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Effect of aluminum on microstructure, mechanical properties and pitting corrosion resistance of ultra-pure 429 ferritic stainless steels

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ABSTRACT

Effect of aluminum on microstructure, mechanical properties and pitting corrosion resistance of ultra-pure 429 ferritic stainless steels has been investigated. Aluminum can significantly increase the ratio of equiaxed crystal grains, but the promotion effect has great relation with aluminum content. Aluminum can stabilize ferrite phase and significantly reduce recrystallization temperature. Increased aluminum content can also lead to the precipitate of AlN and Al_2O_3 at higher temperature. The increased amount of AlN may partly contribute to the reduced nitrogen element to form austenite at high temperature, hence the high temperature phase transformation of $\alpha + \gamma \rightarrow \alpha$ occurs. The fine and large number of Al_2O_3 particles can refine grain size and then promote recrystallization. The highest intensity of γ-fiber texture $\{111\}\langle 112\rangle$ is observed in the steel with 0.19 wt.% aluminum, which can improve the formability of steels. With the increase of aluminum content, the tensile strength increases linearly but the elongation and plastic strain ratio first increase then decrease, the working hardening index varies slightly among the steels. Appearance of Al_2O_3 inclusions with small size and decreased content of MnS benefit pitting corrosion resistance. However, the large dimension Al_2O_3 inclusions have significantly negative influence on pitting corrosion resistance.

1. Introduction

Ferritic stainless steels are widely used in automobile industry, kitchen appliances and manufacturing industries due to the relatively higher thermal conductivities and lower thermal expansions, excellent oxidation and corrosion resistance, and relatively lower cost with respect to austenitic stainless steels [1–8]. The combination of excellent properties and low cost made ferritic stainless steels more attractive in various industrial and civil applications. However, the formability of the conventional ferritic stainless steels was not as good as that of austenitic stainless steels. For example, the defect of ridging behavior has received extensive attention because the excellent surface quality is of great significance for ferritic stainless steels [9]. In order to achieve a comparable or even better performance over austenitic stainless steels, micro-alloying and high purification are applied in ferritic stainless steels [10]. Hence, the development of ultra-pure ferritic stainless steels with improved formability has been introduced.

Ultra-pure ferritic stainless steels stabilized with micro-alloying elements like Ti or Nb are believed to be the suitable replacement for conventional Cr–Ni austenitic stainless steels in specific applications [11]. The addition of Ti or Nb into ferritic stainless steels can refine grain size and improve the equiaxed crystal grain ratio [12]. The severity of ridging has great relation with the solidification structure of ferritic stainless steels. Hamada et al. [13] confirmed that the columnar grain specimen exhibited severer ridging than the equiaxed grain specimen of hot-rolled sheet. For solidification structure of ferritic stainless steels, this means more columnar grains and fewer equiaxed grains. Ever if rolled and heat treated, this kind of structure can also inherit and cause negative impacts on properties of final sheet steel such as bad mechanical and deformation properties.

With the development of metallurgical technologies, it is possible to decrease the amount of C and N to a very low level in ferritic stainless steels and improve the formability. But low C and N contents make the reduction of high melting point inclusions from liquid steel, which leads to the reduced amount of effective nucleation particles in the process of solidification. So elements such as Ti, Al, Nb and Ca were added into ferritic stainless steels to improve the solidification structure by precipitating the high melting point

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particles [14–18]. Among those elements, aluminum is an optimizing candidate because the precipitation temperature of Al_2O_3 is very high, and it suits to be as heterogeneous nucleation particles to increase the ratio of equiaxed crystal grains of casting structure. Villafuerte et al. [19] investigated the columnar equiaxed transition in gas-tungsten arc welds on ferritic stainless steel plates and found that the equiaxed fraction increased and the size of the equiaxed grains decreased with increased aluminum content to about 0.04 wt.%. What is more, aluminum is a very cheap alloy element and it cannot increase the cost of stainless steels.

So the purpose of this study is to investigate the effect of aluminum on microstructure, mechanical properties and pitting corrosion resistance of ultra-pure 429 ferritic stainless steels. The optimized formability has been discussed through equiaxed crystal grain ratio, recrystallization texture and plastic strain ratio analyses. The relationships among improved mechanical properties, pitting corrosion resistance, grain size variation, inclusions and aluminum contents have been discussed by both experimental observations and phase calculations.

2. Experimental details

The chemical compositions of the base and aluminum (Al = 0, 0.08, 0.19 and 0.42 wt.%) modified ultra-pure 429 ferritic stainless steels are shown in Table 1. The steels were prepared in a high frequency induction furnace. The casting ingots respectively designated as A1, A2, A3 and A4 were forged into slabs with a thickness of 40 mm. After being reheated to 1150 °C, the slabs were hot rolled to plates with a thickness of 4 mm. The hot rolled plates were annealed at 900 °C for 4 min, and then cold rolled to the final thickness of 1 mm. Finally, the sheet was recrystallization annealed at 900, 950, 1000 and 1050 °C for 1 min, respectively.

