

COMPARISON OF FRACTURE TOUGHNESS OF CURVED AND FLAT CT SPECIMENS FOR THE GAS PIPELINE INTEGRITY MANAGEMENT

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1. Introduction

When examining the integrity of thin-walled pressure pipelines, we face the problem of ensuring the flatness of the semi-products used for manufacture of fracture specimens. The only available way is the straightening of pipeline bands. Due to plastic strains the semi-product is exposed to during the straightening process, this operation brings internal stresses not only into the semi-product subjected to straightening but also to finished specimens. This is why some fracture mechanical researchers contest the validity of fracture toughness values obtained on specimens made from straightened semi-products although it has been verified by experiments on several pipeline bodies that the prediction of fracture conditions of cracked pipelines, based on fracture toughness values determined on straightened specimens, is relatively exact and reliable.

This paper deals with the problem of the effect of straightening of pipeline bands taken from a gas linepipe on the fracture toughness of finished fracture-mechanics specimens. Some aspects of this issue have already been discussed at the gas industry colloquium [1]. As it is known (e.g. [2], [3]), the fracture toughness may be described by J integral values J_{in} , $J_{0.2}$ or J_m where J_{in} is the so called initiation value of the J integral for the stable subcritical crack growth, $J_{0.2}$ is the value of the J integral corresponding to the actual crack growth $\Delta a = 0.2$ mm at a stable monotonic loading and J_m is the value of the J integral that corresponds to the achievement of the maximum force on the „force – force point displacement“ curve. When verifying the straightening effect on the fracture toughness properties, the objective was (i) to construct the so called R curves [4] both for specimens made from straightened pipeline bands and for curved specimens with natural pipe curvature loaded by a tangential force and (ii) to compare the magnitudes of the fracture parameters for both types of CT specimens.

2. Force Converter

Curved CT specimens simulate, to some extent, stress conditions in the pipeline wall loaded by internal pressure. In order to ensure the application of the load in the hoop direction, it was necessary to design and manufacture a fixture that would enable to convert the straight force, generated by the loading machine, to the tangential one, i.e. a force which would act along a circle of the identical diameter to that of the pipe. Such a fixture was designed and manufactured on the basis of the work of Evans, Kotsikos and Robey [5]. The authors of the work [5] used a scissors device to ensure the tangential action of the force on a curved CT specimen during fracture tests and made a measurement of compliance of curved

CT specimens in relation to the crack length. From the results of compliance measurement they calculated the fracture toughness in terms of the critical value of the stress intensity factor K_{Ic} .

A scheme of taking a specimen from a pipe is shown on Fig.1. In collaboration with RCP Prague we have developed a force converter for tangential loading of curved CT specimens. Its 3D schematic picture is shown on Fig. 2. The straight force, applied at the jaws of the testing machine, is transferred by a pin to the upper and bottom arm of the force converter. Motion of the arms of the force converter around the connecting hinge provides a tangential action of the force at the holes of a curved CT specimen relative to the circumscribed circle around the connecting hinge that goes by central cylindrical area of the specimen.

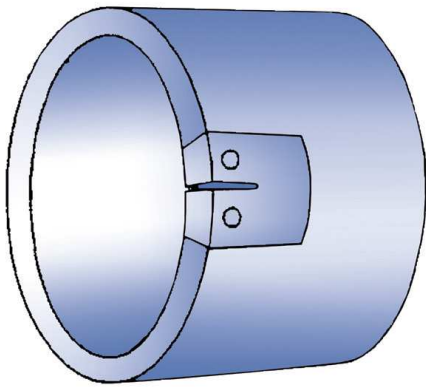


Fig. 1. Schematic illustration of curved CT specimen as taken from a pipe wall

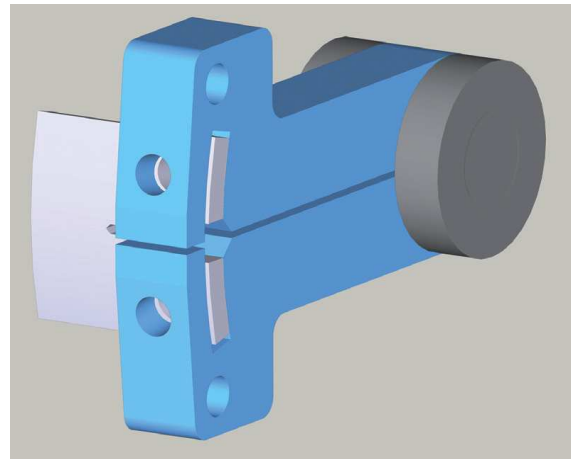


Fig. 2. Force converter

Dependence of the tangential force F_2 at the holes of the curved CT specimen on the vertical force F_1 generated by the loading machine can be determined on the basis of the momentum condition of the equivalence on one half of the specimen using the symmetry (Fig. 3).

