EVALUATION OF CRACKING BEHAVIOR OF PIPELINE X70 STEEL FROM DWTT BROKEN SPECIMENS

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Abstract

Fracture surfaces of X70 steel DWTT broken samples are analyzed using statistical methods and fractal concepts. Applying self-affine fracture profile construction method and the first return probability method the Hurst exponent of ductile fracture areas has been found. Increasing percentage of ductile fracture on broken DWTT sample surface the Hurst exponent grows. Modeling of the DWTT fracture surface area by triangle net the statistical distribution of deviations between normal vectors of two neighboring elementary triangles has been discovered. This distribution behaves as Gaussian mixture. The mean value of deviation angles is lower for ductile than for brittle fracture regions whereas scatter of deviation angles are about the same for the both modes of cracking. Calculated fracture surface map of ductile fracture probability highly corresponds to real distribution of ductile and brittle fracture areas on fracture surface of the broken sample. Newly developed statistical methods of the fracture surface treatment of DWTT broken samples is useful tool for objective evaluation of ductile fracture percentage.

Keywords: X70 steel, DWTT samples, fracture surface, Hurst exponent, statistical analysis

1. INTRODUCTION

By studying local and macroscopic failure processes it is possible to successfully propose the physical-metallurgical and structural conditions for the required relation between strength, toughness and technological properties of steels. A high degree of toughness is conditional upon high dissipation of deformation energy during crack propagation, which enables the initiation of ductile fracture. The requirement for minimum 85 % ductile fracture on the fracture surface in DWTT specimens remains an important technical criterion of resistance to unstable ductile fracture in pipes. The preparation of testing specimens for DWTT, the conditions of testing and the methods of evaluation are normalized [1, 2-4]. Subjective visual assessment of the character of fracture surfaces leads to a range of inaccuracies, and the determination of the ductile fracture percentage is burdened with a high degree of error. For these reasons, and also due to the practical need in some cases to perform assessments of fracture surfaces which do not fully meet the criteria of API [2], ASTM [3] and ČSN [4], it was decided to develop new methods of evaluation providing correct, objective and reproducible results and reflecting with sufficient accuracy the changes in resistance of pipeline steels to long-running ductile fracture.

2. INVESTIGATED MATERIAL AND METHODS

Fracture surfaces of broken DWTT specimens were studied using samples from commercially produced API 5 L X-70 sheets Cr-Mn steel with thickness of 18.7 mm. The steel was austenitized at 1200 °C and rolled with an initial temperature of 985°C and a final rolling temperature of 832 °C. It was then water-cooled from 800°C to 465 ° at 9.1 °C/s. Throughout the thickness of the steel, the microstructure consisted of a mixture of ferrite and pearlite with less pronounced boundedness both longitudinally and laterally to the rolling direction. Basic mechanical properties of the steel at 20 °C were determined by tensile testing on standard specimens with a circular cross-section of diameter 4 mm at deformation speed 0.008 s^{-1}. The yield strength Rp0.2 > 485 MPa and the tensile strength Rm > 570 MPa meet strength criteria specified in [5] for API 5L X-70 steel.

The proposed methods of evaluating the ductile fracture percentage (i.e. the percentage of the fracture surface displaying ductile fracture) were tested on ten DWTT specimens with dimensions 300 x 76 mm and with the same thickness as the sheet steel (18.7 mm). The specimens were press-notched to a depth of 5.1 mm. All DWTT specimens were tested at -20°C. The DWTT specimens were broken by a falling weight of 800 kg on Drop Weight Tester 40 apparatus. Fracture surface of broken DWTT specimen of investigated API 5L X-70 steel at -20°C is given in (**Fig. 1**).

