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THE EVALUATION OF RESISTANCE TO CRACKING IN STRUCTURAL STEELS WITH THE USE OF THE ASPEF METHOD

OCENA ODPORNOŚCI NA PĘKANIE STALI KONSTRUKCYJNYCH METODĄ ASPEF

The paper presents the results of research on fracture toughness defined by destruction mechanics conventional methods and the non-conventional ASPEF method for three different types of low-carbon structural steel. Classical techniques of fracture toughness evaluation, such as the K_{Ic} (stress intensity factor limit for Mode I) determined in a plane strain, Rice's J-integral J_{Ic} and the critical value of the crack-tip opening displacement CTOD, are intricate methods which require up-to-date testing machines and sensors. The procedure of specimen preparation, which requires the introduction of a fatigue precrack of an appropriate length and the even front of its development along the whole thickness of the specimen, presents an additional difficulty. The ASPEF methods is free from these disadvantages. The methods uses cylindrical specimens with a notch characterized by different notch bottom radii. It enables the estimation of the critical value of Rice's J-integral J_{Ic}. There was a high degree of consistency observed for all the materials analysed. In the case of the W1 steel, the J_{Ic} determined by Rice's J-integral was equal to 100 N/mm, and that determined with the use of the ASPEF method was equal to 88 N/mm; in the W2 steel 141 N/mm and 148 N/mm – respectively. For the W3 steel the J_{Ic} was determined on the basis of δ_c and it was equal to 126 N/mm and 103 N/mm in the ASPEF sample.

Keywords: fracture mechanical, Rice's J-integral, Crack-Tip Opening Displacement method, Absorbed Specific Fracture Energy method, structural steels

W pracy przedstawiono wyniki badań odporności na pękanie określone konwencjonalnymi metodami mechaniki zniszczenia oraz niekonwencjonalną metodą ASPEF dla trzech różnych gatunków niskowęglowych stali konstrukcyjnych. Klasyczne techniki oceny odporności na pękanie takie jak krytyczny współczynnik intensywności naprężeń K_{Ic} wyznaczany w płaskim stanie odkształcenia, całka Rice'a J_{Ic} oraz krytyczna wartość rozwarcia karbu CTOD są metodami skomplikowanymi, wymagającymi nowoczesnych maszyn wytrzymałościowych oraz czujników. Dodatkowym utrudnieniem jest procedura przygotowania próbek, gdzie konieczne jest wprowadzenie szczeliny zmęczeniowej o odpowiedniej długości i równym froncie jej rozwoju na całej grubości próbki. Wad tych pozbawiona jest metoda ASPEF, w której wykorzystuje się próbki walcowe z karbem o różnych promieniach zaokrąglenia dna karbu i umożliwia oszacowanie krytycznej wartości całki Rice'a J_{Ic}. Dla wszystkich analizowanych materiałów uzyskano dobrą zgodność wyników. W przypadku stali W1 wartość J_{Ic} określona całką Rice'a wyniosła 100 N/mm, a techniką ASPEF 88 N/mm, w stali W2 odpowiednio 141 N/mm i 148 N/mm. W stali W3 wartość J_{Ic} została określona na podstawie δ_c i wyniosła 126 N/mm, a w próbie ASPEF 103 N/mm.

1. Introduction

Fracture toughness, is apart from the yield point and Young's modulus, one of the basic material characteristics, which are required in constructional calculations. A critical stress intensity factor is a basic indicator which characterizes brittle cracking toughness. When taken into consideration in calculations, this factor protects a construction against the very dangerous phenomenon of sudden and brittle cracking [1].

In constructional materials of high ductility it is difficult to determine this factor since the specimens providing a plane strain would have to be very large in size [1]. That is why for the evaluation of fracture toughness for plastic materials a non-linear elastic fracture mechanics is used along with Rice's J-integral [2] or the CTOD method [3]. The intricate research procedures of these methods and the necessity of using up-to-date testing machines and sensors are the reason for the development of non-conventional research techniques which allow a less complicated way of fracture toughness evaluation. The ASPEF (Absorber Specific Energy to Fracture) techniques is one of such method. The method was developed at the end of the 1970s and the beginning of the

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1980s and and allows the simple and precise evaluation of Rice's J-integral J_{Ic} [4-6]. Despite its simplicity and a good correlation of the results obtained with the use of conventional techniques, this method has not been popular although there is a growing interest in it nowadays [7-11]. The article compares the fracture toughness of three types of structural steels described with the use of classical fracture toughness techniques and the ASPEF method.

2. Materials

Three different types of structural steels marked with the symbols from W1 to W3 were used for research. Their chemical composition is presented in Table 1. The samples for research were taken from 15 mm thick flat bars in a transverse direction in such a way that a cracking process occurred along the direction of rolling. The W1 and W2 materials were subjected to normalizing at a temperature of 920°C for 2 hours, whereas the W3 material was taken from the boiler drum casing after 100000 hours.