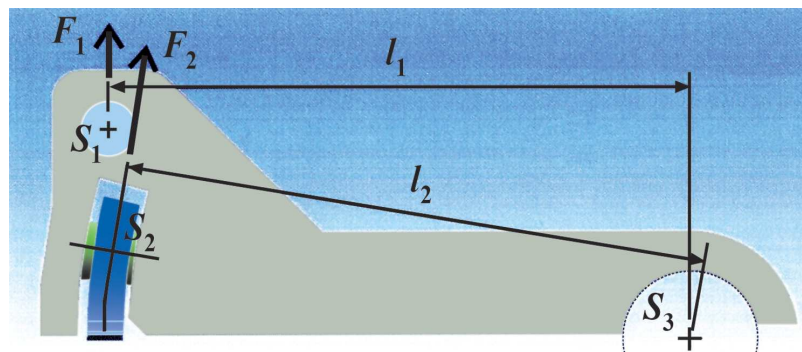


Fig. 3. Loading forces acting at the force converter

Here is:

F_1 - force generated by the testing machine

F_2 - tangential force acting at the hole of the curved CT specimen

s_1 - centre of the hole in the arm of the force converter

s_2 - centre of the hole of the curved CT specimen (point of intersection of the centre line of the pin and the centre line of a curved CT)

s_3 - centre of the connecting hinge of arms of the force converter

l_1 - arm of the force F_1 to the centre of the connecting hinge of force converter arms

l_2 - arm of the force F_2 to the centre of the connecting hinge of force converter arms

The following equation follows from the momentum condition of the equivalence to the hinge centre s_3 :

$$F_1 \cdot l_1 = F_2 \cdot l_2 \quad (1)$$

so that

$$F_2 = F_1 \frac{l_1}{l_2} \quad (2)$$

It is apparent that the force converter is bound only to certain specific cross section dimensions of the pipe. For experimental research of the effect of pipe band straightening on fracture toughness values a gas pipeline DN 250 (Ø 266/8) made from low-C steel ČSN 411353 was chosen.

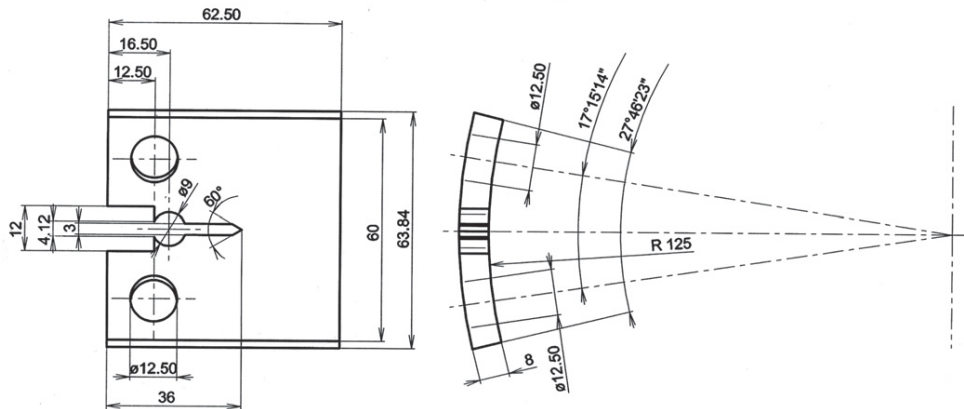


Fig. 4. The shape and dimensions of curved CT specimens used

The reason for this was a high curvature of the cylindrical surface of the pipe so that the eventual effect of straightening of the pipe band could be very apparent. For the shape and dimensions of the curved specimens as they result from the pipe geometry see the Fig. 4.

