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Effects of cerium addition on solidification structure and mechanical properties of 434 ferritic stainless steel

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Abstract: Effects of Ce refiners on the solidification structure and the mechanical property of ferritic stainless steel were investigated, the corresponding mechanisms were also discussed. The results showed that the solidification of the ferritic stainless steel was remarkably refined with 0.011 wt.% Ce and 0.023 wt.% Ce refiners. Ce played a great role of inclusion modification and the shape and size of the inclusions were changed by adding Ce. And after adding rare earth Ce, great amounts of high-melting point rare earth Ce inclusions (Ce_2O_3 and Ce_2O_2S) were formed. The fracture mode of 434 ferritic stainless steel was typical cleavage fracture, however, the ductility and the toughness of ferritic stainless steel was remarkably enhanced with 0.011 wt.% Ce and 0.023 wt.% Ce refiner. But the solidification structure and the mechanical property of 434 ferritic stainless steel could not be improved with 0.034 wt.% Ce refiner.

Keywords: 434 ferritic stainless steel; Ce; solidification structure; mechanical property; rare earths

Ferritic stainless steels constitute approximately one-half of the AISI type 400 series stainless steels. These steels contain 10 wt.% to 30 wt.% Cr along with other alloying elements, notably Mo. Ferritic stainless steels are noted for their excellent stress corrosion cracking resistance and good resistance to pit and crevice corrosion in chloride environments[1]. Ferritic stainless steels are characterized of lower cost, higher thermal conductivity and smaller linear expansion when compared with austenite stainless steels[2–5]. However, the relatively developed columnar structure leads to the weakness of the solidification structure and the mechanical properties of SUS434 ferritic stainless steels because they solidify directly from the liquid to the ferritic phase without any intermediate phase transformation[6]. For this reason, the application of this group of alloys is limited. It is therefore necessary to conduct a study on how to improve the solidification structure and the mechanical properties of ferritic stainless steels[7]. It was reported that the equiaxed solidification structure in the cast strip is the pre-condition for the improvement of formability of 17 wt.% Cr FSS by twin-roll strip casting[8]. To improve the solidification structure, the relationship of the percentage of equiaxed grains in the solidification structure of cast strip and melt superheat was established[9].

It is well known that the rare earths are also beneficial for improving the mechanical properties of steels[10–12]. The addition of rare earth in stainless steels has been reported to suppress the detrimental action of inclusions by forming stable rare earth globular inclusions[13]. Enormous research work has been carried out on the solidification structure and the mechanical properties of austenitic steels[14–17]. However, the solidification structure and the mechanical properties of ferritic stainless steels with rare earth were not detailedly studied.

In this work, we attempted to evaluate the effect of Ce on the solidification structure and the mechanical properties of 434 ferritic stainless steel at room temperature. Finally, the mechanism of Ce on 434 ferritic stainless steel was also studied.

1 Experimental

Approximately 3 kg of alloy with and without refiners were smelted in a vacuum induction furnace protected by argon at a temperature of 1600 ºC. The refiners that lined on a pure iron wire were inserted into a liquid steel after deoxidization with Si-Mn, and the molten steel was then refined for 3 min. When the temperature and composition were uniform, the molten alloy was cast into an iron mould with dimensions of 55 mm at a pouring temperature of 1550 ºC, and finally, air cooled to room temperature. The chemical compositions of 434 ferritic stainless steel and Ce-containing steels are shown in Table 1.

The samples were machined to the required dimensions. The impact samples as shown in Fig. 1(a) were ready for determining impact toughness with an impact

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Table 1 Chemical compositions of tested 434 ferritic stainless steels (wt.%)

Steels	C	Si	Mn	P	S	Cr	Mo	O	Ce
A	0.088	0.48	0.41	0.021	0.031	15.64	0.82	0.011	–
B	0.088	0.50	0.42	0.021	0.017	15.57	0.82	0.008	0.011
C	0.093	0.56	0.44	0.022	0.011	15.59	0.83	0.007	0.023
D	0.091	0.57	0.43	0.021	0.010	15.62	0.82	0.006	0.034

