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Prediction of cannon barrel life

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Analysis and modelling

ABSTRACT

Purpose: Calculation of the fatigue life based on attaining a critical defect size for fast fracture is very important. Cannon is one of the most used parts in military industries and analysis of this component is under consideration. Therefore, the prediction of its longevity to say, the number of cannon ball that can be fired till it is broken down should be under consideration.

Design/methodology/approach: Obviously the number of the cracks and their sizes dictate the life of the cannon's barrel. Since the life of this component directly depends on the inner micro-cracks after numerous firing, the study of these cracks is very important. From this point of view, the stress analysis on crack tip is carried out via ANSYS software in this research. This research was to demonstrate the large changes in total fatigue life caused by the initial crack number and the residual stress at the cannon bore, the fatigue with several cracks is analyzed in the barrel according to the critical explosion pressure.The research is carried out with one, two, three, four and twenty five cracks.

Findings: The methods of testing and analysis are believed to be generally applicable to problems in fatigue life evaluation This analysis shows that the stress intensity on the tip of the crack is a function of its length and increases with the number of these cracks. Since the cannon barrel life is a convert function of the stress intensity of the cracks, multi-cracks condition passes the most fatigue cycling. The shape function of the cracks is also decreased with the number of the cracks.

Originality/value: Characterization of the cracking at a cannon bore is a difficult problem.This analysis shows that the critical cycle life of the cannon barrel occurs at two numbers of the cracks.

Keywords: Fatigue; Monte Carlo; Crack; Life; Cannon

1. Introduction

The history of cannon pipes refers to the thick-walled pipes. The first cannon pipe is built in 14 century. According to the improvement in material properties adopting a policy to prevent the inner surface of these pipes against erosion is under consideration. Cracking phenomena often lead to a few-times decrease in its strength and are peculiarly dangerous in especially brittle material [1]. Even though much achievement has been made in crack modelling techniques, both simple and practical crack modelling technique is still needed, in particular for complex multiple crack growth problems [2]. The prediction and estimation of failure behaviour of elastic-perfectly plastic material containing a crack loaded by two pairs of point tensile forces are of great interest to researchers and engineers in many science and engineering disciplines [3]. The stochastic nature of fatigue-related parameters was correlated to die life and Monte Carlo simulation was used to predict the life distribution of a die under given manufacturing conditions and mechanical properties [4]. For an impermeable interface crack in general anisotropic piezoelectric bimaterials, Suo et al. obtained the crack-tip generalized stress field by solving an eigenvalue problem with four non-ero eigenvalues and four associated linearly independent eigenvectors [5]. The crack geometries provide the original interest in predicting the mixed-mode solutions to the multiple perpendicular crack problems [6]. Numerical methods are widely employed in order to attain the best possible results in engineering problems [7]. Among several elastic two-dimensional modelling strategies by the boundary element method, there exist the multi-domain formulation the stress formulation with regularization and the dual boundary element method [8]. Particularly flows or cracks lying along the interface reduce the strength of the structure significantly[9]. Presence of non-linear fault like a crack brings non-linearity in the originally linear system equations [10]. During the low-cycle tests, the material may be damaged in the conditions of elastic-plastic strain [11]. Even very small differences in internal stresses between the layers close to the strip surface can result in its folding, twisting or similar defects [12]. Monte Carlo method is a suitable and precise fatigue analysis method in cannon barrel. The problem illustrates the case of multi cracks in a cannon barrel, together with the relevant geometry correction factor in the form of stress intensity factor range against crack length defined from the bore of the cannon. This crack geometry is the most dangerous integrity case for the cannon barrel [13]. The stress intensity calibration includes both hoop stress and internal pressure contributions. The barrel of this cannon has an inner radius of 85 mm and an outer radius of 160 mm, and it operates at a firing pressure of 380 MPa. It is made from a 4340 grade steel with a yield strength of 1.131 GPa, a tensile strength of 1.232 GPa and a plane strain fracture toughness value of 125.8 MPa $m^{½}$. In this research 155 mm cannon barrel with one, two, three, four and twenty five cracks on inner surface is fatigue analyzed. The cross section of the cannon pipe is shown in Figure 1.

