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Microstructure and Mechanical Properties of Duplex Stainless steel for Anchor Bolt Application

Gil Hwan Na , Woo Young Jung , and Tae Kwon Ha

Abstract**—**Most buildings have been using anchor bolts commonly for installing outdoor advertising structures. Anchor bolts of common carbon steel are widely used and often installed indiscriminately by inadequate installation standards. In the area where strong winds frequently blow, falling accidents of outdoor advertising structures can occur and cause a serious disaster, which is very dangerous and to be prevented. In this regard, the development of high-performance anchor bolts is urgently required. In the present study, 25Cr-8Ni-1.5Si-1Mn-0.4C alloy was produced by traditional vacuum induction melting (VIM) for the application of anchor bolt. The alloy composition is revealed as a duplex microstructure from thermodynamic phase analysis by FactSage® and confirmed by metallographic experiment. Addition of Nitrogen to the alloy was found to reduce the ferritic phase domain and significantly increase the hardness and the tensile strength. Microstructure observation revealed mixed structure of austenite and ferrite with fine carbide distributed along the grain and phase boundaries.

Keywords**—**Anchor bolt, Duplex stainless steel, FactSage®, Hardness, Thermodynamic phase analysis.

I. INTRODUCTION

RECENTLY unusual change in the weather has been a serious issue all over the world. In the area where strong winds frequently blow, falling accidents of outdoor advertising structures can occur and cause a serious disaster, which is very dangerous and to be prevented. Anchor bolts of common carbon steel are widely used and often installed indiscriminately by inadequate installation standards. Most of the buildings have been commonly using anchor bolts and angles for installing outdoor advertising structures. Mechanical properties of anchor bolts are very important and damages caused by strong winds or poor construction can be reduced through adopting high-performance materials.

A wide variety of bolts and angles are produced from low carbon steels for building and bridge construction. Steels with low carbon content but containing additions of Nb, V, and Ti are called microalloyed or high strength low alloy (HSLA) steels. Usually anchor bolts of the common carbon steel are divided into hypo-eutectoid steel and hyper-eutectoid steel in accordance with 0.8wt% carbon content. Microstructure and strength according to the amount of carbon are very different from each other. With increasing carbon content, the strength of steel generally increases but it can easily break down. [1]

Duplex stainless steels have a mixed structure of bcc ferrite and fcc austenite. The exact amount of each phase is a function of composition and heat treatment. Most alloys are designed to contain about equal amounts of each phase in the annealed condition. The principal alloying elements are chromium and nickel, but nitrogen, molybdenum, copper, silicon, and tungsten may be added to control structural balance and to impart certain corrosion-resistance characteristics. The specific advantages offered by duplex stainless steels over conventional 300-series stainless steels are strength (about twice that of austenitic stainless steels), chloride stress corrosion cracking (SCC) resistance, and pitting corrosion resistance. [2] These materials are used in the intermediate temperature range (about -60 to 300^{o}C) where resistance to acids and aqueous chlorides is required. Duplex stainless steels have found widespread use in a range of industries, particularly the oil and gas, petrochemical, pulp and paper, and pollution control industries.

In the present study, it has been attempted to apply a duplex stainless steel to the construction, especially to installation of outdoor advertizing structures, where both high strength and corrosion resistance are required at the same time. Two ingots were cast in this study for this purpose. Microstructure observation and mechanical tests such as hardness and tensile tests were carried out. Thermodynamic calculation for phase equilibrium has also been carried out and the effect of nitrogen addition has been analyzed.

II. EXPERIMENTAL PROCEDURES

TABLE I
CHEMICAL COMPOSITIONS OF DUPLEX STAINLESS STEELS USED IN THIS STUDY. (WT.%)

No.	Cr	Ni	Si	N	Mn	C	Fe
1	25	8	1.5	0	1.0	0.4	Bal.
2	25	8	1.5	0.3	1.0	0.4	Bal.

