Effect of initial notch depth on fatigue crack initiation and subsequent crack propagation in PVC water pipes

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The effect of the initial notch depth on fatigue crack initiation, fatigue crack growth and crack growth kinetic parameters was investigated for PVC water pipes using an arc segment test specimens. Two different values for the load ratio (R= 0.15 and 0.3) and three different values for the initial notch depth (a_o=3, 4.5 and 6.5 mm) were used. The initial value of the maximum stress intensity factor was kept constant at 2 MPa.m$^{1/2}$ for the whole tests. The load ratio was adjusted by changing the minimum stress intensity factor. From the obtained results, it was found that, increasing of the initial notch depth, suppresses the crack growth causing an increase in both number of cycles for crack initiation and the number of cycles to failure. The number of cycles for initiation per notch depth increases at rates of 0.55 and 2.32 kcycle/mm for R= 0.15 and 0.3, respectively. The total number of cycles to failure per notch depth increases at rates of 1.42 kcycle/mm for R=0.15, and 6.47 kcycle/mm for R= 0.3. The crack growth kinetic parameters decreases as the initial notch length increased. The rate of decreasing of A per notch depth is 1.725x10^{-9}/mm and 1.295x10^{-9}/mm for R=0.15 and 0.3, respectively. The crack growth kinetic parameter, m, decreases as the initial notch depth increases. The rates of decreasing of m per initial notch depth is 0.062/mm and 0.146/mm for R=0.15 and 0.3, respectively. The obtained values of A and m were used to calculate the number of fatigue cycles for both initiation and failure by integration. The average absolute errors between the calculated and the experimental values were found to be in the range 3.08% to 7.66%.

فـــي هذا البحث تم تحضير عينات الاختبار من أنبوبة من عديد كلوريد الفينيل قطرها الخارجي ٣٠٠ مم و سمك جدارها ١٥ مم تم الحصول عليها من مصانع الشريف للأنابيب البلاستيكية. و قد تم اختيار شكل و أبعاد عينات الاختبار طبقا للمواصفات القياســية ASTM. وقــد تم استخدام ثلاثة أعماق مختلفة للشرخ الابتدائي هي ٣ مم، ٤,٥ مم و ٦,٥ مم . و تمت الاختبارات باســتخدام نســبتي أحمــال همــا ٠,١٥ و ٠,٣ (نسبة الحمل= أقل حمل/اكبر حمل) حيث تمت المحافظة على القيمة الكبرى الابتدائــية لمعامل كثافة الإجهاد ثابتة لجميع الاختبارات عند مستوى ٢ ميجابسكال.م ^٢/١^ و في البداية تم تحديد نوع الاجهادات المتبقــية فــي جدار الأنبوبة فوجد أنها تتغير من اجهادات شد على السطح الداخلي للأنبوبة إلى اجهادات ضغط على السطح الخارجــي. و قد وجد أنه كلما ازداد عمق الشرخ الابتدائي ازداد عدد اللفات اللازمة ليبدأ الشرخ في الانتشار و كذلك ازداد عــدد اللفــات اللازمــة للكسر. و قد وجد أنه لنفس القيمة من أكبر معامل لكثافة الإجهاد و أيضا لنفس القيمة من مدى تغير معــامل كثافة الإجهاد فان سرعة انتشار الشروخ يقل كلما زاد عمق الشرخ الابتدائي و يرجع ذلك إلى أن اجهادات الضغط عــند مقدمــة الشرخ تزداد كلما ازداد عمق الشرخ. و قد تم الحصول على المعاملات الكينماتيكية لانتشار الشروخ A و m حيــث وجد أن هذه المعاملات تقل كلما ازداد عمق الشرخ الابتدائي. و قد تراوح معدل النقص في A بين ١,٧٢٥x١٠^-٩^ و ٢,٤٧٥x١٠^-١٠^ ميجابســكال. م ^٢/١^/مــم و قــد تراوح معدل النقص في m بين ٠,١٣٥ و ٠,٠٥ /مم. و قد تم حساب عدد اللفــات اللازمــة لبدء الشروخ و انتشارها بطريقة التكامل العددي باستخدام قيم A و m من مصادر مختلفة و تمت مقارنة النــتائج بالقــيم التي تم الحصول عليها أثناء الاختبارات حيث تراوح متوسط الأخطاء بينهما بين ٣,٠٨ %و ٧,٦٦% و هي نسبة معقولة بالمقارنة بعدد الخطوات التي اتبعت للحصول على قيم A و m.