The equilibrium phase diagrams of the steels were calculated by Thermo-Calc software. Metallography preparation consisted of SiC paper grinding followed by diamond paste polishing and a final etching with the mixed solution of $FeCl_3$: HCl: H_2O = 5 g: 50 ml: 100 ml. The texture samples were prepared from annealing steel sheets with dimensions of 20 mm × 20 mm × 1 mm. The measured surface of sample was prepared by grinding using SiC papers from No. 150 to 1000. Then the measured surface was corroded by diluted hydrochloric acid to eliminate the surface stress. The texture of the samples was investigated by X-ray diffraction (X′ Pert PROMRD of Philip Company).

The morphology and composition of precipitates were analyzed by scanning electron microscopy (FEI Quarter 400 SEM) equipped with energy dispersive spectroscopy (Genesis XM4 EDS). Room temperature tensile tests were carried out by INSTRON 5581 tensile testing machine according to JIS5 standard along the rolling direction. A strain rate of $0.4 \times 10^{-3}\ s^{-1}$ was employed for room temperature tensile tests to determine the mechanical properties including ultimate tensile strength (σ_b), yield strength (σ_s), elongation (ε), plastic strain ratio (r) and work hardening index (n).

Polarization tests of each sample were performed at least three times to ensure the reproducibility of the results by using an EG&G Princeton Applied Research Potentiostat/Galvanostat Model 273A. Pitting corrosion samples were progressively wet ground up to 1200 grit SiC papers and then well rinsed in water, and the edges of the exposed samples were mounted with an epoxy resin. Then the samples with an area of 1 cm^2 were tested in 3.5 wt.% NaCl solution at 25 °C. The saturated calomel electrode (SCE) was used as a reference electrode, a platinum foil was served as the counter electrode, and open circuit potential (V_{OC}) measurements were carried out for 2500 s. The polarization scan started at $-0.3V_{SCE}$ below V_{OC} until $1.0V_{SCE}$ with a scan rate of 1 mV/s.

3. Results and discussion

3.1. Effect of aluminum on microstructure and texture

3.1.1. Ratio of equiaxed crystal grains and microstructure after recrystallization

The ratio of equiaxed crystal grains of the casting structure for A1–A4 steels has been measured. The ratio of equiaxed crystal grains of casting structure is about 30% for A1 steel, and the ratio increases to about 42% with the addition and increase of aluminum to about 0.08 wt.%. The ratio of equiaxed crystal grains gets to the maximum value of about 55% when aluminum content is about 0.19 wt.%. However, the ratio of equiaxed crystal grains decreases to about 47% when aluminum content further increases to about 0.42 wt.%. So aluminum can significantly increase the ratio of equiaxed crystal grains of the casting structure for ultra-pure 429 ferritic stainless steels, but the promotion effect of forming the equiaxed crystal grains has great relation with aluminum content.

The optical micrographs of A1 steel after cold rolling and recrystallization annealing from 900 to 1050 °C for 1 min are shown in Fig. 1. The typical cold rolled structure can be clearly seen from Fig. 1(a), and the thickness of well-developed cold rolling fiber structure varies at different regions after annealing at 900 °C for 1 min. The enlarged inset image shows that very small recrystallized new grains with average size 8–10 μm can be identified at regions with large deformation. More recrystallized new grains appear after annealing at 950 °C for 1 min (Fig. 1(b)) and elongated grain structure along cold rolling direction forms after annealing at 1000 °C for 1 min (Fig. 1(c)). The recrystallization completes and the original small recrystallized new grains grow up after annealing at 1050 °C for 1 min (Fig. 1(d)).

Recrystallization reaches completion after annealing at 900–1050 °C for 1 min with the addition of aluminum into ultra-pure 429 ferritic stainless steels, and Fig. 2 shows the typical morphologies and average grain sizes of A2–A4 steels after cold rolling and annealing at 1000 °C for 1 min. Although the average grain size for each steel is very stable with the increase of recrystallization annealing temperature from 900 to 1050 °C, the average grain size decreases apparently with the increase of aluminum content from about 0.08 to 0.19 wt.% (Fig. 2(a) and (b)), and the average grain size of A4 steel decreases slightly compared with that of A3 steel when aluminum content further increases to about 0.42 wt.% (Fig. 2(c)). So the addition of aluminum can significantly decrease the recrystallization temperature and the increase of annealing temperature does not increase the average grain size dramatically. But the increase of aluminum content can reduce the grain size after cold rolling and following annealing, and the degree of grain size reduction depends on aluminum content (Fig. 2(d)).

Table 1
Chemical compositions of the steels with various aluminum contents (wt.%).

Steel	C	N	O	S	P	Si	Mn	Al	Cr	Fe
A1	0.012	0.012	0.013	0.004	0.017	0.23	0.24	–	15.14	Bal.
A2	0.012	0.012	0.017	0.006	0.017	0.24	0.22	0.08	15.16	Bal.
A3	0.011	0.015	0.016	0.005	0.017	0.27	0.25	0.19	15.17	Bal.
A4	0.011	0.012	0.021	0.003	0.018	0.29	0.26	0.42	15.18	Bal.