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Evaluation of Cracking Conditions of Butt Welded Joints in Polyethylene Pipes

Abstract: *The aim of this paper is a description of butt welding process of polyethylene pipes which by using improper parameters can cause defects in welded joints. Internal defects are especially dangerous.*
The paper presents results of calculations and analysis of critical size of defects in form of internal fissures that can occur in butt welded joints of pipelines from polyethylene. At the critical fissure size, the initiation of cracking process of the welded joint can start. Polyethylene pipelines are used for transmission of liquids and gases of low temperature (cold water, gas fuel) as well as different aggressive liquids and water of high temperature used in technological processes. In this analysis the possibility of earlier occurrence of polymer creep phenomenon in elevated temperature was taken into account.
Keywords: *polyethylene, butt welding, cracking*

OCENA WARUNKÓW PĘKANIA DOCZOŁOWYCH POŁĄCZEŃ ZGRZEWANYCH RUR Z POLIETYLENU
Streszczenie: *Praca zawiera opis procesu zgrzewania doczołowego rur z polietylenu, który przy niezachowaniu prawidłowych parametrów procesu zgrzewania może spowodować występowanie wad w zgrzeinie. Szczególnie niebezpieczne są wady wewnętrzne. W pracy przedstawiono wyniki obliczeń i analizę krytycznych wielkości wad w postaci szczelin wewnętrznych, które mogą zawierać doczołowe złącza zgrzewane rurociągów z polietylenu. Przy krytycznej wielkości szczeliny może nastąpić zainicjowanie procesu pękania złącza rurociągu. Rurociągi z polietylenu są stosowane do przesyłania płynów i gazów o niskiej temperaturze (zimna woda, paliwa gazowe) oraz różnych płynów agresywnych i wody o podwyższonej temperaturze, używanych w procesach technologicznych. W przeprowadzonej analizie uwzględniono możliwość wystąpienia wcześniej zjawiska pełzania tworzywa w podwyższonej temperaturze.*
Słowa kluczowe: *polietylen, zgrzewanie doczołowe, pękanie*

1. INTRODUCTION

Hot plate butt welding is very often used for joining polyethylene pipes for outdoor installations because it allows to join parts of wide diameter range and it can be used in field conditions [1]. In butt welded joints of polyethylene pipelines used for the transmission of gas fuel, water and other liquids [2] some defects – material discontinuities – can occur, for example internal fissures: longitudinal (along pipe axis) as well as transversal [2-7]. Such fissures are formed mostly as a result of improperly prepared frontal surfaces of welded pipes or due to the incorrectness of welding processes. Longitudinal fissures are especially dangerous due to high circumferential stress in a pipe which is two times higher than longitudinal stress. This problem concerns especially internal fissures which are not possible to detect using a visual inspection of a joint. Stress concentration at the fissure front acting perpendicularly to the fissure surface can initiate crack development which, in turn, can cause breaking of the joint (and the leakage of the pipeline). This break can occur as a result of rapid crack propagation (RCP) with a velocity close to the sound velocity [4,8] in the conditions of low polymer temperature T at which its properties are like the ones of elastic-brittle material (for PE-HD at $T \leq 0°C$). It was also proven that when the temperature is lowered, the crack opening displacement in PE-HD material becomes smaller more intensively for the material of the pipe (native material) than in the case of the butt welded joint [9]. It was found that high molecular weight, high crystallinity and narrow molecular weight distribution are important to gain RCP resistance [10]. In the case of the slow crack propagation process (SCP) of externally notched pressurized pipes, the critical notch depth depends on the absolute pipe wall thickness, the resin properties, the temperature and other factors [11]. RCP can even occur in positive temperature (slightly higher than 0°C) in the conditions of external impact force existence especially in pipelines with the large wall thickness of the pipe. At a higher temperature the crack initiated at the fissure front increases slowly causing breaking of the joint too. The initiation of the crack in the incubation period in viscoelastic materials, described in [12, 13], is connected with the proper strain rate at the fissure front, which is the result of the temperature-time balance. This change in the form of cracking is caused by the change in the polymer properties at a higher temperature. Reaching the critical value of the stress intensity factor at the front of a fissure having sufficiently big (critical) size is the condition of the crack process initiation. The notch depth influences the lifetime of polyethylene pipes [14].