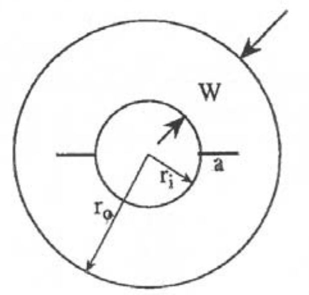


Fig. 1. Cross section of a cannon pipe

Analysis in carried out with ANSYS and ADINA software[14].

2. General conditions

2.1. Characteristics of the cannon barrel cross section

The break down phenomenon usually takes place in the cannon pipes where the explosion pressure is maximum. The characteristics of the critical section is as follows:

- Inner diameter: r_i =85 mm
- Outer diameter: r_o =160 mm
- Thickness : w = r_o - r_i =75 mm

2.2. Mechanical properties of cannon Barrel's material

The material of cannon pipe is 4340 Steel. Its properties is shown in Table 1.

Table 1.
Some useful properties of cannon pipe

Material	E (GPa)	S_y (GPa)	S_{uts} (GPa)	K_{IC} (MPa.m½)
4340 Steel	206.2	1.131	1.232	125.8

2.3. Boundary conditions

The form of the model for any number of the cracks should be symmetric so that, its boundaries could move just in the radial direction and in any other situation; the ramp on boundaries should be zero.

2.4. Loading and the kind of elements

Applied loads on the elements are equal to the maximum explosion pressure which is inserted on the inner surface of the barrel and radial direction on the crack positions. Each element is introduced with a shape function that can be linear.

In finite element analysis of a model there are a lot of equations, sometimes more than twenty thousands that should be simultaneously solved. The number of these equations directly depends on the number of nodes and elements in the model [15, 16]. From this point of view, the less possibly numbers of the elements should be under attention. The kind of element which is used in this research is triangle planed elements.

2.5. C and n parameters determination

Two C and n parameters which are related to the Steel material used in thick-walled pressure vessels and cannon barrels manufacturing, have a specific amount for each steel grade. It is usually determined experimentally. The amount of these parameters for 4340 Steel are[12]; $C = 76\times10^{-12}$, n= 2.29

2.6. Stress intensity factor calculation

Stress intensity factor is a function of the length of the crack and it is increased with this length [17]. This parameter is also a function of geometrical shape of the crack and model. For this thick-walled pressure vessel not Autofrettaged, the variation of stress density is as follows:

$$\Delta K = K_{max} - K_{min} = \bar{K}(P_{max} - P_{min})\sqrt{\pi\times a}$$
$$\Delta K = \bar{K}P_{max}\sqrt{\pi\times a} \qquad (1)$$

Where P_{max} is maximum explosion pressure and P_{min} which is usually zero is its minimum value and a is the length of the crack. K is a coefficient related to the geometrical shape of the crack and sample. This coefficient can be considered as constant value since its variations is very small. To calculate the stress density variations as a function of the crack length, various finite element methods are used. Modelling and its analysis is carried out via ADINA and ANSYS software (See Table 2).

Table 2.
Comparison between stress density factors

a(mm)	0.1	0.3	0.5	0.7	1.1	1.5	1.9
ADINA K_I ($MPa\sqrt{m}$)	20.9	36.21	46.52	54.92	68.56	79.82	89.56
ANSYS K_I ($MPa\sqrt{m}$)	21.32	38.12	47.12	55.18	70.12	81.52	91.56

So that, the cross section is modelled due to one, two, three, four and twenty five cracks and according to the length of various cracks, stress intensity is calculated.

