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INFLUENCE OF CRACK PRESENCE ON OPERATING CONDITIONS OF PRESSURE VESSELS WITH FLAT ENDPLATES

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Abstract

The paper discusses influence of crack presence on operating conditions of boilers and pipes. In the study particular attention is paid to the vessels with flat endplates with circular stress relieve grooves. The endplates with such grooves are common alternative for widely used dished ends, particularly for smaller boiler diameters and also for vessels with non-circular cross-sections. The existing codes set the rules how to calculate the circular groove parameters – the groove radius and the location of the arc centre. These design parameters are limited by set of inequalities, which indicate the ranges for admissible radii values and the groove centre positions. The choice of the optimal values for the endplate design parameters has been worked out in recent Authors' investigations. Such approach provides the minimum stress concentration in the vicinity of the cutout, but this notch area still can be the source of crack nucleation and its propagation leading to the premature fracture of the considered vessel. In standard calculations of pressure boilers, the fracture parameters are not taken into account. The current study concentrates on the assessment of the influence of the crack existence on the stable vessel operation. The cracks existing in inner wall of the vessel are of the main interest, because these are difficult to identify and monitor. In these studies the influence of different parameters like the crack length and orientation, and the fracture toughness were taken into account. The detailed numerical results were obtained by means of the finite element code ANSYS [1] for several crack sizes and locations. The cracks in the weld joining shell and end plate and cracks in the groove area, where the maximum stress concentration appeared were subject of the numerical study. The obtained results show the risk of possible premature failure of boilers with cracks.

Keywords: *pressure boilers, flat ends, cracks, fracture analysis, FEM*

1. Introduction

Application of flat plate ends in pressure boilers is the common alternative for the widely used dished ends. Flat bottoms are particularly suitable for vessels with higher wall thickness and boilers with smaller internal diameters, and the pipes with non-circular cross-section. Such boilers heads are cheaper than traditional ellipsoidal heads and relatively easy to fabrication, but their main disadvantage is the presence of high stress concentration observed in the zone of connection between the pipe shell and the flat plate cover. The existing codes [2, 3] admit different shapes for the covers and the flat end plate with the circular stress relieve groove is one of the design proposal (Fig. 1a). In such solution no continuity of the inner edge curvature is provided, which results in the notch presence and inevitably leads to the stress concentration, which is observed on inner edge of the groove, not far from the weld joining shell and flat end plate (Fig. 2b). The problem of minimization of the notch effect in the groove attracts researchers from many years and several successful proposals how to choose the optimal groove have been described [4-10].

The design code EN 12952:3 sets the endplate thickness according to the formulae:

$$e_h = C_1 \cdot C_2 \cdot C_3 \cdot d_i \cdot \sqrt{\frac{p_c}{f}}\,, \tag{1}$$

where C_2 and C_3 are the constant set to 1.0 if the boiler has the circular cross-section and the end plate has no opening, and constant C_1 depends on the ratio between the applied internal pressure p_c and the admissible stress f (its value varies between 0.41 to 0.82), and is taken form the respective plot included in the code. Here d_i is the internal diameter of the vessel. The circular groove parameters are defined by the radius of the circular part of the arc r_{ik} and by the location of the arc centre depicted by h or alternatively by radius r_{ik} and the minimum thickness e_{h1} of the flat cover (Fig. 1a). The groove parameters are limited by set of inequalities as follow:

$$\begin{cases} e_{h1} \geq e_s \,, \\ e_{h1} + r_{ik} \leq e_h \,, \\ r_{ik} \geq \max\{0.2 \cdot e_s, \quad 5mm\}, \\ e_{h1} \geq 1.3\left(\dfrac{d_i}{2} - r_{ik}\right) \cdot \dfrac{p_c}{f} \,. \end{cases} \tag{2}$$

