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Nitrogen Absorption by Iron and Stainless Steels during YAG Laser Welding

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The nitrogen absorption by iron, Fe-20Cr-10Ni and SUS329J1 stainless steel YAG laser welding in the atmosphere of Ar-N_2 mixture gas was investigated in comparison with those during arc welding using the same materials as in this experiment and equilibrium data. Although the nitrogen contents of YAG laser weld metal increase with the nitrogen partial pressure were as well as those of arc weld metal of arc welding, the nitrogen content during YAG laser welding were quite less than those during arc welding. Blowholes can not be observed in Fe-20Cr-10Ni and SUS329J1 stainless steel and can only be found in iron at lower nitrogen partial pressure during YAG laser welding. A discussion on the difference in nitrogen absorption between YAG Laser and arc welding has suggested that small amount of nitrogen absorption results from less opportunity of nitrogen to touch the surface of molten metal due to the active evaporation of metal which covers the major surface of molten metal during laser welding metal. Additionally, the short-time thermal cycle compared with arc welding may bring insufficient nitrogen absorption in the weld metal during cooling. It can be considered that the nitrogen absorption during YAG laser welding is basically different from that during arc welding.

KEY WORDS: nitrogen absorption; YAG laser welding; arc welding; purified iron; Fe-20Cr-10Ni; duplex stainless steel; solubility of nitrogen; welding atmosphere.

1. Introduction

Nitrogen absorption of iron alloys during arc welding process is characterized by high temperature arc plasma and short-time thermal cycle [1]. When nitrogen gas is included in the welding atmosphere, monatomic nitrogen gas N produced by dissociation $N_2 \rightarrow 2N$ in the arc column enhances nitrogen absorption of molten iron alloy [2-6]. The weld metal contains larger amount of nitrogen than the equilibrium solubility at the molten pool temperature during arc welding [5]. However, the welding thermal cycle does not always give enough time for complete nitrogen absorption of molten metal, when the equilibrium solubility of nitrogen is high, such as high chromium steels [7,8] or pressurized nitrogen atmospheres [9,10]. For the above reasons, the nitrogen absorption of steel during arc welding does not obey Sieverts' law [2,10].

Recent development and application of laser welding are very remarkable. Nitrogen absorption during laser welding may differ from arc welding, but has not been well investigated yet. The purpose of the present study is to clarify the nitrogen absorption of iron and stainless steels during YAG laser welding in comparison with those during arc welding and equilibrium state.

2. Experimental Procedures

A purified iron, Fe-20Cr-10Ni and SUS329J1 stainless steel were used in the experiment. The chemical compositions of the materials are given in Table 1. The iron

Table 1. Chemical compositions of materials used. /mass%

	C	Si	Mn	P	S	Ni	Cr	Mo	O	N
Iron	0.009	0.009	0.003	0.002	0.004	-	-	-	0.0019	0.0034
Fe-20Cr-10Ni	0.001	0.01	0.01	0.001	0.003	9.939	19.705	-	0.0007	0.0107
SUS329J1	0.019	0.50	0.30	0.003	0.002	4.71	25.05	1.90	0.0047	0.1492

and Fe-20Cr-10Ni specimens contain little impurities and with the dimension of 150×50×12 mm. Commercial type 329J1 duplex stainless steel specimens contain high nitrogen content and with the dimensions of 150×50×9mm. The welding apparatus is shown schematically in Fig. 1. The power of YAG laser is 3.5kW, the speed of welding is 0.02m/s, the rate of gas flow is $8.3 \times 10^{-4} m^3/s$. The laser focus position was just on the surface of the weld. Melt-run type bead-on-plate welding by YAG laser was carried out in a shielding box where the nitrogen partial pressure was varied from 0 to 0.1 MPa in Ar-N_2 gas mixture. The bead appearance and penetration were also investigated. The nitrogen content of weld was determined by fusion gas chromatographic analysis in an inert gas(LECO).

