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Fracture Mechanisms During Crack Branching. Part 2. Steel

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Abstract: The mechanism and patterns of rapid crack propagation and branching in carbon steel were studied on the fracture of cylindrical vessels with artificial defects under internal pressure. It was established that microscopic fracture patterns are common for model (polymethylmethacrylate) and structural (carbon steel) materials. SEM fractography shows that fracture occurs via transgranular cleavage; the lateral dimension of the crack formation zone increases along the crack path and decreases immediately before branching. A physical crack branching mechanism was proposed, based on study of patterns of single crack rapid propagation and its transition to branching mode in the model and structural materials. Crack transition from rectilinear propagation to branching occurs when its velocity V reaches its limiting value V^*, at which the flow of elastic strain energy entering the crack tip, G, exceeds energy G^* expended by the material to hold off the growth of the single crack, i.e. at $G>G^*$ (necessary condition) and $V=V^*$ (sufficient condition). The value of G^* depends on the deformation properties of the material at $V\to V^*$ and on the sample thickness.

Key words: *Steel · Cylindrical vessels · Fracture · Crack branching*

INTRODUCTION

Experience shows that catastrophic failures of large, thin-walled metal structures (large diameter natural gas and petroleum pipelines, tanks, pressure vessels, etc.) occur not only with extended propagation of a brittle or ductile crack, but also with crack branching, which leads to fragmented fracture of the metal structure body. An example of this type of failure was the rupture of the Berge–Yakutsk gas pipeline after 30 years of operation, when a crack caused by a weld defect spread along the pipeline with numerous branches [1].

A rather large number of experimental and theoretical papers have been dedicated to the study of the crack branching process; however, questions related to establishing the criteria and explaining the crack branching mechanism in rigid bodies remain unanswered and the conclusions of various authors are often contradictory (Ravi-Chandar *et al*. 1998; Sharon *et al*. 1996, Nemec *et al*. 1970; Naimark *et al*. 2000; Finkel 1970; Duffy *et al*. 1977). It should be noted that crack branching has mainly been studied in model materials (polymethylmethacrylate, epoxy resin, Homalite H-100) [2-5]; only a few papers have studied crack branching in structural materials, including steels [6-7]. This is due to technical difficulties in achieving crack branching during sample fracture and the imperfection of measurement instruments.

The objective of this paper is to study the nature and patterns of crack branching during crack propagation in carbon steel.

Macroscopic Patterns of Single Crack Rapid Propagation and its Transition to Branching Mode: For experimental study of crack branching in steels, a series of full-scale tests were conducted by applying internal pressure to cylindrical vessels with a diameter of 219 mm, length of 1 370 mm and wall thickness of 8 mm, made of air-hardened steel 45 with artificially applied surface stress raisers. The artificial defect in the form of a 2 mm deep and 2 mm wide longitudinal notch was made in the central area of the vessel surface; the notch lengths varied, with values of 50, 60, 70 and 90 mm.

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Fig. 1: The crack branching in steel

Internal pressure was applied to the vessel through the expansion of freezing water: a pressure vessel, filled with liquid and sealed, was cooled to sub-zero temperatures. When the internal hydrostatic pressure reached the critical value, the vessel ruptured as the result of a crack initiating from the artificial defect.

A custom automated measuring system was developed in order to record the change in temperature, deformation and pressure during rupture of the pressure vessel, allowing for real-time recording, processing and analysis of experimental data obtained during testing. In the experiment were used pressure sensors, thermocouples, strain gauges and displacement sensors. Programs in Turbo Pascal 7, Delphi 7 were written for automatic data recording during the experiment and for its subsequent processing.

Fracture microstructure was studied using an XL-20 Philips scanning electron microscope. An SJ-201 Mitutoyo surface roughness tester was used to determine the roughness of the fracture surface.

During vessel testing, crack propagation initiated from the notch in all cases (Fig. 1). Depending on the notch length, the experiment lasted from 8 to 25 hours.

According to strain gauge readings, elastic lateral deformation reached 0.2% at pressures of 38, 32, 30 and 18 MPa for vessels with notches 50, 60, 70 and 90 mm long, respectively; further deformation was plastic. Longitudinal deformation remained within the elastic range until vessel fracture. According to thermocouple readings, the average temperatures were: ambient air: -20°C, vessel walls at fracture: -5°C and inside vessel at fracture: -3°C, which are comparable to operating conditions for underground trunk lines in the permafrost zone.

