Porosity and Nitrogen Content of Weld Metal in Laser Welding of High Nitrogen Austenitic Stainless Steel

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Some problems such as nitrogen desorption and pores always occur in the weld metal during welding of high nitrogen steel. In order to study the nitrogen content and porosity of the weld metal of high nitrogen steel 1Cr22Mn16N, the steel was welded by CO₂ laser welding, and the influence of the shielding gas composition and heat input on the nitrogen content and porosity of the weld metal was investigated. The experimental results indicate that the weld nitrogen content increases slightly with the increase of the nitrogen content in shielding gas under the same laser welding conditions. The nitrogen content of the weld metal decreases with the increase of the heat input when pure argon is used as the shielding gas, whereas that of the weld metal is improved with the increase of the heat input when some nitrogen is added to the shielding gas. The higher the heat input, the less the porosity in the weld metal, and the more nitrogen in the shielding gas, the less the porosity becomes.

KEY WORDS: high nitrogen stainless steel; laser welding; nitrogen content; porosity.

1. Introduction

As a structural steel, high nitrogen austenitic stainless steel (HNS) contains over 0.4 wt% nitrogen and utilizes nitrogen to partly or completely replace nickel to obtain the austenite.1) High strength, high toughness and high corrosion resistance can be achieved in HNS by nitrogen alloying.2–6) However, the wide application of HNS as a structural material depends on its joining characteristics. So it is important to investigate the welding technique of HNS. Some problems will probably occur in welding of HNS, such as nitrogen loss, nitride, hot cracking and so on.7–12) The nitrogen loss in the weld metal consists of the nitrogen desorption and nitrogen pore. Because high properties are attributed to high nitrogen content, the nitrogen loss in the weld metal will result in the decrease of mechanical properties during welding of HNS. Thus, it is essential to prevent the nitrogen loss of the weld metal during welding of HNS.

As an advanced method, laser welding has recently received increasing attention due to its high energy density and low heat input compared with conventional fusion techniques.13–15) Laser welding is expected to be used in welding of HNS. It is supposed that the nitrogen loss can be suppressed by laser welding due to its rapid heating and cooling process. Therefore, the porosity and nitrogen content of the weld metal of HNS were investigated by laser welding in this paper. The influences of shielding gas composition and heat input on the porosity and nitrogen content of the weld metal were discussed.

2. Materials and Experimental Procedure

3 mm thick high nitrogen austenitic stainless steel 1Cr22Mn16N was used for the experiment, and its chemical compositions (mass fraction in percent) are: C 0.148, Si 0.49, Mn 16.00, Cr 22.07, Ni 0.47, N 0.56, P 0.029 and S 0.002. All the specimens were solid solution treated at 1150°C for 1 h followed by water quenching. The microstructure of the steel is austenite with a small amount of δ-ferrite, as shown in Fig. 1.

Laser keyhole welding was performed by using a 3 kW CO₂ laser facility in the experiment. The beam mode was TEM₀₀+₁₁*. A 127 mm focal length lens made of ZnSe was
used to focus the laser beam to the minimum spot of 0.2 mm in diameter, and the focal point was located just on the plate surface. Full-penetration bead-on-plate welding was carried out under four kinds of welding conditions. The laser power is 2.4 kW, and the welding speed is 1.20, 0.80, 0.60 and 0.48 m·min⁻¹, which the heat input corresponding to is 120, 180, 240 and 300 J·mm⁻¹, respectively. For each welding condition, five kinds of shielding gas compositions with gas flow rate of 400 L·h⁻¹ for axial flow are used, in which the nitrogen content (weight percent) is 0, 5%, 25%, 50% and 100%, respectively. All the Ar–N₂ mixtures were premixed. After welding, the welds were inspected by X-ray radiographic examination taken from the top surface to observe the porosity distribution in the weld, and the diameter of pore that can be detected is not less than 0.1 mm. The nitrogen content in the welds was analyzed by an oxygen and nitrogen analyzer, and the location of the sample in the weld used for the nitrogen analysis is shown in Fig. 2. The specimens of the welds for optical observation were mechanically polished and etched with a 10% oxalic acid solution at 5 V for 30 s.

3. Results and Discussion

3.1. Nitrogen Content

Figure 3 shows the nitrogen content of the welds under different shielding gas compositions. It can be clearly found that the nitrogen content of the welds changes within the range of 0.53–0.59%, that is similar with the nitrogen content of the base metal. The nitrogen content in the weld increases slightly with the increase of the N₂ in shielding gas under the same heat input. With pure argon as shielding gas, the nitrogen content of the weld is lower than that of the base metal. When the nitrogen content in the shielding gas is more than a critical value, the weld nitrogen content is lower than that of the base metal. When some nitrogen is added to the shielding gas, the nitrogen content of the weld metal is in Figure 4. The nitrogen content in the weld metal decreases with the increase of the heat input on the weld metal characterized by the following equation:

\[
[N]_{eq} = K_{eq} \sqrt{P_{N_2}} \tag{1}
\]

where \([N]_{eq}\) is the nitrogen concentration in the liquid iron at equilibrium with diatomic nitrogen (wt%), \(K_{eq}\) is the equilibrium constant for Eq. (1), and \(P_{N_2}\) is the partial pressure of N₂ in the atmosphere (atm).