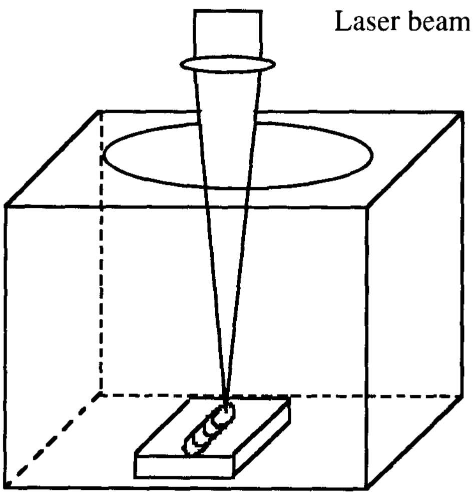

Fig. 1 Schematic illustration of YAG laser welding.

3. Results and discussion

3.1 The nitrogen content of iron weld metal

The relationship between the nitrogen content of iron laser-weld metal and the square root of nitrogen partial pressure(P_{N_2}) is illustrated in Fig. 2. The nitrogen content increases slightly with an increase of P_{N_2}. In order to compare the nitrogen absorption during laser welding with those during arc welding and equilibrium state, Fig. 2 includes the nitrogen content of iron GTA-weld metal and nitrogen solubility at 1900 and 3160K calculated by an equilibrium equation [1,11]. In the calculation, the partial pressure of iron vapor is not considered. Nitrogen content of arc weld metal is much larger than that of laser weld metal.

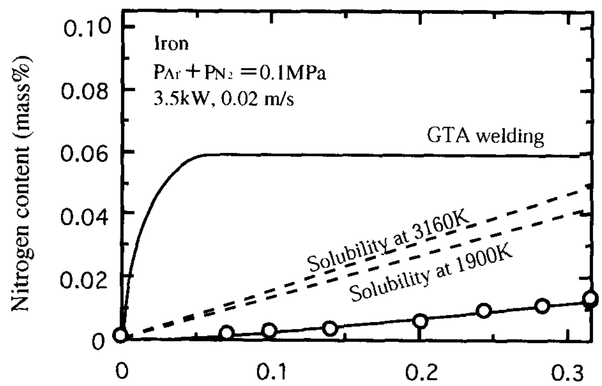

Fig. 2 Comparison of nitrogen content of iron during YAG laser and arc welding, and equilibrium calculation.

The GTA welding was carried out with a welding current of 250A, an arc length of 10mm and a travel speed of 3.33mm/s in Ar-N_2 mixture atmosphere of 0.1MPa using the same iron as in this experiment. The measured temperature of iron molten pool during GTA welding is about 1900K [5]. The boiling point of iron is about 3160k. The temperature of molten iron is supposed to be between the two temperatures. The nitrogen content in the laser welded metal is smaller than nitrogen solubility at two temperatures.

3.2 The nitrogen content of Fe-20Cr-10Ni stainless steel weld metal

The relationship between the nitrogen content of Fe-20Cr-10Ni laser-weld metal and the square root of nitrogen partial pressure(P_{N_2}) is illustrated in Fig. 3. Together with nitrogen contents of arc(GTA and GMA) weld metals and equilibrium solubility at 1800K and 3000K for the same Fe-20Cr-10Ni. The nitrogen content increases slightly with an increase of P_{N_2}. Generally the nitrogen content of GMA weld metal is lower than that of GTA weld metal when the welding parameters are the same [2-5].

The authors have reported that molten pool temperature of SUS304L stainless steel during GTA welding is about 1800K. Since the chemical composition of SUS304L stainless steel is close to Fe-20Cr-10Ni, the nitrogen solubility of Fe-20Cr-10Ni at 1800K is shown in the figure. The boiling point of Fe-20Cr-10Ni is assumed to be around 3000K. The nitrogen content in laser weld metal is much smaller than the nitrogen solubility at 1800K and is a little smaller than nitrogen solubility at 3000K. The nitrogen content obtained during YAG laser weld metal is quite less than that of Fe-20Cr-10Ni arc weld metal. The tendency is similar to the case of the iron weld metal.