The nominal fracture stress values σ for pressure vessels were calculated based on the empirical ratio proposed by A. Duffy [9] and G. Hahn [8] for thin-walled cylindrical steel containers with surface defects:

$$\sigma = \bar{\sigma}\left[\frac{1-\frac{t}{d}}{1-\frac{t}{d}\cdot\frac{1}{M_F}}\right] \quad (1)$$

where M_F is the Folias correction; l is the notch length; R is the vessel radius; t is the vessel wall thickness; d is the surface defect depth; and $\bar{\sigma}$ is the average plastic flow stress for the material, determined experimentally by means of yield strength $\sigma_{0.2}$ and ultimate strength σ_S.

Mechanical characteristics $\sigma_{0.2}$ and σ_S are determined experimentally in the course of standard tensile tests on flat samples using a Zwick Z600 universal testing machine at room temperature. In order to calculate $\bar{\sigma}$, the following regression equation was used [8]:

$$\bar{\sigma} = 0.5(\sigma_{0.2} + \sigma_S) \quad (2)$$

The Table 1 shows experimental data and characteristics of the crack propagation and branching process in vessels. These data show that crack propagation mode in vessels depends on the level of internal pressure P (fracture stress σ): at $P<23$ MPa ($\sigma<422$ MPa), crack propagation is rectilinear; at critical level of internal pressure $P^*>31$ MPa (critical level of fracture stress $\sigma^*>444$ MPa) crack propagation is observed along two branches, forming an angle β (Fig. 1). Fig. 2 shows the values of σ as function of l.

Table 1: The data of a crack propagation in steel

l, mm	*ε*, %	*P*, MPa	*σ*, MPa	Mode of a crack propagation	L_2, mm
0	0,22	23	422	Rectilinear trajectory	-
70	0,43	31	444	Trajectory curving and crack branching in the lower part of a vessel	140
60	1,09	38	473	Trajectory curving and crack branching in the lower part of a vessel	75
50	1,38	51	496	Trajectory curving and crack branching in both parties of a vessel	In the lower part – 3 mm, in the upper part – 40 mm