TABLE 1

Chemical composition of steels

Grade of steel	Chemical composition [wt. %]										
	C	Mn	Si	P	S	Cr	Ni	Cu	Al	Mo	Ti
W1	0,19	1,33	0,31	0,013	0,003	0,18	0,15	0,27	0,03	–	–
W2	0,14	0,63	0,29	0,026	0,015	0,28	0,18	0,13	0,03	–	–
W3	0,18	0,89	0,45	0,029	0,021	0,24	1,11	1,15	–	0,3	0,03

3. Experimental procedures

In order to determine material basic characteristics, i.e. the yield point, tensile strength and Young's modulus, a statistical tensile test on circular samples with the diameter ϕ5mm and the basis Lo = 25mm was carried out. In the ASPEF method, circular samples with a notch of the dimensions presented in Fig. 1 and with the use of the radii of a tip rounding: 0.2 mm, 0.5 mm and 0.8 mm were used. The tensile test and facture toughness evaluation using the ASPEF method were performed on the hydraulic testing machine EU20 with the use strength and elongation extensometers. In the case of classical fracture toughness techniques, the hydraulic testing machine Instron 8511.20 and the Epsilon tip opening sensor were used. Compact specimens of the diameters presented in Table 2 were used for the research. Precracks were introduced by a fatigue testing machine. The obtained values were up to the standard [2] in a range of 1.3 mm to 2.4 mm.

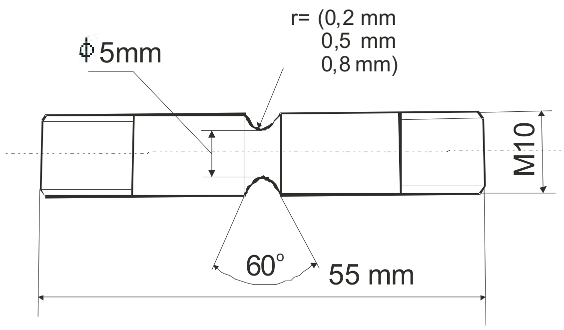


Fig. 1. Cylindrical notched bar test piece used in the ASPEF method

TABLE 2

The representation of mechanical properties and geometrical parameters necessary for the calculation of crack resistance indicators

Grade of steel	Mechanical properties			Conventional methods				
				Geometrical parameters			Crack resistance	
	R_e [MPa]	R_m [MPa]	E [GPa]	B [mm]	W [mm]	a [mm]	δ_c [mm]	**J_{Ic} [N/mm]**
W1	323	563	–	12,0	24,2	13,2	–	**100**
W2	293	450	–	11,96-12,10**	24,9-25,0**	12,56-13,32**	–	**141**
W3	492*	641	211	11,99	25,02	13,22	0,255	**126**

* – $R_{p0,2}$

** – Value range in many specimen methods, B – the specimen thickness, W – the specimen width, a – the initial crack length

3.1. The Rice's J-integral method J_{Ic}

The Rice's J-integral method was chosen for the evaluation of fracture toughness with the use of a classical technique due to fact that it is the most universal technique used for materials of high plasticity. The test was carried out in accordance with the ASTM standard [2]. For the W1 steel an unloading compliance method was used; it allowed the determination of the J_{Ic} with the use of one sample, whereas for the steels W2 and W3 a method of many samples was used.

In the course of a test an unstable development of cracking was observed in the W3 steel, which made the direct determination of the critical value J_{Ic} impossible. That is why the CTOD method was used for a further interpretation of the obtained results and the determination of the critical value J_{Ic}; this was done in accordance with the procedure stated in the standard [3].

3.2. The ASPEF method

It is assumed that the ASPEF is the work of all external forces in a infinitesimal element in the cracking spot which is necessary for the propagation of cracking, thus the total energy is equal to [12]:

$$\mathrm{Wc} = \mathrm{We} + \mathrm{Wp} + \mathrm{Wr}, \tag{1}$$

where:

Wc – the total energy necessary for fracture,

We – the energy of elastic deformation,

Wp – the energy of plastic deformation,

Wr – the energy of crack propagation.

The separation of individual energy components in the cracking process is practically impossible but – since in ductile materials the Wp is significantly bigger than We and Wr – it can be written:

$$\mathrm{Wc} = \mathrm{Wp}. \tag{2}$$

The energy value Wc cannot serve as the indicator of resistance to cracking since it is not a material constant and is dependent on the size and geometry of the sample. The procedure of fracture toughness determination by the ASPEF method is based on looking for a correlation with the values, e.g. with Rice's J-integral. The research [5] proposes a mathematical dependence which links the J_{Ic} value with the values obtained from the ASPEF method:

$$J_{Ic} = \mathrm{Wc} * \mathrm{Lo}. \tag{3}$$

where:

Lo – the length of the plastic deformation zone in the vicinity of the crack tip measured on circular samples with a notch.