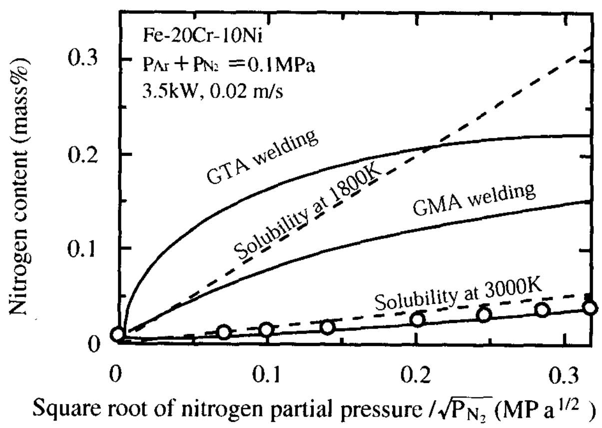

Fig. 3 Comparison of nitrogen content of Fe-20Cr-10Ni during YAG laser, arc welding and equilibrium calculation.

3.3 The nitrogen content of duplex stainless steel weld metal

The relationship between the nitrogen content of SUS329J1 stainless steel laser-weld metal and the square root of nitrogen partial pressure P_{N_2} is illustrated in Fig. 4. Together with nitrogen contents of GTA weld metal and equilibrium solubility at 1880 and 3000K of SUS329J1 stainless steel [1,11].

The GTA welding was carried out with a welding current of 250A, an arc length of 5mm and a travel speed of 2mm/s in Ar-N_2 mixture atmosphere of 0.1MPa using the same SUS329J1 stainless steel as in this experiment. 1880K is the calculated temperature of the molten pool of duplex stainless steel during GTA welding. The boiling point is assumed to be 3000K.

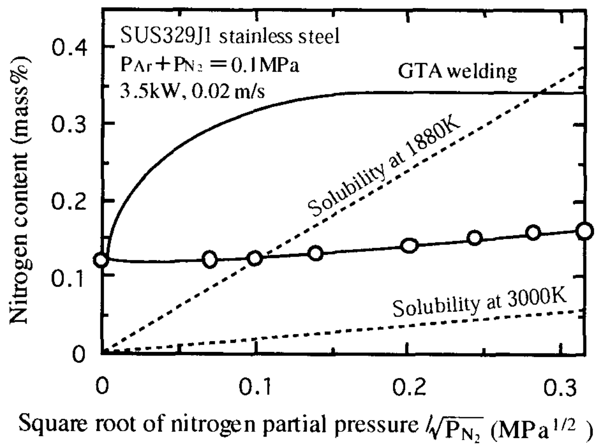

Fig. 4 Comparison of nitrogen content of SUS329J1 stainless steel during YAG laser and arc welding, and equilibrium calculation.

Although the initial value of nitrogen content of duplex stainless steel is somewhat high, the nitrogen content during laser welding is quite less than that absorbed during GTA welding. The absorbed amount of nitrogen content from the atmosphere is comparable between Fe-20Cr-10Ni and SUS329J1 stainless steel. The nitrogen content of laser weld metal is less than the equilibrium solubility of nitrogen at 1880K with the range of high nitrogen pressure, but more than the equilibrium solubility of nitrogen at 3000K.

3.4 Comparison with the three materials

The nitrogen content of the three materials which were used in the experiment are summarized in Fig. 5. The nitrogen contents of all the materials increase with an increase of P_{N_2}. The absorbed amount of laser weld metal increases with Cr content of the material. However, the absorbed nitrogen content in SUS329J1 stainless steel is not much different from the other two materials during laser welding. The nitrogen absorption during YAG laser is very small.