This paper presents the results of the computer simulation of critical size of longitudinal elliptical internal fissure in butt welded joints of pipes made from PE-HD. The results of basic investigation of this polymer's mechanical properties that were used for the simulation are also presented.

2. TECHNOLOGY OF BUTT WELDING OF PE-HD PIPES

Butt welding of pipes is one of the most common methods that allows joining pipes, plates, rods and sections. This process consists in joining the front surfaces of welded elements after heating them up to a specified temperature. PE-HD butt welded pipes of 110 mm diameter were used for the investigation. Georg Fischer 250 welding machine with a resistance heated plate as the heating element was used in the welding process. Several different stages can be differentiated in the butt welding process of pipes. They are presented in Fig. 1 with the time and welding pressure for each of them.

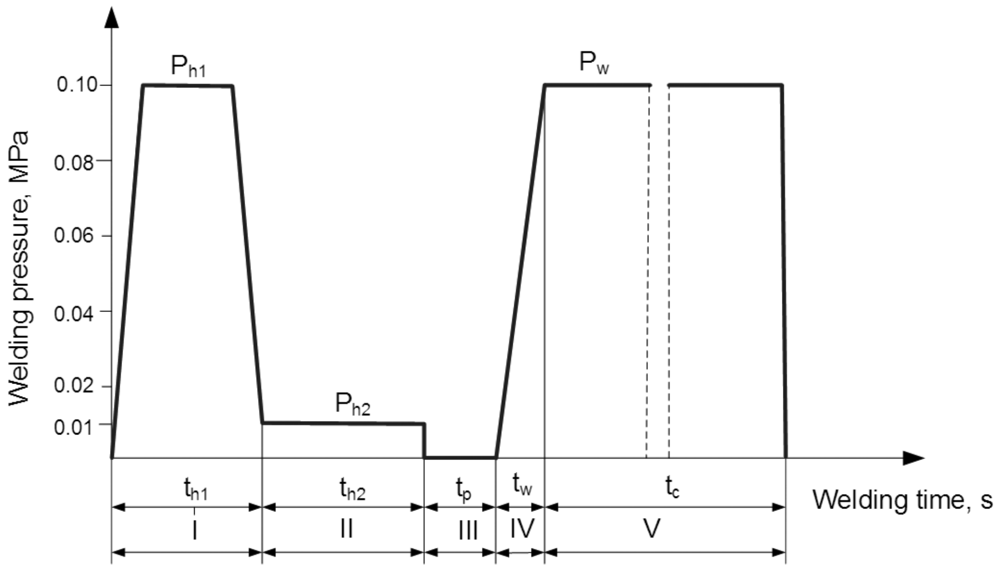

Fig. 1. The program of a welding process of thermoplastic parts with an external heating element [6,15]; description in the text
Rys. 1. Program procesu zgrzewania zewnętrznym elementem grzewczym przedmiotów z tworzyw termoplastycznych [6, 15]; opis w tekście

The butt welding process of thermoplastic elements consists of the following stages: I – flattening of the frontal surfaces of the elements at high pressure P_{h1} in time t_{h1}, II – heating up at low pressure P_{h2} in time t_{h2}, III – removing the heating element in time t_p, IV – increasing the pressure in time t_w, V – welding and cooling of the joint at welding pressure P_w in time t_c.

The basic parameters of butt welding are [8]: welding temperature T_w [°C] in welding time t_w [s], welding pressure: of the heated plate on the welded elements (P_h) and pressure during upsetting (welding) (P_w) [kN], clamping length [mm] that is, the projection length of elements in the jaws of the welding machine, levelling allowance (Δw) [mm], thickness of the layer heated over the softening or melting temperature (Δn) [mm], allowance for the shortening of the heated up elements during the welding, heating and upsetting process (ΔS) [mm], heating time (t_h) [s] and changeover (pause) time (t_p) [s] between the end of the welding process and the applying the force of upsetting pressure [15].

