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Microstructure and Toughness in Weld Metal of High Purity Ferritic Stainless Steel†

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Abstract

Effect of nitrogen and nickel on toughness in weld metal of high purity ferritic stainless steel (19Cr-2Mo) was investigated by means of fractography. GTA welding was carried out using 19Cr-2Mo and SUS316L filler wire in argon, argon containing 0.1% nitrogen and argon containing 0.1% air.

For the weld metal by using 19Cr-2Mo filler metal, the energy transition temperature in Charpy impact test raised 30 K over that of the base metal. Nitrogen caused the extremely increase of the transition temperature. For the weld metal by using 19Cr-2Mo filler wire with 4% Ni, the transition temperature was 40 K lower than that without Ni in each shielding gas atmosphere. The transition temperature of the weld metal contained 7.36% nickel by using SUS316L filler metal was lower than that of the base metal even though in argon contained nitrogen.

The fracture surfaces below the transition temperature in every specimens indicated the brittle fracture with tongue, which occured by the intersection of cleavage fracture and deformation twin. The initiation of the twin caused the brittle fracture, which was inhibited by nickel and accerelated by nitrogen. Consequently, the toughness of the weld metal was improved by the addition above 4% nickel.

KEY WORDS: (High Purity Ferritic Stainless Steel) (Weld Metal) (Toughness) (Deformation Twin) (Fractography)

1. Introduction

High purity ferritic stainless steel has been widely used as the material for corrosion resistance, and has low carbon and low nitrogen by progress of the steel making technology.

However the weld metal of the stainless steel has lower toughness than that of the base metal. This is considered to be due to nitrogen and oxygen contaminated in the weld metal during welding[1] and the precipitation of nitrogen such as Cr_2N in the weld metal is considered to occur easily the brittle fracture[1),2)].

Generally, tongues have been observed in the brittle fracture surface of ferrite steels, and which occured by the intersection of twin plane and cleavage plane[3].

But the relation between the toughness and the initiation of the twin has not been clearly yet.

In this study, the effect of nitrogen on the microstructure and toughness in the weld metal of the high purity ferritic stainless steel has investigated on the basis of the initiation of the deformation twin by means of fractography.

Furthermore, taking aim at the increase in the toughness, the weld metal added 4% nickel consisting of ferrite phase only, and the weld metal having the duplex microstructure consisting of ferrite and austenite using SUS316L filler wire were fabricated, and the mechanism of the progress of the toughness has been investigated.

2. Experimental Procedure

The base metal used in this investigation was 19Cr-2Mo steel, that is high purity ferritic stainless steel. The filler wire used was 19Cr-2Mo steel, and SUS316L steel, and their wire diameter was 2 mm.

The chemical compositions are shown in **Table 1**. The filler wire was degreased in acetone before welding. The schematic layout of the welding process is shown in **Fig. 1**. Argon, air and nitrogen are used as torch gas. The back

Table 1 Chemical compositions of base metal and filler metal used (mass %).

		C	Si	Mn	P	S	Cr	Mo	N	Ni
Base metal(19Cr-2Mo)		0.016	0.49	0.35	0.046	0.068	18.26	1.85	0.022	—
Filler metal	19Cr-2Mo	0.008	0.06	0.12	0.025	0.007	18.82	1.91	0.008	0.009
	SUS316L	0.017	0.39	2.01	0.027	0.009	19.29	2.04	0.039	12.26

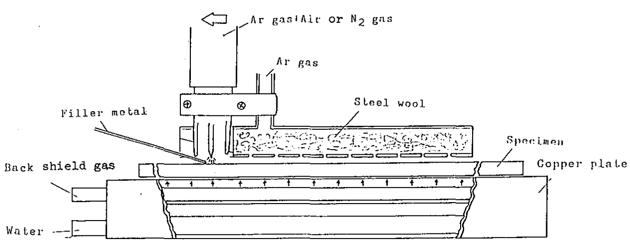

Fig. 1 Schematic layout in welding procedure.

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Table 2 Welding condition for DCSP GTAW.

Volt (V)	Current (A)	Weld.speed (m/s)	Heat input (kJ/m)	Gas flow rate (μm^3/s)
16	160	0.022	1182	20

Table 3 Chemical compositions of weld metal (mass %).

	C	Si	Mn	P	S	Cr	Mo	Ni
19Cr-2Mo	0.010	0.28	0.24	0.044	0.038	18.54	1.98	0.28
19Cr-2Mo+4Ni	0.016	0.33	0.29	0.043	0.058	17.80	1.85	4.41
SUS316L	0.016	0.44	0.34	0.044	0.070	18.64	1.88	7.36

Table 4 Nitrogen content in weld metal (ppm).