It is reported that the nitrogen absorption in iron is enhanced by the monatomic nitrogen partial pressure of atmosphere [1]. During arc welding the partial pressure of monatomic nitrogen is remarkably high in the arc. The molten pool can readily absorb nitrogen during exposure time of the arc and contains somewhat more nitrogen than the solubility [1], although the iron weld metal evolves some amount of nitrogen during cooling after arc leaves. But during laser welding a keyhole is formed due to the vapor pressure of metal. The shape of a keyhole is schematically shown in Fig. 6. The partial pressure of nitrogen may be extremely low in the keyhole during laser welding because of the high pressure of iron vapor, so the nitrogen absorption is strongly interrupted by the iron vapor.

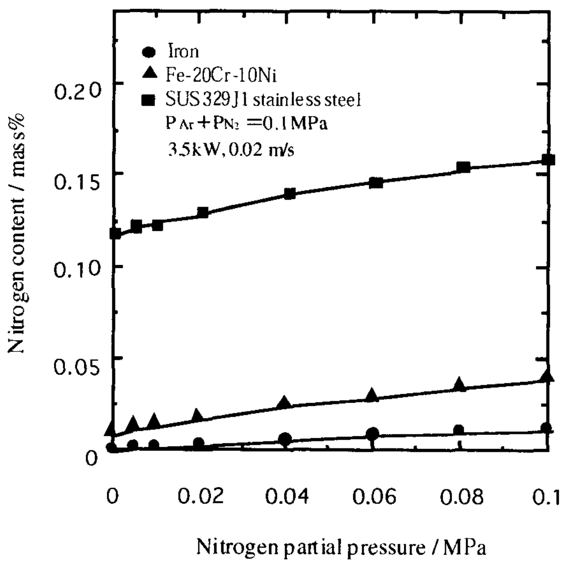

Fig. 5. Relationships between nitrogen partial pressure and nitrogen content of the three materials.

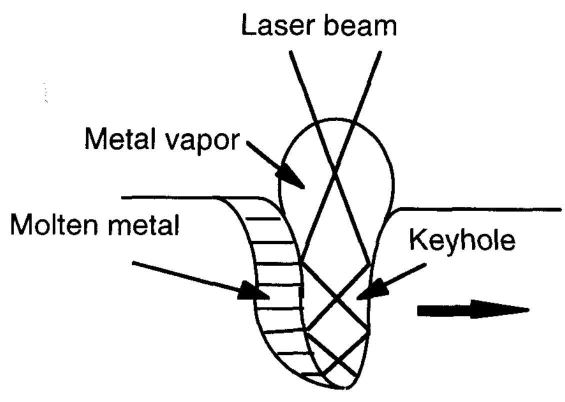

Fig. 6 Schematic illustration of keyhole.

The above discussion suggests that the nitrogen absorption during YAG laser welding may be mainly occur on the out part of the keyhole in the molten pool. However, the nitrogen absorption time during YAG laser welding is shorter than that during arc welding. The short-time thermal cycle may keep nitrogen gas(N_2 and N) from the molten surface during laser welding and leads to quite less nitrogen absorption than that during arc welding. As the same in the discussion of nitrogen content in iron weld metal during YAG laser welding, the nitrogen absorption in high Cr steels is strongly interrupted by metal vapor. The difference in the absorbed amount of nitrogen in the materials is explained with Cr contents in the following way. Although the molten weld pool may continue to absorb nitrogen even during cooling because of the equilibrium solubility of nitrogen increases with a decrease in temperature and also increase the period of time to reach the equilibrium value [2], the short-time thermal cycle may make nitrogen absorption insufficient of the molten weld pool during cooling.

