Title	Welding and Melting of SUS316LN Austenitic Stainless Steel under High Pressure Nitrogen Atmosphere(Materials, Metallurgy & Weldability)
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Citation	Transactions of JWRI. 1992, 21(1), p. 85-92
Version Type	VoR
URL	https://doi.org/10.18910/11520
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Welding and Melting of SUS316LN Austenitic Stainless Steel under High Pressure Nitrogen Atmosphere†

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Abstract

Austenitic stainless steels of SUS316LN were melted by GTA and GMA in high pressure up to 6.1MPa nitrogen atmospheric arc. Melting condition, nitrogen absorption and microstructure of solidified metals have been investigated.

In the case of GTA melting, it was impossible to starting of arc over 2.1MPa of nitrogen atmosphere, because the tungsten electrode was remarkable consumed in high pressure nitrogen. GMA melting is possible to perform up to 6.1MPa of nitrogen atmosphere at constant melting current of 200A and the arc length of 7mm. Arc voltage increased with increasing in pressure of nitrogen atmosphere. The solidified metals have no defect such as blow hole and crack.

Nitrogen content of GMA solidified metal increased from 0.2 to 0.65 mass% with increasing in pressure from 0.1 to 6.1 Mpa. Bending test indicated that there was no micro crack in solidified metal.

Hardness (H_v) of solidified metal also increased from 200H_v to 350H_v with increasing the nitrogen content. The lattice parameters of solidified metal which were measured by means of the X-ray diffraction was increased from 3.60A to 3.62A with increasing in nitrogen content. It was considered that the absorbed nitrogen which existed as interstitial solid solution deform the lattice, which resulted to increase in hardness.

KEY WORDS: (Nitrogen absorption) (High pressure welding) (GTA & GMA welding)

1. Introduction

The structural materials are demanded the properties of paramagnetic, high resistance for corrosion and wear, and high strength according to the development of the electronics, the precision and cryogenic industry. Recently a new material of cold-rolled austenitic stainless steel which contain over 1% of nitrogen is condidate [1].
For example it has been reported that the 0.2% proof stress of these steels reaches to about 800MPa at room temprature [1].

The characteristics for remelting and solidification of the new material aimed welding and joining, however, dose not studied sufficiently yet [1−3]. The basic purposes of this study is proving the behavior of nitrogen in molten metal, solidified defects and microstructural changes on the high nitrogen high strength autenitic stainless steel.

The possibility of joining of high nitrogen steel by using the high pressure nitrogen atmospheric GTA and GMA methods were discussed also. The results of nitrogen content ($\underline{N}$) and properties of solidified metal were also reported.

2. Experimental procedure

The chemical compositions and mechanical properties of steels used were shown in **Table 1**. The material used for melting test is a stainless steel of SUS316LN including nitrogen and the size of specimen is 12mm in thickness, 100mm in width and 200mm in length.

The gas tungsten arc (GTA) and the gas metal arc (GMA) were used as a melting and depositing methods in high pressure nitrogen atmosphere. The elctrode of GTA is made of tungsten including 2% La_2O_3 and its diameter is 3mm. The consumable electrode for GMA is SUS316L type stainless steel wire with 1.6mm diameter.

Figure 1 shows the chamber with 1.8m³ volume capacity for the high pressure melting and joining test. Preparing to melt the steel in high pressure atmosphere, firstly the chamber was evacuated until under 100Pa and then the nitrogen introduced to the test pressure, finally the GTA or GMA melting and depositing were performed. GTA melting was performed using the following conditions; the initial gap between the elctrode tip to the base metal surface was 1.5mm, the electrical current was 160A and the arc moving speed of test plate was 1.67mm/s. In the case of

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

Table 1 Chemical compositions and mechanical properties of materials used.

(mass%)

Material	C	Mn	Si	Cr	Ni	Mo	N	O
Base metal SUS316LN	0.015	1.44	0.29	17.27	10.89	2.71	0.1667	0.0035
GMA wire SUWY316L	0.019	1.75	0.39	19.98	11.20	2.34	0.0169	0.0020

Material	Mechanical properties at room temprature		
	Yield strength MPa	Tensile Strength Mpa	Elongation %
Base metal SUS316LN	363	677	52

GMA, the arc length was approximately 7mm, the current was 200A and the moving speed of test plate were 3.3mm/s and 10mm/s.