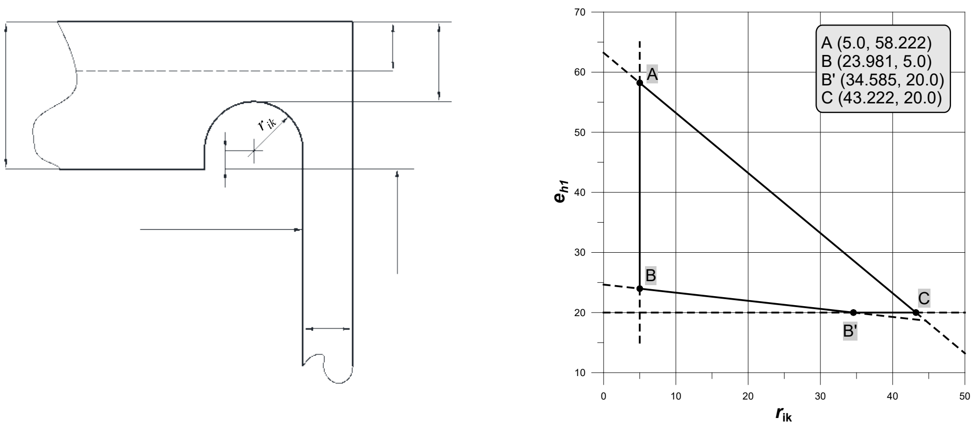

Fig. 1. Stress relieve groove of circular shape (a); admissible area for groove radius and minimum endplate thickness calculated for boiler: Ø406,4×20 made from 16Mo3 steel

The above set gives certain ranges of admissible values for the groove radius and location of its centre, which define polygonal area (Fig. 1b). No clear indication is given in the code, which pair of values for r_{ik} and e_{h1} or h provides the minimum stress concentration. This opens the question how to choose the best values for the groove radii and position of its centre, providing the minimum stress concentration in the whole structure. For that purpose, the optimization procedure can be applied. Due to the presence of only two independent parameters, the simple search method can be used to find the optimal solution. The applied optimality criteria depend on the material model assumed for the pipe and flat end plate manufacturing. The analysis can be performed for the purely elastic material, or for the material exhibiting elastic-plastic properties. One of is the bilinear elastic-plastic material with hardening module of constant value, which in an acceptable way approximates the behaviour of many low carbon and low alloy steels, which are frequently applied for pressure constructions. In case of elastic material, usually the minimum value of the maximum equivalent stress in the whole structure is used for the objective function, while in elastic-plastic material the following criteria are used:

$$F_e = \min\{\max \varepsilon_{pl\_eqv}\}, \tag{3}$$

where ε_{pl_eqv} is the equivalent plastic strain over the whole analysed structure.

The results of these studies are presented in several papers [6, 8-9] and the conclusion of that studies was that the minimum stress concentration is observed when the centre of the groove is located at the level of the bottom of the end plate (h = 0) and the value of the radius r_{ik} is not far from its maximum admissible value. This means that the optimal point is located in point D, which lies on the line AC of the region shown in Fig.1b. This observation was repeated several times for different combinations of the pipe diameters and the wall thicknesses. The exemplary results are presented below in the Tab. 1 and in the Fig. 2, where the elastic-plastic material model was applied. Fig.2a presents the distribution of the maximum equivalent plastic strain value along the line AC (see Fig.1b) and the distribution of the equivalent plastic strains in the part of the structure for the optimal value of r_{ik} = 32.0 mm (point D, Fig. 2b).

