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Quantitative investigation of brittle out-of-plane fracture in X70 pipeline steel

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Abstract

Brittle out-of-plane cracking (by delamination or brittle tilted fracture) affects the impact toughness of pipeline steels. It has been investigated on notched tensile specimens using a local approach to fracture. Smooth and notched bars taken along four directions (including the short transverse direction, ND) have been tested in tension at temperatures between 20°C and -196°C. Delamination partly results from the lower value of the critical cleavage stress along ND, linked to the microtexture anisotropy, but also from the presence of ductile microcracks acting as stress concentrators triggering fracture along the rolling plane. Brittle tilted fracture was associated to a relatively lower value of the critical cleavage stress in that plane, but prior delamination was necessary to trigger it. The relevance of a macroscopic critical stress criterion for delamination is finally discussed.

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Keywords: Delamination fracture; Brittle tilted fracture; Cleavage; Anisotropy, Microtexture

1. Introduction

Brittle out-of-plane cracks are commonly observed during impact tests along the transverse direction of high strength pipeline steels, and particularly for temperatures within the ductile to brittle transition range, Hara (2006). These fracture modes are delamination fracture and brittle tilted fracture (BTF), also called brittle slant fracture by Hara (2006). Delamination fracture, which for these steels involves brittle (cleavage) cracking parallel to the rolling

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plane, has been investigated by many authors such as Shin (2009) and Joo (2012), but underlying mechanisms have only scarcely been investigated (e.g. Baldi (1978)). In BTF, the crack propagates along a plane tilted by 40° with respect to the rolling plane. For a specimen tested along the rolling and the transverse direction, BTF and delamination interact with the main crack and thus affect the steel toughness. From Hara (2006), BTF reduces the shear percentage of the fracture surface after Battelle drop weight tear tests (BDWTTs). The present study aims at quantitatively investigating the anisotropy in resistance of cleavage fracture and its relevance to delamination issues, for a pipeline steel. Following the local approach of fracture, tensile tests were performed on notched specimens to determine the mechanical condition and physical mechanisms of initiation of cleavage cracking including delamination and BTF. An anisotropic yield criterion has been set to analyze the tests and to derive a critical cleavage fracture stress. Finally, the reliability of a critical stress criterion for delamination occurrence is discussed.

2. Material

As in Tankoua (2014), a 19.5-mm thick, ferritic-bainitic API X70 steel coil sample obtained after thermo-mechanical controlled processing was used. Its rolling and transverse directions are respectively denoted as RD and TD. In this material, brittle out-of-plane fracture occurred during BDWTTs (Fig. 1). At low temperature (< -80°C), brittle out-of-plane cracking was also observed after preliminary tensile tests on notched specimens. In the present study, tensile tests on notched bars were chosen for a quantitative investigation of cleavage initiation conditions, so that dynamic loading and contact issues involved in numerical simulation of impact tests were avoided.