3. CONTROL OF WELDED JOINTS

Following the specified rules regarding each element in the quality system is the condition of providing the proper quality of welded joints. The equipment as well as the welded materials are in this case of basic importance. The experience and the skills of a welder are also very important, as is the control system in this process.

The control of welded joints is very important when it comes to the safety and leaktightness of welded installations. The basic control method is a visual valuation (non-destructive test) of a joint, that is, the assessment of the flash. Its equality on the entire joint circumference is evaluated. The proper shape of the flash results in almost 100% reliability of a good joint in the case of a proper manufacturing process. Flash measurements are made with the accuracy of 0.1 mm [4].

A welded joint (Fig. 2 a) has to fulfill several critical conditions regarding dimensions, like:

- groove height k between the weld beds (k>0)
- width of the weld beds b_1, b_2 ($b_1 \geq 0.7b_2$)
- average joint width B_a calculated from the formula (1):

$$B_a = \frac{B_{\max} - B_{\min}}{2} \quad (1)$$

where:

B_{max} – maximum joint width on the entire pipe circumference ($B_{max} \leq 1.1B_a$)

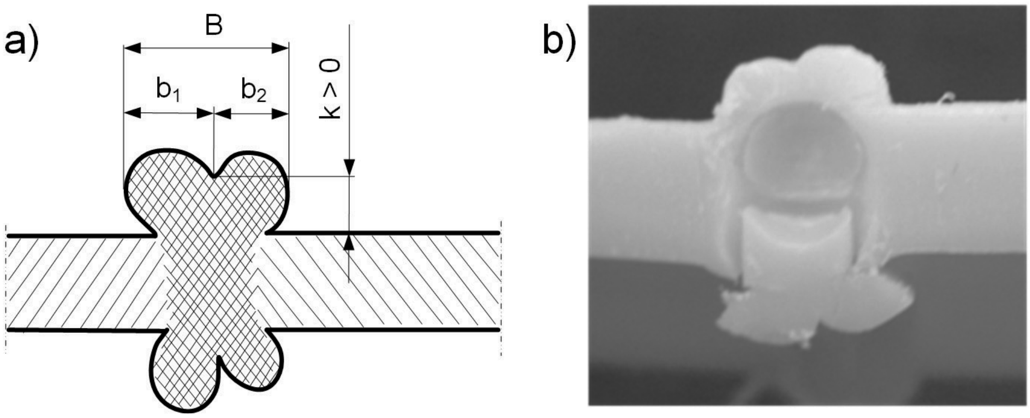

Fig. 2. Scheme (a) [3] and the view (b) of the cross-section of a butt welded joint with internal defect; B – joint width, b_1, b_2 – width of the weld beds, k – groove height between the weld beds

Rys. 2. Schemat (a) [3] i przekrój (b) połączenia zgrzewanego doczołowo z wadą wewnętrzną; B – szerokość zgrzeiny, b_1, b_2 – szerokość wałeczków zgrzeiny, k – wysokość rowka pomiędzy wałeczkami zgrzeiny

B_{min} – minimum joint width on the entire pipe circumference ($B_{min} \geq 0.9 B_a$)

B_a should fulfill the condition: $0.7e \leq B_a \leq 1.0\, e$ (*e* – nominal pipe wall thickness)

However, taking disadvantageous processing conditions of pipe welding into account, even the correct appearance of a welding joint does not guarantee that no internal defects exist in the joint. The scheme of the joint cross-section with the dimensions of the flash for evaluation of the joint is presented in Fig. 2 as well as the internal fissure in the cross-section of the butt welded joint of the pipes. This joint was evaluated as correct after a visual inspection. As a results of weld beds presence, the stress concentration in the area next to the beds can cause material cracking. Material inhomogenity in the joint area results in the high stress intensity factor value and increases the probability of material failure [16].