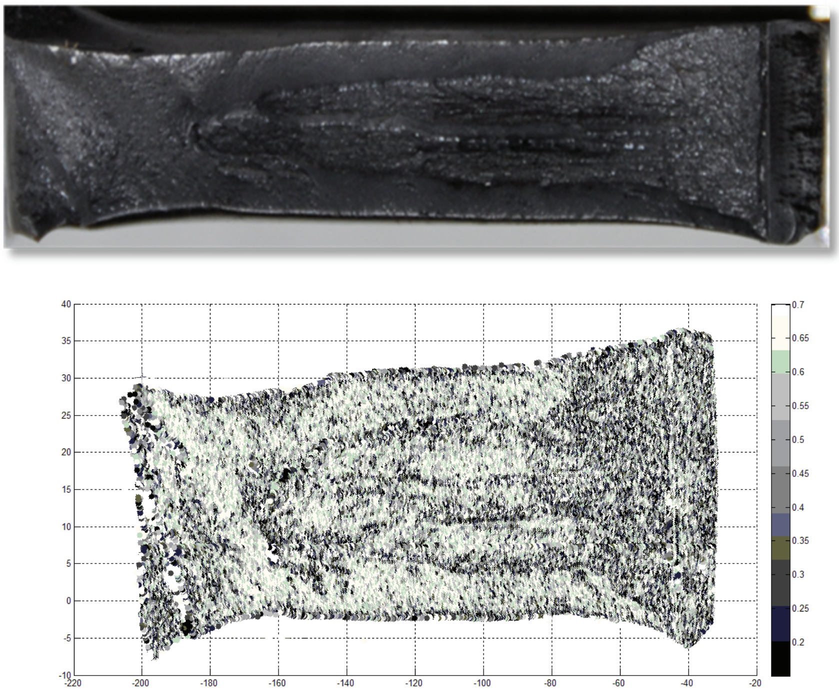

Fig. 1 Fracture surface of broken DWTT specimen - API 5L X-70 steel at -20°*C* and accounting probability field $p_d(\varphi)$ of ductile fracture

It has been shown [6] that fracture surfaces are mostly statistically invariant, suiting a self-affine scaling transformation of the forms $(x, y, z) \rightarrow (\lambda x, \lambda y, \lambda^{\xi} z)$, where $\xi < 1$ is the Hurst exponent. That means that for a self-affine fracture surface, the *z* coordinate characterizing the surface unevenness is statistically dependent on the horizontal coordinates *x*, *y*, however its sensitivity to change is lower than that of coordinates *x*, *y*. This is also projected into the change in distance [7],

$$\Delta z \propto (\Delta x^2 + \Delta y^2)^{\xi} \quad (1)$$

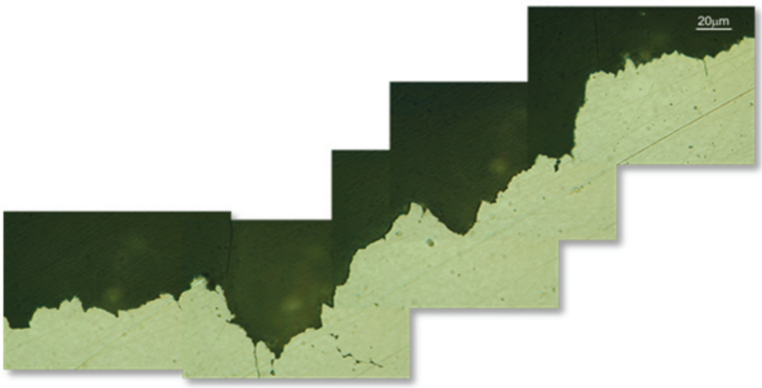

Fig. 2 Profile of the ductile fracture segment in direction of crack propagation on DWTT broken sample of API 5L X-70 steel

To establish change of Hurst exponent for fracture surfaces a method of vertical cuts was employed. The samples were molded and the metallographic cuts, which included the investigated profile, were made as perpendicular to fracture surfaces. After the preparation, fracture profiles were observed by a light microscope with digital camera in different magnifications. Profile of the ductile fracture segment in direction of crack propagation on DWTT broken sample of API 5L X-70 steel is obvious from (**Fig. 2**)

