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Effect of hot rolling and cooling conditions on intergranular corrosion behavior in Alloy625 clad steel

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ABSTRACT

The effects of hot rolling and subsequent cooling conditions on intergranular corrosion behavior in Alloy625 clad steel were investigated. Intergranular corrosion resistance of Alloy625 at finishing rolling temperatures (FT) ranging from 800 °C to 900 °C was almost the same as that of solution treatment. Corrosion rate of 750 °C FT increased due to sensitization by precipitations. Corrosion rate also increased at 1000 °C FT, but this is not due to sensitization. Preferential corrosion at recrystallized grain boundaries due to an anodic reaction concentration is a possible mechanism. Corrosion rate of Alloy625 which was air-cooled after rolling increased owing to grain boundary segregation.

1. Introduction

Corrosion Resistant Alloy (CRA) clad steels have drawn much attention because of their wide variety of fields of application in harsh environments [1–5]. CRA clad steels consist of a CRA layer for corrosion resistance and a carbon steel for mechanical properties. Manufacturing processes for clad steel are categorized into hot roll bonding, explosive bonding and weld overlaying. The hot roll bonding process has an economical advantage over the other processes, as well as better productivity [1,6]. Conventional CRA are solution treated to ensure corrosion resistance. However, solution treatment (ST) is not used with CRA clad steels as the mechanical properties of the carbon steel are deteriorated by γ grain coarsening. Therefore, quench and temper (Q-T), normalizing and the thermo-mechanical control process (TMCP) are preferable for clad steels [7,8]. TMCP which had been developed as steel plate toughening technology makes it possible to avoid the precipitation nose by accelerated cooling after hot rolling of CRA. Thus, CRA clad steels processed through TMCP have a good balance of corrosion resistance in CRA layer and mechanical properties of carbon steels [3,5,9–11].

Nickel based Alloy625 is known to be suitable for harsh environmental conditions such as high concentrations of Cl^-, H_2S, CO_2 and other corrosive chemicals [12–14]. Therefore, Alloy625 clad steel has been applied to oil and gas transportation facilities, pipelines, offshore structures and chemical plants [15–17]. Alloy625 contains Cr and Mo, which ensure corrosion resistance. It was reported that carbides and intermetallics precipitated at the grain boundary in Alloy625 at temperatures ranging from 600 °C and 1000 °C with long holding time, deteriorating the corrosion resistance of Alloy625 under particular corrosion environment such as the Streicher test (ASTM G28 method A) [18,19]. When TMCP is used to manufacture Alloy625 clad steel, the precipitation temperature range is likely to overlap the rolling temperature range. M. Prohaska et al. investigated the effect of finishing rolling temperatures (FT) of 850 °C and 950 °C on intergranular corrosion behavior of Alloy625 with a carbon content of 0.02 mass% by the Streicher test [20], and reported that the corrosion rate with ST was slightly lower than that with TMCP. However, the effects of hot rolling and subse-

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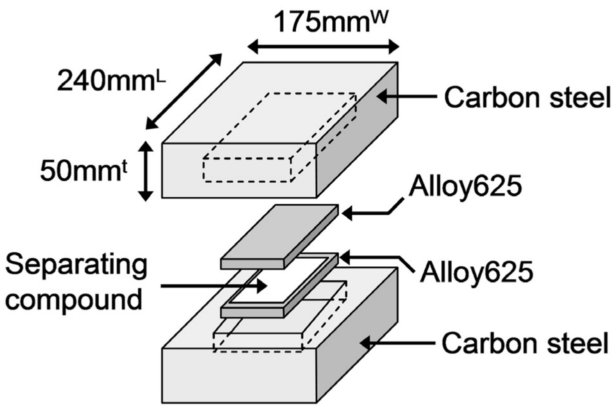

Fig.1. Assembled clad slabs for hot rolling.

Table 1
Chemical composition of examined Alloy625 (mass%).

C	Si	Mn	P	S	Ni	Cr	Mo	Nb	Fe	Al	Ti
0.01	0.13	0.07	0.003	<0.001	61.4	21.9	9.0	3.79	3.2	0.19	0.30

Table 2
Hot rolling conditions of Alloy625 clad steel.

No	Slab reheating temperature (°C)	Finishing rolling temperature (°C)	Cooling condition
a	1150	750	Accelerated cooling
b	1150	800	Accelerated cooling
c	1150	900	Accelerated cooling
d	1150	1000	Accelerated cooling
e	1150	750	Air cooling
f	1150	800	Air cooling
g	1150	900	Air cooling
h	1150	1000	Air cooling

quent cooling conditions on the intergranular corrosion behavior and mechanisms in Alloy625 clad steel have not yet been clarified.