The visual examination on the appearance of the solidified metal (weld bead) was used in order to bring out surface defects. To analyze the nitrogen content ($\underline{N}$) of solidified metal, the samples were extracted from the solidified metal with the size of $3\times3\times4$mm machined and the mass of 0.2g approximately and polished the surfaces, then the total nitrogen were analyzed by LECO equipment (Oxygen and nitrogen analyzer).

The microstructures were observed by the optical microscope EPMA and TEM. The lattice parameters of solidified metals contained nitrogen were measured by means of the X-ray diffraction equipment. The U-shape roller bending test and Vicker's hardness test with the load of 0.98N were applied to solidified metals.

3. Experimental results and discussion

3.1 Melting in high pressure nitrogen atmospheric arc

(1) GTA melting

The variation of arc voltages and the figures of solidified metal in the high pressure nitrogen atmosphere are discussed. **Figure 2** shows the relationships between the arc voltages and atmospheric pressure. At the conditions of nitrogen pressure of 0.1 MPa and current of 160A, the arc condition was maintained stably with 16V of the arc voltage. When the atmospheric pressure increases over 1.1MPa, the arc voltage increases and the normal arc could not obtain.

The surface appearances of solidified metal obtained in high pressure nitrogen atmospheric arc show in **Fig. 3**. Winded bead shapes are known in high pressure arc. The relation between the arc voltage change and the bead appearances at the nitrogen pressure of 0.5MPa is indicated

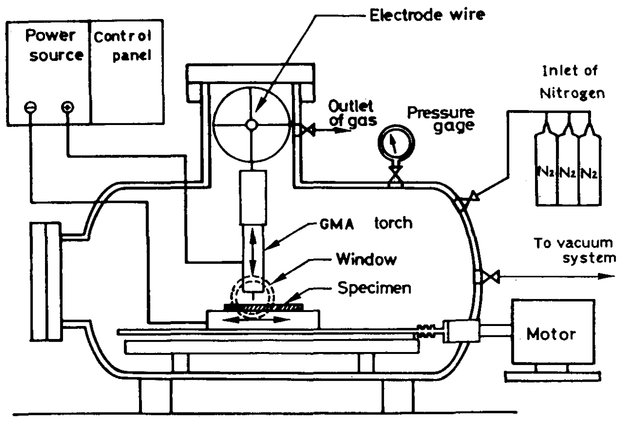


Fig. 1 Test chamber for melting in high pressure nitrogen atmospheric arc.

in **Fig. 4**. It is clear that unstable arc voltages exactly correspond to the wind shape of bead appearance.

Then, it was observed that the consumption and failing of tungsten electrode tip related to the atmospheric pres-

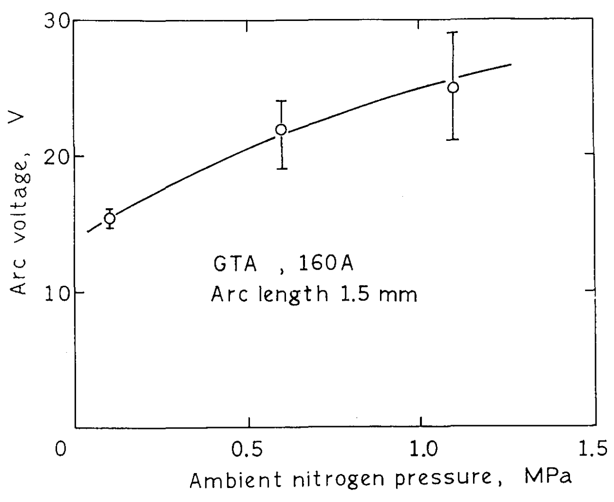


Fig. 2 Effect of the ambient nitrogen pressure on the arc voltage of GTA.