Filler	19Cr-2Mo		19Cr-2Mo+4Ni		SUS316L	
Shield gas	N	O	N	O	N	O
Ar	154	40	150	27	270	18
Ar+Air	—	—	—	—	400	40
Ar+N_2	376	37	301	41	471	15

shielding gas was used argon.

The welding procedure was DCSP GTAW, and the conditions are shown in **Table 2.** The groove was used X type. Two pass welding was carried out. The interpass temperature was room temperature.

Chemical compositions of the weld metal are shown in **Table 3.** The oxygen content and nitrogen content in the weld metal were analysed by using the instrument of LECO corporation. The oxygen and nitrogen content in the weld metals are shown in **Table 4.**

The toughness of the weld metal was evaluated by the energy transition temperature of energy-temperature curve using Charpy impact test. The specimen for Charpy impact test was cut off from the welds. The specimen was sub-size of 5 mm thickness on the basis of JIS No. 4 test specimen. The notch was located by the center of the weld metal.

The microstructure of the weld metal was obtained by the electro-etching technique of 10% oxalic acid solution. The identification of the austenite and ferrite was made by X-ray diffraction technique.

The fracture surface obtained was observed by scanning electron microscopy.

3. Results and Discussion

3.1 Effect of nitrogen and nickel on microstructure of weld metal

Figure 2 shows the optical micrographs of the weld metal using 19Cr-2Mo filler wire, and the base metal. The weld metal welded in argon shielding gas consists of the ferrite microstructure as well as the base metal, and the grain size is very larger than that of the base metal. The ghost like grain boundary is observed in the large grain[4].

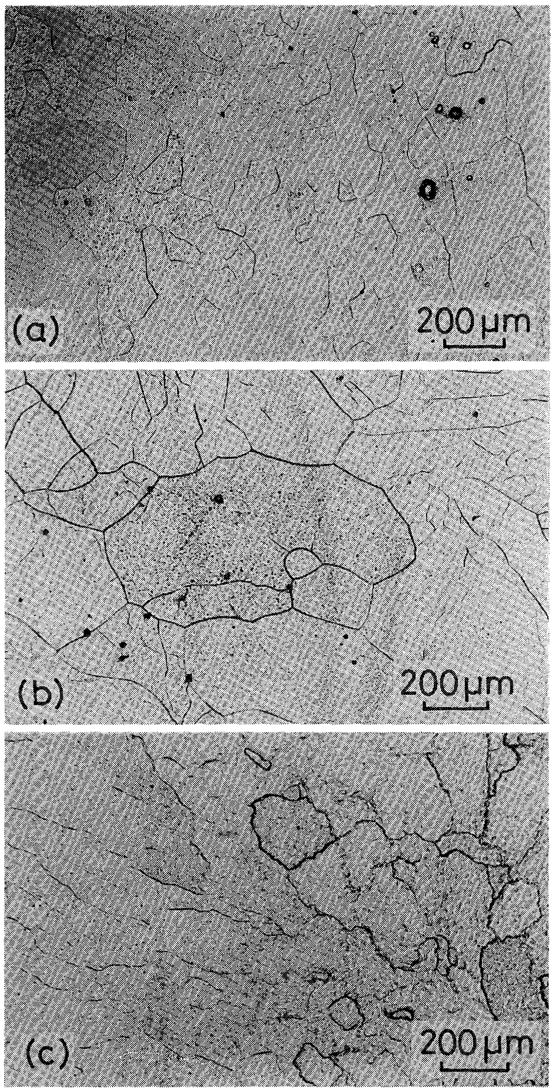

Fig. 2 Microstructures of base metal (a), weld metal by 19Cr-2Mo steel filler metal in argon (b) and weld metal by 19Cr-2Mo steel filler metal in argon + 0.1% nitrogen (c).

The microstructure of the weld metal welded in argon + 0.1% nitrogen was also ferrite microstructure, and the grain size is larger than that of the base metal.

Though nitrogen is austenite stability element, as shown in Table 4, the microstructure of the weld metal at the nitrogen content of 376 ppm consists of ferrite only.

Figure 3 shows the optical micrographs of the weld metal containing 4% nickel by 19Cr-2Mo steel filler metal.

For the weld metal welded in argon, the microstructure of each pass is ferrite as shown in Fig. 3-(a). The addition of 4% nickel makes fine the grain size on the contrary of Fig. 2-(b).