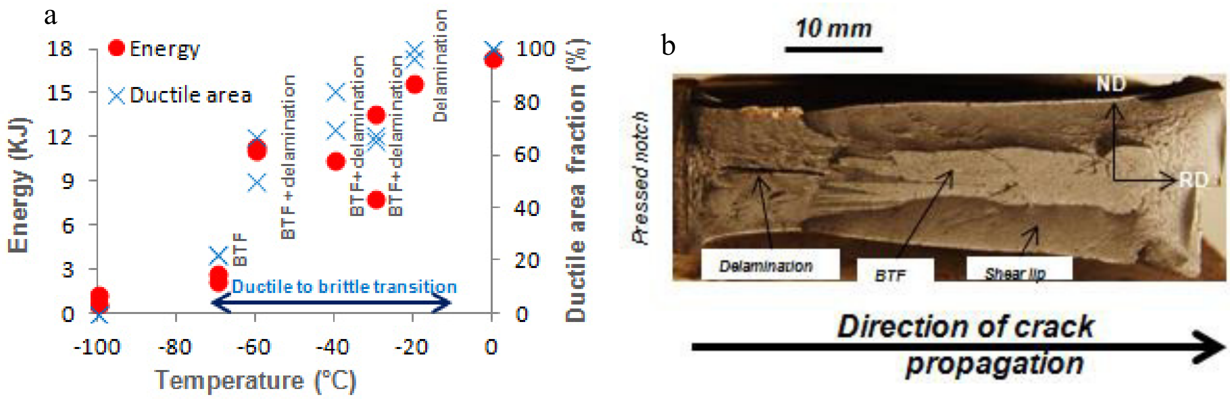

Fig. 1. (a) BDWTT behavior (loading along TD, crack propagation along RD); (b) Fracture surface (T= -40°C).

3. Experimental procedure

Tensile tests on smooth and notched specimens were performed between -196°C and +20°C along the following directions: RD, TD, ND (short transverse direction) and along the normal to the BTF plane denoted as “BTD”. Due to geometrical limitations, a small notched specimen geometry (Fig. 2) with high stress triaxiality ratio (around 1.6), was designed for ND and BTD, and also for RD and TD at -196°C (to avoid failure from threaded ends). Less severely notched larger specimens were used for RD and TD except at -196°C. A radial extensometer was used to measure the reduction in diameter. Notch opening was monitored with a longitudinal extensometer for larger specimens. The effective stress was calculated as the load divided by the initial cross-section and the diameter reduction was normalized by the initial diameter of the minimal section. Lankford coefficients were calculated as the ratio between the minimal and maximal diameter reductions, observed on broken surfaces of smooth specimens tested at -196°C, i.e. without necking. More detailed information about experiments is available in Tankoua (2014).

Fracture modes in competition and cleavage crack initiation sites were investigated with scanning electron microscopy (SEM). A special effort was made to analyze the inside of delamination splits. The microtexture of the four fracture planes of interest, i.e., perpendicular to the four loading directions, was analyzed using electron backscatter diffraction (EBSD) on large polished sections (1×0.5 mm^2) with a step size of 0.5 µm.

4. Experimental results

4.1. Mechanical response under tensile loading

Tensile tests on smooth specimens (Fig. 2.a-b) showed that the stress anisotropy is not significant, but that Lankford coefficients are different from 1, revealing strain anisotropy. Results of tensile tests on notched specimens are presented in Fig. 2.c to 2.f. An abrupt drop of the effective stress was noticed for specimens pulled along RD and TD at lower temperatures. Interruption of one test just after the abrupt drop event (associated to a loud noise), revealed the appearance of a delamination crack. For TD specimens at -100°C and -140°C, the drop of the effective stress was more pronounced and in that case the delamination crack was followed by BTF.