Duplex stainless steels were cast by vacuum induction melting (VIM) into the ingots with dimensions of 350 mm × 350 mm × 100 mm. The chemical compositions of the ingots are listed in Table 1. The ingots were solution heat treated at 1200^{o}C for 2 hrs followed by furnace cooling. Microstructure observation revealed primarily austenite, ferrite, and some carbides precipitated along grain or phase boundaries. To predict thermodynamically stable phases and their fractions, phase equilibrium was calculated with FactSage® and database of FSStel®. After cutting the ingots longitudinally, microstructure of the duplex stainless steels was observed using optical microscopy and scanning electron microscopy. To investigate the stability of microstructure, aging treatment was conducted at 1230^{o}C for 1 to 64 hrs, followed by microstructure observation and hardness test.

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Etchant consisting of 3 parts Nitric acid, 2 parts Hydrochloric acid and 1 part distilled water was used. Hardness was measured by Rockwell B scale using 100 kgf load. Tensile and compression test specimens were also machined along longitudinal direction.

III. RESULTS AND DISCUSSION

Figure 1 is the result obtained from thermodynamic calculation using FactSage® and showing stable phases and their fractions. It is apparent that main constituent phases are fcc austenite and bcc ferrite and that the carbides can occur from the liquid phase. Interestingly, with addition of nitrogen, fraction of austenitic phase at high temperature obviously increases and Cr_2N is expected to precipitate simultaneously with carbides from above 1100°C. Equilibrium fraction of bcc ferrite is above 0.6 at room temperature and sigma phase is expectedly to form at 700°C and disappear below 530°C, which is very important phase determining mechanical property of duplex stainless steel during not only fabrication but application. [3]

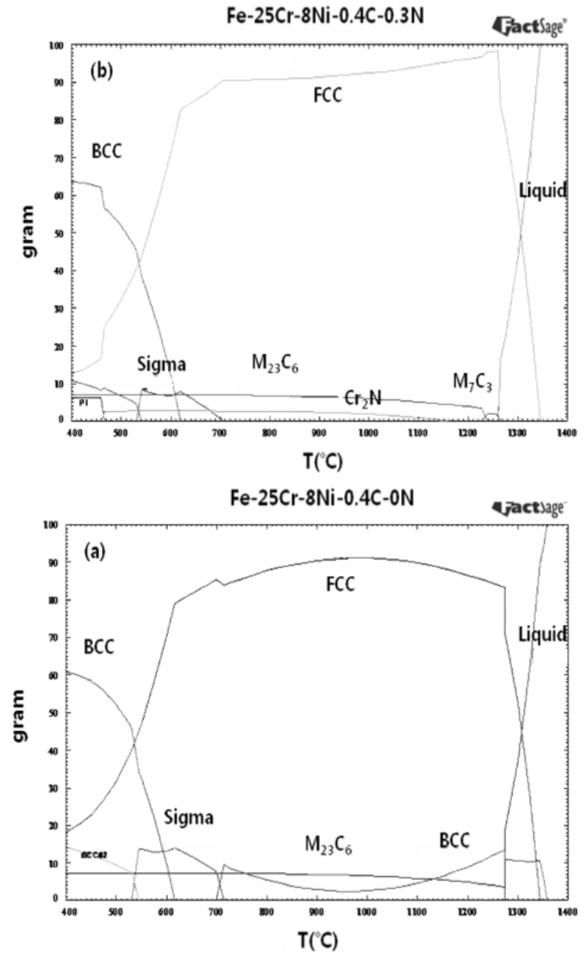

Fig. 1 Calculated phase equilibrium showing stable phases and their fractions for (a) alloy No. 1 and (b) 2

Nitrogen has a multiple effect on stainless steels by increasing pitting resistance, austenite content and strength. [4] This effect is enhanced in the presence of Mo and it has been suggested that Mo and N have a synergistic influence on pitting characteristics. [5] Nitrogen partitions preferentially to the austenite due to the increased solubility in the phase and also concentrates at the metal-passive film interface. [6]