Tab. 1 Values of F_e for three different points belonging to admissible area ABB'C

point	r_{ik} [mm]	e_{h1} [mm]	$F_e = \min\{\max \varepsilon_{pl\_eqv} \times 10^5\}$
A	5.00	58.22	374.3×10^5
C	43.22	20.00	94.0×10^5
D	32.00	31.22	73.5×10^5

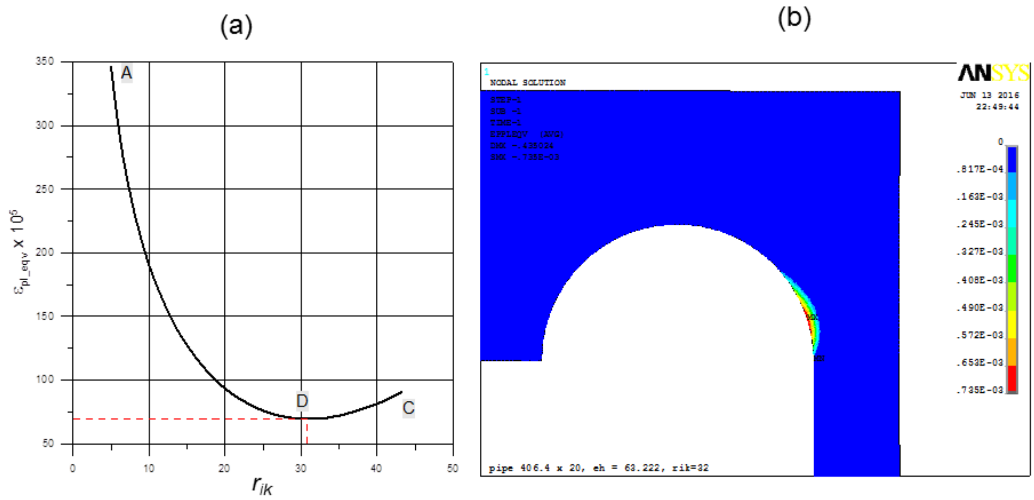

Fig. 2. Distribution of maximum equivalent plastic strains along line AC (see Fig.1b) – (a); distribution of equivalent plastic strains in analysed structure for optimum value of r_{ik} = 32.0 (point D) – (b)

2. Fracture of pressure vessels

Designing of pressure vessels and boilers is strictly controlled due to the safe operation requirements set by respective codes. The pressure vessels of common use are usually made from the high strength steels exhibiting ductile properties. The designed vessel wall thickness is calculated in such a way that for the design pressure and design temperature the stresses induced in the structure remain within the elastic limit. This prevents from the excessive plastic deformations or rupture associated with the yield point exceeding. The presence of cracks can reduce the strength of a pressure vessel. When the fracture crack achieves its critical size it can cause rapid growth of the existing damage and finally result in sudden failure. It should be noted that such failure generally happens under stresses, which are much smaller than the material yield strength [11].

In standard boilers calculations the presence of cracks is not taken into account, as the material is assumed free from flaws, cracks and internal voids. In order to properly asses the influence of cracks presence and its possible evolution on the structure endurance the fracture mechanic approach is applied [11]. This branch of mechanical analysis joins together the influence of the structure loading, fracture toughness and size of the crack and gives the answer what is the critical combination of these three variables, which results in the fracture. In case of the thin-walled pressure vessels with cracks application of linear elastic failure analysis (LEFM) usually gives sufficiently reliable results. In the thick-walled cylinders with cracks, where plastic deformations may occur (particularly for the ductile materials used for the vessel manufacturing), the rupture is usually preceded by the slow and stable crack growth and the elastic-plastic fracture mechanics (EPFM) approach is recommended. In case of thin-walled vessels with flat end with stress relieve grooves both methods should be applied and their results somehow compared and assessed. This emerges from the observation that the shell under the internal pressure works within the elastic regime, while in the groove area some plastic deformations are present. So the mechanism of rupture may be determined by the position of the crack in the vessel. Due to those facts, both the stress intensity factor and the strain energy release (J_C-integral) were numerically calculated in tests for different positions and sizes of cracks.