Keywords: PVC pipes, Initial notch length, Crack initiation, Fatigue crack growth, Crack growth kinetic parameters

1. Introduction

Residual stresses and morphological differences are produced during extrusion process of plastic pipes due to the nonuniform temperature distribution through the pipe wall (temperature gradient) during cooling stage [1]. These residual stresses vary from tensile stress at the inner surface of the pipe to compressive stress at the outer surface of the pipe [2,3]. The effect of residual stress on fatigue life of polycarbonate was investigated

[4]. The obtained results showed that, the compressive residual stress has a significant effect in increasing fatigue life. The influence of residual stress on fatigue crack growth in steel pipes was experimentally and analytically investigated for surface cracks [5]. The results showed that, the compressive residual stress remarkably suppresses the surface crack growth, while the tensile residual stress does not accelerate the crack growth very much. The effect of residual stress on crack propagation in MDPE pipe was investigated [6]. The obtained results showed that, the life based on crack propagation for test samples notched from its outer surface (compressive stress side) was found to be about 2 times that for a test sample notched from its inner surface (tensile stress side). The effect of residual stresses on fatigue crack in metal-matrix composite materials was investigated [7]. It was found that, a residual stress field would clearly have some effect on fatigue crack growth. A compressive residual stress will decrease the crack growth rate while a tensile stress field will increase it. Also it was found that, fatigue crack growth could cause a change in the residual stress field while the applied loading remains unchanged.

The ASTM standards [8] demonstrate that, the ratio between the initial notch depth and the arc specimen thickness can be taken equal to 0.2 and higher. This means that, the residual stress at the initial notch tip will be different from one depth to the other. The crack propagation resistance of PVC pipes was investigated using a single value for the initial notch depth and different values for the load ratio [19]. The question is, does the initial notch depth affect the crack initiation and the subsequent crack propagation? The goal of this paper is to study the effect of the initial notch depth on, crack initiation, crack propagation and the crack growth kinetic parameters A and m in PVC water pipe.

2. Experimental procedure

The material used for this study was PVC water pipe obtained from El-Sheriff factory of PVC pipes. The test specimens were made from PVC pipe having 300 mm outer diameter and 15 mm wall thickness. The test specimens were designed as an arc segments as shown in fig. 1-a. The specimen dimensions were chosen according to ASTM standard E399-81 [8]. 24 test specimens were prepared and divided in three groups (eight specimens each). The specimens of the first group were notched to initial depth, a_o, equal to 3 mm, while, the specimens of the second and the third groups were notched to initial notches of 4.5 mm and 6.5 mm, respectively. Each group was divided to two halves. The first half was tested using a load ratio, R($R=K_{min}/K_{max}$, where K_{min} and K_{max} are the minimum and the maximum stress intensity factors, respectively), of 0.15, while the second half was tested using a load ratio of 0.3. Plastic deformation is occurs ahead the razor blade tip during notching [9]. The size of this deformation affects the crack initiation. To have the same size for the plastic deformations ahead the initial notch tip for all initial notch depths, both the notching speed and the length from the initial notch depth that was made using the razor blade were kept constant for all the specimens. In addition, a new razor blade was used for each specimen. The 3 mm notches were made by introducing the razor blade over the whole notch depth. For the 4.5-mm notches, a hand saw notch, a_{hs}, was introduced for a depth of 1.5 mm, then, a razor blade notch, a_{rb}, was introduced for the next 3 mm depth ($a_o=a_{hs}+a_{rb}$). For the 6.5-mm notch, a hand saw notch was introduced for a depth of 3.5 mm, then, a razor blade notch was introduced for the next 3 mm depth as shown in fig.1-b. The specimens were tested using a load control fatigue machine [10], where, the load is controlled using a spring. The initial value of the maximum stress intensity factor, K_{max}, was kept constant at 2 MPa.m$^{1/2}$ for the whole tests, while the minimum stress intensity factor, K_{min}, was changed according to the load ratio. The testing frequency was adjusted at 0.5 HZ. The crack length was measured at the surface of the specimens using an 8 times magnifying lens.

To classify the type of residual stresses in the used pipe, two rings having 2 mm thickness and 10 mm height were made from the pipe. The first ring was made by using a lathe to remove 13 mm from the pipe wall thickness starting from the pipe outer surface.

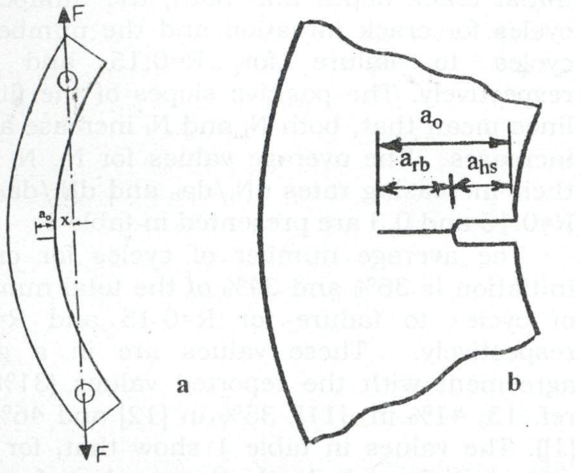

Fig.1. a- Test specimen geometry, b- Magnification for the initial notch zone showing the hand saw notch (a_{hs}) and the razor blade notch (a_{rb}). For a_o = 3 mm, a_{hs} = 0. For a_o = 4.5 mm, a_{hs} = 1.5 mm. For a_o = 6.5 mm, a_{hs} = 3.5 mm.