The design of the fixture ensures that $l_1 = l_2$ and thus $F_2 = F_1$ for the specimen thickness $t = 8$ mm and the distance of the hole axes at the internal wall of the specimen $d \approx 37$ mm. As the figure indicates, the angle of the axis of the cylindrical hole of the specimen and the specimen symmetry axis is approx. 8.5° . The distance of the axes of cylindrical holes at the interior surface of the specimen which corresponds to this angle is approx. 37 mm. This is why it can be considered that both forces, i.e. F_2 and F_1 , are identical.

3. Experimental

3.1 Tensile Tests

Tensile tests of specimens made from straightened bands took place on an electro-mechanical testing machine Testastron with the force capacity 100 kN. The cross section dimensions in the gauge part of straightened tensile specimens and the results of tensile tests are presented on Table 1. The corresponding tensile diagram of the test specimen T1 is presented on Fig. 5.

Specimen	Orientation	Width w (mm)	Thickness t (mm)	Cross section S (mm ²)	A ₅ (%)	Z (%)	R _{p0.2} (MPa)	R _m (MPa)
T1	Hoop	19.85	5.5	109.2	30.1	52.6	286	426
T2	Hoop	20.00	5.5	110.0	31.9	55.2	280	422

Table 1. Cross sectional dimensions of tensile specimens and results of tensile tests

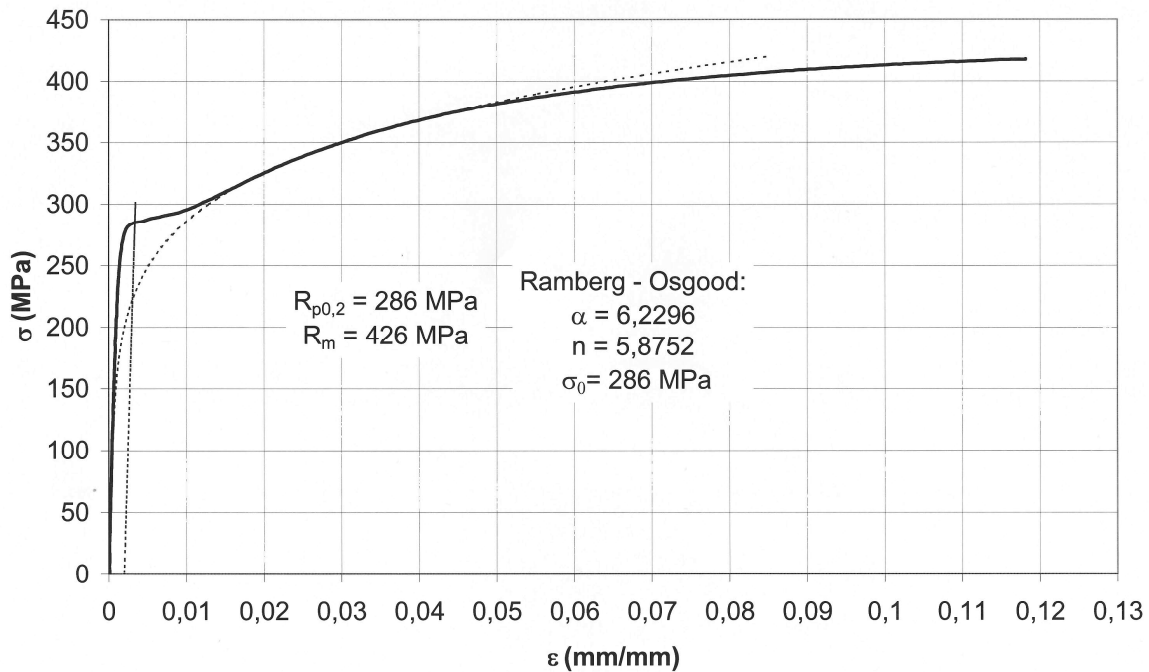


Fig.5. Tensile diagram of the specimen T1

The pipeline material complies with requirements of the standard as all characteristics investigated exceed minimum standard values (R_e , min = 245 MPa; R_m , min = 343 MPa; A_5 , min = 24%). Parameters of the Ramberg-Osgood dependence, corresponding to the tensile diagram of the specimen, are also presented on Fig.5 and the Ramberg-Osgood curve itself is represented here by a dashed line. As is apparent, in the field of engineering interest (strains of the order of several per cents) the conformity with the experiment-defined tensile diagram is excellent.

