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Effect of crystallographic texture on the cleavage fracture mechanism and effective grain size of ferritic steel

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The effect of crystallographic texture on impact transition behavior has been studied in a low-carbon steel. Crystallographic texture was found to influence the general yield temperature through its effect on the plastic constraint factor. The effective grain size depends on the angle between the {001} cleavage planes of the neighbouring crystals, rather than the grain boundary misorientation angle as determined from electron backscattered diffraction analysis considering the angle–axis pair.

Keywords: Cleavage fracture; Plastic constraint factor; Crystallographic texture; Effective grain size

In order to determine impact transition behavior, the usual practice is to carry out instrumented Charpy impact testing over a range of temperatures.

A stress distribution exists in front of a notch/crack and the maximum principle stress can be as high as three times the dynamic yield stress [1]. The plastic constraint factor is the ratio of the maximum principle stress ahead of the crack/notch to the yield stress [2]. However, the effect of crystallographic orientation on the plastic constraint factor has not been considered to date.

Low-angle boundaries (LABs) are reported to be ineffective in retarding cleavage crack propagation, while high-angle boundaries (HABs) deviate or retard crack propagation, depending on the misorientation angle across the boundaries [3,4]. The minimum size of microstructural unit over which the cleavage crack propagates in an uninterrupted fashion defines the "effective grain size" [4]. The effective grain size of a microstructure is usually determined from electron backscattered diffraction (EBSD) analysis by considering only the HABs [5]. A list of the different approaches followed in the literature to define the crystallographic grain size in steel is given in Table 1 [5–10]. The determination of effective grain size based on grain boundary misorientation angle calculated by EBSD analysis from the angle–axis pair is not necessarily the right approach. Rather, the misorientation angle between the {001} planes of two adjacent crystals should be considered in determining the "effective grain size" as the cleavage crack propagates in body-centred cubic metals along the {001} planes [4–9].

Samples from a low-carbon, Nb–V microalloyed steel containing 0.08 C, 0.30 Si, 1.20 Mn, 0.03 S, 0.05 Nb, 0.08 V and 0.007 N (wt.%) were soaked at 1200 °C for 1 h. before rolling. The detailed processing history of these samples is given in Table 2. The investigated samples contained ferrite–pearlite microstructures with optically measured ferrite grain sizes varying over a wide range 5–40 μm, whilst the pearlite fraction remained within a close range of values, 14–16%. Instrumented Charpy impact testing was carried out on the standard V-notch Charpy samples (T-L orientation) over the temperature range +40 to −196 °C. Cleavage fracture stress is measured at the general yield temperature (T_{GY}) from the load vs. time plot, recorded during the instrumented impact testing (Table 3). Macrotexture measurement and EBSD analysis were performed using Pananalytical X-ray goniometer and Oxford HKL Channel 5 system, respectively.

The value of the plastic constraint factor is expected to depend on the orientation of the ferrite grain. In the schematic diagram in Figure 1a the red plane represents the fracture plane of the sample. The grey cube shows a crystal with an arbitrary orientation with respect to the

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Table 1. Threshold criterion used for the determination of effective grain size for different microstructures in steel.

Threshold criterion for effective grain size	Microstructure	Refs.
5° on misorientation angle	ferrite–pearlite, ferrite–martensite	[7]
12° on misorientation angle	ferrite–pearlite	[6]
15–20° on misorientation angle	ferrite–pearlite, ferrite–martensite, bainite, martensite	[5]
Largest grain size among the grains having {001} plane parallel to fracture surface	ferrite–pearlite	[8]
Average grain sizes or largest grain sizes corresponding to the coarse- and fine-grained populations.	bimodal ferrite grain structures	[10]
15° on {001} cleavage plane angle	ferrite–pearlite	present study

Table 2. Processing history of the investigated samples.