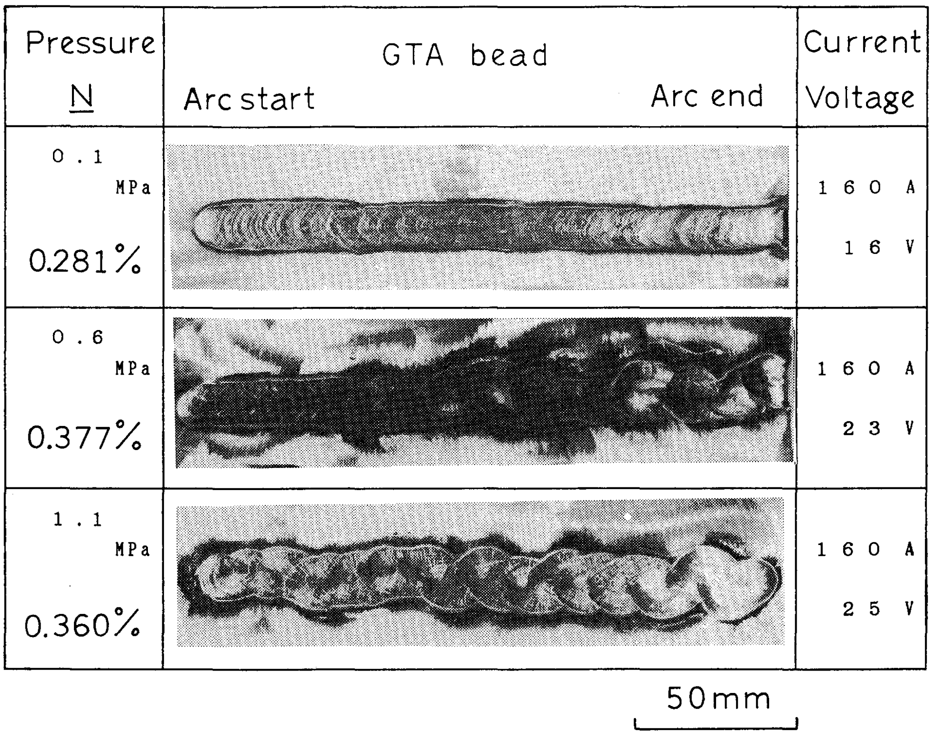


Fig. 3 Geometrics and surface appearance of GTA beads.

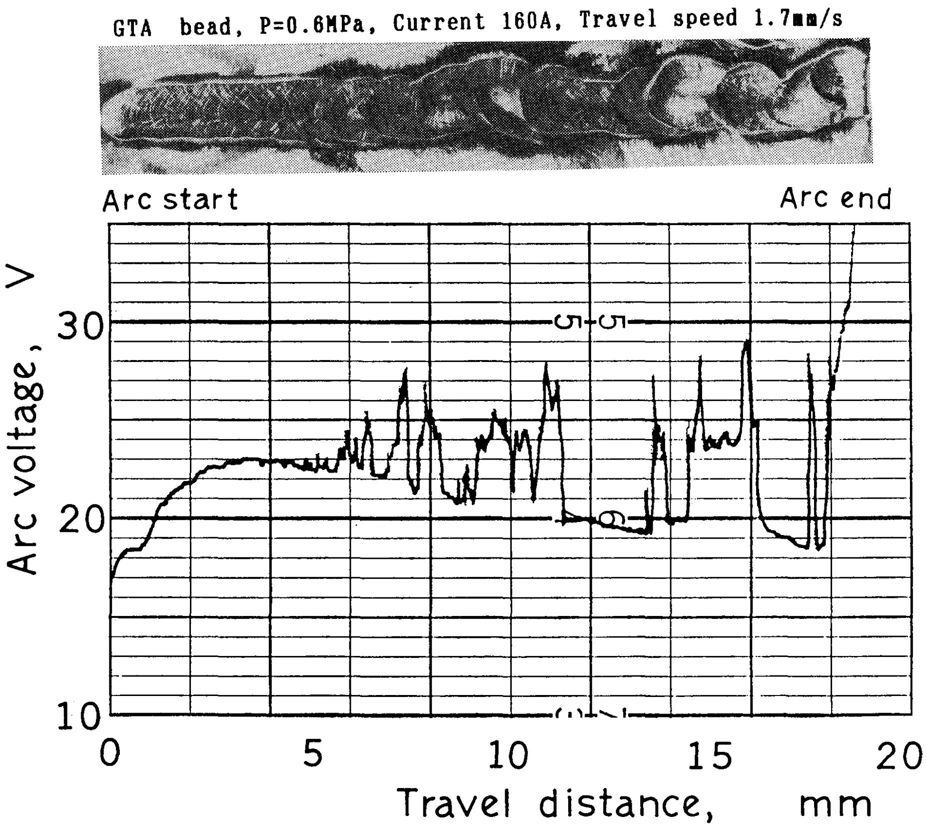


Fig. 4 Relationship between fluctuation of arc voltage and geometry of GTA bead.

sure. The electrode tips were initially grounded to 60 of tip angle and took place to GTA torch.