3.2 Fracture-Mechanical Tests

3.2.1 Flat (Straightened) CT Specimens

Fracture toughness was determined on the basis of the so called R curve that expresses the resistance of material to crack growth. The standard procedure for determination of fracture toughness included the straightening of a pipe band, subsequent manufacture of CT specimens and their stress cycling in order to generate fatigue cracks. Further steps consisted in subjecting all CT specimens to monotonic loading at room temperature to reach various levels of the force point displacement with a simultaneous recording the “force – force point displacement” plots. Areas as below these dependencies were used to determine the J integral corresponding to the load of the respective specimen. After temperature colouring of crack faces (200 °C/2 hours), specimens were cooled down to the temperature of liquid nitrogen and then broken open. Microphotographs of fracture surfaces were made afterwards to determine respective values of crack extension during monotonic loading. Crack extension magnitudes Δa were analysed according to the ASTM procedure. The pairs of J- Δa values, necessary for construction of the R curve, are given in the Table 2.

Specimen	Crack extension Δa (mm)	J integral (N/mm)
CT1	2.17	452
CT2	1.45	417
CT3	1.30	364
CT4	1.10	366
CT5	0.70	246
CT6	1.42	410
CT7	0.47	204
CT8	0.95	332

Table 2. Pairs of measured (Δa , J) values

We have plotted experimental points and so called blunting line in the J – Δa diagram. The blunting line has a form $J = 4 R_{fs} \Delta a$, where the flow stress $R_{fs} = 353$ MPa is an average of the yield stress and the ultimate strength of both tensile specimens. Points positioned at the right-hand side of the offset line 0.15 and at the left-hand side of the offset line 1.5 were fit with a curve of the type $J = c_1 (\Delta a)^{c_2}$. It is the R curve that is shown on Fig. 6. In addition to the experimental points J - Δa , the figure shows also the blunting line and lines running parallel to the blunting line at the distance 0.2 mm and 1.5 mm. The parallel line at the distance 0.15 mm off the blunting line is not plotted in the figure as it is immediately apparent that all experimental points are positioned far away at the right-hand side of the anticipated straight line 0.15.