During prolonged passivation of stainless steels in acid solutions, surface nitrogen enrichment has been witnessed, which explains how nitrogen can influence repassivation. Nitrogen has also been noted to increase the crevice corrosion resistance, which is due to nitrogen altering the crevice solution chemistry or by segregating to the surface, which is in keeping with the mechanism for enhanced pitting resistance. [2]

Another important property of nitrogen is its ability to stabiliser duplex alloys against the precipitation of intermetallic phase, such as sigma and chi, by reducing Cr-partitioning. [7-9] It is also reported that increasing the nitrogen level actually reduces the risk of nitride formation. This may appear contradictory, but is due to an increase in austenite content and so a reduction in the distance between austenite islands.

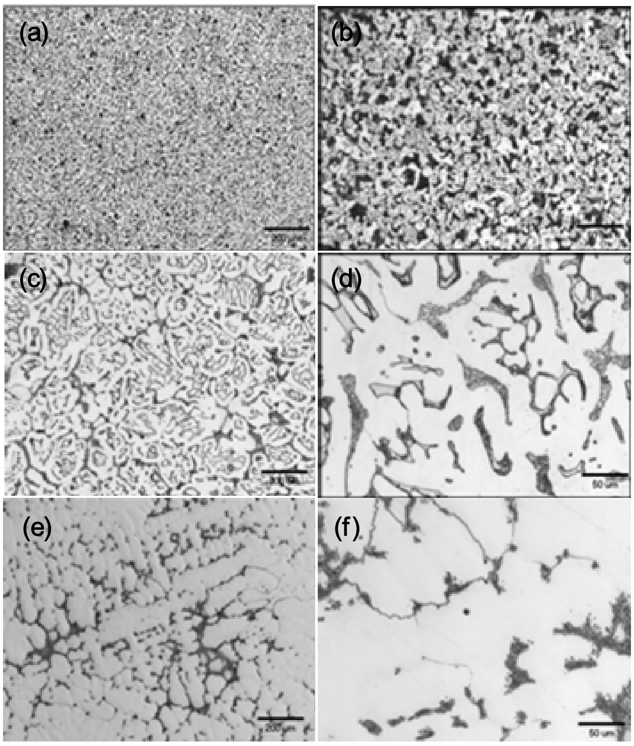

Fig. 2 Optical microstructures of anchor bolt made of medium carbon steel (a and b), the ingot No. 1 (c and d) and the ingot No. 2 (e and f)

Figure 2 shows microstructures of the ingots observed by optical microscope and together with those of anchor bolt made of carbon steel (Fig. 2(a) and (b)). In the case of carbon steel, typical microstructure consisting of bright ferritic phase and dark pearlitic phase was observed. Grain size was very fine and measured as about 10μm. Duplex microstructure is also observed in the ingot without nitrogen (No. 1) as shown in Fig. 2(c) and (d), but is totally different from that of carbon steel. Bright phase in Fig. 2(c) is austenite (γ) and dark one ferrite (α), of which the fraction is measured as about 0.2.

On the other hand, the microstructure of the ingot with nitrogen (No. 2) in Fig. 2(e) and (f) shows nearly austenitic single phase and precipitates along grain boundaries. Precipitates were determined as carbo-nitrides. Phase fraction of ferrite measured was very low comparing with thermodynamic calculation in Fig. 1, which is because the kinetics is not considered in the thermodynamic calculation.