As shown in **Fig. 3-(b),** the microstructure of the weld metal in argon + 0.1% nitrogen consisted of ferrite and austenite.

Austenite precipitates at the grain boundary of ferrite and grows into the ferrite.

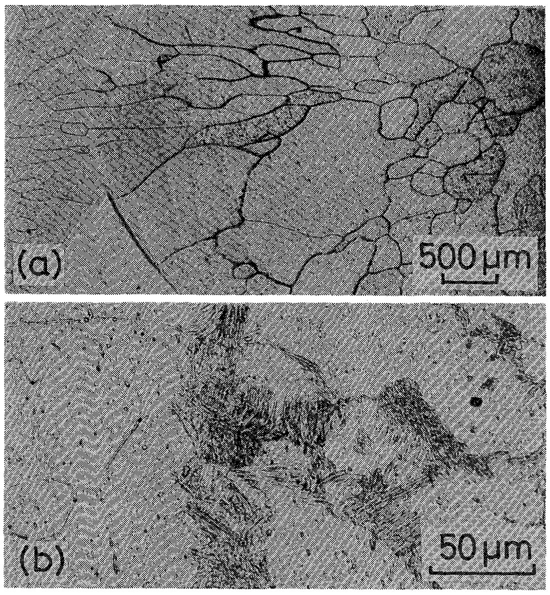

Fig. 3 Microstructures of weld metal containing 4% Ni by 19Cr-2Mo steel filler metal in argon (a) and argon + 0.1% nitrogen (b).

Figure 4 shows the microstructure of the weld metal by type 316L filler metal welded in argon(a) and argon + 0.1% nitrogen (b). The microstructure of the weld metal welded in argon consists of ferrite and austenite. Widmanstätten austenite grows from the ferrite grain boundary. And the austenite also precipitates in the ferrite microstructure. The nickel content of the weld metal was 7.36% as shown in **Table 3**.

By means of X-ray diffraction technique, the volume fraction of austenite was 5%. This means that the addition of nickel in the weld metal causes the minor increase of the volume fraction of the austenite.

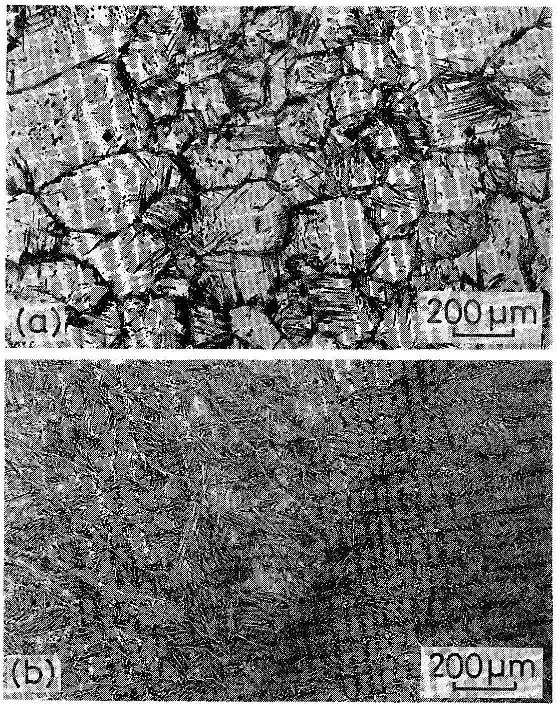

Fig. 4 Microstructures of weld metal by type 316L filler metal in argon (a) and argon + 0.1% nitrogen.

Figure 4-(b) shows the microstructure of the weld metal welded in argon + 0.1% nitrogen. The nitrogen content in the weld metal was 471 ppm. The volume fraction of austenite increases with increasing nitrogen content. Widmanstätten austenite precipitates in the ferrite considerably.

On the basis of the microstructure map of Delong[5]. Cr equivalent was 21.8, and Ni equivalent was 8.91. The microstructure map indicated the mixture of austenite and ferrite.

For the microstructure shown in **Fig. 4-(b)**, the volume fraction of ferrite was 54%, and that of austenite was 46%. It is concluded that the addition of nitrogen to the weld metal causes the increases in the volume fraction of austenite.

3.2 Effect of nitrogen and nickel on energy transition temperature of weld metal

Figure 5 indicates Charpy impact value versus temperature curves of the base metal and weld metal with 19Cr-2Mo steel filler metal. The energy transition temperature of the base metal is 253K. The transition temperature of the weld metal welded in argon is 283K. The temperature of the weld metal welded in argon + 0.1% nitrogen is 368K. The transition temperature of the weld metal welded in argon is higher than that of the base metal. This is considered to be due to the large grain size of the weld metal as shown in Fig. 2. The transition temperature of the weld metal welded in argon + 0.1% nitrogen is higher than that of the weld metal welded in argon.