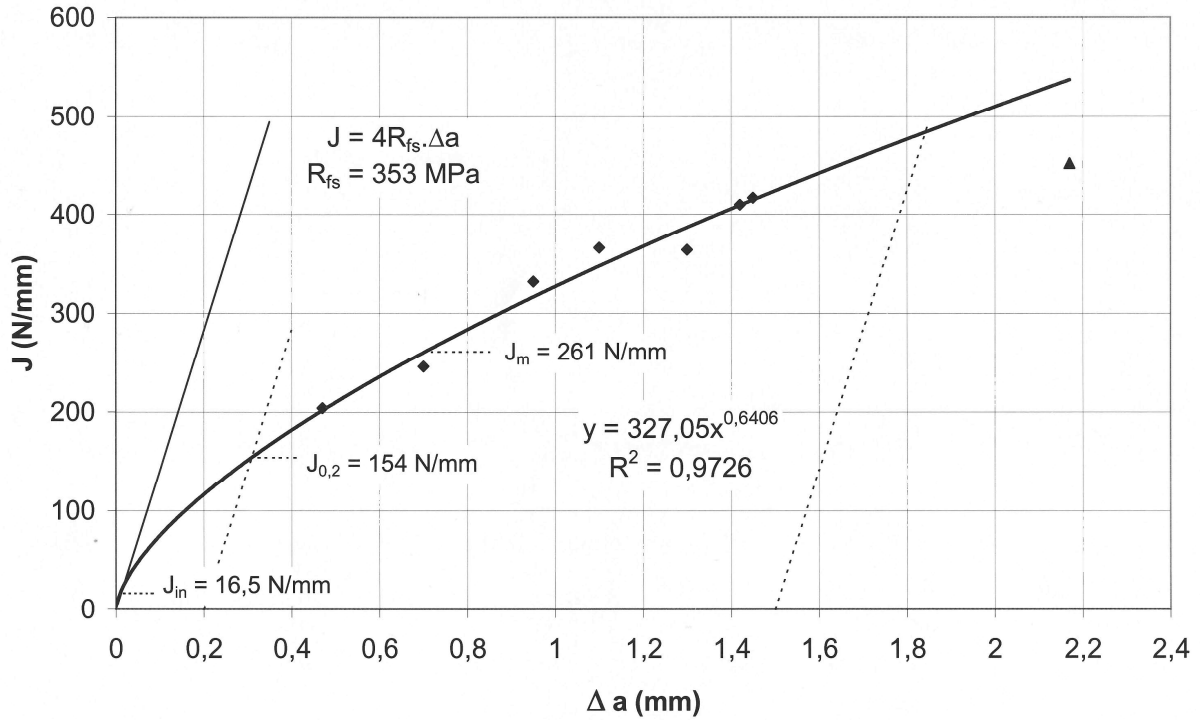


Fig. 6. The R curve for flat (straightened) specimens with indication of J_{in} , $J_{0.2}$ and J_m

The significance of the parallel line 0.2 mm consists in the fact that its intersection with the R curve defines the fracture toughness $J_{0.2}$ corresponding to the crack growth 0.2 mm. The triangle point shown in the figure is a point that is positioned out of valid $J - \Delta a$ values (it corresponds to CT1 specimen). The remaining seven points were fit with a power curve (R curve) expressed as: $J = 327.05(\Delta a)^{0.6406}$. In addition to the power dependence (of the R curve), the figure shows also the reliability value, i.e. the determination coefficient $R^2 = 0.9726$. This coefficient ranges from 0 to 1 and is the higher the more close are experimental points to the mathematically expressed curve. The intersection of the R curve with the blunting line defines the initiation value of the J integral for the stable subcritical crack growth J_{in} . The obtained value J_{in} given by the intersection of the power curve and the blunting line $J = 1412(\Delta a)$ is $J_{in} = 16.5 \text{ N/mm}$. The intersection of the parallel line 0.2 mm and the R curve provides the value of the J integral $J_{0.2} = 154 \text{ N/mm}$. Moreover, the figure shows the J integral value $J_m = 261 \text{ N/mm}$ that corresponds to the point of the achievement of the maximum force on the „force - force point displacement“ curve. It is an average value obtained from six specimens the monotonic loading of which resulted in the achievement of the maximum level of force on the „force – force point displacement“ curve, i.e. it was possible to define the area below this curve up to the value of the force point displacement corresponding to the maximum force. This J integral value is directly connected with fracture of the body since in case of force-controlled loading the crack would start propagating in an unstable way at the moment of achievement of the J_m value.

3.2.2 Curved CT Specimens

Eight curved CT specimens (C-CT specimens) were used for fracture-mechanical tests. Cracks in these specimens were cycled up at the frequency $f = 4 \text{ Hz}$ using a 100 kN electro-hydraulic Instron machine and the force converter. The state of stress at the internal side of the specimen was higher than that at the external side due to the bending moment induced by

the out of axis effect of the vertical component of the tangential force relative to the intersection of the central cylindrical area of the specimen and the specimen symmetry plane. Therefore, the crack growth rate was higher at the internal side of the specimen and it resulted in a different length of the fatigue crack after the completion of cycling. Because of this we bevelled the tip of the starting notch of the specimens C-CT5 through C-CT8 so that the notch was 1 mm deeper at the outer side. By this operation a more even crack tip was obtained at the end of cycling. After crack cycling, all C-CT specimens were subjected to monotonic loading at room temperature to various levels of the force point displacement with a simultaneous recording of the “force – force point displacement”. As an example see Fig. 7 showing the respective record for the specimen C-CT1.