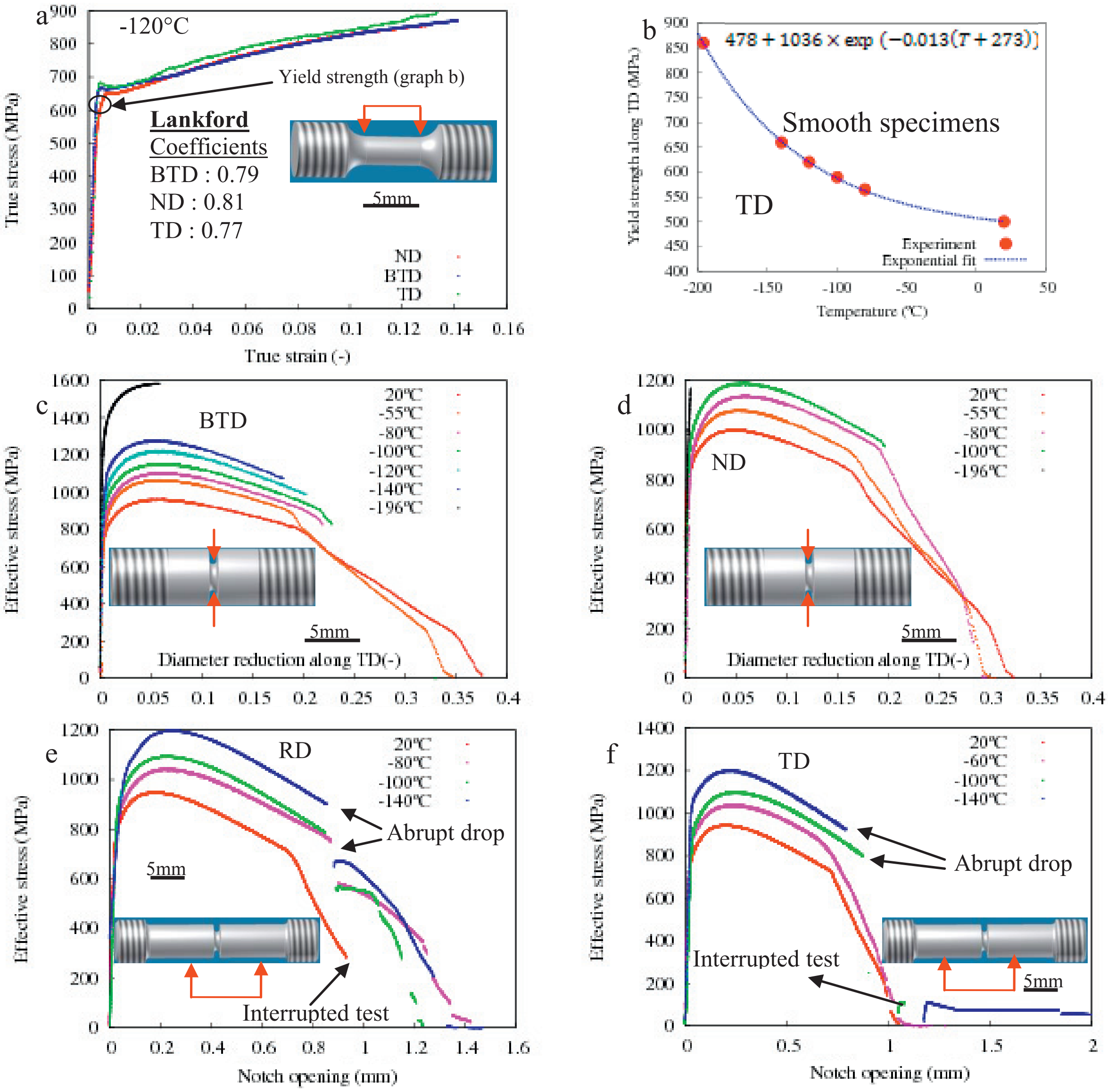

Fig. 2. (a) Tensile curves from smooth specimens at -120°C; (b) Evolution of yield strength with temperature; (c-f) Tensile curves of notched specimens. Red arrows indicate the location of extensometers ends.

4.2. Fracture mechanisms

For specimens pulled along ND, full cleavage fracture occurred for temperatures lower than -100°C and fully ductile fracture for temperatures higher than -80°C. Between -100°C and -80°C, a sharp ductile to brittle transition was observed (Fig. 3.a), with cleavage crack initiation from a ductile microcrack (500µm in size), see Fig. 3.b. For specimens pulled along BTD, delamination occurred along the rolling plane, here tilted by 40° with respect to the loading direction. The final flat cleavage crack initiated from that delamination crack (Fig. 3.c). Even at -90°C where clusters of dimples were observed, flat cleavage crack initiated from micro-delamination (Fig. 3.d). At -196°C, only one specimen broke by flat cleavage fracture without micro-delamination. Along RD, delamination cracks were followed by ductile slant, even at -140°C (Fig. 3.e). No BTF was observed; at -196°C, flat cleavage fracture occurred, despite the presence of micro-delamination cracks. Inside delamination splits, cleavage fracture initiated from a small ductile crack at the centre of the specimen (Fig. 3.f). Along TD, delamination cracks were followed either by ductile slant (T > -100°C) or BTF (T < -100°C) depending on temperature. BTF (Fig. 3.g and 3.h), was still observed for one specimen at -196°C.

