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Materials Letters 61 (2007) 5178–5180
materials letters
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Fracture toughness anisotropy in a API steel line-pipe

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Received 15 October 2006; accepted 10 April 2007
Available online 14 April 2007

Abstract

In this letter, we report recent interesting observation that the specimens taken from a API-X65-graded line-pipe can show strikingly different room temperature fracture toughness according to the notch direction (longitudinal vs. circumferential direction in the line-pipe). The results are discussed in terms of texture which might be developed during pipe-forming process.

Keywords: Deformation and fracture; Mechanical properties; Metals and alloys

1. Introduction

Excellent mechanical performances such as high strength and toughness are essentially required for pipeline steels, which are used for transporting crude oil and natural gas over a long distance. However, the steels' outstanding mechanical properties (often offered by thermo-mechanical controlling process, TMCP) must be carefully re-considered when the line-pipes are ready to be operated, because processes of pipe-forming and welding can result in substantial change in microstructures and mechanical properties, and thus can cause unexpected structural failure [1,2].

The purpose of this letter is to report our recent interesting observation that the specimens notched to different directions in a API-X65-graded line-pipe (longitudinal direction vs. circumferential direction) have strikingly different fracture toughness at room temperature, which might be attributed to the texture conceivably developed during pipe-forming process.

2. Experimental

The samples examined in this work were obtained from a commercial grade API-X65 steel line-pipe, whose chemical composition except for Fe is 0.08C–0.019P–1.45Mn–0.003S–0.31Si (in wt.%) and the thickness and diameter are 17.5 mm and 762 mm respectively. Fig. 1 represents a typical microstructure of the tested sample (for both longitudinal direction and circumferential direction), consisting of a general ferrite (white) — pearlite (black) structure with an average grain size of ~10 μm. As shown in the figure, the 'apparent' microstructure was not significantly varied with orientation.

To measure the fracture toughness, both Charpy V-notch impact tests and crack tip opening displacement (CTOD) tests were carried out according to ASTM E23 [3] and ASTM E1290 [4] respectively using the specimens notched to different directions (i.e., direction of crack propagation is different); longitudinal direction vs. circumferential direction of the line-pipe. The geometry of the CTOD specimen was following a standard single-edge-notched-bending (SENB) specimen having through-thickness notch, and its thickness was 14 mm for the circumferential samples and 12 mm for longitudinal ones. The difference in thickness is due to the existing curvature of the line-pipe from which the samples were taken. While Charpy impact tests were conducted at various temperatures from −120 °C to room temperature (about 25 °C), the testing temperature of CTOD tests was limited to room temperature and −40 °C due to the difficulties in sample preparation. Finally, the texture measurements were performed using samples (with size of 20×20×5 mm) prepared by grinding and electropolishing (10% HF+90% H_2O_2).

3. Results and discussion

The results of Charpy V-notch impact tests are shown in Fig. 2 with respect to the testing temperatures. According to the specification of API 5L [5] for the 16–20 mm-thick pipelines, an average of the Charpy

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doi:10.1016/j.matlet.2007.04.007