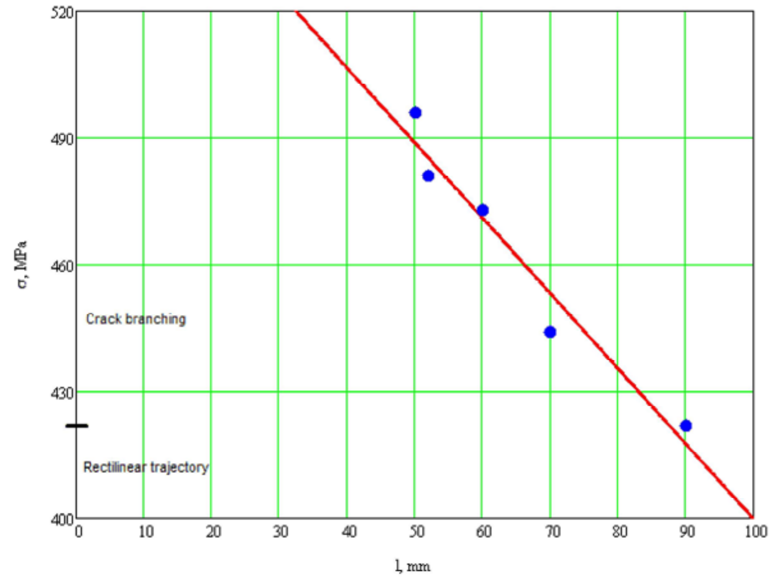


Fig. 2: Dependence of a fracture stress σ on the notch length l

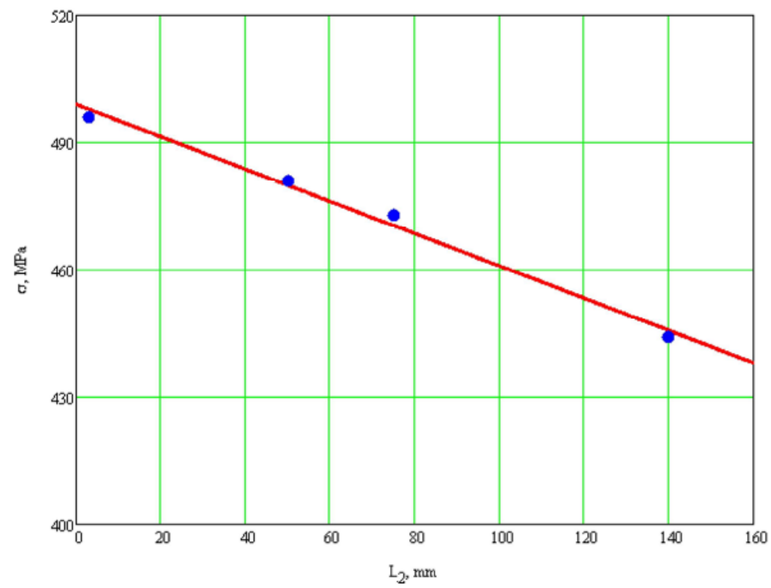


Fig. 3: Dependence of a fracture stress σ on the distance from the notch to the crack branching point L_2

The process of vessel fracture with crack branching is accompanied by the formation of microbranches of length λ, both before and after branching of the main crack, forming an angle α with the main crack. The values α, β and λ take on the following values: α=8–10°, β=40–60° and λ=2–130 mm, i.e. the maximum branching angles are significantly greater than microbranching angles.

The distance from the notch to the crack branching point L_2 depends on fracture stress σ: the greater the fracture stress, the shorter the distance between the notch and the point where the crack transitions to branching mode. Fig. 3 shows the values of σ as function of L_2.

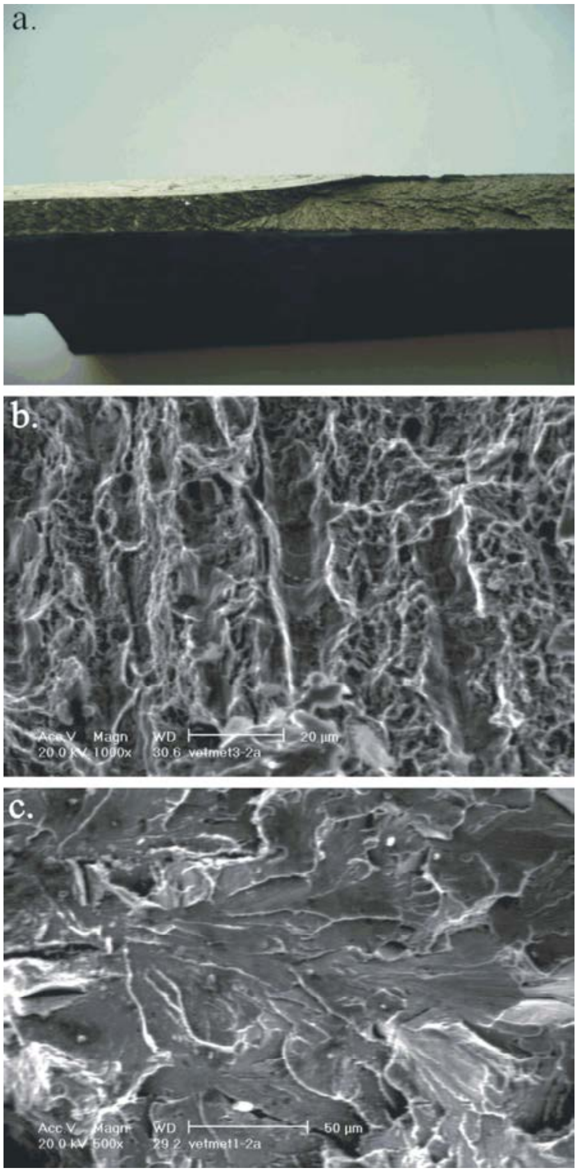


Fig. 4: The fracture surface of a steel at crack propagation with branching: a - general view; b, c - fibrous and radial zones

Microscopic Features of Fracture Surfaces and Discussion of Results: Examination of fracture surfaces (Fig. 4, a) shows that they are perpendicular to the direction of the main stresses and are formed as the result of plane-strain fracture (cleavage). Two distinct types of fracture zones are distinguished in fractures: a small fibrous zone, which forms along the notch over the entire thickness of the vessel wall (Fig. 4, b) and the radial zone, which constitutes the remainder of the fracture (Fig. 4, c).

The fibrous zone corresponds to stable, rectilinear crack propagation; fracture occurs via propagation of the initial crack in the plane of maximum tensile stresses due to integration of micropores. As fracture stress σ increases, the share of the fracture area allocated to the fibrous zone, S_1 / S_2 (S_1 is the area of the fibrous zone and S_2 is the total fracture area) decreases (Fig. 5). Also, as σ increases, the distance from the notch to the branching point decreases. Based on the foregoing, it follows that as the fractures stress σ increases, the energy accumulated at the crack tip increases and the crack transitions to the unstable propagation stage and branching mode sooner.