Thus, except of a visual inspection, when there is a suspicion of the smaller strength of the joint caused by mistakes in the welding process or when the flash appearance put the joint quality in doubts, it is necessary to make non-destructive tests: x-ray or ultrasonic tests [17] in order to check if there are any defects (internal fissures) or leaktightness measurement tests to detect the fissures that come through all the material. Different destructive tests are also made to evaluate the properties of butt welded pipes – for example an examination of strength in a static tensile test, dynamic tensile strength and bending strength. The short-term strength of the PE-HD butt welded joint determined in a static tensile test should be not less than 0.9 of the strength of the native material of the pipe [3].

4. EXPERIMENTAL AND COMPUTATIONAL INVESTIGATION

The joints of pipes of two Standard Dimension Ratio (SDR) values were tested: 11 and 17.6 with their minimum wall thickness respectively: e=10 mm and e=6.25 mm. The pipes of the external diameter d_n=110 mm from high-density polyethylene produced by *Borealis* company had the mechanical properties which are listed in Table 1.

Table 1. Mechanical properties of PE-HD material used in calculations

Tabela 1. Własności mechaniczne polietylenu PE-HD wykorzystanego w obliczeniach

Polyethylene PE-HD (density ρ=930, kg/m^3)	Native material	Joint material
Yield strength σ_y, MPa	21.0	23.3
Tensile strength σ_M, MPa	22.3	23.6
Elongation at break ε_B, %	430	510
Young modulus E, MPa	615	603
Cracking resistance K_{Ic}, MPa·m$^{1/2}$	2.39	1.92

The analysis of the cracking initiation and its propagation in the joint of a pipe containing a fissure of a characteristic dimension *a* was based on the European calculation procedure FITNET (FITness for Service NETwork) and the failure assessment diagram (FAD) [12]. It is described wider in the case of polyethylene pipes in work of Baranowski and Werner [3]. In the FADs the maximum curve $K_r=f(L_r)$ for the reference stress σ_{ref} at the values of load $L_r=\sigma_{ref}/\sigma_y$, valid until $L_r=L_r^{max}$, limits the safe point area (the element with the fissure) with the coordinates $K_r=K_a/K_{Ic}$, L_r [18]. This analysis was made at the zero level, for which, having $L_r \leq L_r^{max}=1$, the knowledge of the yield strength σ_y and the Young modulus E is sufficient to determine the maximum curve $K_r=f(L_r)$ [18]. The stress intensity factor K_a, for characteristic fissure dimension *a* was determined on the basis of stress σ at the fissure tip. For the given stress level L_r value, the fissure will reach the critical size $a=a_c$ (due to the possibility of crack initiation) when the following condition will be met [3]:

$$K_a / K_{Ic} = K_r(L_r) \tag{2}$$

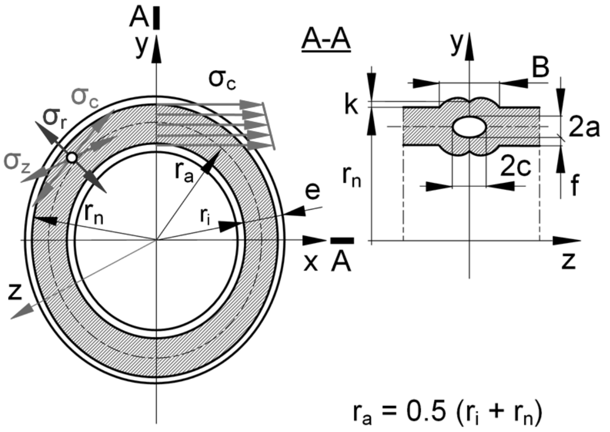

Fig. 3. Cross-section of the butt welded joint of pipes with a longitudinal internal elliptical fissure; r_n – external radius of a pipe, r_a – average pipe radius, r_i – internal pipe radius, e – pipe wall thickness, σ_z – longitudinal stress, σ_r – radial stress, σ_c – circumferential stress, k – groove height between weld beds, B – joint width, a – vertical semi-axis of an elliptical defect, c – horizontal semi-axis of an elliptical defect, f – minimal distance between the fissure front and pipe surface