The additional factor, which influences the crack resistance, is the application of welding in the junction of boiler tube and flat end plate. The welding process causes metallurgical and physical changes of material properties. Generally, in the heat-affected zone hardness and grain size are increased. The microstructure change has significant influence on material toughness, while increase of grain size results in decrease of fracture toughness. The microstructure of the material in the heat-affected zone (HAZ) depends on amount of introduced heat, welding process, steel material chemical composition and its properties. For commonly used in pressure installations 16Mo3 steel the changes of fracture toughness were experimentally set by Dzioba et al. [12]. These data indicated that the lowest fracture toughness J_C occurs in the weld zone. In case of laser welding of 16Mo3 steel parts, the fracture toughness is about 2.5 times smaller in weld joint than that of base material (Tab. 2). It makes weld joint zone the weakest part of the structure with respect to the fracture rupture.

Tab. 2. Fracture toughness of the weld joint connection after laser welding and 16Mo3 steel [13]

zone	Hardness [HV10]	J_C [N/mm]
Base material	155	423
Recrystallized HAZ	170	341
Fine grained HAZ	185	231
Coarse grained HAZ	220	231
Weld material	210	173

The values of the fracture toughness for other materials are given in Tab. 3.

Tab. 3. Fracture toughness of the materials used for manufacturing of pressure vessels [13]

Material	J_C [N/mm]	K_{IC} [MPa·m$^{1/2}$]
S235JR	3.1	25
13CrMo4-5 (base material)	379-513	288-336
13CrMo4-5 (weld material, laser welding)	521-816	338-423
13CrMo4-5 (heat affected zone, laser welding)	293-406	254-299
A533	97	143

3. Numerical results and conclusions

In the paper, the Authors concentrated on the assessment of the internal crack presence and its possible influence on the rupture. These cracks cannot be spotted during the visual inspections and are difficult to detect, and only sometimes are issued by the routine periodic non-destructive tests. The positions of cracks under the investigations are given in Fig. 3a.

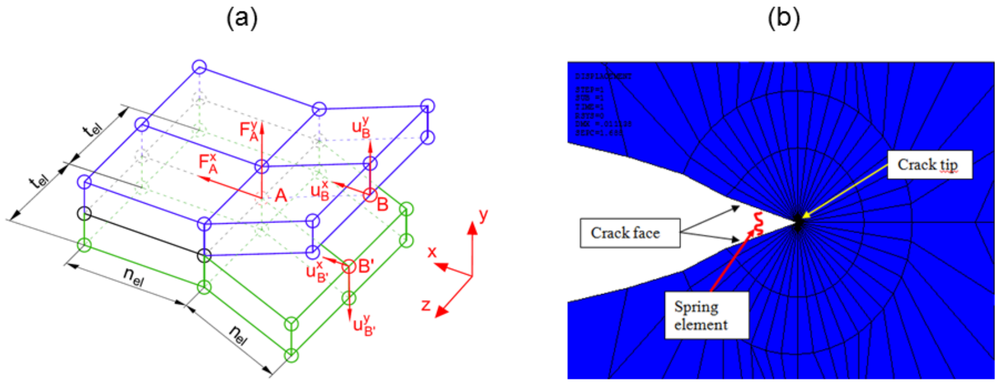

Fig. 3. Circumferential crack position in investigated boiler with flat end plate- (a), Finite element mesh of structure around crack tip- (b)

Two fracture mechanisms – ductile and brittle fracture were under investigation. The primary difference between both above failure mechanisms is the presence of the plastic deformations. In the ductile fracture, the extensive plastic deformation occurs ahead of crack tip, while in brittle fracture they are negligibly small. Therefore ductile materials have larger energy absorption (described as fracture toughness) than brittle materials. For this reason, ductile fracture is usually preferred in engineering applications. Brittle fracture generally occurs in materials, which do not show the yield limit such as ceramic materials, glass, heat-treated steels, etc. Such materials have also low fracture toughness. The brittle fracture mechanism can be characterized by rapid and unstable crack growth. It can lead to sudden catastrophic failure of a structure. For this reason, the brittle fracture is a significant problem during operating of pressure vessels. Because of this, estimations of risk and safety analysis are important engineering issues. Such fracture mechanism can be investigated using the Linear Elastic Fracture Mechanics (LEFM). In the LEFM analysis, it is assumed that plastic strains around the crack tip are negligible small and crack initiation and propagation is independent of plastic deformations. In materials with high fracture toughness (ductile materials), the fracture mechanism is governed by plastic deformations. Analysis of such phenomena requires nonlinear analysis including elastic-plastic characteristic of the material. Characteristic feature of ductile fracture mechanisms is that the large plastic deformations accompany of the process of the crack initiation and growth. Due to large scale of plastic strains, it is necessary to include such effects in the fracture mechanics. Therefore, the Elastic-Plastic Fracture Mechanics (EPFM) must be applied in the calculations.