The first component Wc, with the assumption (2), can be determined by measuring the field under the curve during the stretching of an unnotched specimen. It is determined on the basis of the force F course in the elongation function ΔL. The determined values is true it the energy refers to the volume V.

$$W_c = \int_0^{L_f} \frac{F * dL}{V} \qquad [MJ/m^3]. \tag{4}$$

For the circular specimens, the volume can be expressed by the product of the cross-sectional area A and the lenght L, which yields the following:

$$W_c = \int_0^{L_f} \frac{F * dl}{A * L} = \int_0^{\varepsilon_f} R' * d\varepsilon \qquad [MJ/m^3], \tag{5}$$

thus the absorbed cracking energy in the near vicinity of the cracking area is equal to the area under the stress – deformation curve.

This value is approximately determined from the dependence formulated by L. Gillemot [4,13]:

$$W_c = \frac{R_{el} + 2R_m}{3}\left(\frac{d_o^2}{d_m^2} - 1\right) + \left(R_m\frac{d_o^2}{d_m^2} + R_u'\right)\ln\frac{d_m}{d_u}[MJ/m^3], \tag{6}$$

where:

R_{el} – the yield strength,

R_m – the ultimate tensile stress,

D_m – the diameter at the maximum test load,

D_o – the initial diameter of the specimen,

Ru' – the true stress at rapture,

D_u – the smallest diameter measured after the rapture of the specimen.

The dependence formulated by Harkovetz and Saposnyijov [14] has a practical for the Wc value determination:

$$W_c = (R_{el} + R_u')\ln\frac{d_o}{d_u}[MJ/m^3]. \tag{7}$$

The procedure of the size determination of the plastic deformation zone L_o requires the usae of the specimens with a notch. Since the size of the plastic deformation zone is dependent on the notch radius, which decreases proportionally in size to the decrease of the radius, the most severe conditions one gets are based assumption that r=0. That is why the procedure of the L_o determination is based on the determination of the size of the plastic deformation zone in the sample with a notch with a theorectical radius r=0.

The measurement of this value lies in stretching a few cylindrical speciments (two at a minimum) with different notch radii. In the course of a trial, according to the description in [5], the L' value has to be determined as it defines the tip opening in every examined sample. This value is determined by comparing a notch profile in a sample before and after cracking, as is schematically shown in Fig. 2 [5, 6]. Such a measurement procedure contains quite a significant error, because it is rather difficult to determine the reference point according to which the tip opening measurement should be made. The registration of a specimen elongation with the use of an external dislocation sensor seems to be far simpler and, at the same time, more accurate and provides repeatability of results of L' measurement. Providing that the total deformation is in the vicinity of a notch, one may assume that the elongation measurement of the sample only should accurately determine the value of a tip opening at the moment of cracking. In the paper the value L' was determined on the basis of the increment of the sample elongation, with only a stable elongation taken into account, as shown in Fig. 3.

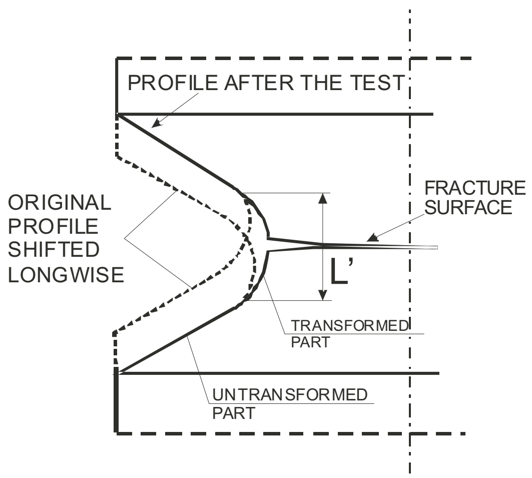


Fig. 2. The determination of the tip opening value with the use of a comparative method

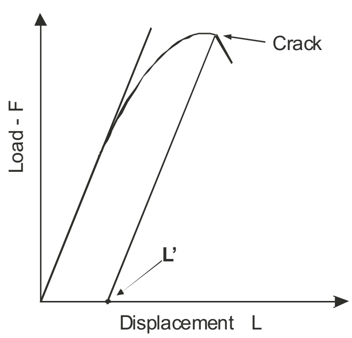


Fig. 3. The tip opening measurement on the basis of the measurement of the elongation sample

The obtained values are plotted on the diagram in the system L' in the function of a notch radius, then the value L' for r=0 is determined by matching a linear function, which is shown in Fig. 4. The read off value is taken into account in the calculations of the length of the plastic deformation zone L_o in accordance with the dependence [5]:

$$L_0 = \frac{L'(r=0)}{\exp(\varepsilon_f) - 1}, \tag{8}$$

where: ε_f – the true deformation value measured on the sample without a notch.