Sieverts’ law implies that the nitrogen solubility limit in the iron alloys can be raised by increasing the partial pressure of the diatomic gas above the melt. However, Sieverts’ law cannot be applied to describe the dissolution of a diatomic gas in the liquid metal in the presence of a plasma. Such a plasma resides above the weld pool during laser welding process. Binary or ternary molecular species in the shielding gas are easily dissociated into a monatomic gas and ion in the high temperature plasma column. The concentration of monatomic nitrogen from the dissociation of diatomic nitrogen in the plasma is much higher than what would be obtained from the consideration of thermal dissociation of diatomic nitrogen for nitrogen induced shielding gas. The partial pressure of monatomic nitrogen gas is far in excess of what is expected under equilibrium conditions from the thermal dissociation of diatomic nitrogen, and the contribution of diatomic nitrogen is insignificant for the absorption of nitrogen in the liquid metal. Therefore, the partial pressure of the monatomic nitrogen gas plays a more important role in the contribution of the nitrogen absorption in the liquid metal.

The nitrogen flux between the weld pool and plasma is determined by the activity difference between them, and the direction of the nitrogen flux will be towards regions with lower nitrogen activity. The nitrogen activity of the plasma is mainly determined by the nitrogen partial pressure in the plasma in this case, which is related to the nitrogen content in the shielding gas. The nitrogen activity of the plasma increases with the increase of the nitrogen content in the shielding gas. When pure argon is used as the shielding gas in the welding of HNS, the nitrogen activity in the plasma nears zero, which is far smaller than that in the weld pool. So the nitrogen diffuses from the weld pool to the plasma. Thus, the nitrogen loss in the weld occurs and the weld nitrogen content is lower than that of the base metal. When some nitrogen is added to the shielding gas, the activity of the plasma is higher than that of the weld pool. So the nitrogen diffuses from the plasma to the weld pool. Thus, the weld nitrogen content is larger than that of

Fig. 2. Location of sample in laser weld used for nitrogen analysis.

Fig. 3. Variation of nitrogen content in welds with different shielding gas compositions and heat inputs.
base metal. In conclusion, some N\textsubscript{2} added to the shielding gas can improve the nitrogen content and nitrogen activity of the plasma, enhance the nitrogen diffusion from the plasma to the weld pool, and increase the nitrogen content of the welds. Because the liquid pool time is very short during laser welding, the weld nitrogen content slightly increases with the increase of the nitrogen content in the shielding gas, and it is similar with that of the base metal. On the other hand, when the nitrogen diffuses from the weld pool to the plasma, higher heat input can enlarge the weld pool surface and increase the liquid pool time compared with lower heat input, and it will promote the nitrogen desorption. So the nitrogen content of the weld decreases with the increase of the heat input. When the nitrogen diffuses from the plasma to the weld pool, higher heat input can promote the nitrogen absorption, and the nitrogen content of the weld increases with the increase of the heat input.

3.2. Porosity

Figure 4 shows the effect of the shielding gas composition and heat input on the porosity of the welds. It can be seen that nitrogen pores occur in the welds when the heat input is 120 J·mm\textsuperscript{-1}. The photo of X-ray inspection with pores in the weld is shown in Fig. 5(a). When the heat input is 180 J·mm\textsuperscript{-1}, nitrogen pores will not occur in the welds with the nitrogen content in the shielding gas more than 25%. When the heat input is 240 J·mm\textsuperscript{-1}, nitrogen pores will not occur in the welds with the nitrogen content in the shielding gas more than 5%. No nitrogen pore occurs in the welds when the heat input is 300 J·mm\textsuperscript{-1}, and the photo of X-ray inspection without pores in the weld is shown in Fig. 5(b). Thus, nitrogen pores can more easily occur in the welds under lower heat input compared with higher heat input, and the increase of the nitrogen content in the shielding gas can suppress the tendency of porosity in the weld metal.

