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Brittle-to-ductile transitions and its relation to the deformability of cementite in fully pearlitic steels

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ABSTRACT

Temperature dependence of the absorbed impact energy in fully pearlitic steels was investigated. Two-step brittle-to-ductile transitions were observed. The value of the activation energy associated with the first transition is comparable to that of low carbon ferritic steels, indicating that the first transition is the brittle-to-ductile transition of ferrite phase in pearlitic steels. It suggests that the first transition is controlled by the dislocation glide in ferrite. The value of the activation energy associated with the second transition is higher than that of the first transition. Micrographs of fracture surfaces and side surfaces after fracture tests suggest that the activation energy associated with the second transition should relate to the deformability of cementite in pearlite, that is, the second transition is controlled by the dislocation activity in cementite of pearlite.

1. Introduction

Pearlitic steels have been widely used as structural materials. Possible parameters which control their mechanical properties are prior austenite grain size, block size, colony size, inter-lamellar spacing and carbide thickness [1–3]. It is fairly in agreement that the inter-lamellar spacing controls the yield stress in the following form:

$$\sigma_y = \sigma_o + kS_p^{\alpha}, \tag{1}$$

where σ_y denotes the yield stress, σ_o and k are constants, S_p denotes inter-lamellar spacing where there is still an open issue whether $\alpha = -1$ or $-1/2$ [1,2]. Fracture stress and deformability of pearlitic steels depend also on such parameters [2,4–11]. Salischvef et al. [12] showed, using impact tests, that the reduction of the inter-lamellar spacing increases the value of energy for crack initiation and propagation in ferrite–pearlite steels. TEM observation demonstrated that cleavage planes of fully pearlitic steels at low temperatures are {100} planes of ferrite [13], and (001), (120), (100) or (001) in cementite [14]. Cuddy and Bassim [4] showed that a crack initiated at cementite because the stress concentration near the ferrite–cementite interfaces propagates to ferrite in ductile fracture. Takahashi et al. [15] concluded that block size is the controlling parameter of deformability of pearlitic steels, compared with the relationships between the deformability and several parameters, which changed with heat treatment conditions.

A brittle-to-ductile transition (BDT) is one of the most important mechanical properties in steels, which is widely seen in bcc metals and covalent crystals. Fig. 1 shows a schematic drawing of the impact-absorbed energy as a function of the testing temperature in fully annealed ferritic steels with conventional grain sizes. The absorbed energy, denoted by a solid line in Fig. 1, keeps a lower level at low temperatures, which is called a lower-shelf. Then, the absorbed energy significantly jumps around at a certain temperature. It is defined as the BDT temperature, T_{BDT}, by taking the mid-point temperature of the temperature range of the absorbed energy change. It is reported that BDT temperatures depend on the deformation rate. When the deformation rate in fracture tests increases, the BDT curves shift to the side of higher temperatures as shown with the dotted line in Fig. 1. St. John [16] demonstrated that the relationship between the strain deformation rate ε and the BDT temperature is given by the Arrhenius type equation:

$$\dot{\varepsilon} = \varepsilon_0 \exp\left(\frac{-G}{kT_{BDT}}\right), \tag{2}$$

where $\dot{\varepsilon}$ is a strain rate, ε_0 is a constant, G is an activation energy of deformation process which controls the BDT, k is the Boltzmann constant, and T_{BDT} is the absolute BDT temperature. It has been elucidated that the value of the activation energy in Eq. (2) is close to that of the dislocation glide at around the BDT temperature, which indicates that the BDT is controlled by the thermally activated processes of dislocation glide [16–18]. The concept built

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in single crystalline materials has been also applied to the studies on the polycrystalline metals [19–21], suggesting that the controlling mechanism behind the BDT in multi-phase steels such as pearlitic steels can also be elucidated by experimentally determining the value of activation energy in Eq. (2).

Sirithanakorn et al. reported [22] that there are two steps in the temperature dependence of absorbed energy in fully pearlitic steels, which denotes a two-step BDT in those steels. On the analogy of the fact that the onset of the BDT is controlled by dislocation glide in single phase materials with high Peierls potential as mentioned, the two-step BDT should have different mechanisms behind the onset of each transition. In the present study, therefore, the impact-absorbed energy was first measured with different temperatures and deformation rates. The value of activation energy was obtained from the deformation rate dependence of the BDT temperature. The controlling process of the BDT in pearlitic steels was discussed, presuming that the dislocation glide is also the key mechanism behind the two-step BDT in fully pearlitic steels.