Assuming that $\varepsilon_f = \ln \frac{d_o^2}{d_u^2}$ we get:

$$L_0 = \frac{L'(r=0)}{\exp(\ln \frac{d_o^2}{d_u^2}) - 1}. \tag{9}$$

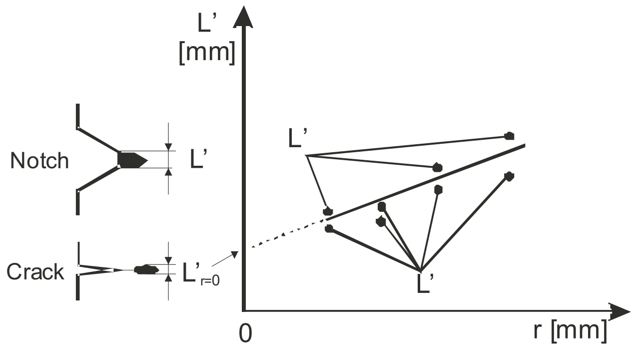


Fig. 4. Graphical determination of the tip opening value L' for the radius r=0

4. Results and discussion

The results obtained of the measurement of the Rice's J-integral critical value carried out with conventional methods and the ASPEF technique for all materials analyzed correlate well. The values obtained with the use of traditional methods and the sizes of the used samples for all materials analyzed are shown in Fig. 2, and for the ASPEF technique – in Table 3.

TABLE 3

The parameters essential for the J_{Ic} values determination with the ASPEF method

Grade of steel	ASPEF method									
	D_o [mm]	D_u [mm]	R_u [MPa]	$L_{0,2}$ [mm]	$L_{0,5}$ [mm]	$L_{0,8}$ [mm]	$\mathbf{L'_{r=0}}$ [mm]	$\mathbf{L_0}$ [mm]	W_c [MJ/m^3]	J_{Ic} [N/mm]
W1	5,00	2,98	1096	0,194	0,207	0,220	0,185	0,102	858	**88**
W2	4,99	2,61	1171	0,389	0,405	0,433	0,373	0,141	1047	**148**
W3	5,01	3,62	992	0,191	0,221	0,236	0,178	0,194	530	**103**

The techniques of the determination of fracture toughness indicators used in the research, i.e. Rice's J-integral and the CTOD method, belong to the basic methods used for polycrystalline materials, which are characterized by high ductility. Today, the unloading compliance method is the most frequently applied technique for the evaluation of the J_{Ic}. The method requires only one sample. However, the method has its limitations since it requires the use of an up-to-date testing machine with feedback. This technique was used for the W1 steel, and the J_{Ic} value determined in compliance with the ASTM standard was equal to 100N/mm; shown in Fig. 5.