Rys. 3. Przekrój złącza doczołowo zgrzewanych rur z wzdłużną, wewnętrzną szczeliną eliptyczną; r_n – zewnętrzny promień rury, r_a – średni promień rury, r_i – wewnętrzny promień rury, e – grubość ścianki rury, σ_z – naprężenie wzdłużne, σ_r – naprężenie promieniowe, σ_c – naprężenie obwodowe, k – wysokość rowka pomiędzy wałeczkami zgrzeiny, B – szerokość zgrzeiny, a – pionowa półoś elipsy w przekroju wady, c – pozioma półoś elipsy w przekroju wady, f – minimalna odległość czoła szczeliny od powierzchni rury

During the exploitation of industrial pipelines used for the transmission of different technological liquids and water of higher temperature (*T*=20°C – 70°C), creep process and degradation due to ageing has a significant influence on polymer properties. The influence of creep process on cracking was analyzed in this work. As a result of polymer creep, its Young modulus *E* decreases causing a decrease in cracking resistance K_{Ic}.

The critical dimension of fissure a_c was determined for normal conditions of pipeline work, that is, for the positive ground temperature – close to 0°C (a_{c0}) and for the pipeline exploitation temperature *T*=23°C i *T*=40°C ($a_{c(t)}$) in industrial technological processes conditions. The decreased cracking resistance K_{ct} (3) after time *t* being the creep result in high temperature was determined on the basis of the initial cracking resistance of polyethylene K_{Ic} for a low temperature and Young modulus *E* decreased after time *t* to the value of E_t [8, 19, 20].

$$K_{ct} = K_{Ic}\frac{E_t}{E} \tag{3}$$

The Young modulus E_t at a higher temperature was determined on the basis of the creep curves $E=f(t, \sigma)$ of high-density polyethylene (PE-HD) for nominal stress σ in the pipe joint cross-section [21, 22].

The internal fissure type of a semi-elliptical shape was considered (Fig. 3) in the joint in the range of its dimension *a*: from *a*=0 to the half of the wall thickness of the pipe (*a*=*e*/2).

The aim of the analysis of cracking of polyethylene pipes joints was the calculation of the critical depth a_c of a fissure (defect) occurring in a butt welded joint – in the welded area [6]. Circumferential (tangential) stress σ_o (Fig. 3) in the joint was calculated for the nominal gas pressure value *p*=0.5 MPa in a pipe of SDR 11 and the nominal water pressure *p*=1.0 MPa in a pipe of SDR 17.6 and for *p*=1.25 MPa in case of a SDR 11 pipe [4, 7, 19]. The stress σ_o was calculated for the extreme joint dimensions (however, in the conditions of acceptance, defined in