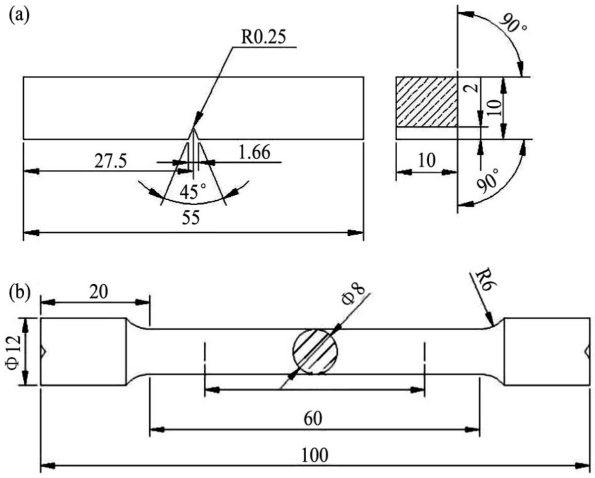

Fig. 1 Dimensions of tensile and impact specimens
(a) Impact specimen; (b) Tensile specimen

test machine at room temperature. And the tensile samples were performed according to GB/T228.1-2010 standards as shown in Fig. 1(b) and requirements for determining room temperature (25 ºC) tensile with a tensile testing machine. The following forging process was performed before final machining.

Properly etched samples were examined on a Carl Zeiss optical microscope (OM). Scanning electron microscopy (SEM) was used to study the fracture surfaces and inclusions in the steels. The corresponding spectrum analysis of inclusions of the steels was undertaken by energy spectrum analysis (EDS).

2 Results

2.1 Solidification structures

Fig. 2 illustrates macrostructures under various contents refiners. The corresponding characteristic parameters of the solidification structure are shown in Table 2. At the same casting temperature, without addition of Ce refiners, the solidification structure of the steels is mainly composed of coarse columnar grains, and only a small amount of equiaxed grains are in the center, however, the columnar grains of solidification structure become obviously shorter and thinner, the equiaxed grain ratio increases, the equiaxed grain size decreases with 0.011 wt.% Ce and 0.023 wt.% Ce, and the solidification structure of the steels is well improved. When the content of rare earth Ce is 0.034 wt.%, the solidified structure of ferritic stainless steel can not be improved.

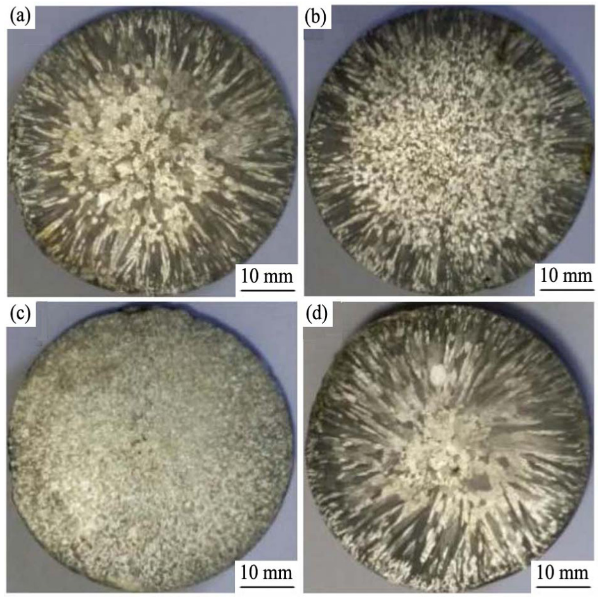

Fig. 2 Macro solidification structures of cylindrical ingots with different contents of Ce
(a) Without Ce; (b) With 0.011 wt.% Ce; (c) With 0.023 wt.% Ce; (d) With 0.034 wt.% Ce

Table 2 Relationship of Ce addition and characteristic parameters of solidification structures

Steels	Content of Ce/wt.%	Equiaxed grain ratio/wt.%	Average equiaxed grain size/mm
A	–	34.72	1.77
B	0.011	50.64	0.88
C	0.023	92.85	0.53
D	0.034	18.01	1.72

2.2 Microstructures of the four steels after forging

The microstructures of the four materials after forging are shown in Fig. 3. Using Image-Pro Plus software, statistic analysis was performed to determine the average diameters and shape factors of the grains in the microstructures of steels, as shown in Fig. 3. The structures of steel B and steel C are small, and the average sizes of each grain are 18.93 and 14.17 μm, respectively. In addition, the microstructure of ferrite uniformly distributed in the steel B and steel C. The structures of steels are larger when the content of Ce is 0 or 0.034 wt.%, and the average diameter of the grain is 34.04 μm and 32.25 ppm, respectively, as shown in Fig. 3.

2.3 Mechanical properties

The effect of Ce on room temperature tensile properties of 434 ferrite stainless steel is shown in Table 3. Each of the samples shown in this table represented the average of three samples.

The tensile strength and yield strength of steel A are 1135 and 845 MPa, respectively. However, the tensile strength and yield strength of steel B are 1200 and 885 MPa, respectively, which are 5.73 wt.% and 4.73 wt.% higher compared with steel A. Similarly, the tensile