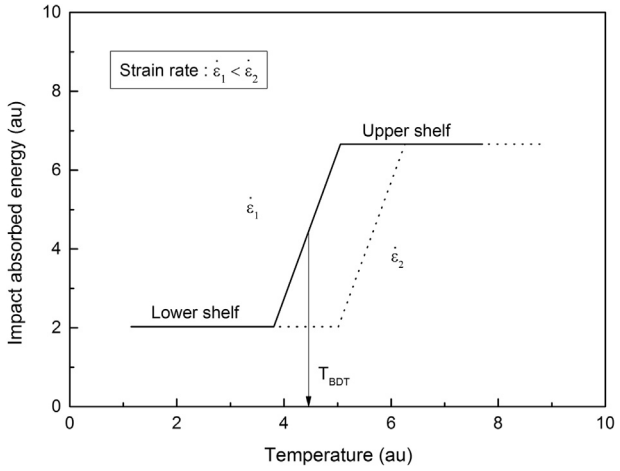

Fig. 1. Schematic drawing of impact-absorbed energy as a function of temperature with 2 different strain rates.

Table 1
Chemical compositions of SWRS92A used.

C	Si	Mn	P	S	Cu
0.90–0.95	0.12–0.32	0.60–0.90	< 0.025	< 0.025	< 0.20

2. Experimental procedures

SWRS92A patented fully pearlitic wires with the diameter of 5.5 mm were employed, the chemical composition of which is shown in Table 1. Test pieces were first cut from the patented wires to be $1.5 \times 1.2 \times 20$ mm^3 in dimension, and then three sides of the pieces were polished while a notched side was left as cut. The final dimension of the samples was approximately $1.2 \times 0.8 \times 20$ mm^3. Fracture tests were carried with the impact blade speeds of 0.0033, 0.033, 0.33, and 3.3 m/s, respectively, followed by SEM observations using an angle selective backscattered electron detector in Ultra-55 (Carl Zeiss).

3. Results

Fig. 2(A) shows an SEM micrograph of the longitudinal section of the specimen after deep etching. The directions of cementite lamellae demonstrate the colony size is in the range of 5–15 μm, showing that the grain orientations are randomly distributed. Fig. 2(B) shows an inversed pole figure map of the cross section. Fig. 2(C) is a grain map constructed from Fig. 2(B). Here each grain was filled with one color, where grain boundaries were defined with the mis-orientation angle being larger than 15°. Black dots in the figure indicate the points where CI values are less than 0.1. It was found that the block sizes are in the range of 10–60 μm, with an average of 25.8 μm (by area).

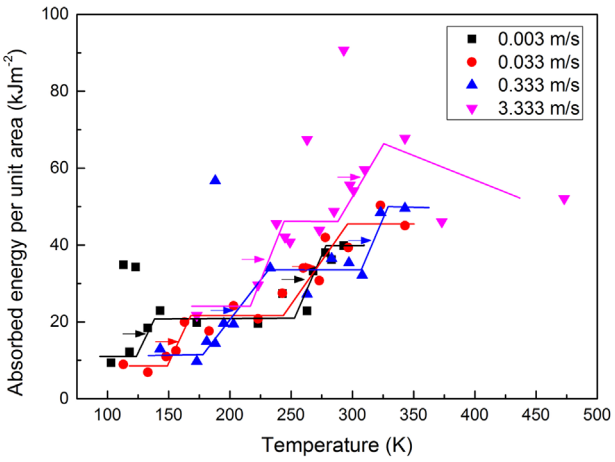

Fig. 3. Temperature and blade speed dependences of the absorbed energy per unit area. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

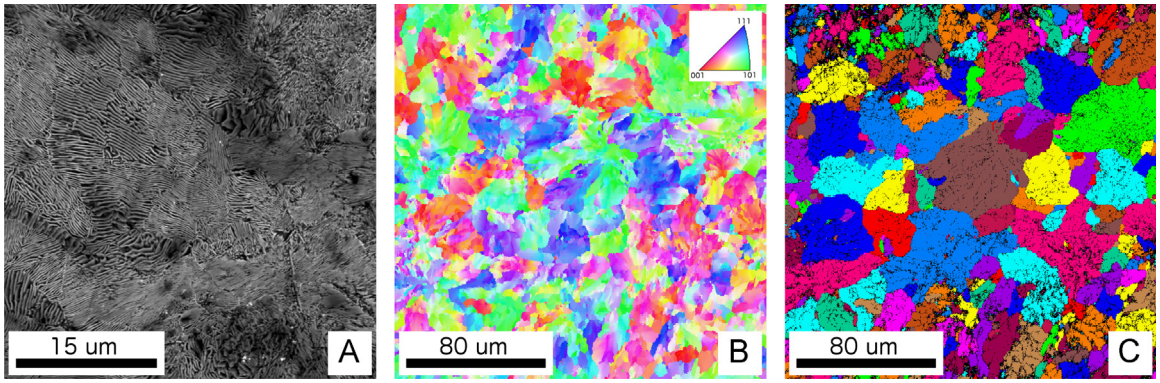

Fig. 2. (A) is SEM micrograph of the cross section of the wire after deep etching, (B) and (C) are inverse pole figure maps of ND and the unique color grain map constructed with the criteria of 15° difference, respectively (cf. online version for colored image). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)