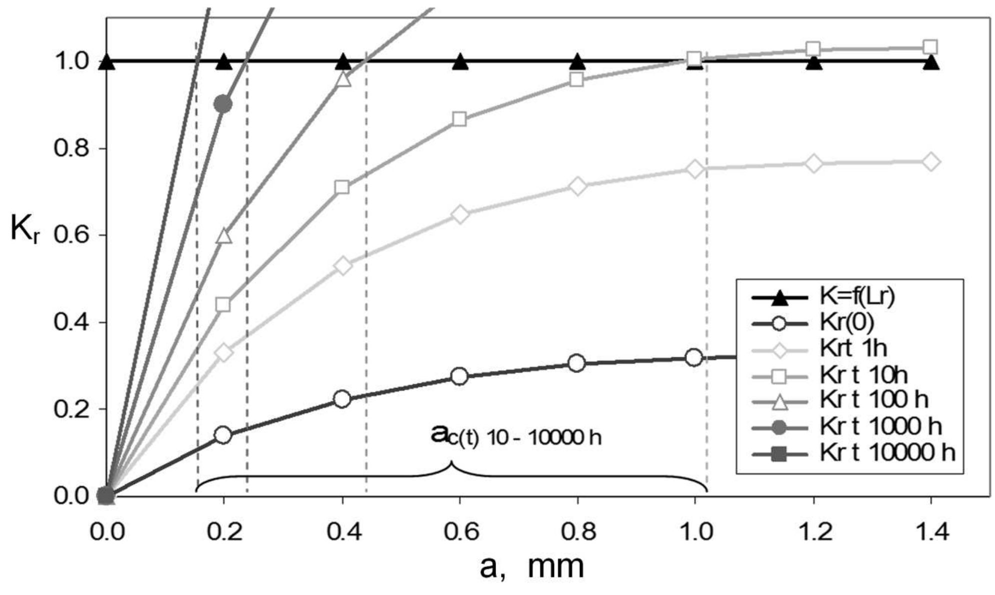

Fig. 4. The failure curves of the pipe joint with the elliptical fissure. SDR 17.6; p=1 MPa; k=0.25 mm; f=0.1 mm; c=3 mm; T=23°C

Rys. 4. Krzywe zniszczenia złącza rury ze szczeliną eliptyczną. SDR17,6; p=1 MPa; k=0,25 mm; f=0,1mm; c=3 mm; T=23°C

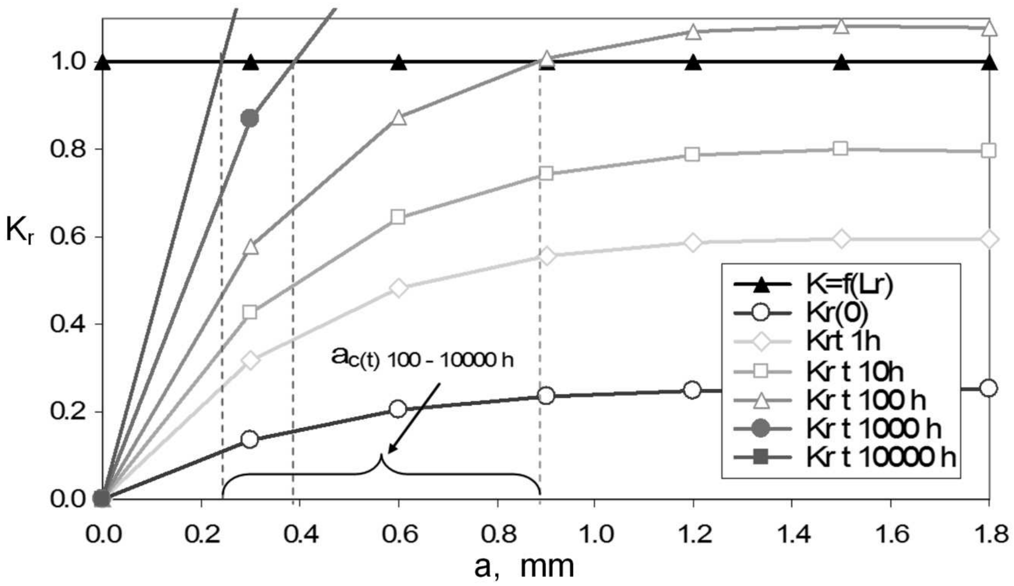

Fig. 5. The failure curves of the pipe joint with the elliptical fissure. SDR 11; p=1.25 MPa; k=0.25 mm; f=0.1 mm; c=3 mm; T=23°C
Rys. 5. Krzywe zniszczenia złącza rury ze szczeliną eliptyczną. SDR11; p=1,25 MPa; k=0,25 mm; f=0,1 mm; c=3 mm; T=23°C

work of Pusz, [4]) – for the total weld beds *B*=*e* and the distance from the bottom of the groove between the beds to the pipe surface *k*>0 (assumed as minimum, *k*=0.25 mm). In the standards of the acceptance of a joint, the height of weld beds is not determined but usually for the joint of pipes of the diameter d_n=110 mm this value is about 2.5 mm for a SDR 17.6 pipe and about 4 mm for a SDR 11 pipe. The stress calculation in the joint was made for the area of the transversal cross-section in the groove plane, of the external diameter d_e=d_n+2*k*. A small disturbance in the stress distribution in the joint (assumed as a geometrical notch) was neglected because of the small width of the weld beds (B/2) [4, 6, 21].

