Determination of the Fracture Toughness of Thermoplastic Materials using the J Integral Method

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The J integral method was used to characterize the dependence of stresses and strains in the vicinity of the crack tip in thermoplastic materials with nonlinear deformations. This method makes it possible to establish the correlation between crack growth resistance of the material based on the stable propagation and the crack extension by means of J-R curve, which is an indicator related to the toughness of the material. The paper presents the results of experimental researches carried out on three-point bending test specimens of thermoplastic high density polyethylene - type PE 100, taken from the pipes with 110 mm diameter.

Keywords: J-integral, J-R curve, toughness, thermoplastic materials, polyethylene PE 100

In recent years, fracture behaviour of polymeric materials has become a major concern, because the diversity of industrial areas where they have applications. One of the most important fields where thermoplastics (polyethylene - PE, polypropylene - PP, Polyvinylidene fluoride - PVDF) are applied is that of pipelines meant for the transport of pressure fluids. Being a field in an ever-growing trend, the field of installations requires solutions to become more efficient regarding the production of new materials with improved characteristics and long service life. Another important application of thermoplastics is in sandwich structures, usually like faces.

A current concern of researchers is to expand the concepts of fracture mechanics to plastics, ceramics and composites. Thermoplastic materials are generally viscoelastic which means that their mechanical properties reflect both characteristics: liquids viscosity and elasticity of the solids [1-4].

Toughness characterization of materials is an important aspect of fracture mechanics. Application of fracture mechanics concepts in design, for example, involves establishing a mathematical relationship between fracture toughness, applied stress and defect size.

Fracture behaviour of polymeric materials, depending on the operating or testing conditions, may be in the linear elastic region or, as often happens, in the elastic-plastic region.

While linear-elastic or elastic-plastic fracture mechanics are focused on time-independent materials, viscoelastic and viscoplastic fracture mechanics include materials in which time is an important variable. Of the many types of behaviour at break, through which materials are generally characterized, i.e. elastic-plastic, viscoelastic and viscoplastic behaviour can be grouped in a special field, specific to nonlinear fracture mechanics [5].

Most often used parameter to characterize fracture of polymeric materials is the J integral [6, 7].

A pipeline system may fail from a variety of causes and failure mechanisms, which may include: poor design, poor materials, improper installation, operating conditions, environmental factors, different thermal or chemical agents and other factors which cause premature aging of the material [8].

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Fracture phenomena occurring in thermoplastic pipelines, are one of the most common ways of damage, and may manifest themselves in different ways causing various side effects.

Pipeline fracture is actually a phenomenon linked to the stable or unstable propagation of a crack in the pipeline's material. A certain existing crack may remain stable from a geometrical point of view, or it can manifest instability and increase, according to the variation of the stress in the pipe wall due to the actual conditions of loading.

In case of relatively high toughness values of a material, it has the important feature to inhibit the growth of pre-existing imperfections, so preventing a subsequent crack initiation and propagation.

Pipelines cracking is one of the most obvious elements that denote a local exceeding of material fracture toughness, which can thus lead in time to the failure of the pipeline.

This paper aims to determine the toughness of materials with viscoelastic behaviour such as high density polyethylene, type PE 100, using the J integral (J-R curves) to further establish correlations between toughness, stress and allowable size of imperfections.

Experimental part

In the case of thermoplastic materials with a partially crystalline structure, including the polyethylene PE 100 types, characterization of fracturing phenomena can not be based on the classical theory of linear elastic fracture mechanics.

Specific aspects of thermoplastics fracture behaviour, that are characterized by large deformations prior to fracturing through the material flow at the crack tip, remain subject of the attention of researchers in order to develop a number of suitable methods to characterize the field of stress - strain in the vicinity of the crack tip, for materials with nonlinear deformation [5].

One of the global energetic methods recommended to be used in the case of thermoplastics, which allows analysis of crack extension during a slow loading, is the J integral method. ASTM D 6068 presents the testing method for determining the crack growth resistance of the material by J-R curves, the J integral being the energy available per unit length of the crack in extension [9].

Using the J-R curves, one can describe the crack growth resistance of a thermoplastic material regarding its ability to inhibit the growth of a stable crack, after initiation from a preexisting sharp flaw.

Experimental researches have been conducted using samples taken from PE 100 polyethylene gas pipes, having 110 mm in diameter and 10 mm thickness.

Single Edge Notched Bending SE(B) specimens were machined according to ASTM D 6068 requirements. The configuration and dimensions of the specimens are shown in figure 1.