Generally, the addition of nickel to the ferritic steel causes the increase in the toughness[6]. Then it is expected that the addition of nickel to the weld metal also causes the increase in the toughness.

Figure 6 shows Charpy impact value versus temperature curves of the base metal and weld metal containing

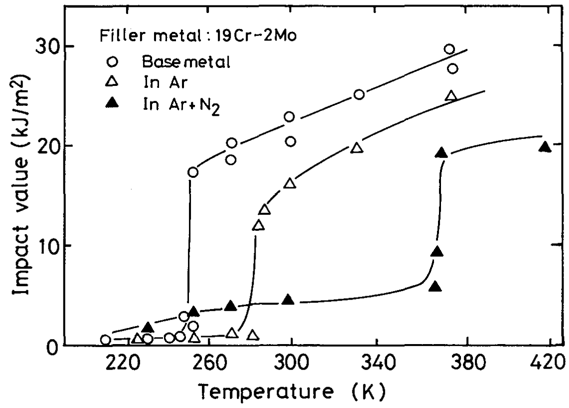

Fig. 5 Charpy impact value versus temperature curves of base metal and weld metal with 19Cr-2Mo steel filler metal.

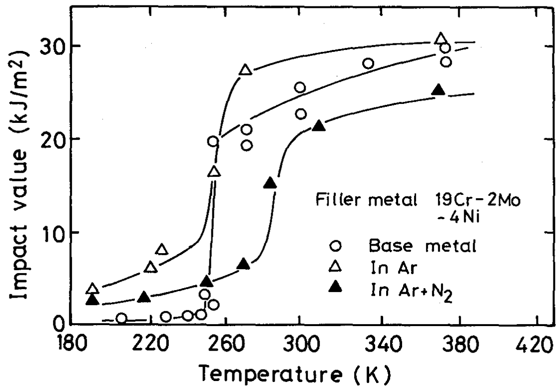

Fig. 6 Charpy impact value versus temperature curves of base metal and weld metal containing 4% Ni by 19Cr-2Mo steel filler metal.

4% nickel by 19Cr-2Mo steel filler metal. As shown in Fig. 5, the transition temperature of the weld metal without nickel is higher than that of the base metal. As shown in Fig. 6, the transition temperature of the weld metal with 4% nickel welded in argon is almost same as that of the base metal.

The increase in the transition temperature by the addition of nitrogen in the weld metal will be suppressed by the addition of 4% nickel.

Considering the progress of the toughness for the weld metal, the duplex structure consisting of the ferrite and austenite is considered to be promising.

Figure 7 indicates Charpy impact value versus temperature curves of the weld metal by type 316L filler metal. Air or nitrogen causes the increase in the transition temperature, but the transition temperature of the weld metal with nitrogen is lower than that of the base metal shown in Fig. 5. The presence of austenite in the ferrite structure causes the increase in the toughness as shown in Fig. 5.

Figure 8 indicates energy transition temperatures for various weld metals welded in argon or argon + 0.1% nitrogen shielding gas, as the weld metals were made by using various filler metals.

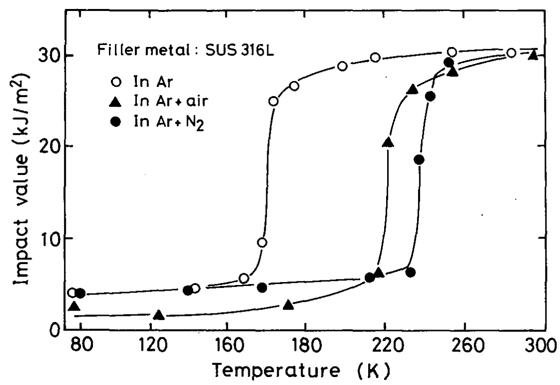

Fig. 7 Charpy impact value versus temperature curves of weld metal by type 316L filler metal.