The results of the crack initiation analysis made for the joint with a longitudinal elliptical internal fissure showed that at the pressure *p*=1.0 MPa the risk of crack initiation occurs for a joint with such a fissure of a small semi-axis *c*=3 only after the creep of polymer in the temperature of 23°C, just after the creep time *t*=10 h (Fig. 4). The critical dimension a_c of the fissure after this creep time was slightly above 1 mm. Even smaller values of a_c occurred after a longer creep time of such a fissure and were as follows: after *t*=100 h – a_c=0.44 mm, after *t*=1000 h – a_c=0.24 mm and after *t*=10000 h – a_c=0.16 mm.

There is a similar risk of crack initiation for a joint of SDR 11 pipes with the same elliptical fissure (*c*=3 mm) at the nominal working pressure *p*=1.25 MPa (Fig. 5).

The values of the critical dimension a_c at which crack initiation and development can occur are influenced by: the groove height between the weld beds *k* and the location of the fissure tip in relation to joint surface *f* as well as the dimension of its semi-axis *c*. The values of the critical dimension a_c for the case of a SDR 11 pipe with a longitudinal elliptical fissure at *p*=1.25 MPa are presented in Table 2.

Table 2. The critical size of elliptical fissure in joint of SDR 11 pipe at *p*=1.25 MPa; *T*=23°C
Tabela 2. Krytyczny wymiar szczeliny eliptycznej w złączu rury SDR11 przy *p*=1,25 MPa; *T*=23°C

k=0.25 mm *f*=0.1 mm; *t*=100 h				
c, mm	3.5	4.0	4.5	5.0
a_c, mm	0.88	0.80	0.73	0.70
c=3.5 mm; *k*=0.25 mm; *t*=100 h				
f, mm	0.10	0.15	0.020	0.25
a_c, mm	0.88	1.15	1.44	2.00
c=3.5 mm; *f*=0.1 mm; *t*=1000 h				
k, mm	0.25	0.50	1.00	2.00
a_c, mm	0.38	0.42	0.50	0.72

The results of the calculations in Table 2 indicate that an increase in the fissure dimension *c* causes a decrease in its critical dimension a_c, for example – with the increase of *c* from 3.5 to 5.0, the dimension a_c changes by 0.18 mm – about 20%. The increase of the *f* parameter results in a significant increase in the critical dimension, for example an increase of *f* from 0.10 to 0.25 results in an increase of a_c by about 127%. As a result of the *k* parameter's rise from 0.25 to 2.00, the critical dimension a_c rises by about 90%. On the ground of the analysis made, it can be generally stated that the increase of *f* and *k* parameters results in a smaller risk of crack initiation in a joint but the increase of the *c* dimension increases the risk.

In the case of a SDR 11 pipe with an internal elliptical fissure (*c*=3 mm) and low pressure *p*=0.5 MPa used in gas transmission there is no risk of crack initiation – both in the exploitation of a pipeline in low temperature as well as after the creep in a higher temperature of 23 °C. The K_{rt} curves for this temperature do not cross with the limiting