2.7. Fatigue life calculation

The fracture toughness is obtained experimentally; then, the critical length of the crack can be calculated from the following equation:

$$K_{IC} = \bar{K} P_{max} \sqrt{\pi \times a_{cr}} \tag{2}$$

Where K_{IC}, $\bar{K}$ and a_{cr} are fracture toughness, average coefficient in un-cracked manner and the length of critical crack respectively. The amount of fracture toughness for 4340 Steel is shown in Table 1. By integration of Paris Formula [18]:

$$N_f = \int_{a_0}^{acr} C^{-1} [\Delta K = f(a)]^{-n} \, da \tag{3}$$

Where N_f is cycle life and a_0 is the length of initial crack. In this case the main problem is the length of initial crack which should experimentally be obtained. A crack with special length (for example a_0 = 0.2 mm) is created on the surface of the sample which is prepared for testing. This sample will be analyzed when the crack reaches to its critical length (a_{cr}). According to the equation (2) the critical length of the crack is a function of fracture toughness and the material of the cannon barrel. So that, the length of the crack is less that its critical length in any conditions otherwise, the cannon barrel will be failured. The value of stress intensity factor usually is calculated via modelling first. Then the length limitation of the cracks are determined with the determination of the critical length of the cracks. In this case, the cracks with less than critical length will be modelled and the value of the stress intensity will be calculated. Figure 2 shows a standard sample which is used to calculate the fracture toughness experimentally [19].

Modelling section depends on the number of cracks. For instance, in one crack case the modelled section is the half of pipe's cross section and in 25 cracks case, it is a portion of pipe's cross section with centre angle of 7.2 degree. The cross sections modelled in 2 and 25 crack cases is shown in Figure 3.

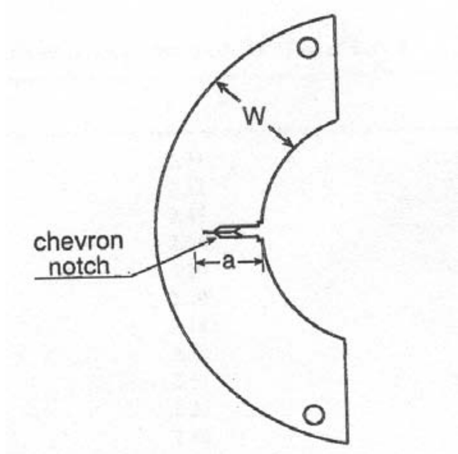
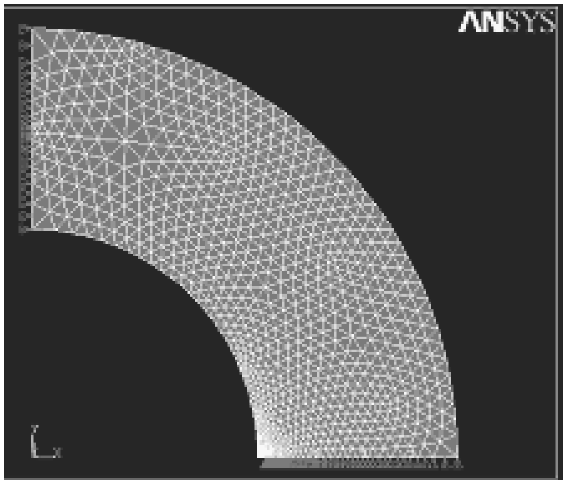


Fig. 2. A standard sample for fracture toughness determination

a)



b)

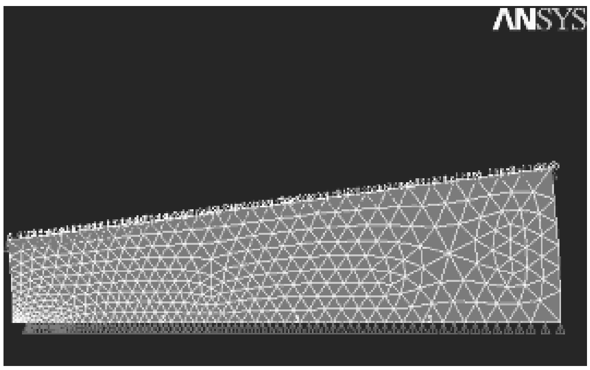


Fig. 3. Schematic cross-section modelled with (a)-two cracks and (b)- Twenty five cracks

It is noticeable that in general case when the number of cracks are n, then the modelled section is a portion of circle with b=180/n central angle.