The inner surface of this ring is the inner surface of the pipe while the outer surface is the machined surface. The second ring is made by removing 13 mm from the pipe wall thickness starting from the pipe inner surface. The outer surface this ring is the outer surface of the pipe while the inner surface was the machined surface. A very low lathe speed and a coolant were used to avoid any overheating for the pipe material. The rings were cut and the movement of the two cutting edges was observed to classify the type of residual stresses.

3. Results and discussions

Fig. 2-a shows the ring that was prepared from the inner surface of the pipe. The cutting edges are separated from each other, which means that the inner surface of the pipe is subjected to tensile residual stresses. Fig. 2-b shows the ring that was prepared from the outer surface of the pipe. The cutting edges are overlapped which means that, the outer surface of the pipe is subjected to compressive residual stresses [2, 3, 6].

In order to increases the results reliability, four specimens were tested for each initial notch depth under the same load ratio. For a similar test specimen geometry, manufactured from the same resin by the same company, the examination of the fractured surfaces of the specimens showed that, the crack at the specimen surface, a_s, is found to be about 0.7 of that at the specimen core, a_c as shown in fig. 3-a. In this work, the examination of the fracture surfaces of the broken specimens for the three different values of the initial notch depth showed the same ratio between the surface crack and the core crack as shown in fig. 3-b. So, the measured crack (surface crack) is corrected to obtain the core crack using the following equation [10]:

$$a_c = 1.91a_s - 0.91a_o + 0.49 \,. \quad (1)$$

Figs. 4, 5 show the relations between the crack length, a, and the corresponding number of fatigue cycles, N, for the two load ratios and the three different values of the initial notch depths. It is obvious that, for the same load ratio, the fatigue life increases as the initial notch depth increases.

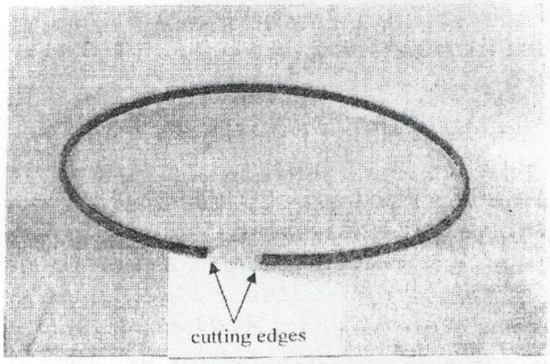

Fig. 2. a- A ring from the inner surface of the pipe.

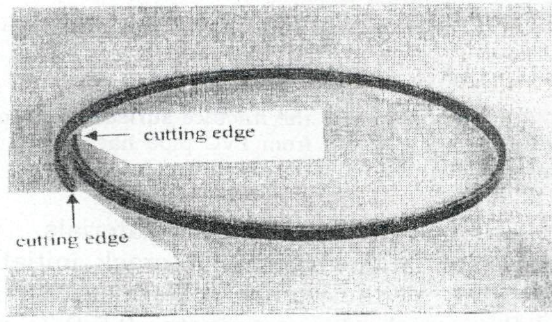

Fig. 2. b- A ring from the outer surface of the pipe.

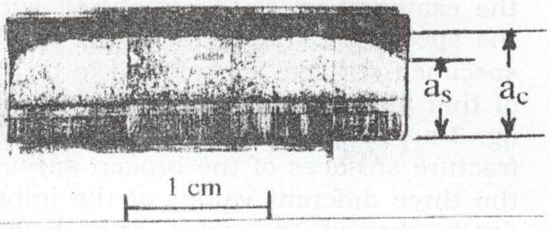

Fig. 3-a. Photograph for the fracture surface of a broken test specimen prepared from PVC pipe having 200 mm outer diameter and 9.6 mm wall thickness [10].

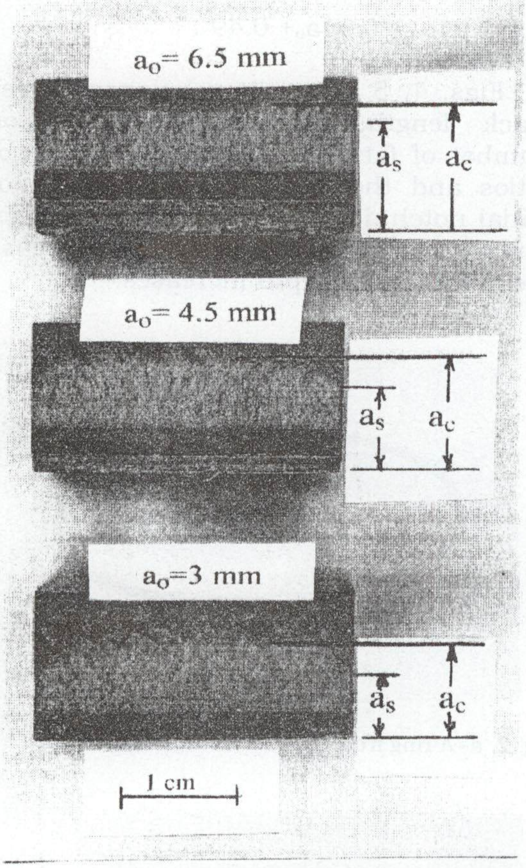

Fig. 3-b. Photograph for the fracture surface of a broken test specimen prepared from PVC pipe having 200 mm outer diameter and 9.6 mm wall thickness [10].