To determine the Hurst exponent ξ of the fracture profile, the first return probability method was applied. Let the understand *z*-coordinate of the surface is a function *f* of *x*-coordinate. For every point x_0 of the profile with the *z*- coordinate $f(x_0)$, we see the minimum distance *d*, such that $f(x_0+d)= f(x_0)$. The distribution of the *d* distances built for all the points of the profile is called the first return probability distribution $p_1(d)$. For self-affine profiles, it can be shown, that the first return probability satisfies:

$$p_1(d) \sim d^{\xi-2}. \qquad (2)$$

Using logarithmic binning the previous form can be modified as follows:

$$log\left(p_1(d)\right) \sim d^{\xi-1}. \qquad (3)$$

The Hurst exponent ξ can be obtained by using the least square method from the previous relationship.

Fracture surface areas to identify differences between brittle and ductile fracture surface has been applied. This method consists into the following steps. The fracture surface was firstly covered with the net of triangles, and Delaunay triangulation was used [8]. The vertices of any triangle correspond to real measurements of the fracture surface (**Fig. 3**). Every triangle is evaluated by the greatest angle of its normal vector with normal vectors of neighboring triangles of φ. Distribution of angles of normal vectors on areas with brittle or ductile fracture was described as a Gaussian mixture using the EM algorithm [9].

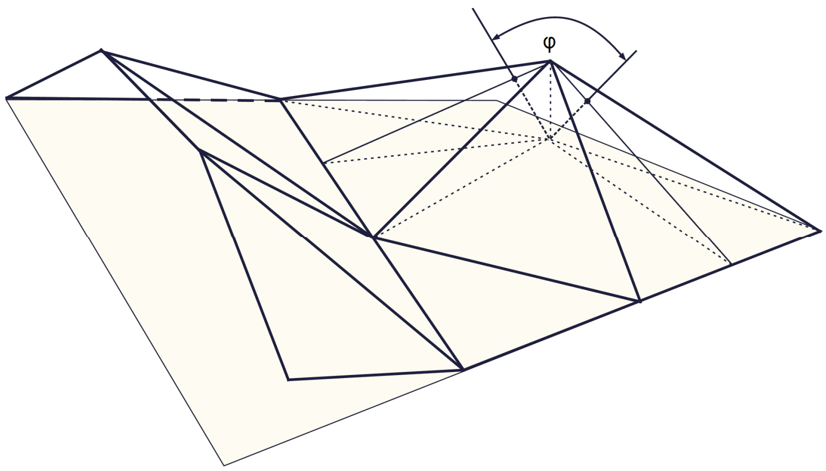

Fig. 3 The triangular net model of fracture surface and angular deviation of neighboring elementary areas

The distributions of angles in a ductile and brittle area were described with two-component Gaussian mixtures. For every angle φ of the DWTT fracture surface there was calculated the probability $p_d(\varphi)$ that the φ belongs to the ductile fracture area. The probability $p_d(\varphi)$ was computed by using the following formula

$$p_d(\varphi) = \frac{f_d(\varphi)}{f_d(\varphi)+f_b(\varphi)} \qquad (4)$$

where $f_d(\varphi)$, $f_b(\varphi)$ are Gaussian mixtures distributions of angular deviations φ of the ductile and brittle fracture.

3. RESULTS AND DISCUSSIONS

Applying the proposed procedure the Hurst exponent distributions has been found for demonstrably brittle and ductile fracture surface areas of broken DWTT samples. Totally have been investigated 672 number of vertical cuts in ductile and 987 number of cuts in brittle regions of fracture surfaces. Both statistical sets exhibit two parametrical Weibull distributions with clearly lower size parameters $\alpha_b=0.77$ for brittle fracture area, and higher size parameter $\alpha_d=0.82$ ductile fracture regions. Conversely shape parameter $\beta_b=6.87$ is higher for brittle fracture area, than the shape parameter $\beta_d=6.34$ for the ductile fracture area (**Fig. 4**).