3. Fatigue analysis

Paris Formula is used in fatigue analysis so that, the relation between stress density and the length of the crack is determined via EXEL and then this is replaced in Paris Formula and afterwards, fatigue equation is obtained via integration. This analysis is carried out according to the following conditions:

- Maximum explosion pressure(P_{max}): 380 Mpa
- Minimum explosion pressure(P_{min}): 0
- Initial length of crack(a_0): 0.2 mm
- Fracture toughness(K_{IC}): 125.8 MPa.m^{½}

4. Results

Before fire, the ball passes a distance inside the cannon's barrel as thick-walled cylindrical vessel so that, the explosion pressure behind it reaches to its maximum amount. In this passing distance, there is a critical section which is fatigue analyzed here. Tables 3, 4, 5, 6, 7 show stress intensity factor values in one, two, three, four and twenty five crack conditions respectively.

Table 3.
Stress intensity values with one cracks

Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)	Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)
0.25	3.113	33.151	2.75	3.094	109.281
0.5	3.111	46.853	3	3.092	114.066
0.75	3.109	57.346	3.25	3.089	118.609
1	3.107	66.175	3.5	3.088	123.046
1.25	3.106	73.963	3.75	3.086	127.282
1.5	3.104	80.970	4	3.085	131.414
1.75	3.102	87.401	4.25	3.084	135.415
2	3.101	93.406	4.5	3.082	139.225
2.25	3.099	99.008	4.75	3.080	142.973
2.5	3.096	104.262	5	3.079	146.670

Table 4.
Stress intensity values with two cracks

Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)	Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)
0.25	3.139	33.428	2.75	3.119	110.164
0.5	3.137	47.245	3	3.117	114.988
0.75	3.134	57.808	3.25	3.114	119.569
1	3.133	66.729	3.5	3.111	123.963
1.25	3.131	74.558	3.75	3.109	128.231
1.5	3.129	81.622	4	3.107	132.351
1.75	3.126	88.077	4.25	3.105	136.337
2	3.124	94.098	4.5	3.103	140.199
2.25	3.127	99.902	4.75	3.101	143.948
2.5	3.122	105.138	5	3.099	147.593

Table 5.
Stress intensity values with three cracks

Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)	Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)
0.25	2.909	30.979	2.75	2.855	100.839
0.5	2.900	43.685	3	2.851	105.175
0.75	2.891	53.325	3.25	2.848	109.355
1	2.886	61.468	3.5	2.843	113.284
1.25	2.881	68.605	3.75	2.841	117.177
1.5	2.876	75.022	4	2.835	120.765
1.75	2.871	80.892	4.25	2.831	124.306
2	2.867	86.357	4.5	2.825	127.638
2.25	2.864	91.250	4.75	2.819	130.858
2.5	2.861	96.348	5	2.816	134.131

Table 6.
Stress intensity values with four cracks

Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)	Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)
0.25	2.859	30.446	2.75	2.817	99.497
0.5	2.858	43.043	3	2.814	103.810
0.75	2.853	52.624	3.25	2.812	107.973
1	2.849	60.680	3.5	2.809	111.929
1.25	2.847	67.795	3.75	2.806	115.734
1.5	2.844	74.188	4	2.801	119.316
1.75	2.843	80.104	4.25	2.799	122.901
2	2.839	85.514	4.5	2.795	126.283
2.25	2.823	90.190	4.75	2.791	129.558
2.5	2.819	94.934	5	2.788	132.811

Table 7.
Stress intensity values with twenty five cracks

Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)	Length of cr.(mm)	K	K_I ($MPa\sqrt{m}$)
0.25	2.345	24.973	2.75	2.317	81.837
0.5	2.342	35.272	3	2.314	85.365
0.75	2.341	43.180	3.25	2.309	88.659
1	2.339	49.818	3.5	2.307	91.926
1.25	2.334	55.579	3.75	2.304	95.029
1.5	2.331	60.806	4	2.299	97.932
1.75	2.329	65.621	4.25	2.295	100.771
2	2.325	70.031	4.5	2.292	103.556
2.25	2.323	74.216	4.75	2.288	106.209
2.5	2.319	78.096	5	2.283	108.740

Stress intensity increases with the length of cracks (Figures 4-8).