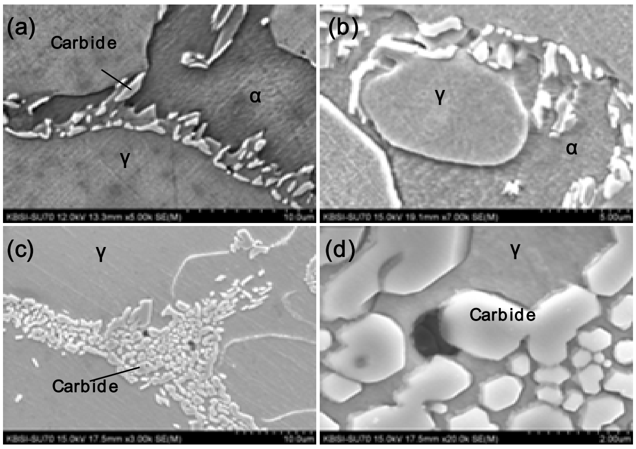

Fig. 3 Back scattered SEM images of the ingot No. 1 (a and b) and No. 2 (c and d)

Figure 3 is scanning electron micrograph showing constituent phases, obtained by back scattered electron mode. In both ingots, a lot of carbides particles can be observed along the grain or phase boundaries. In the case of the ingot with nitrogen, typical appearance of eutectic carbide (Fig. 3(c)) is apparent. It is very interesting to note that island type austenite phase has been observed with carbide particles distributed near interfaces.

The addition of C and N strengthens both ferrite and austenite by dissolving at interstitial sites in the solid solution. And yet, as carbon is undesirable in stainless steel, due to the risk of sensitization, the addition of nitrogen is preferred. Further, as nitrogen is a strong austenite stabiliser its addition to duplex stainless steel suppresses austenite dissolution and encourages austenite reformation in the heat affected zone (HAZ) in a weldment.

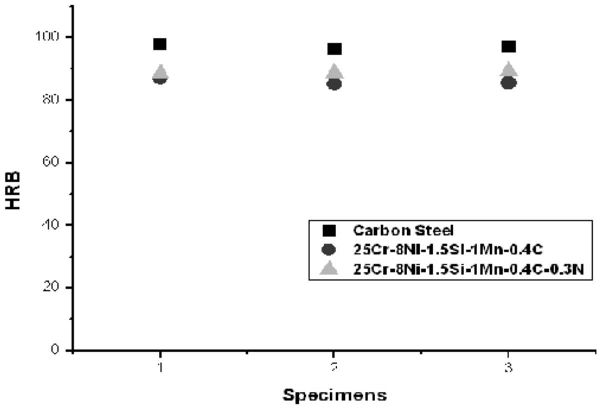

Fig. 4 Hardness test result obtained from solution treated ingots and medium carbon steel

Figure 4 shows hardness test result obtained from the ingots after solution treatment. Hardness of anchor bolt, which has been widely used, made of medium carbon steel was given together. Interestingly, hardness of medium carbon steel is comparable with and somewhat higher than those of duplex stainless steel fabricated in this study. Pearlitic phase in high fraction and small grain size of medium carbon steel are attributed to the high value of hardness. The existence of high amount of pearlite is, however, detrimental to ductility, corrosion and fatigue resistance.

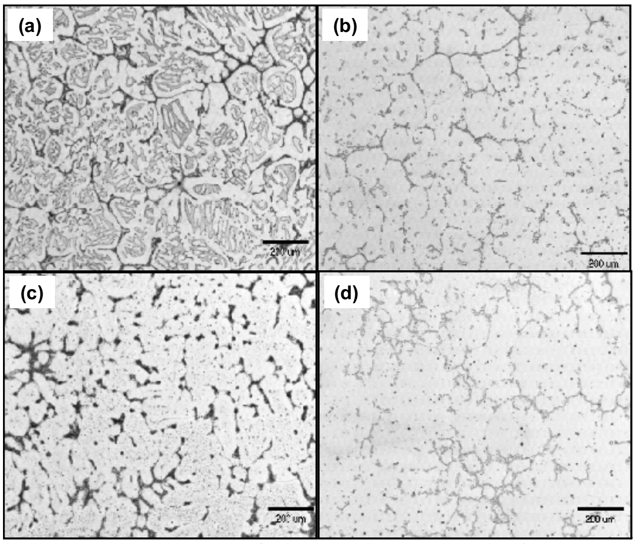

Fig. 5 Micrographs obtained after annealing the ingot No. 1 for 1 hr (a) and 64 hrs (b) and the ingot No. 2 for 1 hr (c) and 64 hrs (d) at 1230^{o}C