Figure 5 indicates that the electrode tip deformed after arcing in high pressure nitrogen. It was observed that the electrode was consumed remarkably in higher nitrogen pressure, which should caused to unstable of arc over 1. 1MPa. In the case of 2.1MPa, it became to be impossible to start arc because of the blunting tip of tungsten electrode. Therefore, in this experimental conditions, the critical pressure of GTA is approximately 1.1MPa.

(2) GMA depositing and welding

It was previously reported [4] that constant arc length condition was suitable for formation of sound bead in high pressure atmosphere. In this study, also using GMA with the constant current source, the beads were formed by the conditions of 7mm of constant arc length, 200A of constant current and 3.3mm/s of moving speed. In above conditions, the effect of atmospheric pressure naturally influence to arc voltages similar to the case of GTA. **Figure 6** shows the relationships between the arc voltage and the atmospheric pressure. The arc voltage indicates from 40V at 0. 1MPa and increased to 90V at 6.1MPa. Because the density of gas molecules increased in high pressure atmosphere, and the cooling action of the gas against the arc also increased [5], then higher voltage was needed to maintain the arc.

The increasing rate of arc voltage in nitrogen comparing to argon atmosphere [4] is more remarkable than that in argon atmosphere previously reported [4]. Comparing with the single atomic gas of argon, the diatmic gas of nitrogen consumed extra energy for dissociation, which related to large arc cooling action.

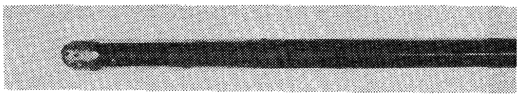
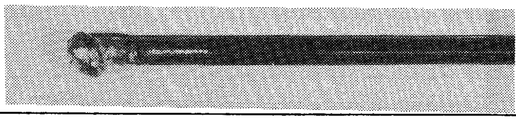
Observing the appearance of bead metaled in 6.1MPa nitrogen as shown in **Fig. 7**, there is no solidification defect on the bead surface like a void or crack. The geometry of bead was almost smooth and same to that in 0.1MPa nitrogen.

The measurement results of width and penetrated depth of bead are shown in **Fig. 8**. The width increased a little with increasing pressure up to 1.1MPa and shows to constant value. The penetration depth is almost constant regardless of the pressure.

From the above observations, the GMA with constant arc length using the constant current source is the most suitable for welding in high pressure nitrogen atmosphere, this situation is same to the case of argon atmosphere described previous paper [4] .

3.3 Nitrogen content of solidified deposition metal

Figure 9 and **10** indicate the nitrogen content (<u>*N*</u>) in

Pressure	Tungsten electrode	Current Voltage
1.1 MPa		160 A 29 V
2.1 MPa		

10mm

Fig. 5 Geometries of tungsten electrode after GTA melting.

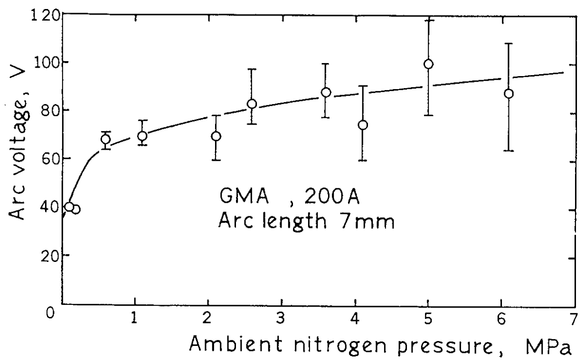


Fig. 6 Effect of the ambient nitrogen pressure on the arc voltage of GMA melting.

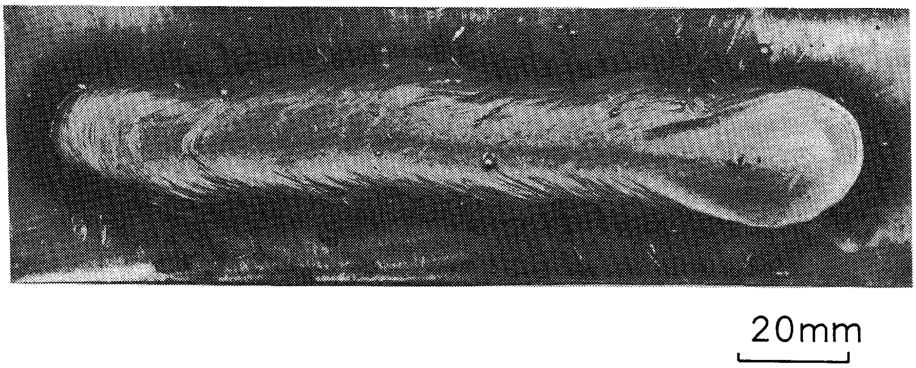


Fig. 7 Geometriy and surface appearance of GMA bead.