Adjacent to the fibrous zone is the radial zone – the area where a crack transitions from slow growth to unstable propagation. In this zone, fracture occurs via propagation of the cumulative crack front, which consists of fronts moving along several offset levels that are joined by cleavage steps or microshear areas – the so-called radial seams. The radial seams are directed toward the free surface of the vessel and form a chevron pattern, which emerges due to misalignment between the propagation directions of the cumulative crack front along the vessel and of each part of the crack front, which is the shortest distance to the free surface of the vessel wall. Fracture in the radial zone occurs via brittle transgranular cleavage; fractography shows that its morphology consists of cleavage facets with a river line – cleavage steps between local cleavage facets of one common cleavage plane.

By us it is shown, for nominally brittle materials such as PMMA, dynamic crack propagation is accompanied by intensive formation of microcracks at various depths below the mean fracture surface. Some of them merge with the main crack, forming cleavage steps. Thus, the fracture surface does not reflect the fracture processes that occur in distant layers of the process zone and the dimensions of this zone are not limited to fracture morphology and width of the sample. PMMA is a transparent material, which made it possible to measure the fracture process zone [10].

In the vessels studied, fracture occurs via propagation of a single crack and the the fracture surface morphology fully reflects the dimensions of the process zone. At the same time, it is not sufficient to consider roughness as the only qualitative parameter of the fracture surface morphology since, on a defined measurement basis, the average roughness cannot distinguish between the fracture processes that occur by different mechanisms: by fracture in the plane of maximum

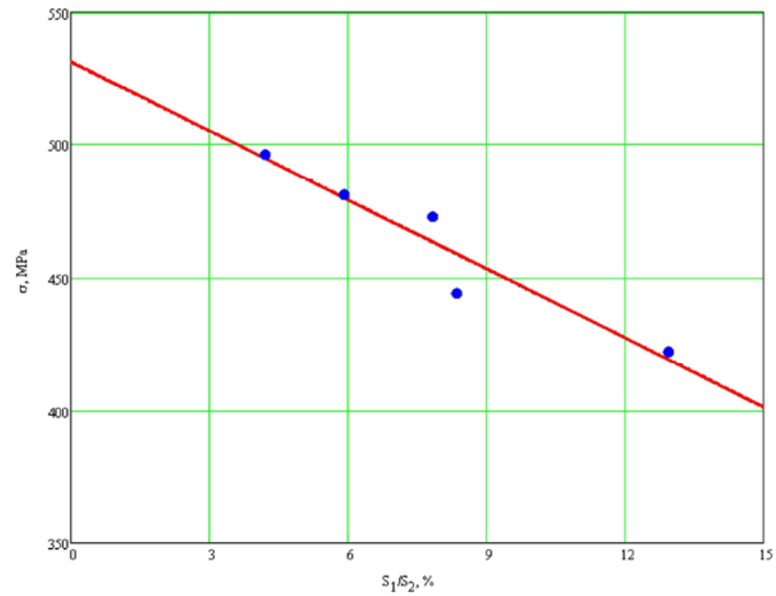


Fig. 5: Dependence of the relation of the fibrous zone area to the total area of fracture S_1/S_2 on fracture stress σ