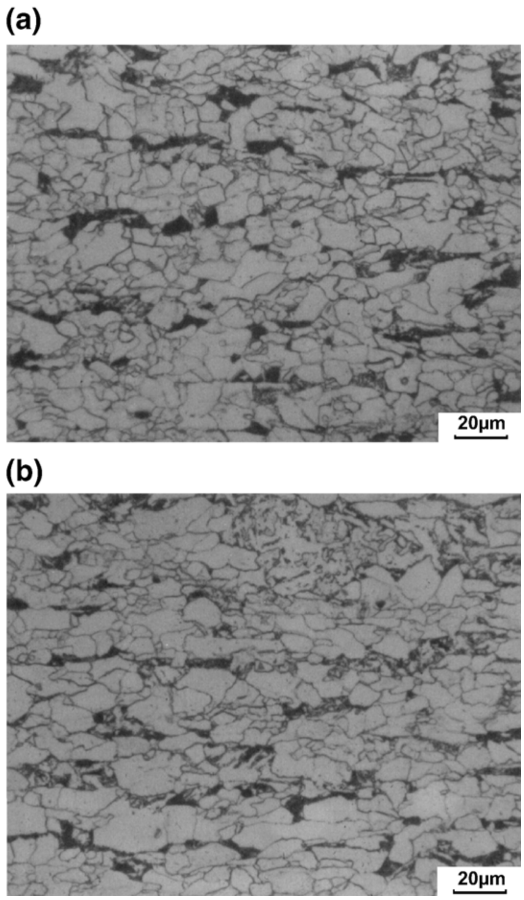

Fig. 1. Optical micrograph showing typical microstructure of the API-X65 line-pipe steel studied in this work: (a) longitudinal and (b) circumferential direction.

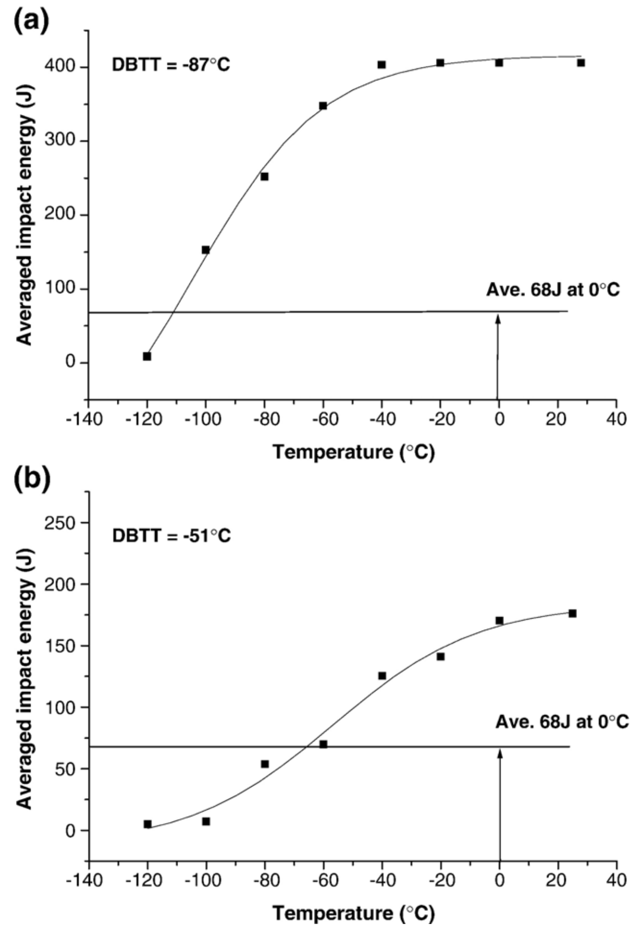

Fig. 2. Ductile-to-brittle transition curves of the samples notched to (a) circumferential direction and (b) longitudinal direction.

impact energy is required to be 68 J (with a minimum of 27 J) at 0 °C. As shown in Fig. 2, all the specimens tested in present work met the requirement of the API specifications. Surprisingly, however, it was found that the room temperature impact energy of the sample notched to longitudinal direction of the line-pipe is much lower than that of the sample notched to circumferential direction (by about 220 J). This is interesting since the microstructures observed by optical microscopy (for example, see Fig. 1) did not display any significant anisotropy such as elongated grains along circumferential (pipe-rolling) direction. It should be also noted that at −120 °C, the impact toughness values did not show any dependency on the direction and almost identical (close to 0 J).

Table 1 lists the results of CTOD tests which were performed at room temperature (about 25 °C) and −40 °C respectively in order to obtain the toughness based on fracture mechanics. Similar to Charpy impact test results, the CTOD values show a serious anisotropy depending on notch direction; the CTOD values in longitudinal direction are much lower than those in circumferential direction (by about 0.7 at room temperature).