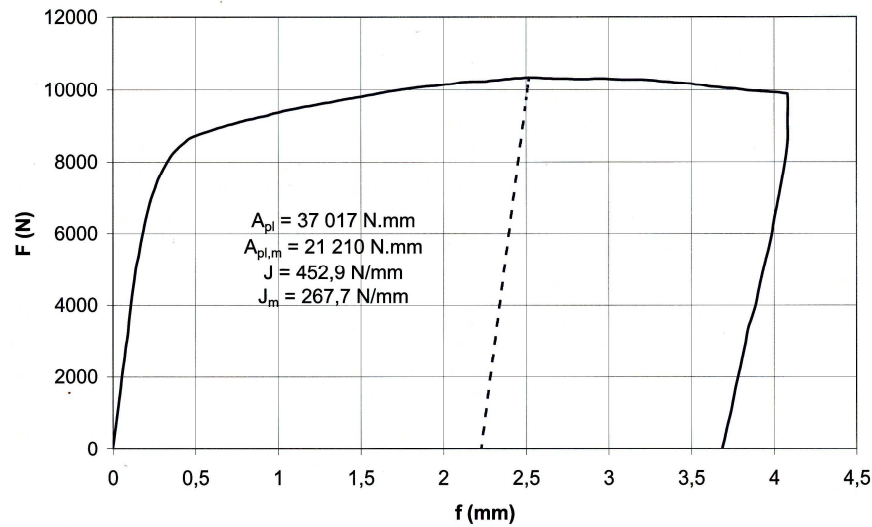


Fig. 7. „Force – force point displacement“ dependence for the specimen C-CT1

Areas below the dependencies “force – force point displacement” were used to determine the J integral corresponding to the respective loading of a specimen. After temperature colouring of crack faces (200 °C/2 hours), specimens were cooled down to the temperature of liquid nitrogen and were broken open. Microphotographs of fracture surfaces were made for determination of respective values of the crack extension during monotonic loading.

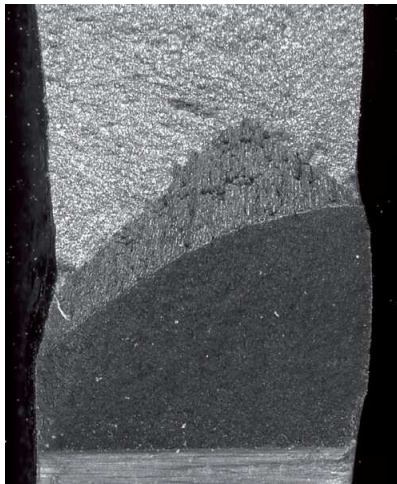


Fig. 8. Fracture surface of the specimen C-CT2



Fig. 9 Fracture surface of the specimen C-CT8

For a comparison see on Fig. 8 the fracture surface of the specimen C-CT2 with the straight tip of the starting notch and on Fig. 9 the fracture surface of the specimen C-CT8 with a bevelled tip of the starting notch.

Crack extensions Δa were analyzed from microphotographs of fracture surfaces by the ASTM procedure. The pairs of J - Δa values, which are needed for construction of the R curve, are presented in Table 3.

Specimen	Crack extension Δa (mm)	J integral (N/mm)
C-CT1	2.57	452.9
C-CT2	1.81	368.2
C-CT3	1.44	315.8
C-CT4	0.97	258.8
C-CT5	1.27	290.5
C-CT6	1.91	452.9
C-CT7	0.3	153.7
C-CT8	1.26	329.6

Tab.3 The measured pairs of (Δa , J) values

When constructing the R curve, we proceeded in the same way as for flat CT specimens, i.e. we plotted experimental points and so called blunting line determined on straightened flat tensile specimens to the diagram $J - \Delta a$. Strictly speaking, only points defined right off the offset line 0.15 (a line parallel to the blunting line at the distance 0.15 mm) and left off the offset line 1.5 (a line parallel to the blunting line at the distance 1.5 mm) should be included into the analysis. In our case, three points (C-CT1, C-CT2, C-CT6) were positioned behind the limiting „offset line 1.5“.

While the overhang of the specimen C-CT1 was expressive, the other two specimens showed an insignificant overhang. Therefore, these two points were included into the analysis. All points (except for the point corresponding to the specimen C-CT1) were fitted with a power curve of the type $J = c_1 \cdot (\Delta a)^{c_2}$ in order to get the R curve (Fig. 10).