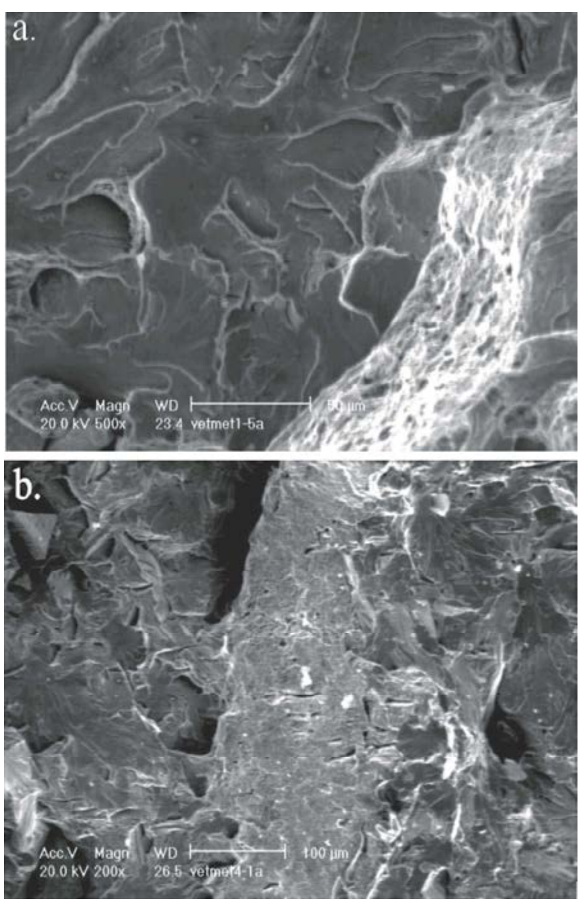
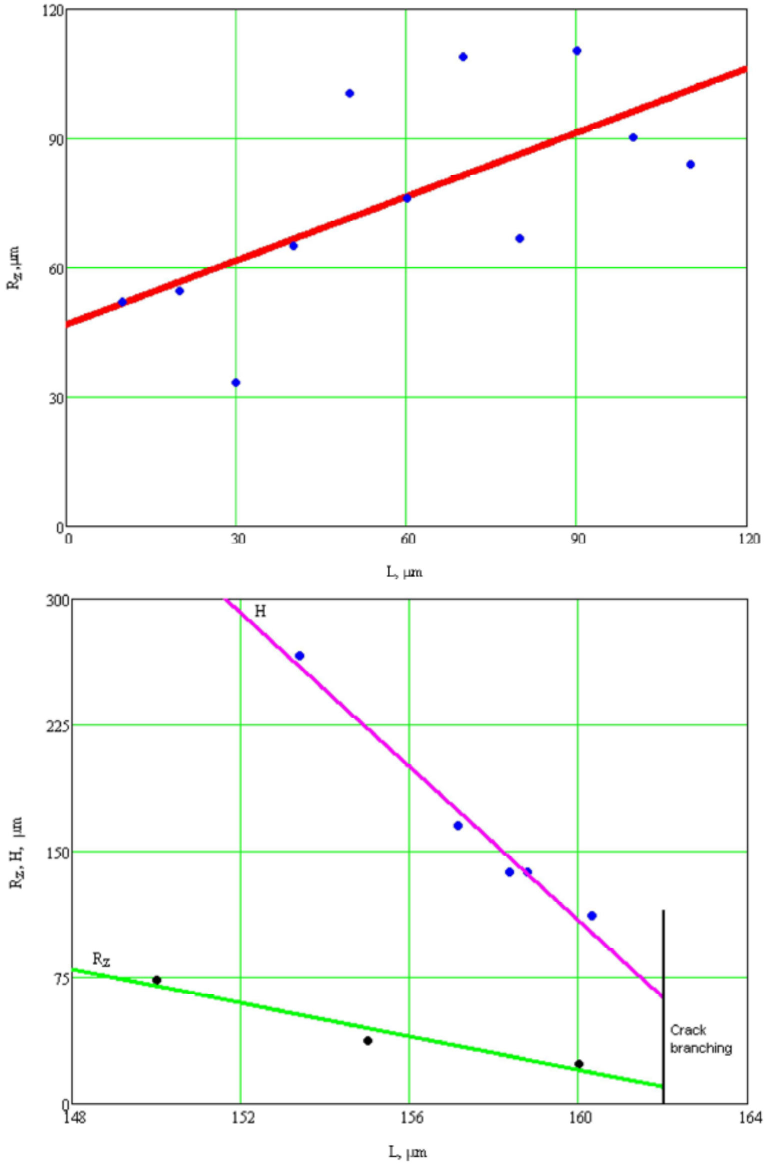


Fig. 6: The structure of radial seams: a- at distance of 20 mm from the notch; b - at distance of 153 mm from the notch

tensile stresses or by cleavage via disruption of connections of the material between parts of the crack fronts moving along parallel planes. Therefore, two qualitative parameters were used to characterize the dimensions of the process zone in the pressure vessels studied: profile roughness height R_Z, evaluated at 10 points within the base line (GOST 2789-73) passing through the fracture area between radial seams and the height of the radial seams *H*.

Roughness was measured using a surface roughness tester along three straight lines on the cracks propagation path at 5–10 mm intervals. The length of the base line was 0.25–0.8 mm. The minimum measurement interval and base line length were maintained starting at 15 mm to the branching point. The distance between seams was on the order of 1–5 mm. The height of radial seams was measured using SEM images of the fracture surfaces obtained with sample inclination of 30°.