For polyethylene pipe materials, the number of fatigue cycles for crack initiation was taken as the number of cycles required for the crack to propagate 0.5-0.7 mm [1,11,12]. So, in this work, the number of cycles for crack initiation, N_i, is assumed to be the number of cycles required for the crack to extend for 0.5 mm from the initial notch tip. Figs. 6 and 7 show relations between the initial crack depth and both, the number of cycles for crack initiation and the number of cycles to failure for R=0.15 and 0.3 respectively. The positive slopes of the fitting lines mean that, both N_i and N_f increase as a_o increases. The average values for N_i, N_f and their increasing rates dN_i/da_o and dN_f/da_o for R=0.15 and 0.3 are presented in table 1.

The average number of cycles for crack initiation is 36% and 34% of the total number of cycles to failure for R=0.15 and R=0.3 respectively. These values are in a good agreement with the reported values (31% in ref. 13, 41% in [11], 35% in [12] and 46% in [1]). The values in table 1 show that, for the same initial notch depth, the number of cycles for initiation and the number of cycles to failure for R= 0.15 are approximately 30% of that for R=0.3. This means that the number of fatigue cycles increases as the load ratio increases and consequently, the crack speed decreases [12,14,15].

To calculate the crack growth kinetic parameters A and m, the crack speed, da/dN, must be calculated. So, the crack length, a, is fitted against (N_f-N) in the form [14]:

$$a = C_1 + C_2 \ln (N_f - N). \quad (2)$$

Where, C_1 and C_2 are fitting constants.

The crack speed, da/dN, can be calculated by differentiating eq. 2 with respect to the number of cycles N. A relation between the crack length and N_f-N is shown in fig. 8. The presented fitting curves represent one sample for each initial notch depth at load ratios of 0.15 and 0.3. Fig. 9 shows a relation between the initial notch depth and the fitting constants C_1 and C_2. It is obvious that, C_1 increases with increasing both, the initial notch depth and the load ratio (i.e. C1 increases with increasing the fatigue life), while C_2 can be considered constant regardless the initial notch depth and the load ratio.

In thermoplastic glassy polymers, cracks are initiated and propagated by the crazing mechanism. The plastic deformation takes place ahead the crack tip. The accumulation

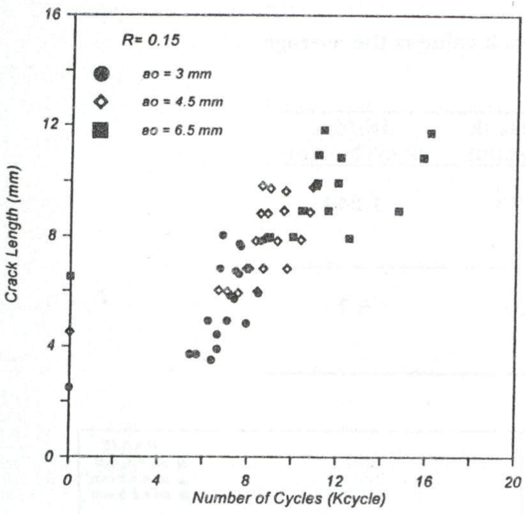

Fig. 4. Relation between the crack length and the number of cycles for a load ratio of 0.15 and three different values for the initial notch depth.

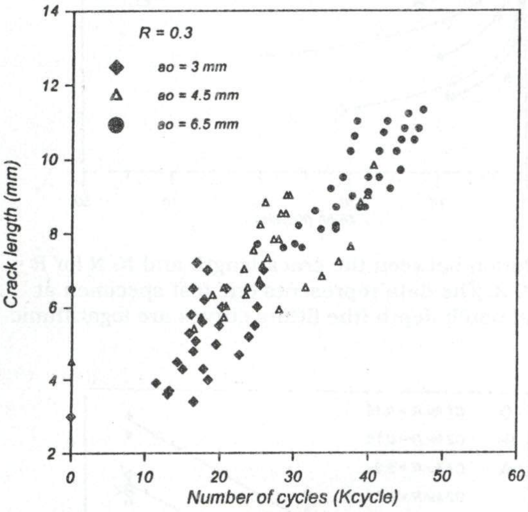

Fig. 5. Relation between the crack length and the number of cycles for a load ratio of 0.3 and three different values for the initial notch depth.

