Materials and Design 33 (2012) 306–312

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Effect of rare earths on impact toughness of a low-carbon steel

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ARTICLE INFO

Article history:
Received 7 September 2010
Accepted 21 June 2011
Available online 5 July 2011

Keywords:
A. Ferrous metals and alloys
E. Fracture
F. Microstructure

ABSTRACT

Studies of an industrial low-carbon steel (B450NbRE) suggest that the impact toughness is unexpectedly low under its practical service, probably resulting from the unstable recovery of rare earths (RE) in steelmaking. The purpose of this work is to investigate the effect of RE on the impact toughness in low-carbon steel. The B450NbRE steels with content of 0.0012–0.0180 wt.% RE were produced by vacuum induction furnace. The impact toughness and microstructure were investigated after hot rolled. The Gleeble-1500 thermal simulator was used to validate the effect of RE on the microstructure. The results indicate that the microstructure of hot-rolled steels is characterized by polygonal ferrite, quasi-polygonal ferrite, bainite and pearlite. The impact toughness increases with RE contents reaching the peak with content of 0.0047 wt.% RE, such a change exhibits the same rule as the case of the ferrite amount. However, this improvement in impact toughness is not only due to an increase in ferrite amount, but also the fine grained structure and the cleaner grain boundaries. And content of 0.0180 wt.% RE is excessive. Such an addition of the RE resulted in the martensite precipitates at the grain boundaries, which are extremely detrimental to impact toughness.

1. Introduction

The effects of rare earths (RE) on steelmaking have been extensively studied [1–5], focusing on the purification of liquid steel and the modification of inclusions by the addition of RE into steels. Since RE has a strong affinity for oxygen and sulfur, it has been used to deoxidize and desulfurize in steels. Some studies also demonstrated that RE can be used to modify the type of sulfides, so that the sulfides can often keep globular and do not deform into stringers during rolling, and the inclusion spacing also increases, resulting in a significant improvement in the toughness [2,6]. However, RE is no longer popularly used in steelmaking, because steel can now be readily purified using modern refining techniques, and calcium is effective in the low-cost modification of inclusions.

However, as the cleanliness of steels has been greatly improved, the RE is realized to be crucial as microalloying element in steels. It has also reported that the RE can improve significantly the corrosion resistance of low-carbon steels [7,8]. The 09CuPTiRE, 16MnRE and BNbRE steels have been well developed in China and widely used for over 30 years [9,10]. Recently, a new B450NbRE steel for the middle-beam of train has been developed in Baotou Iron and Steel Corp. [11], in which Mn, Ni, Nb and V are alloyed to obtain the desired strength and toughness, while Cu and RE are employed to improve the corrosion resistance. Nevertheless, the impact toughness of the B450NbRE steel is unexpectedly low under its practical service, probably resulting from the unstable recovery of RE in steelmaking [12].

In the present work, the effect of RE additions on the microstructures and properties of the B450NbRE steel is systematically investigated, focusing on the establishment of the relationship between RE content and the impact toughness.

2. Experiments

The B450NbRE steels were prepared by vacuum induction melting furnace. The type 20# steel with a chemical composition (wt.%) of 0.2C, 0.05Si, 0.12Mn and balance Fe was used as the starting material, in which Si, Mn, Nb, V, graphite, pure iron, the RE, among others, were subsequently added. The final compositions are summarized in Table 1. Here, the RE is composed of 50 wt.% La and 50 wt.% Ce in this study. The as-made B450NbRE steels were forged into 75 mm × 75 mm ingots, and reheated to 1200 °C and held for more than 30 min, then hot rolled and the finish rolling temperature at above 950 °C, eventually air cooled to room temperature (Fig. 1). Finally, the B450NbRE steel was hot rolled into thick plates with dimensions of 12 mm × 180 mm.

Charpy v-notch impact test specimens with dimensions of 10 mm × 10 mm × 55 mm were prepared by spark cutting from the thick plates and then mechanically polished. The impact toughness tests were conducted according to ASTM E23 [13], with an Amsler RKP 450 testing machine at 20 °C and −40 °C, respectively.

Metallographic observations were carried out on the hot-rolled specimens subjected to impact tests. The thermal simulator

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doi:10.1016/j.matdes.2011.06.042

Table 1
Chemical composition of B450NbRE steels (wt.%).

No.	C	Si	Mn	Ni	Cu	V	Nb	RE
1	0.088	0.578	1.590	0.33	0.32	0.089	0.044	0.0012
2	0.092	0.530	1.588	0.33	0.34	0.093	0.045	0.0031
3	0.094	0.522	1.629	0.32	0.32	0.085	0.040	0.0047
4	0.078	0.498	1.516	0.30	0.35	0.087	0.037	0.0087
5	0.088	0.562	1.591	0.33	0.34	0.091	0.041	0.0140
6	0.082	0.562	1.544	0.31	0.32	0.093	0.046	0.0180

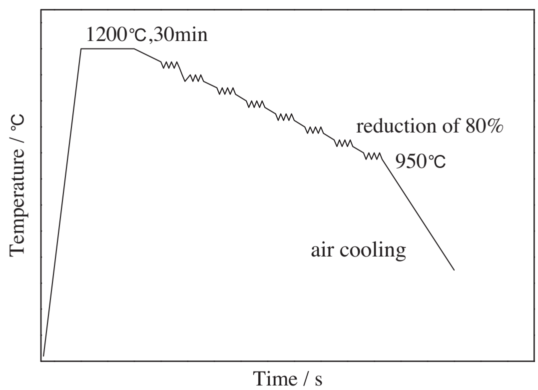

Fig. 1. Schematic of hot-rolled B450NbRE steels.