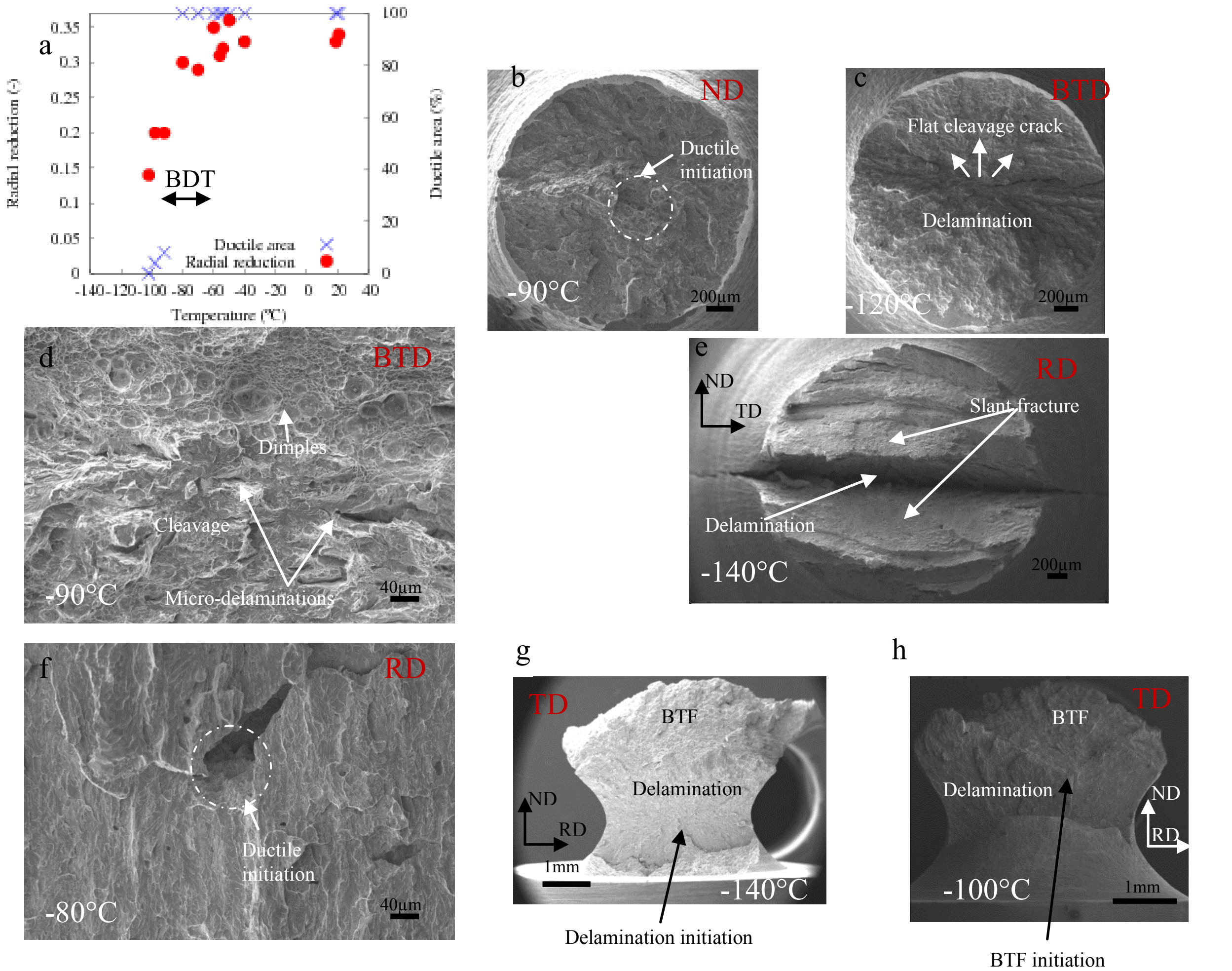

Fig. 3. (a) Ductile to brittle transition curve of notched specimens pulled along ND; (b) Fracture surface appearance in the brittle to ductile transition range (along ND); (c-d) Fracture surface of specimens pulled along BTD; (e) Fracture surface of a specimen pulled along RD (delamination + slant fracture); (f) Initiation of cleavage fracture inside a delamination split (-90°C); (g-h) Fracture surface of specimens pulled along TD, showing delamination crack and final fracture by BTF.