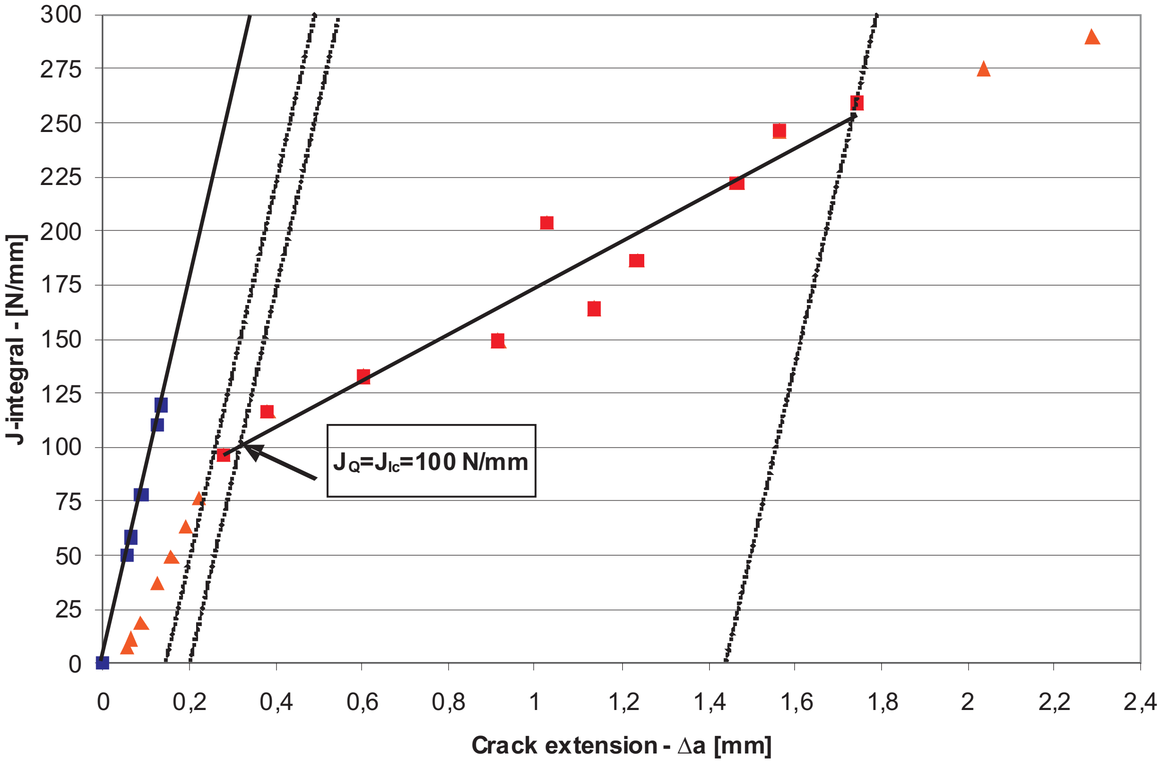


Fig. 5. The determination of the critical value J_{Ic} for the W1 steel – the unloading compliance method

The method of many samples used for the W2 steel is a far more time-consuming technique which requires significantly more samples. The advantage of this method is its ability to truly evaluate the cracking length increment Δa in the J integral value function, while the need for the preparation of at least four samples according to the standard [2] is its disadvantage. Nevertheless, in the case of older testing machines it is the only technique which enables accurate determination of the J_{Ic} value. The critical value of Rice's J-integral for the W2 steel was equal to 141 N/mm; shown in Fig. 6.

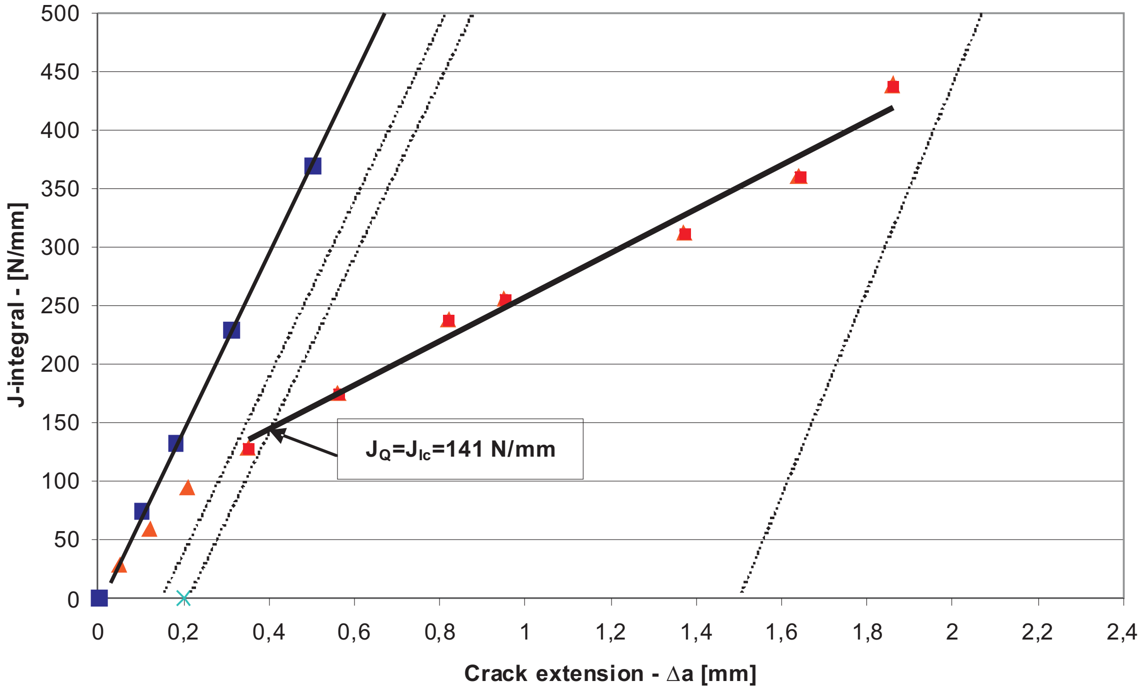


Fig. 6. The determination of the critical value J_{Ic} for the W2 steel – the method which uses many specimens