In general, the cause of porosity in HNS weld metal can be that nitrogen gas is escaped as porosity due to a difference in nitrogen gas solubility between molten and solid metals, which is related to the solidification mode. Solidification behaviors of the stainless steel weld metal can be classified into four modes, A, AF, FA and F, according to their general microstructures and the morphologies of the delta (\(\delta\)) ferrite. In welds of A mode, the weld metal solidifies completely to austenite (\(\gamma\)) and no further transformation takes place during cooling process. For AF mode, the \(\gamma\) is the leading phase and \(\delta\) ferrite, if any, solidifies from the rest melt between the cells. Solidification in FA mode welds is probably the inverse of this, the \(\delta\) ferrite being the leading phase and austenite solidifying from the rest melt. At lower temperature the majority of the ferrite is transformed to \(\gamma\) either by an equiaxial or acicular mechanism, depending on the supercooling of \(\delta\). For F mode, weld metal solidifies completely to \(\delta\) ferrite and \(\gamma\) is precipitated from the solid ferrite at lower temperatures. It nucleates preferentially at the grain boundaries and grows into the interior of the grains by an acicular mechanism as a consequence of pronounced supercooling. If the solidification model is the F or FA mode, due to the lower solubility of nitrogen in delta phase and weak convection between dendrite arms, there is a nitrogen concentration build-up in the front of solid phase. The convection can only enter a small way beyond the liquidus isotherm, which is identical to the dendrite tips. The diffusion build-up will increase the nitrogen activity in dendrite arms. Besides the phenomenon of constitutional supercooling, the nitrogen pore formation will be possible. Due to the high local nitrogen potential pressures, in most circumstances the formation of nitrogen pores is unavoidable. In this mixed convective diffusive model, part of nitrogen is delivered to the rest melt outside the diffusion boundary layer, which means that the situation will be worsened by the effect of macro-segregation. If the solidification assumes the A or AF mode, there is no nitrogen discharged from the solidified phase because the austenite can accommodate more nitrogen than corresponding liquid phase, and it leads to no build-up or even a zone of nitrogen depleted near dendrites. In this way, there can be no sudden build-up of nitrogen pressure between dendrites and so no danger of porosity. Such a solidification mode can suppress the tendency of pore formation.\textsuperscript{23}

The solidification modes of weld metals are well described using the chromium (\(Cr_{eq}\)) and nickel equivalent (\(Ni_{eq}\)). According to the references\textsuperscript{23,24} the solidification mode is divided by the ratio \(Cr_{eq}/Ni_{eq}\) as follows;

\[
\text{F mode: } 1.95 \leq \frac{Cr_{eq}}{Ni_{eq}}
\]

\[
\text{FA mode: } 1.48 \leq \frac{Cr_{eq}}{Ni_{eq}} = 1.95
\]

![Fig. 4. Effect of shielding gas composition and heat input on porosity of welds.](image)

![Fig. 5. Images of welds inspected by X-ray radiographic examination taken from the top surface.](image)
A, AF mode: \( C_{eq}/Ni_{eq} = 1.14 \)

\[ C_{eq} = Cr\%+Mo\%+1.5\times Si\%+0.5\times Nb\% \ldots \ldots \ldots \ldots \ldots (2) \]

\[ Ni_{eq} = Ni\%+30\times C\%+0.5\times Mn\% \ldots \ldots \ldots \ldots \ldots (3) \]

Nitrogen is an austenizer in the weld metal. So Eq. (2) can be modified for HNS as follows;

\[ Ni_{eq} = Ni\%+30\times C\%+0.5\times Mn\%+\beta \times N\% \ldots \ldots \ldots \ldots \ldots (4) \]

According to the references,11,25) \( \beta \) is in the range of 13.4 to 30. So the ratio \( C_{eq}/Ni_{eq} \) is between 0.77 and 1.11 for the high nitrogen steel 1Cr22Mn16N, which means that the solidification mode is the A or AF mode. Figure 6 shows the microstructure of the weld metal, and the \( \delta \)-ferrite occurs in the weld. Thus, the modification is the AF mode and there can be no sudden difference in nitrogen solubility between molten and solid metals.

In this case, the porosity is determined by the laser welding conditions. The equilibrium between monatomic nitrogen and diatomic nitrogen occurs in the weld pool, shown in Eq. (5). The weld nitrogen content similar with that of molten and solid metals.

\[ \frac{1}{2} N_2 (\text{gas}) \leftrightarrow N (\text{dissolved in liquid iron}) \ldots \ldots (5) \]

4. Conclusion

The influence of the shielding gas composition and heat input on the nitrogen content and porosity in the weld metal were investigated in laser welding of high nitrogen steel. The following conclusions can be obtained.

1. The weld nitrogen content increases slightly with the increase of the nitrogen content in shielding gas under the same heat input. The nitrogen content in the weld metal decreases with the increase of the heat input when pure argon is used as the shielding gas, whereas that of the weld metal is improved with the increase of the heat input when some nitrogen is added to the shielding gas.

2. Nitrogen pores can more easily occur in the welds under lower heat input compared with higher heat input, and the increase of the nitrogen content in the shielding gas can suppress the tendency of porosity in the weld metal.

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Fig. 6. Microstructure of weld metal containing austenite and \( \delta \)-ferrite.