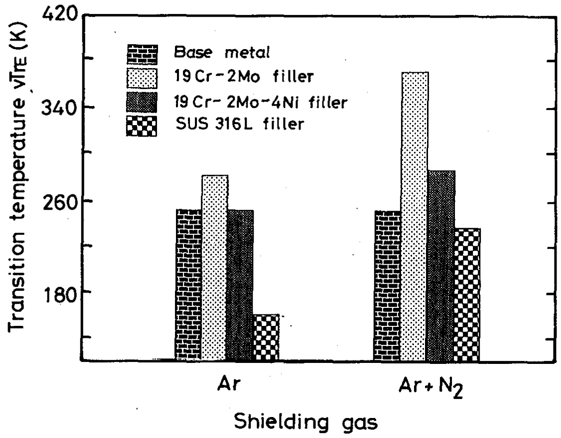

Fig. 8 Energy transition temperatures for various weld metals in argon or argon + 0.1% nitrogen shielding gas, as the weld metals were made by using various filler metals.

For using argon shielding gas, the transition temperature of the weld metal using 19Cr-2Mo filler wire is higher than that of the base metal. But, the increase of the transition temperature of the weld metal is suppressed by the addition of 4% nickel, and is the same temperature as that of the base metal. The transition temperature of the weld metal using SUS316L filler wire is far larger than that of the base metal.

For argon + 0.1% nitrogen shielding gas, the transition temperature of the weld metal using 19Cr-2Mo filler wire is far higher than that of the base metal. The transition temperature of the weld metal using SUS316L filler wire is almost same temperature as that of the base metal even though nitrogen above 400 ppm is included in the weld metal.

3.3 Fractography of the base metal and weld metal

Figure 9 shows tthe fracture morphology of the base metal using Charpy impact test. The fracture morphology tested at 300 K in the energy transition curve shows dimple pattern as shown in **Fig. 9-(a)**. The fracture morphology of the weld metal tested at 253 K showed the mixture mode of dimple fracture and partially cleavage fracture. The cleavage fracture morphology is shown in **Fig. 9-(b)**, and it is characteristic river pattern.

The fracture morphology of the weld metal tested at 243 K is observed the tongue on the cleavage fracture surface as shown in **Fig. 9-(c)**. The tongue occurs by the intersection of the deformation twin plane and cleavage plane.

Figure 10 shows the fracture morphology of the weld metal by 19Cr-2Mo steel filler metal. The fracture morphology of the weld metal tested at 293 K shows cleavage fracture with river pattern as shown in **Fig. 10-(a)**. This fracture pattern is same as that of the base metal shown in **Fig. 9-(b)**. The tongue is observed on the cleav-

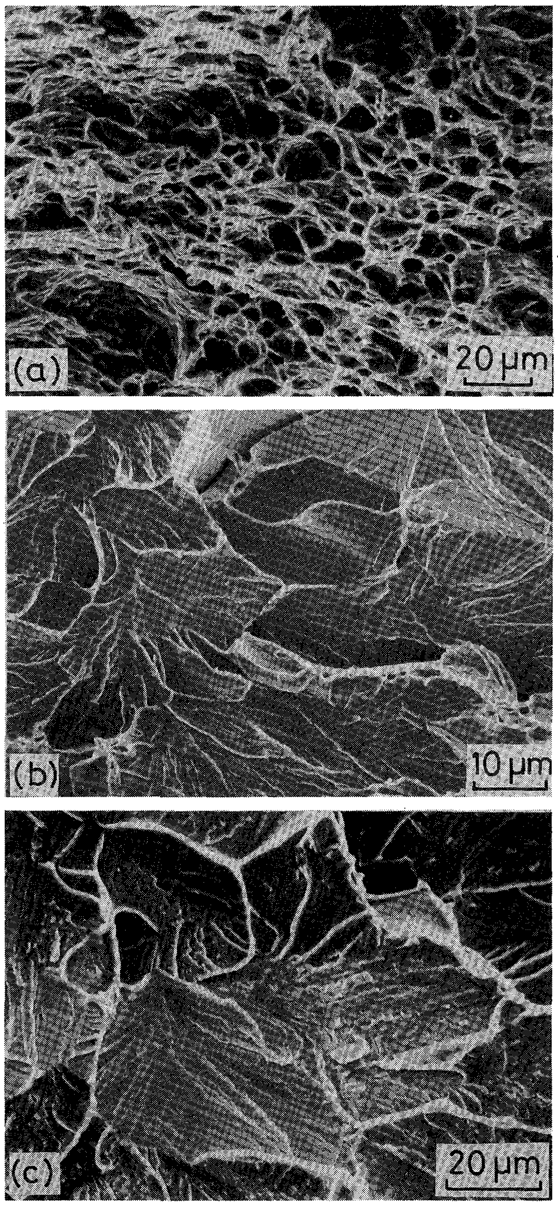

Fig. 9 Fracture morphology of base metal.
(a) Tested at 300 K., (b) Tested at 253 K., and
(c) Tested at 243 K.

age fracture partially. The facet size of the cleavage fracture of the weld metal is larger than that of the base metal. The fracture morphology of the weld metal tested at 273 K shows cleavage fracture with many tongues as shown in Fig. 10-(b). This fracture morphology shows that the considerable deformation twin occured during deformation prior the fracture.

