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Microstructural analysis on cleavage fracture in pearlitic steels

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ABSTRACT

Microstructural features controlling cleavage fracture in pearlitic structures were investigated by means of scanning electron microscopy and electron backscattered diffraction. It was found that pearlite block size corresponds well to the cleavage facet size, and a single cleavage facet usually contains multiple pearlite colonies. Pearlite block size and cleavage facet size decrease with the refinement of prior austenite grain size, while pearlite colony size only changes slightly. The cleavage crack can largely deflect at block boundaries rather than at colony boundaries. Pearlite block can act as the dominant substructure on cleavage crack propagation in pearlitic steels.

1. Introduction

The lamellar pearlitic structure composed of alternating lamellae of ferrite and cementite can be hierarchically divided into two domains: pearlite colony and pearlite block. Pearlite colony refers to a region in which cementite lamellas have nearly the same direction. Pearlite block, proposed by Takahashi et al. [1], corresponds to a region sharing nearly the same crystallographic orientation of ferrite and being the final stage of a pearlite nodule that nucleates at an austenite grain boundary.

The mechanical properties of pearlite therefore can be related to the microstructural parameters, especially interlamellar spacing, colony size and block size. Generally, the interlamellar spacing strongly controls the strength of lamellar pearlite. In medium-high carbon pearlitic steels, quasi-cleavage or cleavage fracture frequently occurs even at room temperature. However, the structural unit controlling the toughness or cleavage fracture in lamellar pearlitic structures has not been clearly clarified. Previously, Gladman et al. [2] studied the effect of microstructural parameters on toughness in pearlitic steels by regression analysis, they suggested that pearlite colony size is an important parameter, since colony boundaries can act as obstacles to cleavage crack propagation. Further investigations [3,4] revealed that pearlite colony size, however, has only a minor influence. Park [4] examined the orientation relationships between pearlite colonies by thin foil transmission electron microcopy, and the result showed that adjacent colonies often have close ferrite orientations so as to produce a single cleavage facet and the microstructural unit for cleavage fracture could be austenite grain size controlled. Takahashi et al. [5] also reported that the ductile fracture become more dominant with decreasing pearlite block size. However, previous studies have not yet established the direct correspondence between cleavage facet size and pearlite colony/block size. In recent studies, electron backscattered diffraction (EBSD) has been widely used for crystallographic orientation analysis on pearlitic structures [6–8], but little work has been conducted on the observation of cleavage crack propagation path by EBSD analysis in pearlitic steels.

In this work, the relationship between microstructure and cleavage fracture of pearlitic steels was investigated, including the correspondence between cleavage facet size and pearlite colony/block size, and the role of pearlite colony/block boundaries on cleavage crack propagation, in order to clarify the dominant microstructural feature on cleavage fracture in pearlitic steels.

2. Material and methods

A medium carbon steel containing 0.55 C, 0.89 Si, 0.78 Mn, 0.16 Cr and 0.074 V (mass %) was used in this study. Samples of $12 \times 12 \times 60$ mm^3 in size were cut from the hot-rolled steel, and then austenitized at various temperatures ranging from 860 to 1250 °C for 1 h, followed by air cooling, to form ferrite-pearlite microstructures. Charpy V-notch impact test was conducted at −20 °C for the study of cleavage fracture. Optical microscopy (OM), scanning electron microscopy (SEM) and EBSD were used for microstructural analyses. EBSD measurements were performed at an accelerating voltage of 20 KV

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and a step size of 0.5 μm. Pearlite colony and cleavage facet sizes were measured by the linear intercept method from SEM micrographs and SEM fractographs, respectively. Pearlite block size was determined as the region surrounded by high angle boundaries of ferrite >15° on EBSD mappings. Some fracture surfaces of the specimens were nickel plated for the analysis of cleavage crack propagation and etched in saturated aqueous solution of picric acid to show the lamellar structure in cleavage facets.

3. Results and discussion

3.1. Microstructural parameters

OM and SEM observations revealed that the microstructures of all specimens consist of lamellar pearlite and a small amount of proeutectoid ferrite (Fig. 1a and b show the microstructure of the specimen austenitized at 1050 °C). The ferrite fraction decreases as austenitizing temperature increases (proeutectoid ferrite can be included into the measurement of the block size). Prior austenite grain size varies from 20 μm to 400 μm which was estimated from grain boundary ferrite. Observation of fracture surfaces indicated that the cracking is dominated by cleavage at the test temperature of −20 °C (Fig. 1c).