of this plastic deformation form a craze (plastic zone), then, the crack growth by means of the breakdown of the fibrillar structure of this craze [16, 17]. This means that, as the plastic zone size increases, the crack speed increases causing a decreasing in the fatigue life and vice versa. The plastic zone size was found to be proportional to the square of the maximum applied stress intensity factor, K_{max}^2 [10,18,19,20]. So, the crack speed can be expressed as a function of K_{max} as [15]:

$$\frac{da}{dN} = A(K_{max})^m , \qquad (3)$$

where, A and m are crack growth kinetic parameters and they are constants for the same testing conditions. K_{max} is given by [8,21]:

$$K_{max} = \frac{F_{max}}{Bt^{1/2}}\left[\frac{3x}{t} + 1.9 + 1.1\frac{a}{t}\right] \left[1 + 0.25\left(1-\frac{a}{t}\right)^2\left(1-\frac{r_1}{r_2}\right)\right] f\left(\frac{a}{t}\right). \qquad (4)$$

Where F_{max} is the maximum applied force and

$$f\left(\frac{a}{t}\right) = \left[\frac{\left(\frac{a}{t}\right)^{1/2}}{\left(1-\frac{a}{t}\right)^{3/2}}\right] \left[3.74 - 6.3\left(\frac{a}{t}\right) + 6.32\left(\frac{a}{t}\right)^2 - 2.43\left(\frac{a}{t}\right)^3\right].$$

Figs. 10 and 11 show a log-log relations between K_{max} and the crack speed for R= 0.15 and 0.3, respectively. To obtain average values of the parameters A and m for each initial notch depth, one fitting line will be used to fit the data of four test specimens having the same initial notch depth.

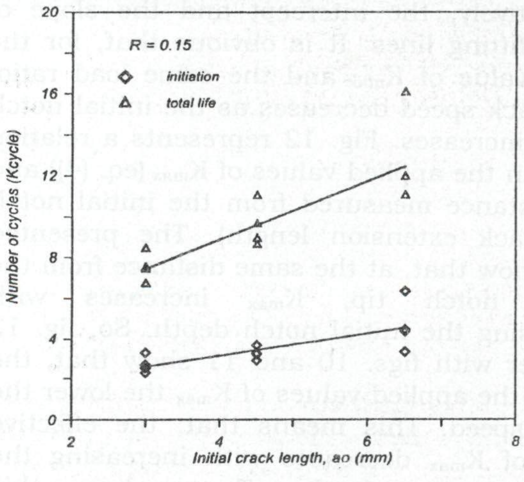

Fig. 6. Relation between the initial notch depth and both, the number of cycles for crack initiation and the number of cycles to failure, for R = 0.15.

Table 1
The average values for the data of figs. 7 and 8 (each value is the average of four values)

R	a_o (mm)	N_I (k cycle)	N_f (k cycle)	dN_i/da_o (k cycle/mm)	dN_f/da_o (k cycle/mm)
0.15	3	2.7	7.5	0.473	1.244
	4.5	3.26	9.53		
	6.5	4.6	12.48		
0.3	3	6.8	20.5	2.03	5.7
	4.5	10.4	31.2		
	6.5	15	43.2		

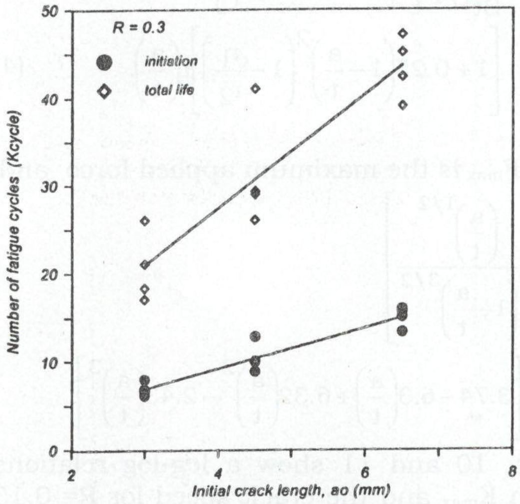

Fig. 7. Relation between the initial notch depth and both, the number of cycles for crack initiation and the number of cycles to failure, for R = 0.3.

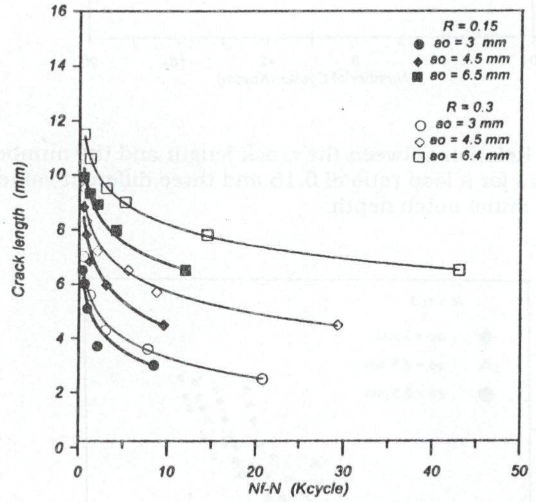

Fig. 8. Relation between the crack length and N_f-N for R = 0.15 and 0.3. The data represents one test specimen at each initial notch depth (the fitting curves are logarithmic fittings).