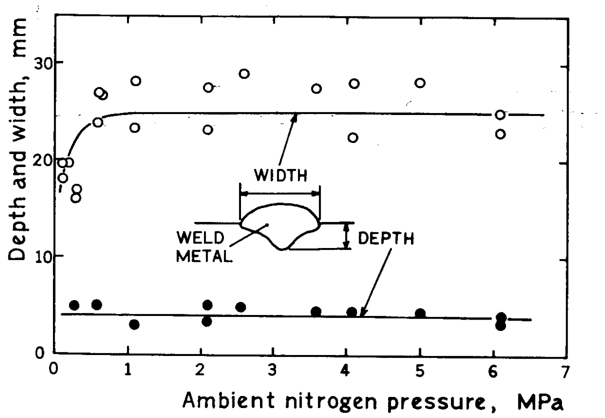


Fig. 8 Effect of the ambient nitrogen pressure on the width and penetration depth of GMA bead.

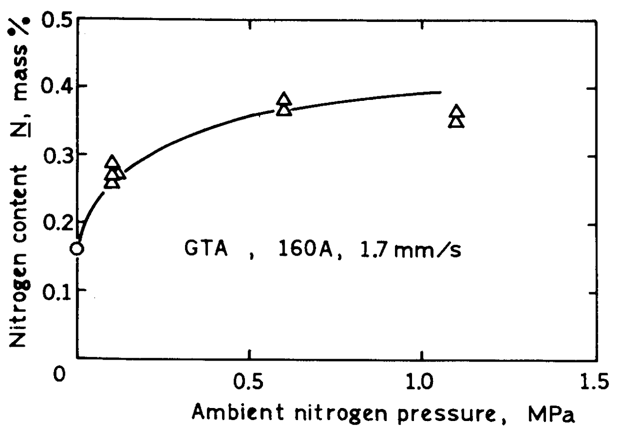


Fig. 9 Effect of the ambient nitrogen pressure for GTA melting on the nitrogen content of solidified metal.

melted metal as a function of the nitrogen pressure. In the case of GTA as shown in Fig. 9, the volue of $\underline{N}$ increases to 0.38% at 1.1MPa of nitrogen pressure. The values of measured $\underline{N}$ have considerable scatter because the arc length varied with the consuming of electrode. At the nitrogen pressure condition of over 1.1MPa, it has not measured value of $\underline{N}$, because it was hard for GTA to start.

On the other hand, GMA was possible to deposit in higher pressure than the case of GTA as shown in Fig. 10.

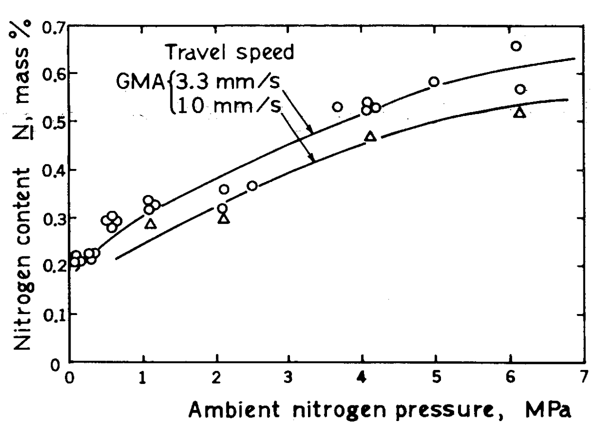


Fig. 10 Effect of the ambient nitrogen content of solidified metal.

The values of $\underline{N}$ increase with increasing in the pressure and nitrogen content reaches 0.65% at miximum pressure 6. 1MPa in this study.

The present experimental values of $\underline{N}$ were compared with that by Kuwana etc. [6] and the calculated nitrogen content equilibrium data [6,7] as shown in **Fig. 11**.

Assuming that the temperature of melting pool is 1873K and the nitrogen pressure is 6.1MPa (60 atm), the theoretical equilibrium nitrogen content is about 1.87%. The actual experimental value, however, was measured to 0.65% that was not seemed to reach the equilibrium value.