5. Estimate of the critical cleavage stress

Finite element simulations of tensile tests were performed to determine the condition of fracture initiation for notched specimens. An elastic-plastic constitutive model, with an isotropic hardening rule coupling a linear and an exponential term (Voce equation) was chosen and identified from tensile tests. An anisotropic yield criterion (Barlat (1991)) was chosen to reproduce this anisotropy. The identification of anisotropy parameters was performed at -196°C, and these parameters were taken independent of temperature. Except at 20°C and -196°C, hardening was also supposed independent of temperature in agreement with experiments. The yield stress was a function of temperature (Fig. 2.b). Ductile damage was not taken into account in that model. Finite element calculations were performed using quadratic bricks with full integration, finite strain formalism, a Newton-Raphson iterative scheme for global convergence and an implicit integration scheme for constitutive equations. A minimum element size at notch root equal to 50µm was considered for calculations. Because of symmetry only one eighth of the specimen was modeled. A uniform displacement was prescribed at the end together with usual symmetry conditions, see Tankoua (2014). The experimental results and the results predicted by the model were in good agreement (discrepancy lower than 5% for almost all experimental curves on notched and smooth specimens).

The macroscopic critical cleavage stress along the four principal directions was determined by extracting the value of the maximum principal stress at the cleavage initiation site (Table 1). Only notched specimens with flat cleavage fracture were chosen, so that local stress concentration induced by out-of-plane microcracks could generally be avoided. However, for specimens taken along RD and TD, micro-delamination cracks were observed at all temperatures. Thus, the critical cleavage stress estimated along those directions could be underestimated, because of micro-delamination cracks, which act as stress raisers.

Finally, the stress state at the center of the specimen was investigated at the delamination event (test along RD at -80°C). The value of the stress perpendicular to the delamination plane was estimated to 750 MPa. This value is much lower than the macroscopic critical cleavage stress estimated along ND.

Table 1. Macroscopic critical cleavage initiation stress along tested directions

ND	BTD	RD	TD
1780 MPa	2050 MPa	2270 MPa	2200 MPa

6. Analysis of the microtexture (potential cleavage facets)

Potential cleavage facets defined as zones where {100} planes are almost perpendicular to the sample axis/loading direction, were determined from EBSD maps. From quantitative fractography results of Tankoua (2014), internal misorientations up to 15° were allowed to define every potential facet. Fig. 4 presents the potential cleavage facets associated to the four investigated directions. Larger elongated potential cleavage facets (120 µm in length) were observed in the plane perpendicular to ND. Relatively large potential cleavage facets (80 µm in length) were also observed for the plane perpendicular to BTD. On the other hand, for RD and TD, only small potential cleavage facets were observed (less than 40 µm in size).

7. Discussion and concluding remarks

A strong anisotropy of the critical cleavage initiation stress was observed, from notched bars, in this study. Its value was lowest along ND, relatively low along BTD and higher along RD and TD. This difference between these values agrees well with potential cleavage facet sizes obtained by EBSD. The larger the potential cleavage facets, the lower the macroscopic critical cleavage initiation stress.

Observations of the inside of delamination splits showed that delamination cracking initiated from ductile micro-cracks which act as stress concentrators. Thus, delamination was partly caused by the lower value of the critical cleavage stress along ND, but stress concentrators such as ductile micro-cracks were necessary for its initiation. Quantitatively, during a tensile test along RD or TD, the macroscopic stress along ND observed at the delamination occurrence (750MPa) was much lower than the macroscopic critical cleavage stress extracted from tests along ND

(1780 MPa). Consequently, a macroscopic critical stress criterion is not relevant to predict delamination during tensile tests of notched specimens. The local stress concentration induced by the presence of ductile micro-cracks should be taken into account.