Probability density functions of angular deviation of neighboring elementary areas φ of the ductile $f_d(\varphi)$ and brittle fb(φ) fracture regions of DWTT broken samples have been successfully approximated by two members of Gaussian mixtures distributions using EM algorithm [9]. The mean value of angular deviation of neighboring elementary areas φ is lower for ductile fracture region than for brittle fracture area. According to Eq. (4) for any investigated elementary area probability of ductile fracture $p_d(\varphi)$ has been calculated. The example of probability of ductile fracture $p_d(\varphi)$ represented as probability field is given in **Fig. 1**. This field very good corresponds to mechanisms of fracture on real DWTT broken sample.

The both analyses of the character of fracture surfaces in DWTT specimens were performed with reference to the entire fracture surface. Taking into account local changes in controlling mechanisms of crack propagation could reveal more about the non-homogeneity of the fracture process, and for this reason local fractal analysis is very useful. The formation of steps on the fracture surface with sudden changes of height or surface defects of intensively deformed material could thus be accurately quantified using fractal analysis methods. This also has practical impacts on the evaluation of new sources of toughness in steels for the production of pipeline systems.

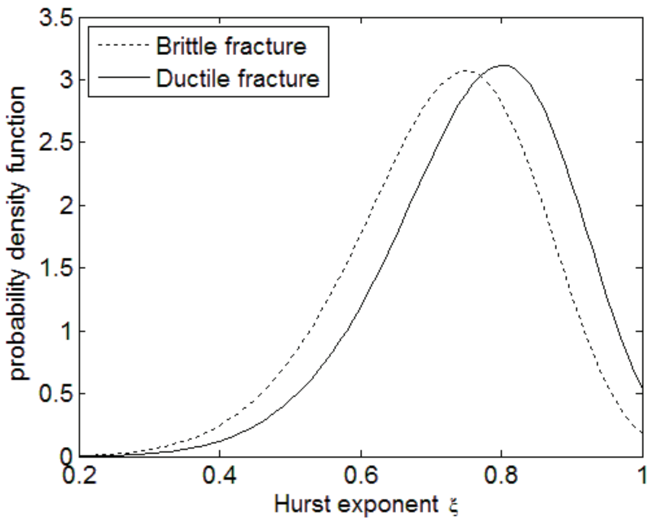

Fig. 4 The Weibull statistical distributions of Hurst exponent of ductile and brittle fracture regions of DWTT broken samples

4. CONCLUSIONS

A detailed quantitative fractographic analysis of fracture surfaces of X70 steel DWTT specimens was performed in order to investigate all possible ways of evaluating its character, especially the ductile fracture percentage, independently of individual observation. The assessment of relations between basic quantitative indicators of unevenness in fracture surfaces and failure mechanisms opens up possibilities for the objective determination of mechanisms of deformation energy dissipation in relation to steel microstructure. The analysis of fracture surfaces of X70 steel DWTT broken specimens led to the following conclusions.

The roughness of the brittle fracture is higher than the ductile fracture of tested X70 steel at -20°C. Thus the ductile fracture area is represented by higher Hurst exponents. The distribution of Hurst exponents of elementary investigated fracture areas exhibit for the both mechanisms of fracture the Weibull distribution.

These distributions differ significantly both in the size and the scale parameter. New approach how to identify character of the fracture surface has been presented. Angular deviation of normal vectors of neighboring elementary areas φ behaves as sensitive parameter differentiating clearly ductile and brittle fracture area. Angular deviation of normal vectors of neighboring elementary areas is definitely larger on brittle fracture area than on ductile fracture area. Using simple Baeys' formula given by Eq. (4) the probability of ductile fracture of the whole fracture are has been calculated. This result rightly corresponds to mechanisms of fracture on real DWTT broken sample.

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