In generally, when the nitrogen absorption does not reach to theoretical equilibrium value, it is considered that the experimental value increases and closes to equilibrium one with increasing in the reaction time and reaction area [6]. It is considered that the reaction time increase with longer arc length and lower moving speed. Figure 10 demonstrated that the value of $\underline{N}$ increased with decreasing of moving speed from 10 to 3.3mm/s, as a result of closing to the equilibrium value.

Comparing with $\underline{N}$ content reported by Kuwana in Fig. 11, present results are larger than tose because the difference of arc length and formation of deposited metal. Namely, in the case of constant arc voltage that was

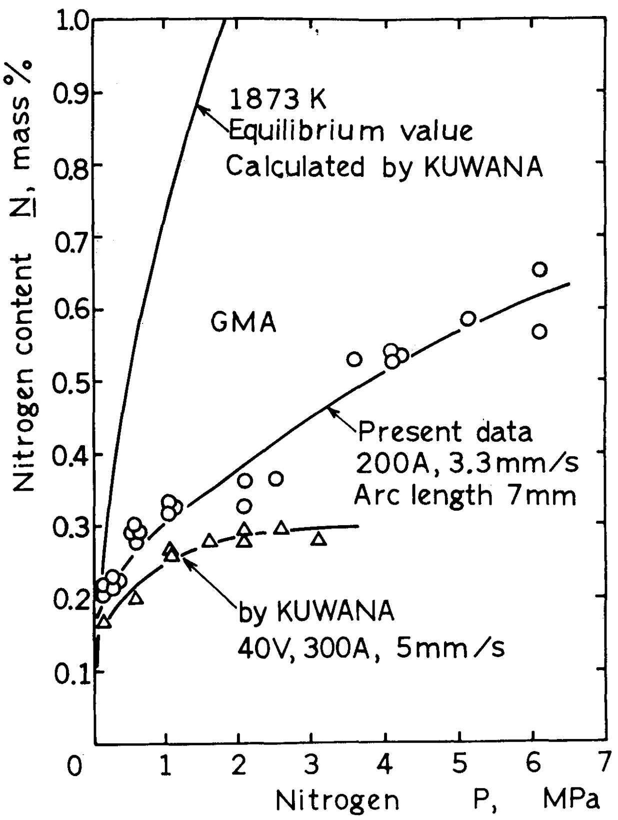


Fig. 11 Comparison of calculted equilibrium balue of nitrogen content, present experimental voues and Kuwana's measured.

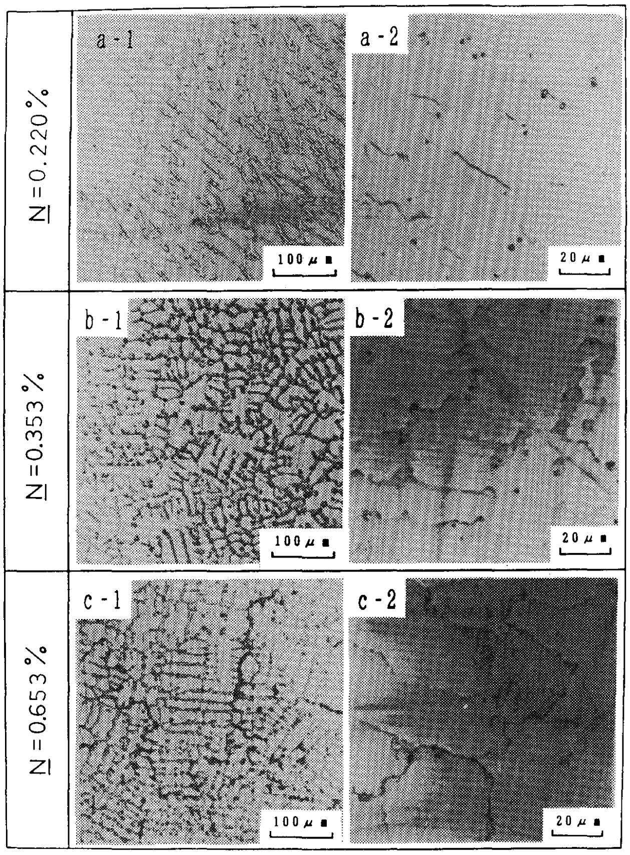


Fig. 12 Microstructures of solidified metals containing nitrogen.

applied by Kuwana, the arc length decrease with increase in nitrogen absorption became to difficult probably.