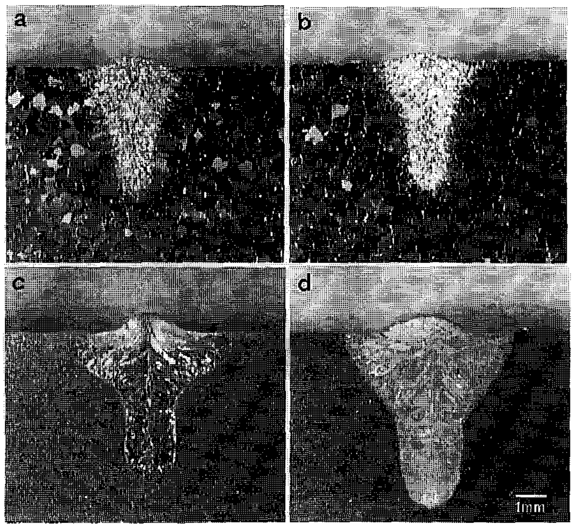

Fig. 7. Cross sections of YAG laser welds: a) Iron / Ar, b) Iron / N_2, c) Fe-20Cr-10Ni / N_2, d) SUS329J1 / N_2.

Cross sections of YAG laser welds are shown in Fig. 7. The bead surface of all the weld metals revealed that the penetration depth and bead which change scarcely with the partial N_2 pressure and nearly keep the same constant. The YAG laser weld metals were free of porosities, only except for iron weld metals produced at 0.01 and 0.02MPa nitrogen partial pressure. The bead width of stainless steels is a little wider than that of purified iron.

3.5 A thermodynamical discussion on the nitrogen absorption of weld metal during YAG laser welding

The metal vapor plays an important role in the nitrogen absorption during YAG laser welding. The effect of metal vapor is considered in the equilibrium state as follows.

The relationship between the nitrogen content of liquid iron($\underline{N}$) and the nitrogen partial pressure(P_{N2}) is described by the following equations [12].

$$1/2\ N_2 = \underline{N} \tag{1}$$

$$K = a_N/P_{N2}^{1/2} = [\%N]\, f_N/\, P_{N2}^{1/2} = [\%N]/P_{N2}^{1/2} \tag{2}$$

$$\log K_2 = -188/T - 1.248 \tag{3}$$

$$\Delta G^\circ = 860 + 5.71T \pm 100 \tag{4}$$

a_N : activity of nitrogen in liquid iron.
P_{N2} : nitrogen partial pressure of the atmosphere.
f_N : activity coefficient of nitrogen.
K : equilibrium constant.
ΔG° : standard free energy.

In the equilibrium state, molecular N_2 and dissociated atomic N gases are coexisting at a temperature and the partial pressures of these gases, P_N and P_{N2}, determine the nitrogen content of liquid iron. It can be considered that the following three equations exist at the same time.

$$1/2\ N_2 = N \qquad K_1 = P_N/\, P_{N2}^{1/2} \tag{5}$$

$$1/2\ N_2 = \underline{N} \qquad K_2 = [\%N]/P_{N2}^{1/2} \tag{6}$$

$$N = \underline{N} \qquad K_3 = [\%N]/P_N \tag{7}$$

P_{N2} : partial pressure of molecular nitrogen.
P_N: partial pressure of atomic nitrogen.
[%N] : nitrogen content in liquid iron.

During the arc welding process, the temperature of gaseous phase in the arc column is considered to be 5000~7000K, so the molecular N_2 is easily dissociated into atomic N, which contributes to nitrogen absorption of weld metal and leads to higher nitrogen content in the weld metal than the equilibrium solubility of nitrogen and does not obey Sieverts' law.

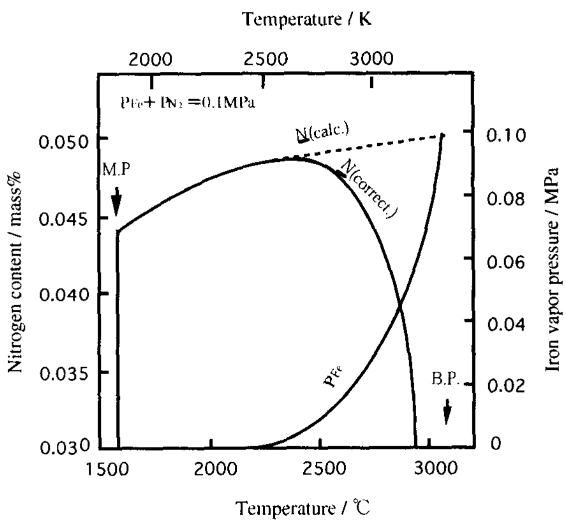

Fig. 8. Effect of iron vapor on nitrogen solubility of iron.