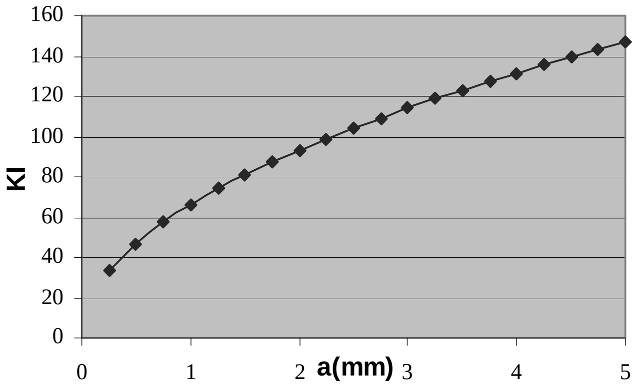


Fig. 4. Stress density variations with the length of the crack in one crack condition

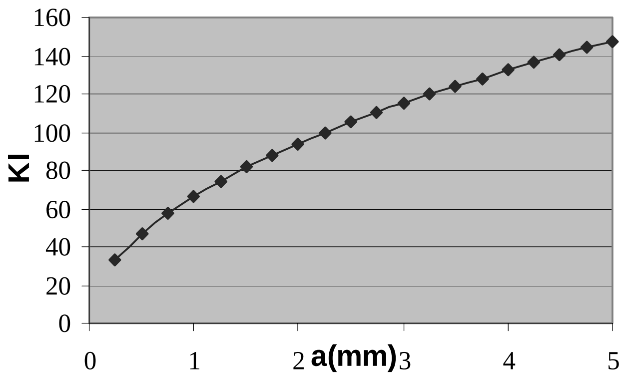


Fig. 5. Stress density variations with the length of the crack in two cracks condition

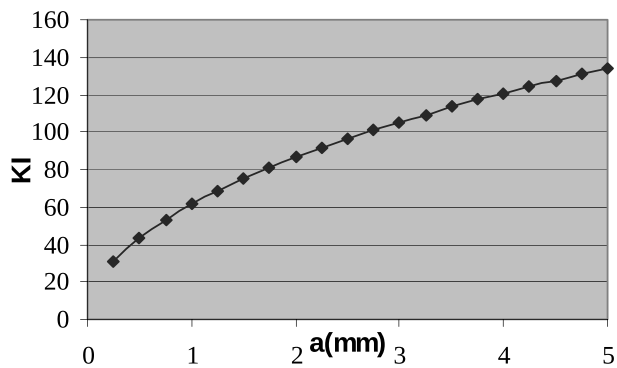


Fig. 6. Stress density variations with the length of the crack in three cracks condition

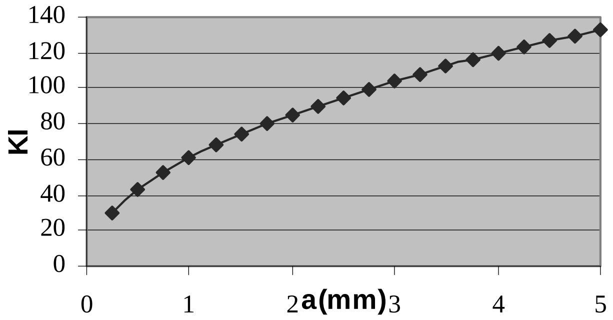


Fig. 7. Stress density variations with the length of the crack in four cracks condition

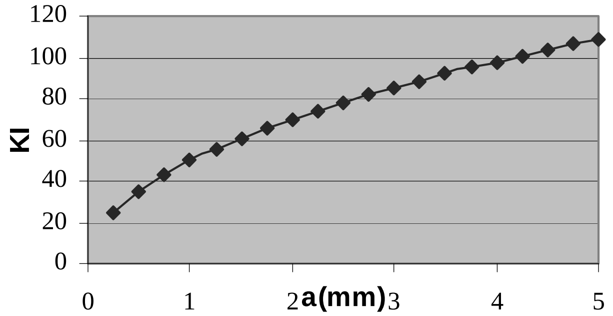


Fig. 8. Stress density variations with the length of the crack in twenty five cracks condition

Figure 9 shows the comparison between the stress density variations with the length of the cracks in various conditions.