The aims of this paper are to investigate the effects of hot rolling and subsequent cooling conditions on intergranular corrosion behavior in Alloy625 by the Huey test and the Streicher test, and to consider the mechanisms responsible for changes in the corrosion rate from the microstructural viewpoint

2. Experimental

2.1. Clad slab assembly

Slabs with dimensions of 100 mm^t × 175 mm^W × 240 mm^L for Alloy625 clad steel were assembled in a "sandwich" type like general commercial slabs, as shown in Fig. 1. The chemical composition of the Alloy625 examined in this research is shown in Table 1. Two Alloy625 plates of 10 mm thickness were set in drilled holes in carbon steel slabs, Al_2O_3 powder was placed between the two Alloy625 plates to separate the top and bottom clad plates, and the frame of assembled slabs was welded by electron beam welding under a vacuum of 10^{-4} torr, after which the slabs were hot rolled.

2.2. Hot rolling and heat treatment

The assembled clad slabs were hot rolled in the laboratory under the conditions shown in Table 2. The slabs were reheated to 1150 °C and rolled down to a 20 mm thickness with FT of 750 °C, 800 °C, 900 °C and 1000 °C. The rolled clad plates were cooled by accelerated cooling (ACC) by water or air-cooled (A.C.) after hot rolling. The cooling rate was approximately 7 °C/s in ACC and 0.5 °C/s in A.C. In ACC, the accelerated cooling stop temperature was controlled to around 500 °C, followed by air-cooling to room temperature. For comparison, sample (h) was also used to prepare the heat-treated sample (i) by solution treatment. As shown in Table 3, this ST sample was heat treated at 1150 °C and water quenched. Circumference of rolled and heat treated plate was cut off and a couple of clad steel plates were obtained from each plate. The thickness of the Alloy625 clad steel plates after hot rolling was 10 mm.

Table 3
Heat treatment condition of Alloy625 clad steel.

No	Heat treatment condition
i	Solution treatment : 1150 °C-30 min

Table 4
Chemical content of test solutions in the Huey test and the Streicher test.

Corrosion test	Chemical content of solution
The Huey test	65 mass% HNO_3
The Streicher test	50 mass% H_2SO_4 – 25g/600ml $Fe_2(SO_4)_3$

2.3. Specimens

Specimens with dimensions of 1.5 mm^t × 20 mm^W × 30 mm^L were machined from the covered Alloy625 in the clad steel for use in intergranular corrosion tests and electrolytic extraction. These specimens were wet-grinded up to 600 grit, degreased with ethanol, and then dried in blowing air. Specimens of the longitudinal cross section were etched by 400 ml hydrochloric acid (HCl), 100 ml nitric acid (HNO_3), 100 g iron (III) chloride ($FeCl_3$), 50 g benzenesulfonic acid sodium salt ($C_{18}H_{29}NaO_3S$), 50 ml surface-active agent and 25 ml water for microstructural observation. The microstructure of Alloy625 at the quarter thickness was observed with an optical microscope.

2.4. Intergranular corrosion test

Intergranular corrosion tests were conducted by the Huey test (ASTM A262 Practice C) and the Streicher test (ASTM G28 method A) [21,22]. In the Huey test, the specimens were immersed in boiling nitric acid (NO_3) for 48 h, after which the weight loss was measured. This procedure was repeated five times, and the average corrosion rate was evaluated. In the Streicher test, the specimens were immersed in boiling ferric sulfate ($Fe_2(SO_4)_3$) and sulfuric acid (H_2SO_4) for 120 h, after which the weight loss was measured. The chemical content of test solutions in the Huey test and the Streicher test is shown in Table 4. The Huey test is an examination to evaluate corrosion resistance near the transpassive region, while the Streicher test is used to evaluate corrosion resistance at a lower corrosion potential than that of the Huey test [23–25]. The surface of corroded specimens was observed with a scanning electron microscope (SEM) at the accelerating voltage of 15 kV.

2.5. Precipitation analysis by XRD

Analysis of precipitation in Alloy625 was conducted for hot rolled and heat-treated specimens. Electrolytic extraction was carried out with a constant current at 20 mA/cm^2 by 10 vol.% acetylacetone ($C_5H_8O_2$), 1 mass% tetramethyl ammonium chloride ($C_4H_{12}NCl$) and methanol (CH_4O). The extracted residues of each specimen were caught with a membrane filter with a pore size of 0.2 mm and analyzed by X-ray diffraction (XRD).