Computations of the fracture parameters (strain energy release rate G) were made using Virtual Crack Closure Technique (VCCT) with the use of the ANSYS software [1]. It is assumed that the crack grows in a self-similar manner. It allows to calculate the forces and the displacements at the nearby to the crack tip using one numerical model. The force F_A can be estimated using spring or contact element. Such problems require using of special mesh grid in a form presented in Fig. 3b. The authors perform both LEFM and EPFM analyses. The strain energy release rate (G = J-integral) is the most appropriate parameter for analysis of elastic-plastic fracture mechanism. The energy G was estimated using the given below formula:

$$G(A) = \frac{1}{2}\frac{F_A \Delta u_{B-B'}}{n_{el} t_{el}}, \tag{1}$$

where:
points A, A’, B, B’, n_{el}, t_{el} (finite element size), force are shown in Fig. 4a. In this Figure F_A is the force which is necessary to close existing gap (calculated numerically using additional spring element in the nearest nodes to the crack tip), and $\Delta u_{B\text{-}B'}$ – relative displacement between nearest nodes behind the point A. In the 2-D axisymmetric model t_{el} is assumed as $2\pi l$, where l is the distance between the axis of vessel and location of the crack tip.

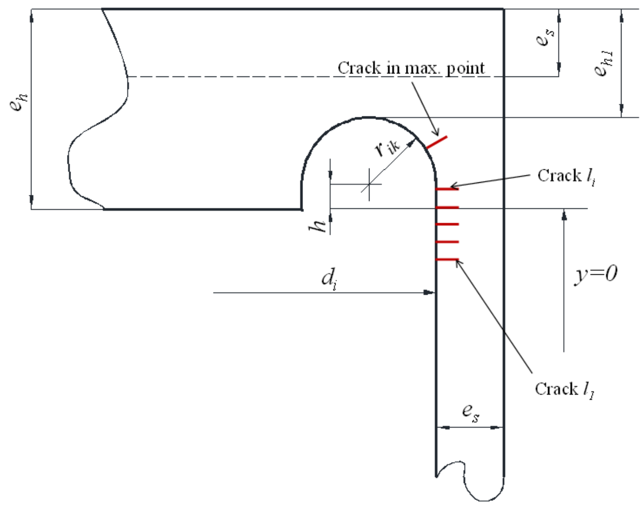

Fig. 4. Considered positions for cracks

The respective numerical studies were performed for two different values of radii of stress relieve groove (Fig. 4). The elastic-plastic analysis of the boiler structure allows for selection of two different groove geometries with optimal and non-optimal radii value. In the first one, which is also assumed as the optimal shape, the geometrical parameters are equal r_d=32 mm (point D in Tab. 1), which gives the minimum value of the maximum equivalent plastic strain in the investigated structure In the second investigated example the largest equivalent plastic stains occurred (radius value of r_d=5.0, point A, Tab. 1). This configuration was assessed as the worst one with non-optimal geometry, but still admissible by codes.

Three mode of the gap opening can be distinguished in the fracture mechanics: mode I associated with tensile stress and mode II and mode III caused by shear stresses – in-plane and anti-plane, respectively. The participation of particular modes was investigated using 3D model of vessels with the flat end. It was observed that in a pipe both shear modes have negligible small levels and they can be neglected in further analysis. However, in the flat end the second mode achieves significant values and must be included in the fracture analysis.