On the other hand, in the case of constant current and arc length like this study, the nitrogen absorption was not disturbed by changing to arc length because the moving distance of melted particles were almost same.

Considering the above experimental results, the stainless steel including maximum nitrogen of 0.65% was possible to melted without the defect like a voids or cracks in the high pressure nitrogen atmosphere of 6.1MPa.

3.4 Properties of high nitrogen contained solidified metal

Figures 12(a), **(b)** and **(c)** indicate the metallurgical microstructures of solidified metals by GMA in high pressure nitrogen atmosphere. The microstructures were observed by optical microscope after electrical etching in th 10% oxalic acid.

The microstructure were consisted from the austenite single phase but the network like structure were developed according to the nitrogen absorption. Observing the network by high magnification, there is no evidence of clear boundary between network and matrix. Consequently, the network is continuous from matrix in crystallographic aspect. The network structure may be correspond to the dendrite which was delayed to solidify and Cr was segregated, and This consideration was supported EPMA analysis. No micro void or crack were observed in the solidified metals.

Figure 13 shows the transmissionelectron micrographics and the elctron diffraction pattern of solidified metal. There is no evidence of nitride and the diffraction pattern indicates typical gamma structure.

3.4.2 Solidified defect

The micro fissure is one of the hot cracking that were generally observed in solidified full austenitic steel. There is possibility of cracking because the structures of solidified metal is full austenite without ferrite phase.

The possibility of cracking was investigated by observing the surface bending test which was sampled from solidified metal and machined to size of 3×12×100mm then it was bent with 20% strain.

Figure 14 indicates the microstructures before and after bending test at same position. Many slip lines formed by bending were observed but there was no evidence of cracking as shown in Fig. 14(b). One of the reason of no cracking is few constrain in solidified metal produced by

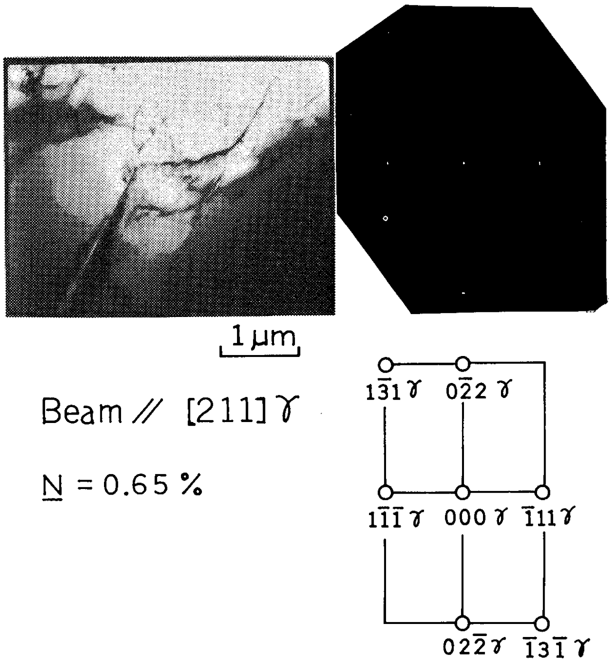


Fig. 13 TEM structure of solidified metal containing 0.65% nitrogen and electron diffraction pattern of solidified metals.

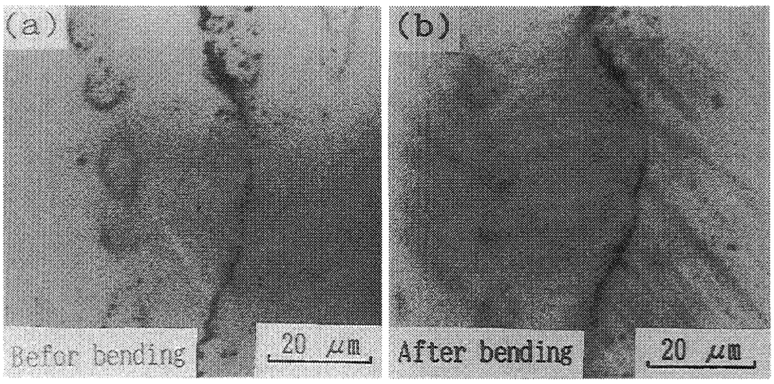


Fig. 14 Microstructures of solidified metals before and after bending test.

bead on plate with no restrain

3.4.3 Hardness of solidified metal

The hardness of solidified metals were measured by Vicker's hardness tester with the load of 0.98N. As shown in **Fig. 15**, the hardness increased with increasing of nitrogen content in solidified metal, for example the metal including 0.65% nitrogen indicated $350H_V$.