Sample Code	History
FRT820	finish rolled at 820 °C
FRT730	finish rolled at 730 °C
FRT650	finish rolled at 650 °C
HT940	normalized at 940 °C for 5 min after being finish rolled at 730 °C
HT1150	normalized at 1150 °C for 1 h after being finish rolled at 730 °C

fracture plane. As the cleavage crack propagates along the {001} cleavage planes of the crystals and crystals are oriented differently throughout the material, the cleavage crack path deflects around the macroscopic fracture plane of the sample. There can be three possible {001} cleavage planes through which the cleavage crack propagates; those planes are marked 1, 2 and 3 in Figure 1a. The angles between the cleavage planes of the crystal and the fracture plane of the sample can be calculated using the following set of mathematical expressions.

$$\mathbf{C}_\mathrm{C} = \mathbf{G}\mathbf{C}_\mathrm{S}$$

$$\mathbf{C}_\mathrm{S} = \mathbf{G}^{-1}\mathbf{C}_\mathrm{C}$$

$$\mathbf{C}_\mathrm{S} = \mathbf{G}^{-1}\begin{bmatrix}1\\0\\0\end{bmatrix}_C$$

$$\theta = \cos^{-1}(\mathbf{Fp}.\mathbf{C}_\mathrm{S}) \tag{1}$$

where $\mathbf{C_c}$ represents the plane-normal in crystal reference frame, $\mathbf{C_s}$ represents the same in sample reference frame, **G** represents the orientation of any ferrite grain in the sample reference frame, **Fp** represents the fracture plane of the sample, and θ represents the angle between the cleavage plane of the crystal and the fracture plane of the sample.

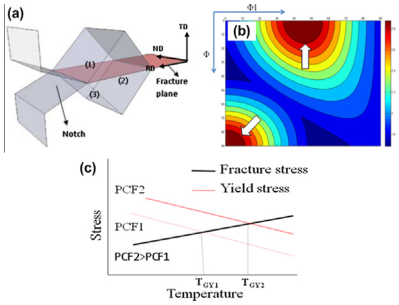

Figure 1. (a) Schematic diagram showing a crystal with an arbitrary orientation with respect to the fracture plane of the sample. RD, TD and ND are the rolling direction, transverse direction and normal direction, respectively. (b) Variation in the plastic constraint factor with the crystal orientation represented by colour code on the $\varphi_2 = 45°$ section of Euler space. (c) Schematic diagram showing the increase in general yield temperature from T_{GY1} to T_{GY2} with the increase in the plastic constraint factor from PCF1 to PCF2.

Let us suppose the angle between the cleavage planes 1, 2 and 3 (as marked on Fig. 1a) and the fracture planes are θ_1, θ_2 and θ_3, respectively, and of these three angles θ_1 is the lowest. The cleavage plane of the crystal (say, plane 1), which makes the minimum angle ($\theta_{\min} = \theta_1$) with the fracture plane of the sample, is considered to be the active cleavage plane. Hence, the cleavage crack will actually propagate through cleavage plane 1. Considering angle $\theta_{\min}$, the plastic constraint factor (PCF) can be evaluated using the following Eq. (2) [1]:

$$PCF = (1 - n - m - mn + m^2 + n^2)^{-\frac{1}{2}} \tag{2}$$

$$\text{Where:}\quad m = \frac{(1-\sin\frac{\theta_{\min}}{2})}{(1+\sin\frac{\theta_{\min}}{2})} \qquad n = \frac{2\nu}{(1+\sin\frac{\theta_{\min}}{2})}$$

and ν is the Poisson's ratio. The angle $\theta_{\min}$ will vary depending on the orientation (G) of the crystals in front of the notch. Therefore, the plastic constraint factor will be different for different crystal orientations. The plastic

Table 3. Microstructure, texture, impact toughness and fractographic parameters of the investigated samples.

Sample code	Average ferrite grain size, ECD (μm)	Low-angle boundary fraction (%)	Effective grain size, grain boundary misorientation (μm)	Effective grain size, (100) cleavage plane angle (μm)	Facet size(μm)	Average plastic constraint factor	T_{GY} (°C)	Cleavage fracture Stress (MPa)
FRT820	9.6 ± 3.3	11.9	12.4	11.1	10.3 ± 1.1	1.95	−96	1394
FRT730	8.2 ± 3.0	55.9	19.5	19.3	18.2 ± 2.1	2.09	−62	1525
FRT650	5.9 ± 2.6	65.6	26.2	20.8	21.0 ± 3.4	2.2	−44	1447
HT940	9.7 ± 3.6	6.3	10.5	10.2	9.2 ± 0.8	2.23	−86	1459
HT1150	40.7 ± 7.9	2	41.1	40.8	40 ± 3.8	2.11	−10	914