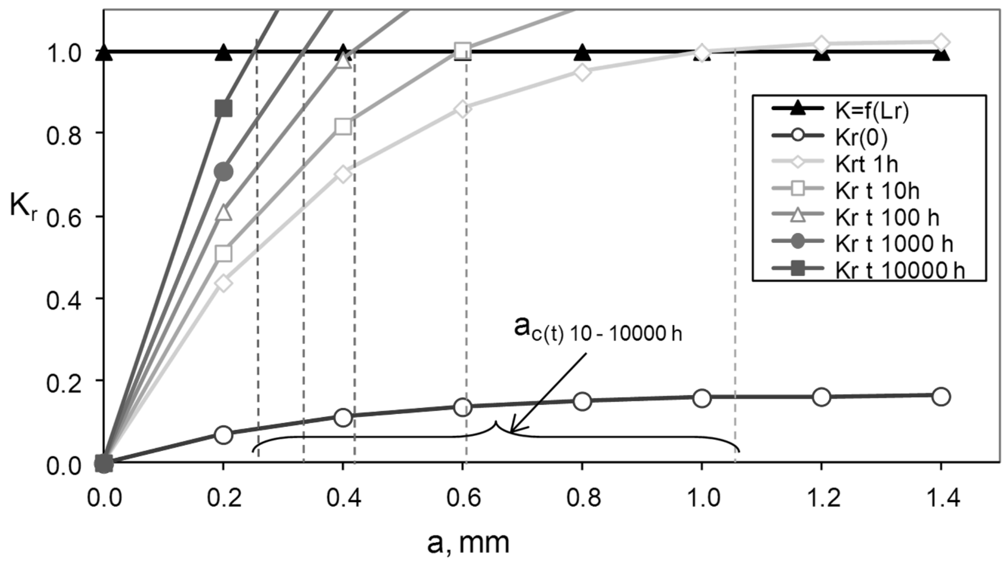

Fig. 6. The failure curves of the pipe joint with the elliptical fissure. SDR 11; p=0.5 MPa; k=0.25 mm; f=0.1 mm; c=3 mm; T=40°C
Rys. 6. Krzywe zniszczenia złącza rury ze szczeliną eliptyczną. SDR11; p=0,5 MPa; k=0,25 mm; f=0,1mm; c=3 mm; T=40°C

curve $K(L_r)$ even in case of a big fissure (of length $2c \approx B$) assuming that other parameters are disadvantageous, i.e. a small distance *f*=0.1 mm between its tip and the internal surface of the joint and a small depth of the groove bottom *k*=0.25 mm. However, a high risk of crack initiation with an internal elliptical fissure occurs after polymer creep in the temperature *T*=40°C even for a small fissure (*c*=3 mm) after a short creep time (Fig. 6).

It was not stated that there is a risk for a joint with this fissure in normal working conditions (curve $K_r(0)$ in Fig. 6).

5. CONCLUSIONS

On the basis of the analysis of the results of the critical fissure dimension calculation it was found out that the risk of crack initiation in the joint of butt welded SDR 17.6 pipes with an elliptical internal fissure at pressure *p*=1 MPa occurs after polymer creep in temperature 23°C in time *t*=10 h. The critical dimension a_c of the fissure of the small semi-axis *c* = 3 mm in these conditions is only 1 mm. After a longer creep time the critical dimension values of such a fissure are even smaller. A similarly high risk of crack initiation occurs for the joint of SDR 11 pipes with an elliptical internal fissure at nominal internal pressure *p*=1.25 MPa after creep occurring at this temperature for 100 h. The critical dimension of this fissure is in this case only 0.9 mm.

The critical dimension of an elliptical internal fissure – a_c – at which crack propagation in the pipes joint can occur, depends also on the joint parameter *k* (distance between the groove in the joint and the pipe surface) and the location of the elliptical fissure tip in relation to the joint surface – i.e. on *f* parameter. Generally, it can be stated that when *k* and *f* parameters increase, the critical value of the elliptical fissure a_c increases too, which practically means a smaller risk of a joint cracking process initiation. On the other hand, an increase in length 2*c* of the elliptical fissure makes this risk higher (value a_c decreases). However, a high risk of cracking initiation in a joint with an elliptical internal fissure occurs after polymer creep in temperature *T*=40 °C even for a small fissure (*c*=3 mm) after a small creep time.

Regarding the risk of cracking of polyethylene pipes joints with a defect – an elliptical longitudinal internal fissure – which have worked at a high temperature, it is recommended to subject butt welded joints to non-destructive control, for example using an ultrasonic method, in order to detect and measure the size of the defect.

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