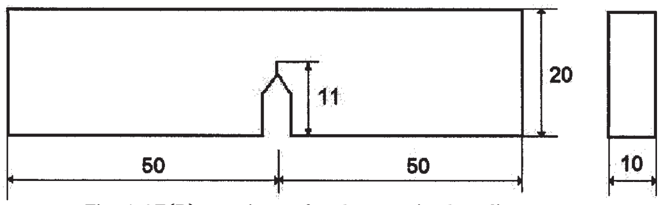

Fig. 1 SE(B) specimen for three point bending test

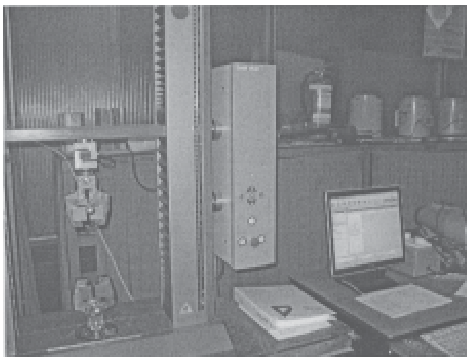

Fig. 2. Static testing machine Zwick Z005

The experimental test program consisted of bending seven specimens machined with notch and then precracked, with similar configurations and size, respectively an unnotched test specimen was prepared for determining the indentation displacement and energy corrections.

The bending tests were performed using a Zwick Z005 machine, with maximum force of 5 kN (fig. 2) at a rate of 1 mm/min, at 27 ° C.

The aim of these tests was to obtain the J-R curve, which expresses the correlation between the J integral values and the corresponding increase in crack length Δa. Thus using this method, named with multiple specimens, a single point on the J-R curve was determined by each tested specimen.

Specimens with markings from 1 to 7 were loaded at various testing forces, corresponding to specific displacement values of the force application point: 2, 2.5, 3, 3.5, 4, 4.5 mm and respectively 13.8 mm – displacement recorded at the maximum force 386 N (figs. 3 and 4).

In order to identify the crack front on the fracture surface of the test specimens, as a result of the bending test, the specimens were cooled down to a temperature of - 40 ° C for one hour and then they were subject to Charpy impact testing. In this way it was possible to highlight specific areas of ductile fracture obtained by bending test and to identify the resulting crack front. For example, figures 5 and 6 show the macroscopic appearance of the fracture surfaces for specimens 4 and 7.

Using SigmaScan Pro software the measurement of crack extension for each specimen was made, at five equidistant points, centered to the middle of the specimen and at a distance of 0.1 mm from its edges (fig. 7). Calculation of medium size of the crack extension Δa was performed first, by doing the arithmetic mean of the two measurement sides (a_1 and a_5) and then combining the result with the three measurements from the central part (a_2, a_3, a_4) resulted in the final arithmetic mean of these four values.

The indentation specimen was loaded at 110% of the maximum force recorded during the bending tests on notched specimens, in order to find the indentation energy values.

Determination of the J integral values, assumes calculating the energy required for crack extension. The total energy U_T is the area under the force-displacement curve, obtained by summing the energy U corresponding to the reference force for each tested notch specimen and the indentation energy U_i.

Since the indentation test of the specimen was achieved by supporting it on two rollers in contact, as specified by ASTM D 6068 for specimens of type SE(B), U_i energy component values were obtained by selecting values recorded on the load - displacement curve of indentation test, corresponding to the maximum load achieved for each bending specimen.

J integral values were calculated with the following equation:

$$J = \frac{\eta U}{B(W - a_o)} \quad (1)$$

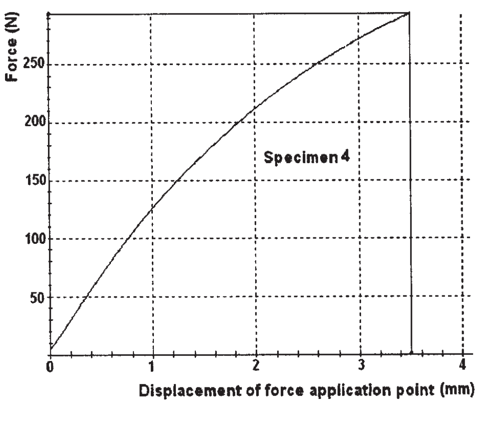

Fig. 3. The force-displacement curve for specimen no. 4

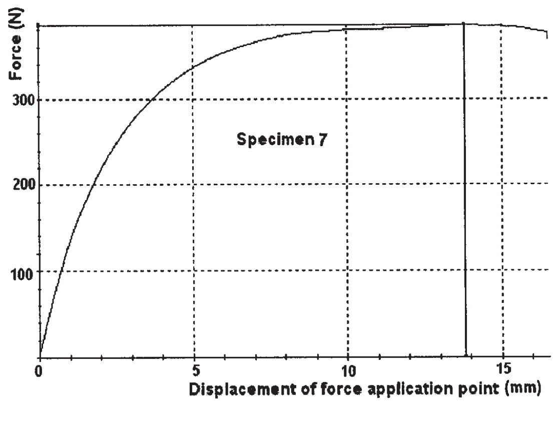

Fig. 4. The force-displacement curve for specimen no. 7

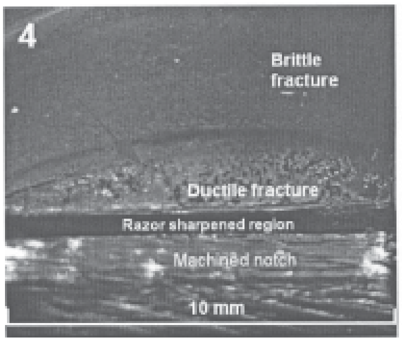

Fig.5. Fracture surface of the specimen no. 4

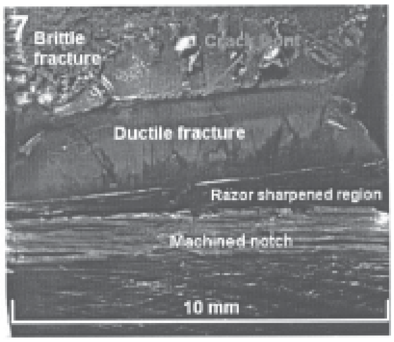

Fig. 6. Fracture surface of the specimen no. 7

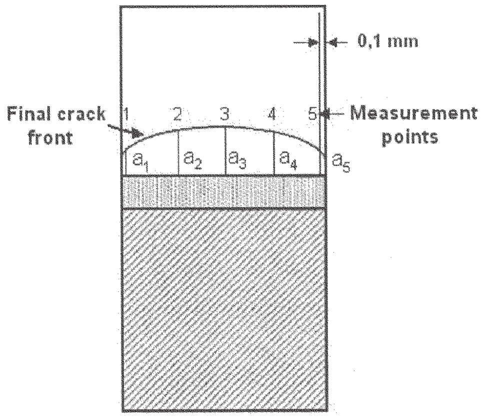

Fig. 7 Measurement of crack extension

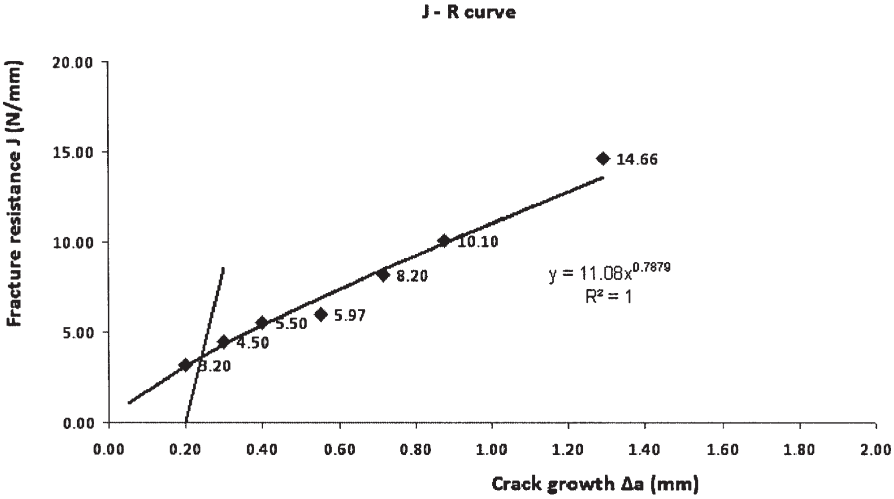

Fig.8. J-R curve

where:

η = 2 for specimens subject to bending,
B = specimen thickness,
W = width of the specimen,
a_o = initial length of the crack.

Results and discussions

The experimental results of the J-integral values versus the crack extension Δa are plotted in figure 8, and interpolated as a power function of the form:

$$J = C_1 \Delta a_p^{C_2} \qquad (2)$$

where:

Δa = average value of crack extension,
C1, C2 = power law coefficients.

Given that the average values for the crack extension, recorded for the displacement of the force's application point over 4 mm were higher than the pursued value for Δa - about 1 mm, the J-R curve using the 4 points with displacements up to 3.5 mm was plotted, and then further 4 points corresponding to the average value of the crack extension less than 0.4 mm were determined by interpolation (fig. 8).

In order to establish the fracture toughness value - J_{IC} prescriptions provided by ASTM E 1820 were used, and a line with the origin in Δa= 0.2 mm was plotted inclined at an 88° angle to the abscissa axis [10]. By intersecting of the J-R curve with the constructed line was determined fracture toughness J_{IC} for PE100 material used in the experimental research.

Conclusions

The elastic - plastic fracture toughness of the PE 100 material, used in pipelines for the transport of natural gas under pressure, was experimentally determined using the J integral method.

Starting from the three-point bending tests the J-R curve was plotted, using the correlation between the J integral values and the corresponding increase of the crack length Δa.

The obtained results, led finally to the determination of fracture toughness of the analyzed material PE 100 - J_{IC} = 3.6 N / mm corresponding to an increase of the crack length Δa = 0.242 mm.

These data are particularly useful in order to establish correlations between toughness, stress and allowable size of imperfections, through which to ensure high safety in operating of thermoplastic pipelines.

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