Brittle tilted fracture was also associated to the relatively low value of the critical cleavage initiation stress along BTD. However, prior delamination cracks (i.e., stress concentrators) were again necessary for its initiation. For tests along TD, BTF in this steel for most of the case might be considered as a simple tilt deviation of the delamination crack; in some instances, no initiation site of BTF from the delamination crack could even be found. BTF was not observed on notched specimens pulled along RD. In fact, in that case, the BTF plane could not be followed by a simple tilt of the delamination crack: a macroscopic twist deviation of the delamination crack is necessary, but appears to be experimentally impossible in investigated tensile testing conditions.

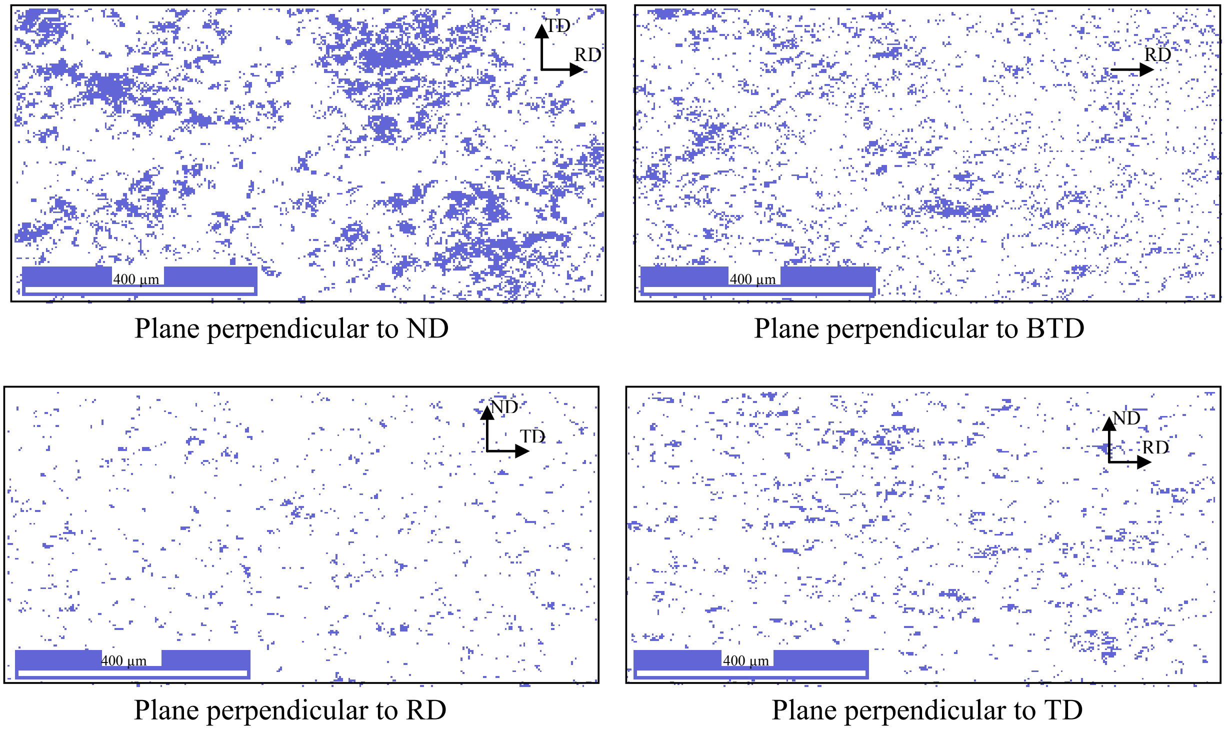

Fig. 4. Potential cleavage facets associated to the four directions: ND, BTD, RD, and TD.

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