The parameters A and m of eq. (3) are, respectively, the intercept and the slope of these fitting lines. It is obvious that, for the same value of K_{max} and the same load ratio, the crack speed decreases as the initial notch depth increases. Fig. 12 represents a relation between the applied values of K_{max} (eq. (4)) and the distance measured from the initial notch tip (crack extension length). The presented data show that, at the same distance from the initial notch tip, K_{max} increases with increasing the initial notch depth. So, fig. 12 together with figs. 10 and 11 show that, the higher the applied values of K_{max} the lower the crack speed. This means that, the effective value of K_{max} decreases with increasing the initial notch depth, To explain this phenomenon consider the effective value of the stress intensity factor in the form [22]:

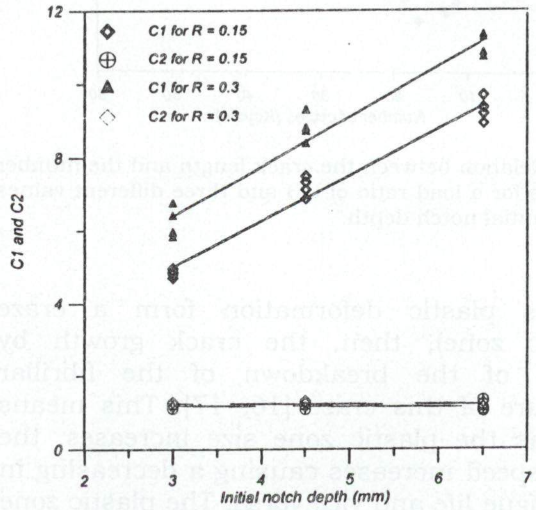

Fig. 9. Relations between the initial notch depth and fitting constants of eq. (2), C1 and C2.

4- The crack growth kinetic parameters A and m decrease as the initial notch depth increases.
5- The values of the crack growth kinetic parameters can be used successfully to predict the number of cycles for crack initiation and the total number of cycles to failure.
6- The errors between the experimental number of cycles and the calculated one are very reasonable.

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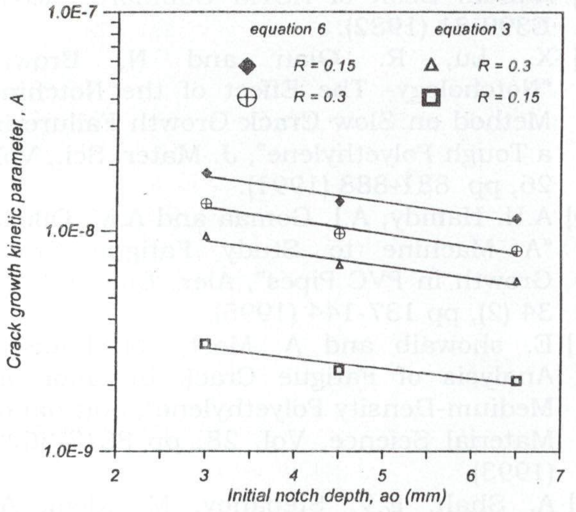

Fig. 15. Relationship between the initial notch depth and the crack growth kinetic parameter A.

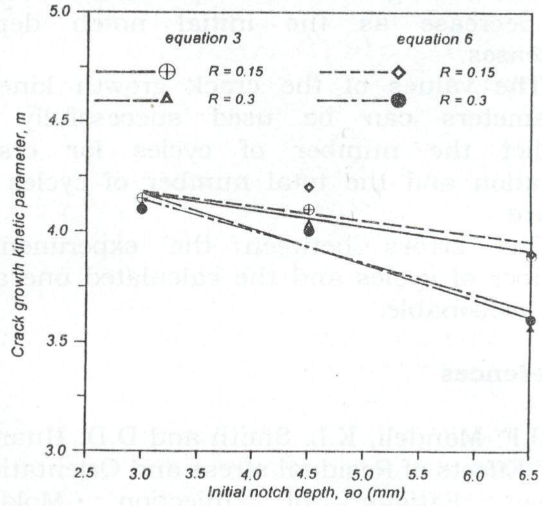

Fig. 16. Relationship between the initial notch depth and the crack growth kinetic parameter m.

Table 2
Average absolute error between the experimental and calculated number of cycles for initiation and the total number of cycles to failure

Method of calculation of the number of cycles for initiation , Ni, and the number of cycles to failure, N_f	Average absolute errors %			
	R= 0.15		R=0.3	
	N_i	N_f	N_i	N_f
Eqs.(7 , 8) using kinetic parameters A and m which were obtained from figs. 10 and 11	6.07	5.53	4.8	5.8
Eq. (7, 8) using kinetic parameters, A and m, calculated from the equations of the fitting lines in figs. 15 and 16	5.19	5.07	3.43	4.9
Eqs. (9, 10) using kinetic parameters, A and m, from figs. 13 and 14	7.66	3.23	3.85	3.57
Eqs. (9 , 10) using the kinetic parameters, A and m, calculated from the equations of the fitting lines in figs. 15 and 16	7.26	4	3.08	3.45

Eqs. (7, 8, 9 and 10) are used to calculate N_i and N_f. The number of cycles which is obtained by integration, $N_{integ.}$, is compared with the average values of the experimental number of cycles, N_{exp}.(data in table 1) to calculate the percentage error due to the fitting equations especially eq. (2). Table 2 presents the percentage error for the three different values of initial notch depth and the two load ratios.

$$\text{Error\%} = \frac{N_{exp} - N_{integ}}{N_{exp}} * 100 . \qquad (11)$$

The excepted absolute error from eq. (4) is 3% [8]. A comparison between these values and the values in table 2 show that the errors due to the use of the fitting equations especially eq. (2) are very reasonable.