For the argon + 0.1% nitrogen shielding gas, the fracture morphology tested at the temperature near the upper shelf energy indicated the mixture mode of the dimple pattern and partially cleavage fracture, as same as Fig, 9-(b). But many tongues are observed in the cleavage fracture. The fracture morphology of the weld metal tested at 370 K shows cleavage fracture with many tongues as shown in **Fig. 10-(c)**.

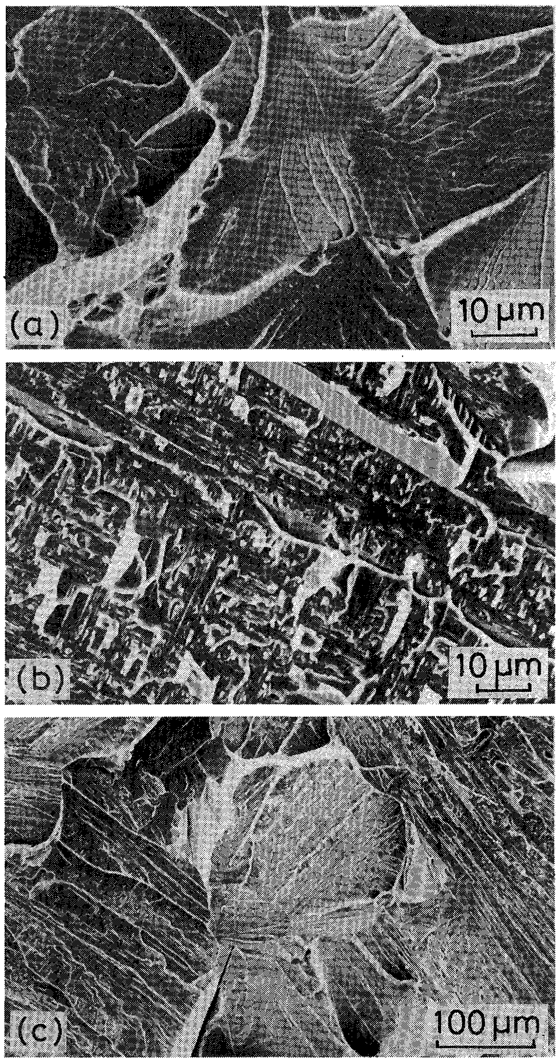

Fig. 10 Fracture morphology of weld metal by 19Cr-2Mo steel filler metal.
(a) Welded in argon, and tested at 293 K.
(b) Welded in argon, and tested at 273 K.
(c) Welded in argon + 0.1% nitrogen, and tested at 370 K.

Thus, the cleavage fracture with many tongues is observed in the high temperature side of the transition temperature for the weld metal included nitrogen. Consequently, it is concluded that nitrogen causes the deformation twin easily. It means that the temperature that the deformation twin occurs increases by the addition of nitrogen.

Figure 11 shows the fracture morphology of the weld metal containing 4% nickel by 19Cr-2Mo steel filler metal.

For the argon shielding gas, the fracture morphology of the weld metal tested at 250 K shows cleavage fracture with river pattern. The tongue on the cleavage fracture is hardly observed, namely, it means that the deformation twin hardly occured at the testing temperature. The fracture morphology of the weld metal tested at 288 K shows cleavage fracture with a little tongue as shown in **Fig. 11-(b)**.