(Gleeble-1500) was used to validate the effect of the RE on the microstructure. The thermal simulation test specimens were cut from the hot-rolled thick plates, and reheated to 1200 °C for 3 min holding. Then they were rolled with a reduction of 20% or 40% at 950 °C followed by 30 s holding time, and eventually the specimens were cooled down to 200 °C with the cooling rate of 0.5 °C/s and 1 °C/s, respectively, as schematically indicated in Fig. 2.

The heat treatment was also used to validate the microstructure with high RE content. The specimens with dimension of 10 mm × 10 mm × 15 mm were cut from the hot-rolled thick plates. Then they were reheated to 700–900 °C for 30 min holding, and eventually air cooled to room temperature.

Optical microscopy (Olympus BX51 and Neophot 32) was used for metallographic observations. The impact fracture surface features and heat treatment microstructure were examined by scanning electron microscopy (SEM EVO 50) equipped with energy dispersive X-ray spectroscopy (EDX). The microstructure was characterized with transmission electron microscopy (TEM TECNAI G20). Thin foils used for TEM characterizations were cut from the Charpy impact test specimens, and then mechanically thinned down to 100 μm thick, and finally polished in acetic acid containing 10% perchloric acid by conventional double-jet method.

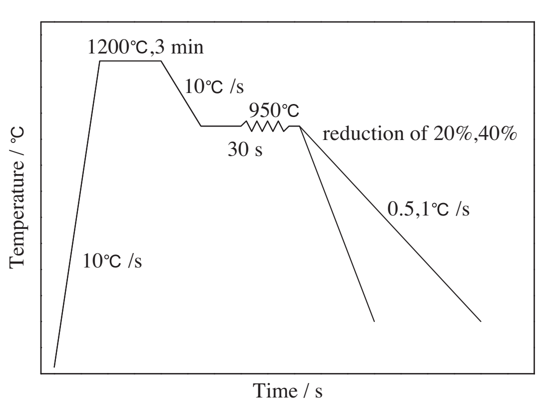

Fig. 2. Schematic of the hot deformation tests with the cooling rate of 0.5 and 1 °C/s.

3. Results

3.1. Impact toughness of hot-rolled steels

The relationship between RE content and the impact toughness of the B450NbRE steel at both 20 °C and −40 °C are presented in Fig. 3. The dimensionless method is used to facilitate the comparison in the present work.

The impact toughness increases with RE content reaching the peak with a content of 0.0047 wt.% RE. Subsequently, it decreases with further increasing RE content. An appropriate RE content can improve significantly the impact toughness of the B450NbRE steel.

The impact fracture surface features of the specimens with contents of 0.0012, 0.0047 and 0.0180 wt.% RE are shown in Fig. 4 for comparison. The fracture surface of the No. 3 specimen containing 0.0047 wt.% RE consists of dimples, showing a typical ductile fracture characteristic [14,15] (Fig. 4b). However, the fracture surfaces of Nos. 1 and 6 specimens are cleavage and quasi-cleavage fractures, respectively, and tearing ridges with obvious secondary cracks are also observed in the No. 6 specimen. The result shows that crack initiation and propagation is relatively easy in the No. 6 specimen.

3.2. Microstructure of hot-rolled steels

The microstructure of the hot-rolled steel with different RE content is shown in Fig. 5. It can be inferred that all the microstructure is composed of ferrite, bainite and pearlite. For the No. 3 specimen, the microstructure is mostly fine polygonal ferrite (Fig. 5c), with the average grain size of 21.1 μm. While for the other specimens, the microstructure is quasi-polygonal ferrite, with the grain size much larger than the No. 3 specimen. In addition to the differences in the shape of the ferrite, the differences in the amount of the ferrite are also significant. Statistical analysis of microstructure suggests that the ferrite amount firstly increases with RE content, and then decreases after the RE content reaches a certain level. The maximum ferrite amount is 92.4 vol.% with a content of 0.0047 wt.% RE, as shown in Fig. 6. These microstructure character-

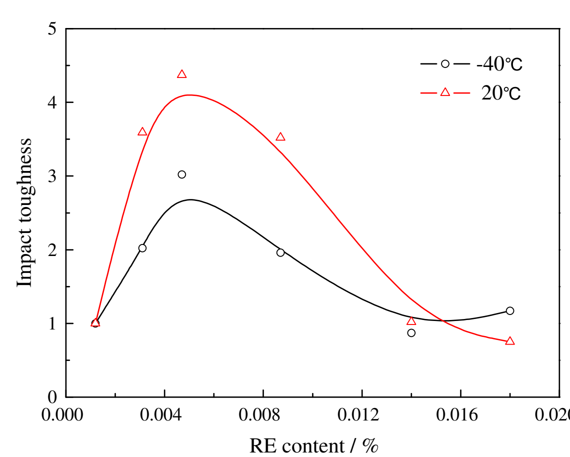

Fig. 3. Effect of RE content on the impact toughness of B450NbRE steels at 20 and −40 °C using the dimensionless method.