For the W3 steel, the critical value δ_c was determined on the sample in which a critical cracking propagation took place, Fig. 7, and then the value J_{Ic} was calculated. On the samples in which the increase in critical was not noticed thermal dyeing and breaking in the temperature of -196°C were performed in order to observe the development of cracking. The first signs of the crack increase were observed in the sample opened to the value of 0.7 mm, Fig. 8a, and the fracture in the sample used in the CTOD calculations is presented in Fig. 8b where a sudden increase in the lenght of cracking may be observed. On the basis of the determined value δ_c, the calculational value of Rice's J-integral J_{Ic} was determined and equalled 126 N/mm. The measurements of the J_{Ic} integral performed using the ASPEF technique were conducted in accordance with the above-described procedure. A graphical illustration of the value L' for r=0 determination is shown in Fig. 9 to 11. The way in which the parameter L' for r=0 is determined is the factor which significantly influences the obtained values. Hence the accurate determination of a notch radius and the L' value measurement are of great importance. The values of the integral J_{Ic} obtained with this method for the W1 to W3 materials equalled 88 N/mm, 148 N/mm and 103 N/mm, respectively. The smallest difference was obtained for the W2 material where a method of many samples was used, whereas the biggest difference was in the W3 steel where the unstable development of cracking was observed and the CTOD technique was used.

The results obtained show that the ASPEF technique allows the evaluation of the real J_{Ic} value and that it may be treated as an alternative method to traditional techniques. Nevertheless, further comparative studies along with the determination of accurate mathematical correlations between this method and conventional techniques are necessary.

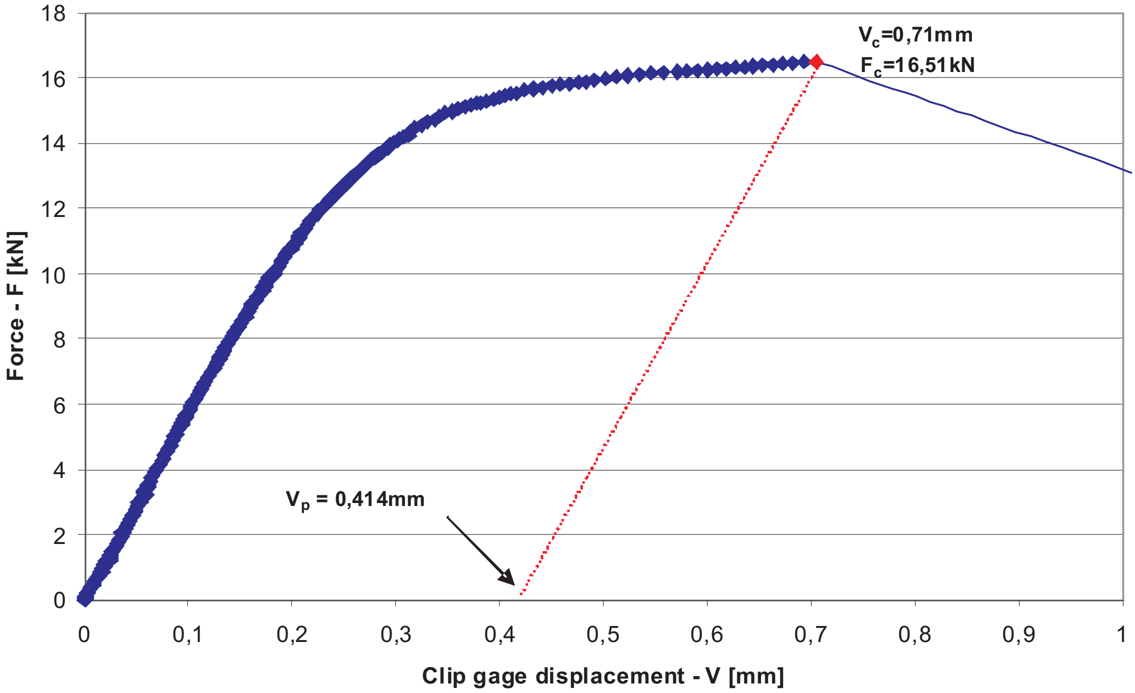
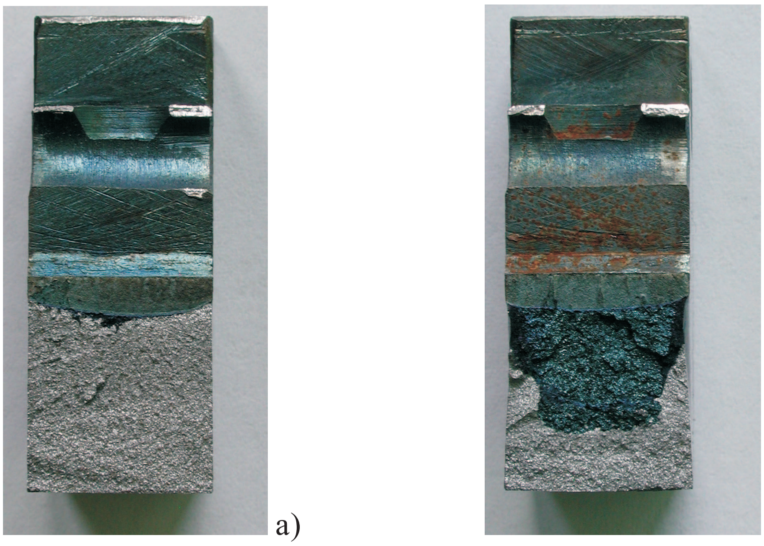