On the other hand, Iron vapor pressure is described by the following equations [12].

$$Fe(l) = Fe(g) \quad (8)$$

$$\log P_{Fe}(mmHg) = -19710\, T^{-1} - 1.27 \log T + 13.27 \quad (9)$$

The nitrogen solubility of iron by Pehlke et al [12]. and iron vapor pressure Kubaschewski et al [13].in 0.1MPa atmosphere ($P_{N2}+P_{Fe}$= 1atm) are shown in figure 8. The nitrogen content of molten iron should increase with the temperature if the phenomenon of iron vapor did not occur. When iron vapor is considered in the atmosphere, the nitrogen content solubility researches a maximum value ($\underline{N} \fallingdotseq 0.047\%$) and then decreases due to the decrease of partial pressure of nitrogen in the atmosphere and becomes zero at the temperature of boiling point of Fe (about 3160K).

Deep penetration which characterizes laser welding is produced by metal vapor pressure in the keyhole. Metal vapor pressure should be considered in nitrogen absorption during laser welding. The metal vapor which covers the major surface of molten metal may impede the nitrogen absorption during laser welding unlike arc welding. Additionally, little nitrogen dissociation in the welding atmosphere caused by YAG laser may also be one of the reasons for the inactive absorption of nitrogen during YAG laser welding in comparison with arc welding.

4. Conclusion

The nitrogen contents of weld metals absorbed from the atmosphere during laser welding are quite less than those absorbed during arc welding. The small amount of nitrogen absorption is assumed to result from the low nitrogen pressure in the keyhole due to metal vapor by laser. The opportunity for nitrogen to touch the surface of molten metal is impeded by the active evaporation of metal which covers the major surface of molten metal. The contribution of monatomic nitrogen to nitrogen absorption is not effective during laser welding. Additionally, the short-time thermal cycle compared with arc welding may make nitrogen absorption in weld metal during cooling insufficient. Blowholes can not be observed in Fe-20Cr-10Ni and SUS329J1 stainless steel and can only be found in iron at lower nitrogen partial pressure during YAG laser welding. It can be considered that the nitrogen absorption during laser welding is basically different from that during arc welding.

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REFERENCES

1) T. Kuwana, H. Kokawa and M. Saotome: Mathematical Modelling of the Weld Phenomena 3, ed. by H. Cerjak, The Institute of Materials, London, (1997), 64.
2) T. Kobayashi, T. Kuwana and Y. Kikuchi: Welding in the world, 5 (1967), 58.
3) T. Kobayashi, T. Kuwana and Y. Kikuchi: Trans. JWS, 1(1970), 1.
4) T. Kuwana and H. Kokawa: Trans. JWS, 17(1986), 20.
5) T. Kuwana, H. Kokawa and K. Naitoh: Trans. JWS, 17, (1986), 117.
6) T. A. Palmer, K. Munder and T. Debroy: Mathematical Modelling of the Weld Phenomena 3, ed. by H. Cerjak, The Institute of Materials, London, (1997), 3.
7) T. Kuwana, H. Kokawa and N. Muramatsu: Trans. JWS, 20(1989), 10.
8) T. Kuwana, H. Kokawa and K. Naitoh: Trans. JWS, 21(1990), 157.
9) T. Kuwana, H. Kokawa and S. Matsuzaki: Trans. JWS, 18(1987), 12.
10) T. Kuwana, H. Kokawa and S. Matsuzaki: Trans. JWS, 18(1987), 100.
11) H. Wada and R. D. Pehlke: Metal. Trans. B, 8(1997), 675.
12) R.D. Pehlke and J.F. Elliott: AIME Trans. 218(1960), 1088.
13) O. Kubaschewski and E.LL. Evans: Volume1, Metallrugical Thermochemistry, Pergamon Press, London, (1965), 324.