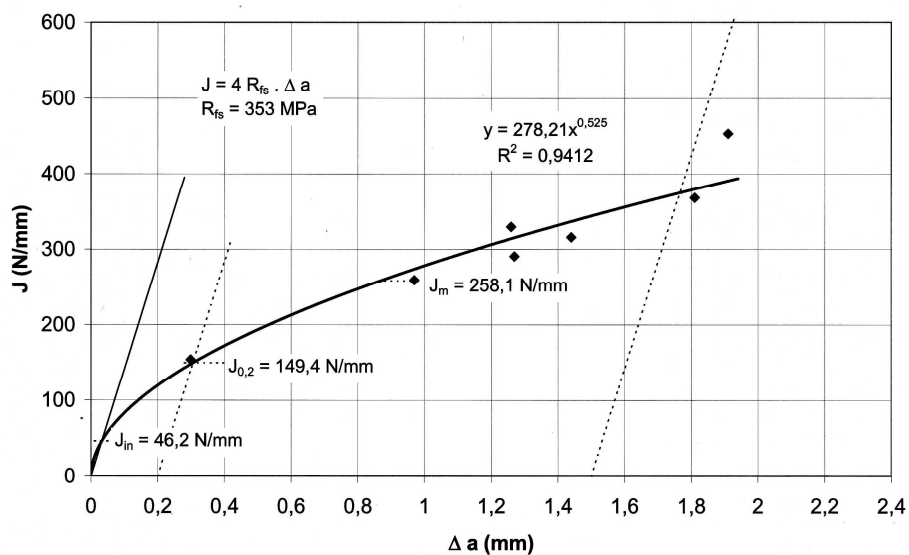


Fig. 10. R curve for curved CT specimens with indicated values J_{in} , $J_{0.2}$ and J_m

The figure shows also individual experimental points $J - \Delta a$ as well as the blunting line and lines parallel to the blunting line at the distance 0.2 mm and 1.5 mm. The parallel line at the distance 0.15 mm from the blunting line is not shown identically to the flat CT specimens as it is immediately apparent that all experimental points are positioned at the right-hand side of the anticipated 0.15 mm straight line. The obtained R curve is expressed as follows:

$$J = 278.21(\Delta a)^{0.525}.$$

Similarly to flat CT specimens, we considered the blunting line to be $J = 4R_{fs} \cdot \Delta a$, where $R_{fs} = 353$ MPa. The resulting value J_{in} determined by the intersection of the power R curve with the blunting line $J = 1412 \cdot (\Delta a)$ is $J_{in} = 46.2$ N/mm. The intersection of the parallel line 0.2 mm and the R curve gives the J integral value $J_{0.2} = 149.4$ N/mm.

We established also the average value of the J integral J_m based on seven specimens the monotonic loading of which resulted in the achievement of the maximum level of the force on the “force – force point displacement” curve, i.e. it was possible to define the area below this curve up to the value of the force point displacement corresponding to the maximum force. For the J_m values see the Table 4. The ascertained average value of the quantity J_m , as given in the table, amounted to $\bar{J}_m = 258.1$ N/mm. In addition to values $J_{in} = 46.2$ N/mm and $J_{0.2} = 149.4$ N/mm, the value $\bar{J}_m = 258.1$ N/mm is also shown in the diagram, Fig. 10.

Specimen	J_m (N/mm)
C-CT1	267.7
C-CT2	261.7
C-CT3	251.3
C-CT4	258.8
C-CT5	225.0
C-CT6	280.2
C-CT8	278.9
mean	258.1

Table 4. Measured values of the J integral J_m

4. Conclusion

By comparing R curves for flat (straightened) and curved CT specimens it is clear at the first sight that the R curve obtained on curved CT specimens exhibits a lower gradient than that determined on flat (straightened) specimens. The higher gradient of the R curve determined on flat CT specimens is very likely to be associated with strain hardening of the semiproduct during straightening. The mathematical description of the R curve determined on curved CT specimens includes not only a lower exponent but also a lower constant, owing to which this R curve lies below that determined on flat specimens. On the other hand, the lower position of the R curve determined on curved specimens does not mean any significantly lower values of fracture toughness characteristics. For example, the J_m value is lower by 1.1 %, the $J_{0.2}$ value is lower by less than 3 %, and the J_{in} value is even higher than that obtained on flat (straightened) CT specimens. In terms of absolute values these differences are 2.9 N/mm for J_m , 4.6 N/mm for $J_{0.2}$, and 29.7 N/mm in favour of curved CT specimens.

When considering a scatter of the results in the form of $(J - \Delta a)$ points given by both the natural process of the subcritical crack growth and inaccuracies in determination of the J

integral, especially crack extension during monotonic loading of specimens, it can be stated with a high reliability that the fracture toughness of the pipe material determined on straightened CT specimens is practically the same as that obtained on curved CT specimens.

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