Fig. 7. The diagram of force dependence in the crack opening function showing an unstable development of cracking in the W3 material



a) b)

Fig. 8. Sample fractures after breaking: a) a sample opened up to about 0.7 mm, b) an unstable increase of cracking in the analyzed sample

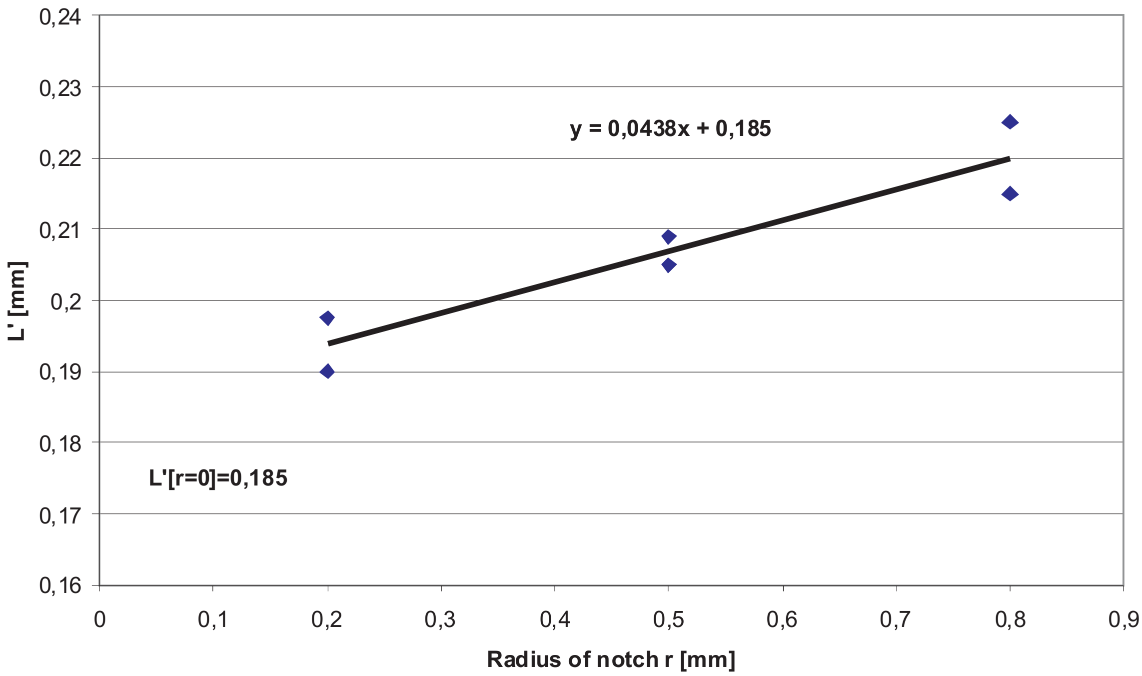


Fig. 9. Graphical determination of the tip opening value L' for the radius r=0 in the W1 steel