4. Conclusions

From the obtained results it can be concluded that:

1- PVC pipes have tensile residual stresses at their inner surfaces and compressive residual stresses at their outer surfaces, i.e., different values for the initial notch depth mean different values for the residual stress at the crack tip.

2- The number of cycles for crack initiation increases as the initial notch depth increases.

3- The total number of cycles to failure increases as the initial notch depth increases.

and 14 are log-log relations between ΔK and the crack speed, da/dN, for R=0.15 and 0.3, respectively. Each line fits the data of four test specimens having the same initial notch depth. The parameters A and m of eq. (6) are the slope and the intercept of these fitting lines, respectively. The presented data in the two figures show that for the same value of ΔK, the crack speed decreases as the initial notch depth increases. Fig. 15 represents a relation between the initial crack depth and the values of the crack growth kinetic parameter A that obtained from figs. 10, 11, 13 and 14. The negative slope of the fitting lines means that, for the two load ratios and the two eqs. (3) and (6), the parameter A decreases with increasing the initial notch depth. The values of the parameter A which obtained based on eq. (3) decreases with a rates of $8.65x10^{-10}$/mm and $2.475x10^{-10}$/mm for R= 0.15 and 0.3, respectively. While these rates based on eq. (6) are $1.725x10^{-9}$/mm and $1.295x10^{-9}$/mm for R= 0.15 and 0.3 respectively. Fig. 16 shows a relation between the initial notch depth and the values of the crack growth kinetic parameter m that obtained from figs. 10, 11, 13 and 14. The negative slopes of the fitting lines mean that, m decrease with increasing the values of the initial notch depth. For the same load ratio, the fitting line of the values, which obtained based on eq. (3), is very close to that obtained based on eq. (6). For R = 0.15, the rates of decreasing of m are 0.065/mm and 0.05/mm based on eqs. 3 and 6, respectively. For R=0.3 these rates are 0.135/mm and 0.125/mm based on eqs. (3) and (6), respectively.

To calculate the accumulative error due to using of the fitting equations to analyze the crack growth in PVC pipes, the values of A and m will be used to integrate eqs. (3) and (6) to calculate the values of N_i and N_f. The integration form of eq. (3) will be as follow:

$$N_i = \int_{a_o}^{a_o+0.5} \frac{da}{A(K_{max})^m} \text{ and} \tag{7}$$

$$N_f = \int_{a_o}^{t} \frac{da}{A(K_{max})^m} . \tag{8}$$

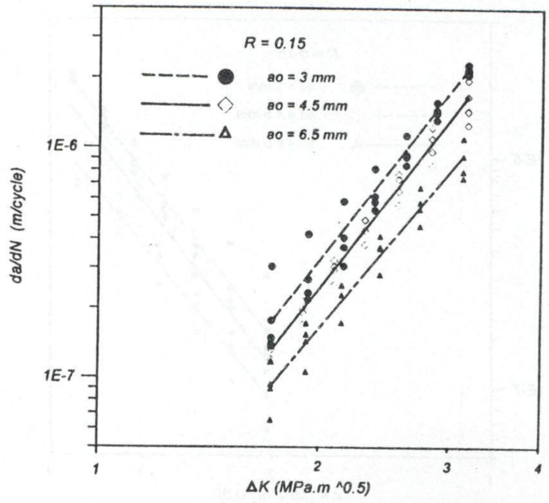

Fig. 13. Relation between l the crack speed and the stress intensity factor range for a load ratio of 0.15 and the three different values for the initial notch depth.

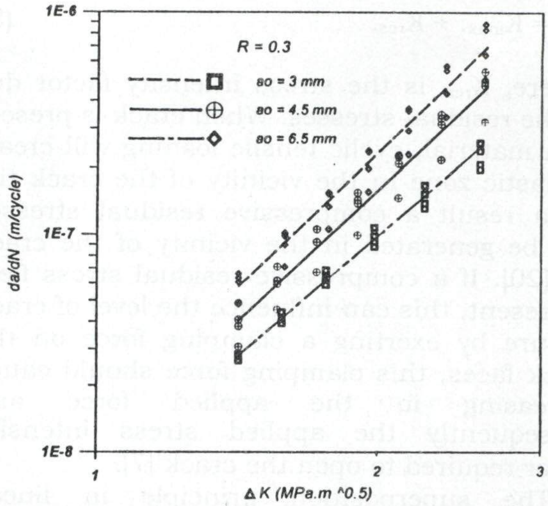

Fig. 14. Relation between l the crack speed and the stress intensity factor range for a load ratio of 0.15 and the three different values for the initial notch depth.