The comparison of results of strain energy release rate G in pipe for crack with length 3.8 mm is given in Tab. 4. The difference in results is caused by different crack length in circumferential direction. In 2D axisymmetric model, the crack is assumed around the full circumference. In 3D model, the crack length in circumferential direction was equal 3.927mm × 2 mm (1/12 % of full circumference).

Tab. 4. Comparison of results for 2D and 3D model, optimal shape, crack length 3.8 mm, crack location: pipe: y =-10

Model	strain energy release rate		
	G_I	G_{II}	G_{III}
3D (at the centre of the crack)	2.63	1.81E-2	2E-6
2D – ELFM	3.01	1.65E-2	-
2D – EPFM	2.30	1.3E-2	-

The influence of the radius of stress relieve circular groove and location (parameter *y,* Fig. 3a) and size of the crack on the fracture strength was studied for both ELFM and EPFM. The studies were performed using 2D models with axial symmetry and steel 16Mo3 for the boiler. Here, the calculations were made for different location of crack for optimal and non-optimal geometry of the relief groove (Fig. 5). In all cases the cracks were perpendicular to the internal surface of the pipe if parameter (y<0, see Fig. 4) or to the contour of stress relieve groove of the flat end (y>0, Fig. 4). The centre of the weld joint is located on y=zero. In calculations, the crack length was assumed as 4.216 mm, which corresponds to 21.08% of the pipe thickness.

The further propagation of the perpendicular crack in a pipe (y<0) can be caused by the tensile mode I of the crack opening. The in-plane shear mode II is about two times smaller than mode I. The relation between the first and the second crack mode changes in the stress relieve groove area of the flat end. The maximal mode I occurs in the stress relieve groove area, close to the point, in which the maximal equivalent stress occurs.

Application of the PERM approach for the vessel with optimal shape of the stress relieve groove results in decrease of strain energy release rate in a pipe but also leads to significant increase of the tensile mode I in the groove area and weld joint between flat end and pipe (Fig. 5a). In the case of non-optimal shape of the stress relieve groove the results of strain energy release rate were similar both for the ELFM and for the EPFM (Fig. 5b). Application of the EPFM approach leads to relief of the crack tip zone and reduces of the strain energy release rate.