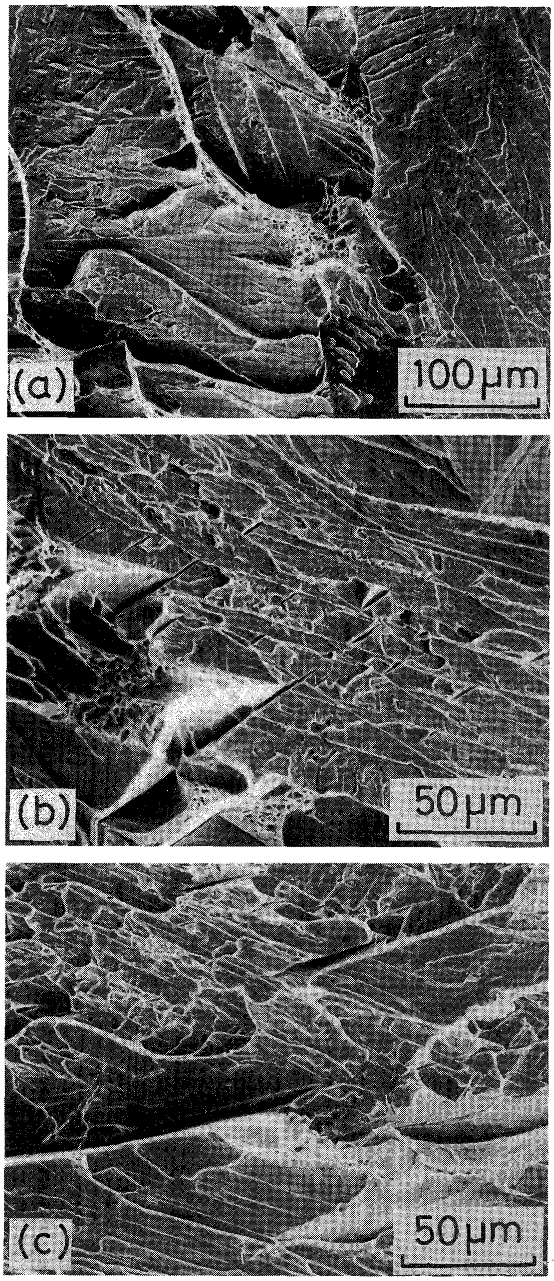

Fig. 11 Fracture morphology of weld metal containing 4% Ni by 19Cr-2Mo steel filler metal.
(a) Welded in argon, and tested at 250 K.
(b) Welded in argon, and tested at 288 K.
(c) Welded in argon + 0.1% nitrogen, and tested at 253 K.

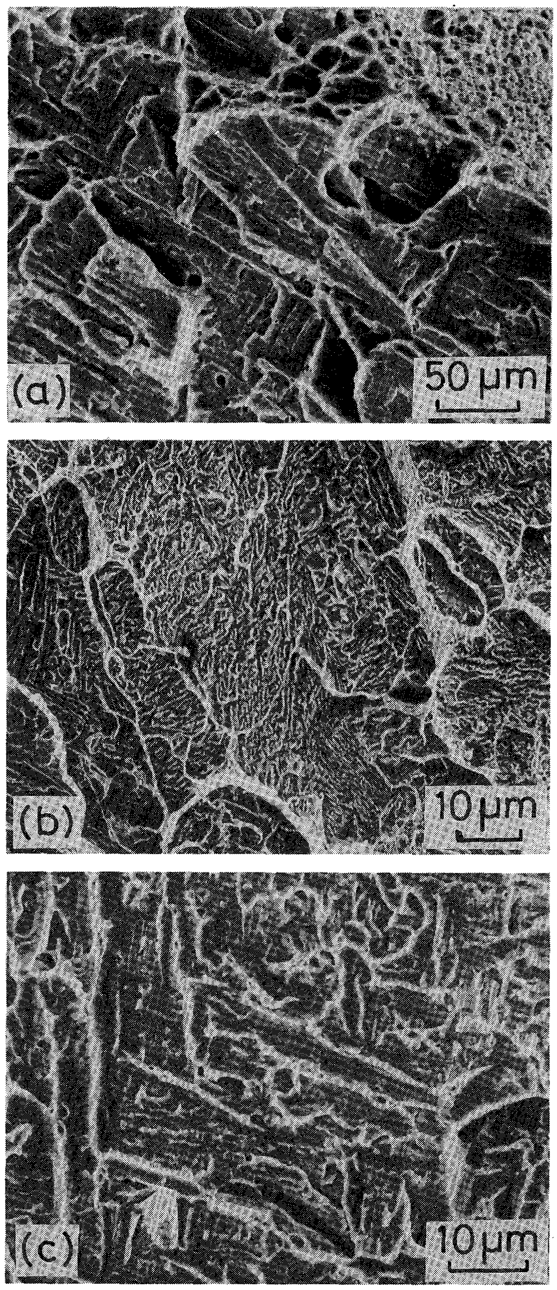

Fig. 12 Fracture morphology of weld metal by type 316L filler metal.
(a) Welded in argon, and tested at 123 K.
(b) Welded in argon + 0.1% nitrogen, and tested at 123 K.
(c) Enlarged (b).