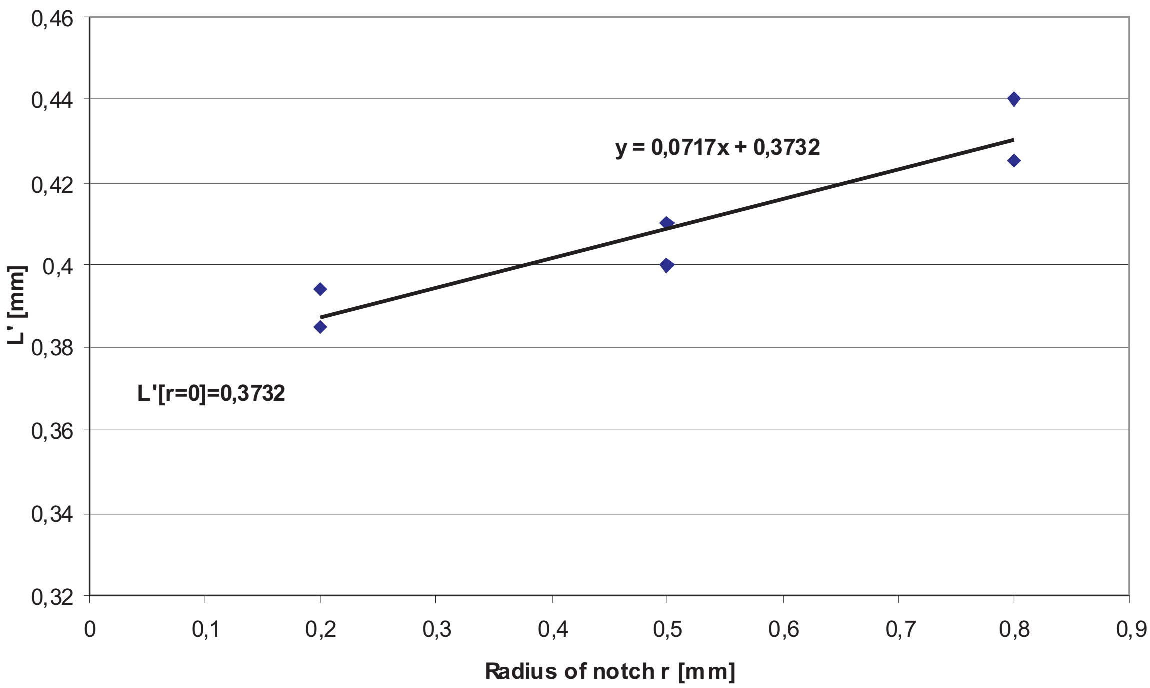


Fig. 10. Graphical determination of the tip opening value L' for the radius r=0 in the W2 steel

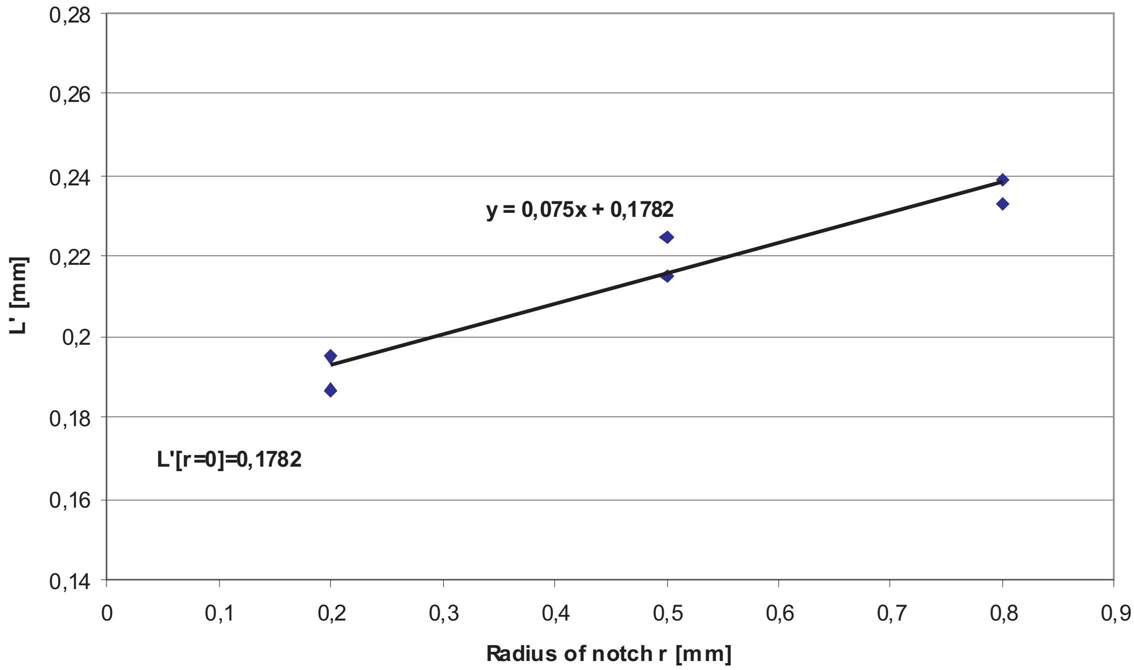


Fig. 11. Graphical determination of the tip opening value L' for the radius r=0 in the W3 steel

5. Conclusions

1. The results of the J_{Ic} values obtained with the use of the conventional methods of mechanical fracture and the ASPEF technique correlate well with each other.
2. Good compatibility of the J_{Ic} values obtained with the use of the ASPEF method and the conventional techniques suggets that the measurement of a sample elongation increment made with the extensometer may be used for the evaluation of the plastic deformation zone size on the cracking front.
3. The best compatibility was noted for the method of many samples which allows the determination of the real cracking increment Δa in the function of the change in the potential energy on the cracking front. It enables a very accurate evaluation of the critical value of Rice's J-integral and shows indirectly a possibility for the use of the ASPEF technique for the J_{Ic} evaluation.
4. The biggest value discrepancy equalled 23 N/mm and was obtained for the W3 steel. It probably results from the recalculating of the critical opening δ_c into the J_{Ic} value, which is handicapped with a certain error.

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