It was established that as the distance from the notch (crack propagation velocity) increases, radial seams form with less roughness and without details (Fig. 6, a, b). Roughness of the fracture surface steadily increases along the crack path (Fig. 7, a) and decreases starting at a distance of approximately 15 mm before the branching point (Fig. 7, b). Radial seam height also steadily decreases approaching the branching point (Fig. 7, b). Thus, the fracture surface morphology, i.e. the dimensions of the process zone, in case of crack propagation with branching, is greatest at a certain distance before the branching point and decreases before branching.



a.

b.

Fig. 7: Dependence of surface roughness R_Z and height of radial hems H on distance from the notch L at rectilinear

In the pressure vessels studied that failed with crack branching, microbranches form both before and after branching of the main crack. Just as in flat samples of PMMA with initial side notches that failed with branching under tension [10], microbranches occupy part of the sample thickness and take on a wedge shape due to achieving two-dimensional stress condition upon reaching the lateral surfaces of vessels. The microbranch and the main crack repel each other: a wide microbranch propagates along the trajectory of the main crack, causing the trajectory to curve; a thin microbranch forms an angle with the main crack, which continues on its previous trajectory.

Material fracture in sections corresponding to microbranching and branching occurs via the same mechanism of transgranular cleavage as in the remaining section of the radial zone (Fig. 8). When a branch (microbranch) occupies the entire width of a plate, two equivalent branches form with identical stress fields.

Experimental work dedicated to measuring the terminal velocity of cracks in steel, i.e. upon branching, has established that terminal velocity in ШХ15 hardened tool steel, at which crack branching is observed, is several times greater than the same parameter for carbon structural steels [6]. Thus, terminal velocity of crack propagation depends on the material a nd is not

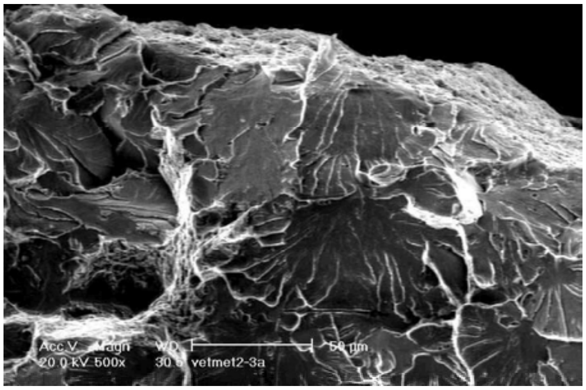


Fig. 8: The structure of the site of the fracture surface corresponding to formation of a microbranch

determined in accordance with the continual theory, but by the processes controlling fracture in the given material.

The limiting velocity of crack propagation can be defined as

$$V^* = \mu v \quad (3)$$

where μ is the linear dimension of the activation volume in the fracture process zone and v is the frequency of breakage of interatomic bonds in said zone at $V \sim V^*$. If we assume V^*=2000 m/s [7] and v in case of brittle fracture to be equal to the natural frequency of atomic oscillation of a solid body v_0 (for iron atoms v_0=8.7·10^{12} s^{-1}), then the minimum dimension of the fracture localization zone in hardened tool steels is $\mu \sim 2 \cdot 10^{-10}$ m, which is comparable to the interatomic distance in the crystal lattice of steel.

In other words, achieving terminal velocity mode of crack propagation entails transition of the fracture process to the underlying structural level and in nominally brittle materials occurs on the typical scale of the primary (atomic) level of structural damage, i.e. via breaking interatomic bonds.

CONCLUSION

An original method for testing cylindrical vessels with artificial surface defects under internal pressure was used to study patterns of rapid crack propagation and branching in carbon steel and the following conclusions were reached.

- Macroscopic fracture patterns are common for the model (polymethylmethacrylate) and structural (carbon steel) materials.
- In carbon steel, fracture with rapid crack propagation follows the transgranular cleavage mechanism; the lateral dimension of the crack formation zone increases along the crack path and decreases immediately before branching.
- Crack branching in both materials occurs when its velocity V reaches its limiting value V^* at which the flow of elastic strain energy entering the crack tip, G, exceeds energy G^* expended by the material to hold off the growth of the single crack, i.e. at $G>G^*$ (necessary condition) and $V=V^*$ (sufficient condition). The value of $G^*$is a function of the deformation properties of the material at $V \rightarrow V^*$ and of the sample thickness.

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