To analyze the interesting phenomena of toughness anisotropy, we performed a texture analysis through pole figure measurement. Fig. 3 represents the variations in volume fraction of {100}, {110}, {111} and {112} planes with the angle to the circumferential direction (0, 25, 45, 75, 90°), which were calculated from measured texture intensities. It is seen that each volume fraction of the {100}, {111}, and {112} planes is fairly uniform and almost independent of the direction, and thus the distribution of these planes is unlikely to affect the anisotropy of the fracture toughness at room temperature. However, the proportion of the {110} planes changes significantly with the angle to the circumferential direction, which might be a result from the pipe-forming process.

In upper-shelf regime, fracture occurs in a ductile manner (i.e., by the nucleation and coalescence of microvoid) and thus severe plastic deformation is inevitably accompanied. It is well known that in BCC (body-centered cubic) crystal-structured ferritic steels such as API steel examined in this work, possible slip planes are {110}, {112}, and {123} planes [6]. Among them, the most densely packed planes in BCC metals are {110}, while there are no close-packed planes such as the octahedral planes of the FCC (face-centered cubic) or HCP (hexagonal close-packed) materials. This implies that the increase in the volume of the {110} planes might conceivably lead to the increase in the amount of plastic deformation and thus fracture toughness in upper-shelf regime. Therefore, at room temperature (i.e., in the upper-shelf range of the tested material, as shown in Fig. 2), much higher fracture toughness in

Table 1
Averaged CTOD values measured from the samples notched to different directions

Temperature	Direction	
	Circumferential direction	Longitudinal direction
Room temperature (~25 °C)	1.328	0.575
−40 °C	1.232	0.530

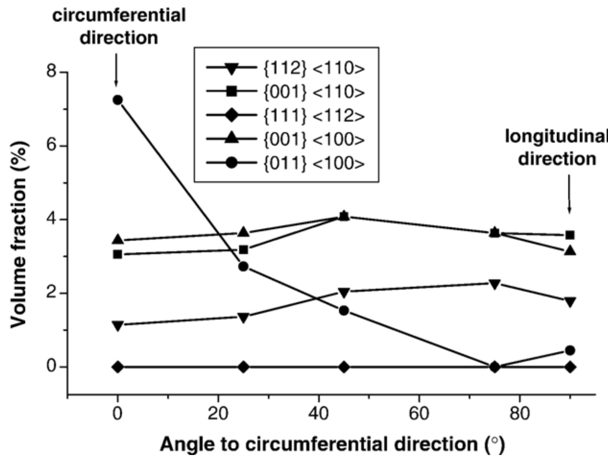

Fig. 3. Change in volume fraction of various crystallographic planes with angle to circumferential direction.

circumferential direction than those in longitudinal direction can be explained by the larger volume fraction of the {110} planes. Note that in this work, the volume fraction of {112} planes is not seriously changing with the direction (see Fig. 3), although {112} planes are also one of the possible slip planes of BCC metals.

On the other hand, in lower shelf regime where fracture occurs in a brittle way, the distribution of the {100} planes is more critical than that of {110} and {112} simply because {100} planes in BCC metals are cleavage planes along which brittle fracture occurs very easily [6]. Indeed, it has been reported [7,8] that the direction-dependent anisotropy of the impact energy at low temperatures is closely related with the variation in amount of {100} cleavage planes. In this work, the volume fraction of the {100} planes are approximately independent of the direction although they are higher than the fractions of {111} and {112} planes. This result might explain why there is no direction-dependent anisotropy of fracture toughness at low temperature such as −120 °C.

4. Conclusion

Here we report that in API-X65-graded steel line-pipe, the room temperature fracture toughness values measured along longitudinal direction are much lower than (almost half) those along circumferential direction. From the analyses of the texture intensities, it was revealed that the anisotropy of the toughness at the room temperatures might be conceivably attributed to the variation in the volume fraction of {110} plane with the angle to the circumferential direction.

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