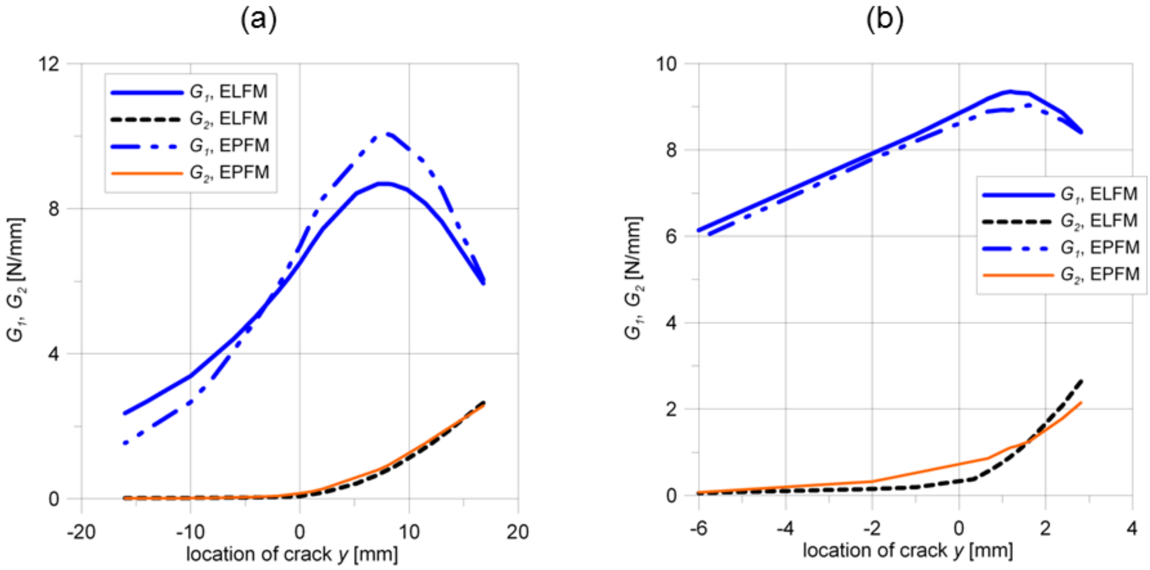

Fig. 5. Strain energy release rate G for different location of cracks, 2D axisymmetric model, crack length 4.216 mm, optimal shape of stress relieve groove (a), not-optimal shape (b) – results for 16Mo3 steel

It can be observed that the G_I achieve larger values in pipe and weld joint for not-optimal shape of relief groove. In flat end, G_I is smaller due to the large thickness of the flat end. However it should be noted, that the most dangerous place is the surroundings of the weld joint. In such connection, the fracture toughness is generally decreased with respect to the base material. However, for such size of a damage and ductile material with high the fracture toughness the failure process is related to crack propagation caused by cyclic loading.

The critical size of the damage was estimated for the location in which the mode I achieves the largest values (y = 8.04 mm, Fig. 5a). For the 16Mo3 steel and laser welding technique the critical size of the crack is about 0.7÷0.75 of the thickness of the flat measured in the same direction as the crack line (Fig. 6a). The more accurate value of the critical length may be estimated using multiaxial fracture criteria. Such criteria make possible to estimate how the mode II influences on the mode I. For comparison, the similar results for the structure made of S235JR steel are presented in Fig. 6b. It can be seen that for these steel the risk of the rupture, particularly brittle fracture is much probable than for steel 16Mo3. In this case, the critical length of crack is about 0.2 of the pipe wall thickness. This confirms the advantage of usage of Cr-Mo alloy steels for boiler construction rather than ordinary weldable, constructional steel.

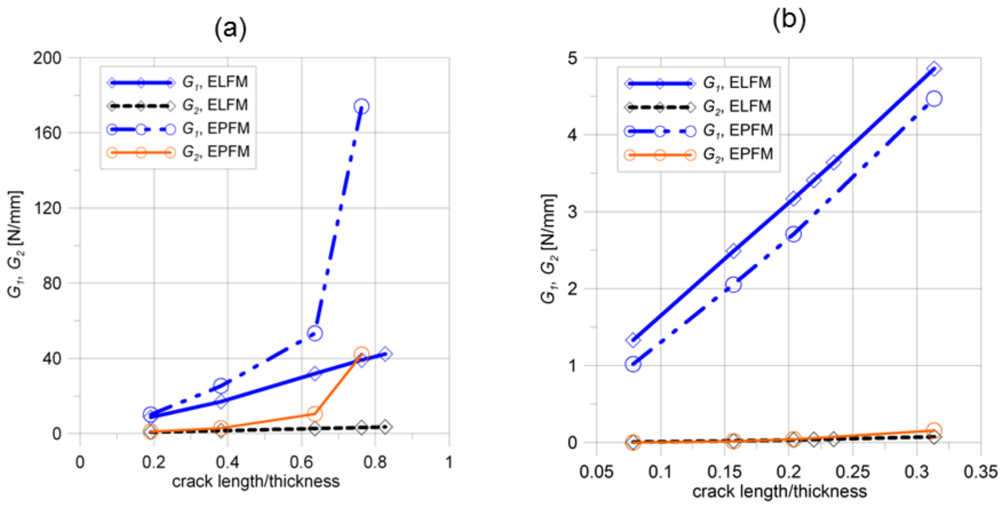

Fig. 6. Strain energy release rate G_1 for different crack length, 2D axisymmetric model, y = 8.04 mm, optimal shape of relief groove; steel 16Mo3 – (a); steel s235JR – (b)

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