The fracture morphology of the weld metal welded in argon + 0.1% nitrogen shows cleavage fracture with river pattern as shown in **Fig. 11-(c)**. The large tongues are observed on the cleavage fracture surface. This means that the deformation twin is suppressed by the addition of 4% nickel. It is considered that the deformation twin as well as slip deformation plays an important role for the initiation of the cleavage fracture on the basis of the direct and undirect observation technique.

The initiation of the twin or slip deformation depends on the Petch's relationship. Namely, the temperature that the deformation twin occurs increases with increasing grain size. And the initiation of the deformation twin causes the cleavage fracture or unstable fracture.

The presence of nitrogen in the metal causes the cleavage fracture. Consequently, the decrease of toughness for the weld metal is due to the large grain size on the contrary to the base metal, and nitrogen suppress the slip deformation and makes case of the deformation twin.

Generally, the addition of nickel to the weld metal plays the following roles. It makes fine the grain size[6], inhibits or accelerates the initiation of twin[9),10)], and makes the cross slip[11].

In the present study, the addition of nickel to the weld metal makes fine grain size, and suppress the initiation of the tongues on the fracture surface. It is considered that the addition of nickel makes the ease of cross slips, and suppress the initiation of the deformation twin. Nitrogerr suppress the slip deformation and accelerates the deformation twin, but the complexity effect occurs in the weld metal with both nitrogen and nickel.

Figure 12 shows the fracture morphology of the weld metal by type 316L filler metal. The fracture morphology of the weld metal welded in argon, and tested at 123 K shows cleavage fracture with tongue and tear ridges as shown in **Fig. 12-(a)**. The dimple pattern is also observed in the fracture surface. The austenite shows hardly cleavage fracture, but shows dimple pattern. Consequently, it is considered that tear ridges occurs in the austenite, and cleavage fracture occurs in the ferrite.

The fracture morphology of the weld metal containing 0.1% nitrogen, tested at 123 K shows quasi-cleavage fracture as shown in **Fig. 12-(b)**. In the fractographs enlarged (b) as shown in **Fig. 12-(c)**, considerable tear ridges are observed on the cleavage fracture.

Considering the microstructure shown in Fig. 4, the tear ridge occurs in the austenite and the area between tear ridge shows cleavage fracture with many tongues in the ferrite.

Consequently, the presence of nitrogen in the weld metal causes the inhibitation of the slip deformation and makes the ease of the deformation twin at elevated temperature and then causes the cleavage fracture at further high temperature.

However, the presence of nitrogen causes the increase of the volume fraction of the austenite, and results the progressing the toughness of the weld metal. The increase of the volume fraction of the austenite inhibits the decrease of the toughness, and the toughness becomes higher than that of the ferrite only.

For the duplex microstructure consisting of austenite and ferrite, the energy transition temperature is lower than that of the ferrite only. The reason is shown as follows. It is considered that the addition of nickel makes easy the cross slip, but inhibits the initiation of the deformation twin. The presence of the austenite causes the solution in the austenite of nitrogen, and nitrogen content in the ferrite decreases, and suppress the precipitation of Cr_2N in the ferrite and results the inhibitation of the deformation twin.

The presence of the austenite in the ferrite makes fine grain size of ferrite, as a result, the slip deformation occurs easily, and inhibits the deformation twin.

4. Conclusion

Effect of nitrogen and nickel on the toughness in weld metal of high purity ferritic stainless steel (19Cr-2Mo steel) was investigated by means of fractography. The results obtained in the present study are summarized as follows.

(1) For the weld metal by using 19Cr-2Mo steel filler metal in argon, the energy transition temperature in Charpy impact test raised to the value 30 K over that of the base metal. For the weld metal in argon + 0.15% nitrogen, the transition temperature raised 120 K. The fracture morphology at the transition-temperature of the weld metal containing 370 ppm nitrogen shows cleavage fracture with many tongues, and nitrogen makes easily the initiation of the deformation twin.

(2) For the weld metal by using 19Cr-2Mo steel filler wire with 4% nickel, the transition temperature was 40 K lower than that without nickel in each shielding gas. The fracture morphology at the transition temperature of the weld metal showed cleavage fracture with minor tongue. The addition of the 300 ppm nitrogen to the weld metal causes the increase of the transition temperature, but the increase of the temperature for the weld metal with 4% nickel is lower than that without nickel.

(3) The transition temperature of the weld metal containing 7.36% nickel by using type 316L filler metal was lower than that of the base metal, even though in 0.1% nitrogen containing argon.
The initiation of the twin causes the brittle fracture, which was inhibited by nickel and accelerated by nitrogen.
Consequently, the toughness of the weld metal was improved by the addition of nickel above 4%.

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