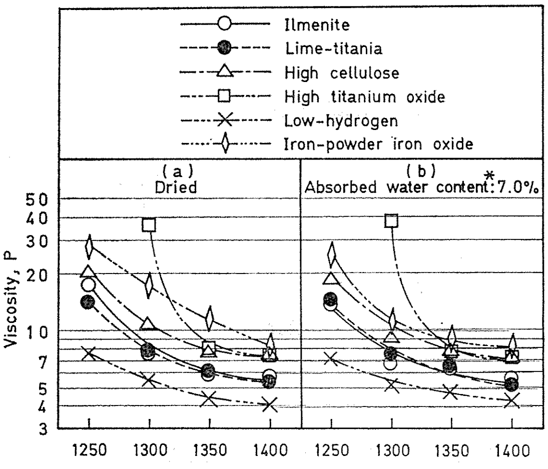


Fig. 3. Effect of temperature on viscosity of molten slags by dried and moistened various covered electrodes

note: *: absorbed water content of iron-powder iron oxide electrode: 3.0%.

3. 3. Effect of types of fluxes on the escape of hydrogen from molten metal

Table 2 shows the results of the diffusible hydrogen content or relative porosity (vol. %) of solidified metal which was formed under ilmenite or low-hydrogen molten slag in a hydrogen atmosphere.

Table 2. Diffusible hydrogen content and porosity of solidified metals under ilmenite and low-hydrogen fluxes.

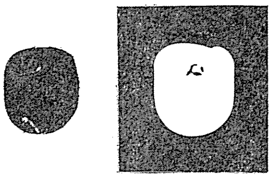
Types of fluxes	Diffusible hydrogen content, cc/100g metal	Porosity, vol. %
Ilmenite	9.9	0.76
	9.4	1.78
	8.3	0.51
	8.4	0.29
Low-hydrogen	7.5	2.52
	7.2	3.01
	6.3	4.65
	6.4	11.03

Note: Additional amount of dried flux: 6g

According to this table, though molten metal absorbed equal amounts of hydrogen, the diffusible hydrogen content of solidified metal which was covered by a low-hydrogen molten slag was about 6.3~7.5cc/100g. Its diffusible hydrogen was lower than that of ilmenite molten slag 8.3~9.9cc/100g, while the occurence of porosity of low-hydrogen molten slag was more remarkable. Then it was deduced that under low-hydrogen slag, gas was able to rise more easily and molten metal was apt to bubble before and during solidification.

Photo. 3 shows examples of X-ray photographs and macro-photographs of a section of these solidified metals. In solidified metals covered by low-hydrogen molten slag, as shown in (b), great porous areas were formed compared with the solidified metal covered by ilmenite molten slag.

Then, the surface of molten slag, through which hydrogen bubbles of molten metal escaped, was continuously photographed by cinecamera during the


(i) Radiograph (ii) Section
(a) Ilmenite flux

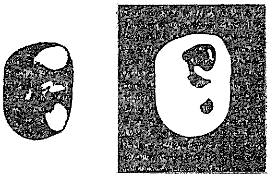

(i) Radiograph (ii) Section
(b) Low-hydrogen flux

Photo. 3. Radiographs and sections of solidified metals under ilmenite and low-hydrogen fluxes (additional amount of dried flux: 6g).

solidification period. Gas bubbles or blisters, which were observed on the molten slag surface, were remarkably different with different kinds of flux. In the case of low-hydrogen slag, several small bubbles were observed on the surface of molten slag after 17sec from the switch off of the furnace, and these bubbles vanished immediately. Cycles of generating and vanishing bubbles in the same place were very short. While in the case of ilmenite slag, bubbles on the surface of molten slag began to be observed after 38 sec from the switch off of the furnace and these bubbles almost became blisters. These blisters grew larger like a balloon and vanished explosively.

Time from the switch off of the furnace till solidification of the molten metal and slag was measured. Namely, the molten metal and slag was taken out of the tammann crucible under an argon atmosphere at various intervals of elapsed time from the switch off of the furnace, and the fluidity and solidification process of the molten metal and molten slag were observed. The result was that the difference of time after the switch off of the furnace until metal solidification was not determined by types of flux, and the time was always 28 sec. While, as for slag solidification, the time was 147 sec for low-hydrogen slag and 129 sec for ilmenite slag. When molten metal was covered by low-hydrogen molten slag, it was deduced from the above results that gas from molten metal rose and escaped through molten slag during solidification process because the required time for bubble formation at the surface of the molten slag was 17 sec, and the time for metal solidification was 28 sec after the switch off of the furnace. While, in the case of ilmenite slag after the switch off of the furnace time for bubble formation at the surface of the molten slag was about 38 sec and the time for metal solidification was 28 sec respectively as shown schema in Fig. 4. This means that saturated gas from molten metal under low-hydrogen slag rises and escapes through molten slag before solidification of the molten metal, accompanied by bubbles of molten metal. On the other hand, a large quantity of gas escapes through molten ilmenite slag after completion of solidification of molten metal.

From these experimental results, it was deduced that low-hydrogen molten slag was apt to escape but ilmenite molten slag was not apt to, and in the case a higher pressurized gas explosively escaped through viscous molten slag after solidification of molten metal.