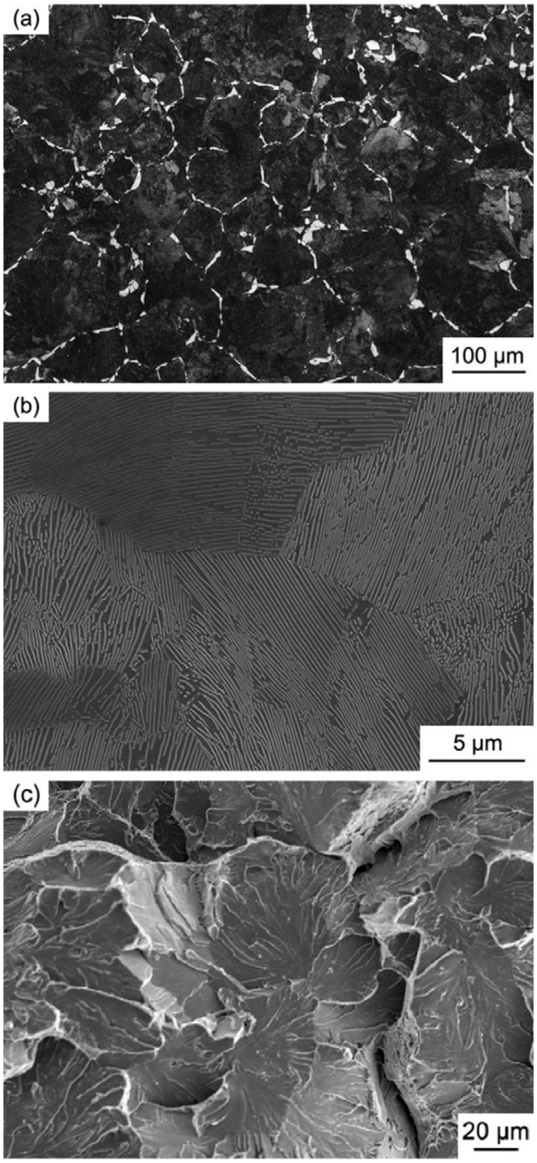

Fig. 1. Optical micrograph (a), SEM micrograph (b) and SEM fractograph (c) of the specimen austenitized at 1050 °C.

Fig. 2 shows the measured microstructural parameters. As shown in Fig. 2a, all the specimens show a narrow size distribution of pearlite colony (with no sizes >25 μm), almost independent of the prior austenite grain size. However, there is a relatively wide range of pearlite block (Fig. 2b) and cleavage facet sizes (Fig. 2c), especially for a large prior austenite grain (e.g., pearlite block and cleavage facet with sizes up to ~250 μm are formed at austenitizing temperature of 1250 °C). Variations of the mean cleavage facet size and pearlite block/colony size with various prior austenite grain sizes are shown in Fig. 2d and Table 1, it is clear that refinement of austenite grain size results in the decrease of cleavage facet and pearlite block sizes. However, the mean pearlite colony size only varies between 4 μm and 8 μm. This agrees with the reported results in Refs. [9,10]. Furuhara et al. [9] explained that the formation of pearlite block corresponds to the case of grain boundary nucleation, while the weak dependence of colony size on the prior austenite grain size is attributed to an intragranular nucleation mechanism that a new colony can nucleate at the boundary between austenite and pre-existing colony. In addition, the block size corresponds well to the cleavage facet size. The impact absorbed energy values of the specimen are also shown in Table 1. As the austenite grain size decreases from 400 μm to 20 μm, the impact absorbed energy increases from 4 J to 16 J. However, the absorbed energy values are very similar when austenitizing temperature is beyond 1050 °C. Since a cleavage facet represents an orientation unit and more orientation units make more resistance to cleavage crack propagation, the aforementioned results imply that pearlite block size can have a significant influence on the toughness of pearlitic steels.

3.2. Microstructure observation in fracture surface

Fig. 3a and b show the microstructure in cleavage facets of the specimen austenitzied at 860 °C and 1250 °C, respectively. It was found that cleavage facets are frequently formed by individual pearlite colonies in the specimen with a small prior austenite grain size of 20 μm (Fig. 3a), while in the specimen with a large prior austenite grain size of 400 μm (Fig. 3b), a single cleavage facet usually contains multiple colonies. The microstructure observed in fracture surfaces is similar to the morphology of pearlite reported by Pickering et al. [11]. The result is in accordance with the difference between the measured pearlite colony size and cleavage facet size (see in Fig. 2d). This means the adjacent colonies within a cleavage facet should have similar ferritic orientations, so that it is easy for the crack to propagate. It can be confirmed in the EBSD analysis.

3.3. Cleavage crack propagation

To further understand the relation between cleavage crack propagation path and pearlite block/colony boundaries, we analyzed the crystallographic nature of the cleavage fracture by EBSD. Fig. 4a shows the crystallographic orientation map of ferrite and high angle boundaries >15° (representing pearlite block boundaries) below the fracture surface in the specimen austenitized at 1050 °C, and the misorientation between adjacent zones are listed in Table 2. It can be seen that crack deflects frequently at pearlite block boundaries. The corresponding SEM micrograph of zones 3 and 4 is shown in Fig. 4b. When cleavage crack encounters zone 3, it easily propagates through several contiguous colonies without changing direction until meeting the block boundary. This indicates that the ferrite/cementite interfaces and pearlite colony boundaries cannot obstruct crack propagation effectively. Note that in colony/zone 4, the crack also changes the direction of propagation within this same colony. This may be due to a geometric constraint of the macroscopic fracture direction of the impact specimen. Moreover, the crack traversing a block boundary between zone 5 and 6 is also observed. These will be discussed below.