Since the hardening behavior seems to relate to the solid solution hardening by nitrogen. So, the variation of lattice parameter were measured by X-ray diffraction method (CuK_α, $\lambda = 1.5418$ Å) as shown in **Fig. 16**. The lattice parameter increased with increasing the nitrogen content, which indicated nitrogen solved makes strain the lattice of matrix. In this experimental condition, the increase in nitrogen content is well correspond to the variation in lattice parameter. Imai et al. [8] also studied about the variation of lattice parameter in solidified metal by nitrogen using rolled steels and the results indicated the same tendency of present data.

Therefore, it is considered that most of nitrogen exists as solid solution in solidified metal and the nitride [9] scarcely exist. From the above considerations the hardening behaviors were depend on the strain hardening resulted from interstitial type nitrogen.

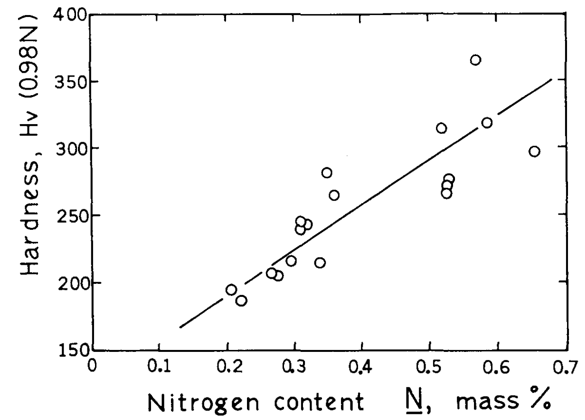


Fig. 15 Effect of the nitrogen content on the hardness (H_v) of solidified metal.

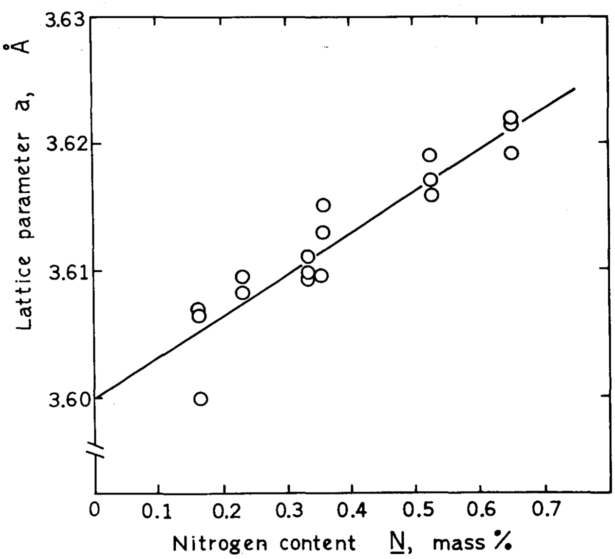


Fig. 16 Effect of the nitrogen content on the lattice parameter of solidified metal.

Conclusions

GTA and GMA melting and depositing of SUS316LN steel were performed in the high pressure nitrogen atmosphere as a basic study of joining (welding) in high nitrogen stainless steel. The results were summarized as follows.

(1) GTA melting is impossible in high pressure nitrogen of over 2.1MPa because of the remarkable consuming in tungsten electrode. On the other hand, GMA melting is successfully performed up to 6.1MPa of nitrogen.

(2) In the case of GMA with constant arc length of 7mm, the arc voltage increases with increasing in the pressure of nitrogen and is reached to 90V approximately at the pressure of 6.1MPa.

(3) In the case of GMA melting at maximum nitrogen pressure of 6.1MPa, the solidified metal contains 0.65% of nitrogen content and indicates no macro and micro defect.

(4) The nitrogen content of solidified metal does not reach to the equilibrium value.

(5) The hardness of solidified metal increases with increasing nitrogen content. The hardness is $240H_v$ in initial metal and measured $350H_v$ in melted metal with 0.65% nitrogen content.

(6) The lattice parameter linearly increases with increasing in the nitrogen content, so the nitrogen is considered to be exist in solidified metal as a solid solution, which increases the hardness of solidided metal.

The authors wish to express thanks to Professor Dr. K. Kumagai of Akita Univ. for his co-operation.

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