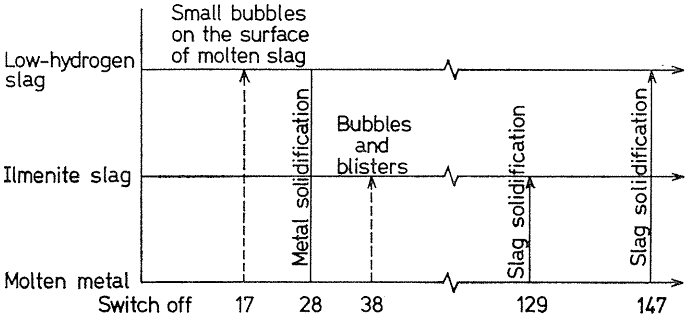


Fig. 4. Relative durations of bubble formation, metal and slag solidification of low-hydrogen and ilmenite slags.

3. 4. *Effect of amount of flux on escape of hydrogen from molten metal*

It was deduced from the above experimental results that porosity of weld metal may depend on the degree of escape of gas through molten slag before solidification of molten metal. And the easier the gas escapes through molten slag, the more porosity is apt to form in the molten metal.

In addition, the effect of the amount of flux on the escape of hydrogen through molten slag and porosity formation was investigated using low-hydrogen and ilmenite type fluxes.

Fig. 5 shows the effect of the amount of fluxes on relative porosity in weld metal by moistened covered electrodes with the same flux in additional groove of specimens. According to this figure, relative porosity in weld metal by low-hydrogen electrodes slightly decreased in proportion to the increase of amount of additional flux. This may be attributed to the fact that thicker covered slag makes it difficult for gas in molten metal to escape through the molten slag layer. On the other hand, weld metal by moistened ilmenite electrode revealed no difference of porosity in weld metal with or without additional flux.

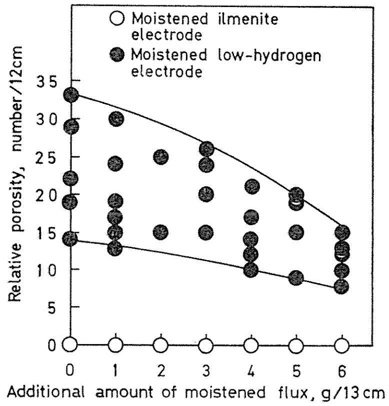
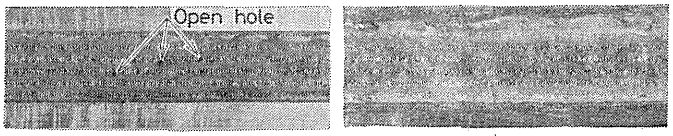


Fig. 5. Effect of additional amount of moistened ilmenite and low-hydrogen fluxes (absorbed water content: 7.0%) on relative porosity of beads by the same type electrodes.

Photo. 4 shows the appearance of solidified slag by low-hydrogen electrode. As shown in Photo. 4 (a), a large number of small open holes were observed in the moistened low-hydrogen solidified slag without additional flux. It was deduced that these small open holes were made by gas released from the molten metal. This type of open hole, however, was hardly ever observed in the case of solidification slag with additional flux in Photo. 4(b).



(a) No additional flux

(b) Additional flux: 6g/13cm length of bead

Photo. 4. Appearances of solidified slags by moistened low-hydrogen electrode (absorbed water content: 7.0%) with and without additional flux.


(a) No additional flux (b) Additional flux: 6g/13cm length of bead

Photo. 5. Appearances of solidified slags by moistened ilmenite electrode (absorbed water content: 7.0%) with and without additional flux

Photo. 5 shows the appearance of solidified slag by ilmenite electrode. This appearance of the slag differed remarkably from that of the small open hole on the surface by low-hydrogen slag.

Table 3 shows the diffusible hydrogen content of deposited metals by moistened ilmenite and low-hydrogen electrodes with and without additional fluxes. In the case of ilmenite electrodes, diffusible hydrogen content was increased with additional flux. On the other hand, in the case of low-hydrogen electrodes, diffusible hydrogen content revealed no difference with or without additional flux. This means that saturated gas in molten metal under low-hydrogen slag generates consistency to form bubbles and to escape through the molten slag layer. Therefore, a small difference in the amount of slag did not give a difference of diffusible hydrogen of weld metal.

Table 3. Diffusible hydrogen content of deposited metals by moistened ilmenite and low-hydrogen electrodes with and without additional fluxes.

Types of covered electrodes	Absorbed water content, wt. %	Additional flux, g/13 cm length of bead	Diffusible hydrogen content, cc/100g deposited metal
Ilmenite	7.0	No additional flux	41.1
		6	48.4
Low-hydrogen	7.0	No additional flux	16.5
		6	16.8

4. Conclusions

This study was carried out to clarify the reason why weld metal by a low-hydrogen lime type electrode was sensitive to porosity in spite of its lower diffusible hydrogen content.

The experimental results were as follows:

1) From the lower viscosity of molten slag, porous solidified slag and quietly wavy molten pool by low-hydrogen electrode, it is deduced that saturated gas in molten metal might consistently generate to form bubbles and easily rise through covered molten slag.

2) Saturated gas in molten metal with other types of electrodes should hardly

generate and rise through molten slag with higher viscosity. In contrast higher pressurized gas under viscous molten slag should rise as larger blisters in slag just after solidification of molten metal.

3) Before and during the solidification period, small hydrogen bubbles formed under low- hydrogen slag, through which hydrogen could consistently rise and escape from molten metal through molten slag. In contrast larger hydrogen blisters grew under ilmenite slag, through which hydrogen explosively escaped after completion of solidification.

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