Figure 5 shows optical microscopy results of specimens obtained from high temperature exposition annealing at 1230^{o}C up to 64 hrs to examine the stability of microstructure. With annealing time increased up to 64 hrs, it is apparent that duplex phase structure (Fig. 5(a)) became single phase structure of austenite (Fig. 5(c)). Dissolution and reprecipitation of carbides were also observed in both ingots. In the early stage of annealing dissolution of carbides occurred and followed by reprecipitation and spheroidization after 16 hrs. Reprecipitation of carbides occurred not only along the interfaces but also in the grain matrices, which increased hardness of duplex stainless ingots as shown in Fig. 6. In the figure, for comparison, hardnesses of as cast ingot measured before annealing experiment are displayed with solid rectangular marker together. It is obvious that annealing at 1230^{o}C increase the hardness although the extent is small and this is caused by reprecipitation of carbides.

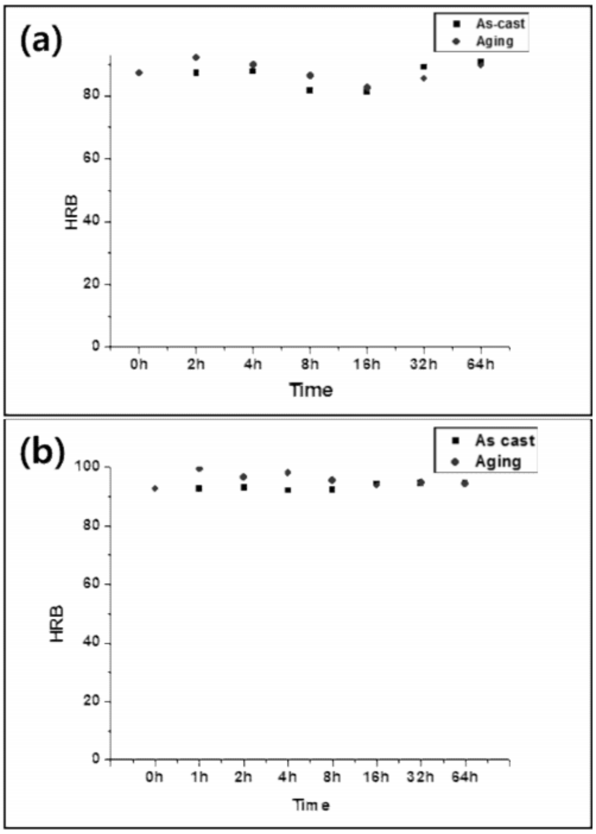

Fig. 6 Hardness test result obtained after annealing the ingot No. 1 (a) and No. 2 (b) at 1230^{o}C for up to 64 hrs

IV. CONCLUSIONS

Duplex stainless ingots were cast and evaluated to attempt application of the alloy to the construction, especially to installation of outdoor advertizing structures, where both high strength and corrosion resistance are required at the same time. Microstructure observation, high temperature annealing test and hardness test were carried out. Thermodynamic calculation for stable phases and their fractions revealed that main constituent phases are fcc austenite and bcc ferrite and that the carbides can occur from the liquid phase.

Duplex microstructure was observed in the ingot without nitrogen, austenite (g) and ferrite (a), and the fraction of ferrite was about 0.2. On the other hand, the microstructure of the ingot with nitrogen showed nearly austenitic single phase and precipitates along grain boundaries. With annealing at 1230^{o}C, duplex phase structure became single phase structure of austenite and dissolution and reprecipitation of carbides were also observed. Reprecipitation of carbides occurred both at interfaces and in the matrices, which increased hardness of duplex stainless ingots.

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