The integration form of eq. (6) will be as follow:

$$N_i = \int_{a_o}^{a_o+0.5} \frac{da}{A(\Delta K)^m} \text{ and} \tag{9}$$

$$N_f = \int_{a_o}^{t} \frac{da}{A(\Delta K)^m} . \tag{10}$$

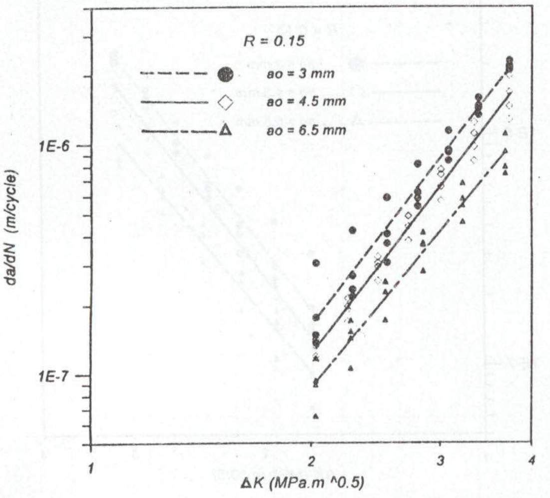

Fig. 10. Relation between the crack speed and the maximum stress intensity factor for a load ratio of 0.15 and the three different values for the initial notch depth.

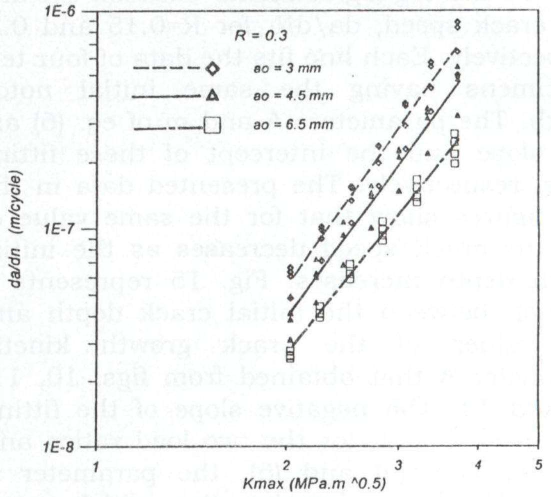

Fig. 11. Relation between the crack speed and the maximum stress intensity factor for a load ratio of 0.3 and the three different values for the initial notch depth.

$$K_{eff} = K_{max.} + K_{res.} \quad (5)$$

Where, $K_{res.}$ is the stress intensity factor due to the residual stresses. When crack is present in a material, cyclic tensile loading will create a plastic zone in the vicinity of the crack tip. As a result a compressive residual stresses will be generated in the vicinity of the crack tip [20]. If a compressive residual stress field is present, this can influence the level of crack closure by exerting a clamping force on the crack faces, this clamping force should cause increasing in the applied force and consequently the applied stress intensity factor required to open the crack [7].

The superposition principle in linear elastic fracture mechanics demonstrates that, the stress intensity factor is affected by the residual stress fields in the material [20]. So, the superposition of compressive residual stresses due to the plastic deformation ahead the crack and the compressive residual stresses due to the manufacturing process will increase the value of the compressive residual stresses at the crack tip. Then, the negative values of K_{res} will increase. Since, the applied value for K_{max} is constant, The result from eq. (5) will be a reduction in K_{eff} and consequently a reduction in the crack speed where, the crack speed is often the best indicator of the effect of residual stress field [7].

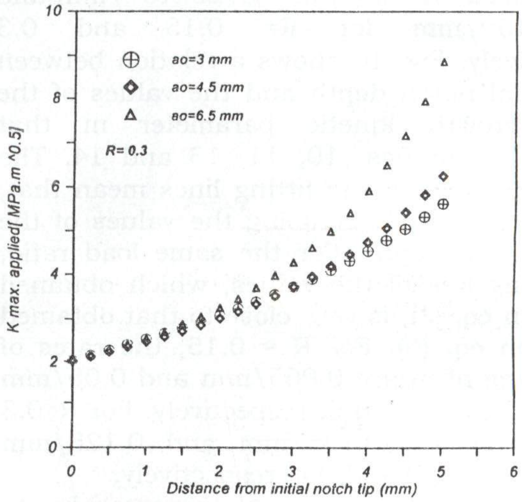

Fig. 12. Relation between the crack speed and the stress intensity factor in eq. (3) and the distance measured from the initial notch tip.

The crack speed can be also expressed in terms of the stress intensity factor range, ΔK, this relation is given by Paris [23] as:

$$\frac{da}{dN} = A(\Delta K)^m . \quad (6)$$

The crack growth kinetic parameters A and m have different values than that of eq. (3). The values of ΔK can be obtained from eq. (4) by replacing F_{max} by ΔF ($\Delta F = F_{max} - F_{min}$). Figs. 13

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