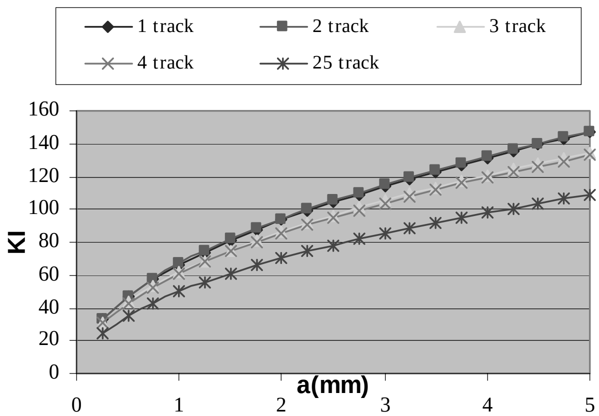


Fig. 9. Stress density variations with the length of the cracks in several conditions

Figures 10-14 show the variations of dimensionless coefficient K with the length of the cracks.

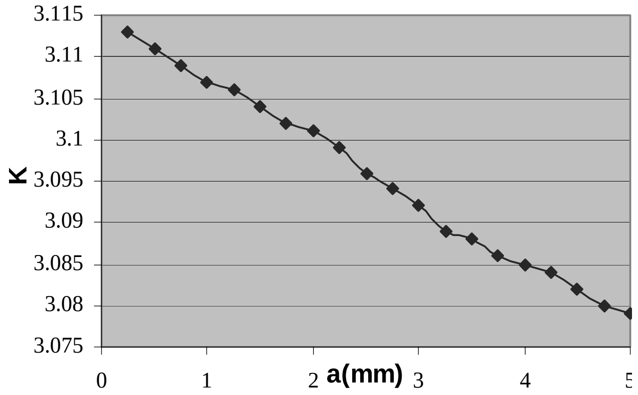


Fig. 10. Variations of K coefficiant with the length of cracks at critical section and one crack

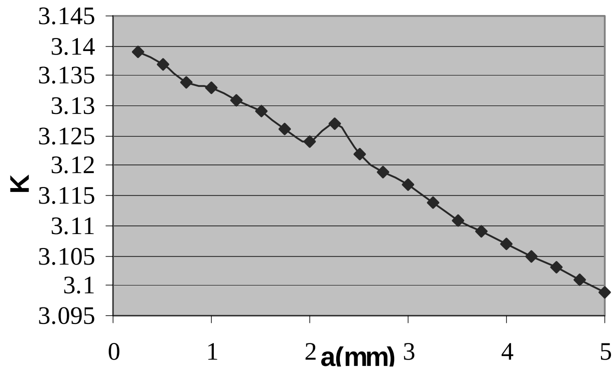


Fig. 11. Variations of K coefficiant with the length of cracks at critical section and two cracks

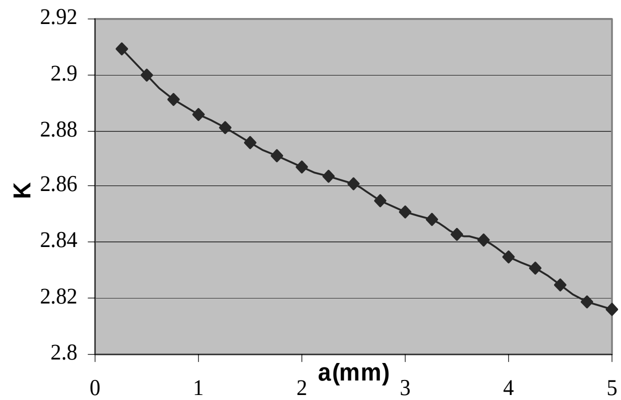


Fig. 12. Variations of K coefficiant with the length of cracks at critical section and three cracks

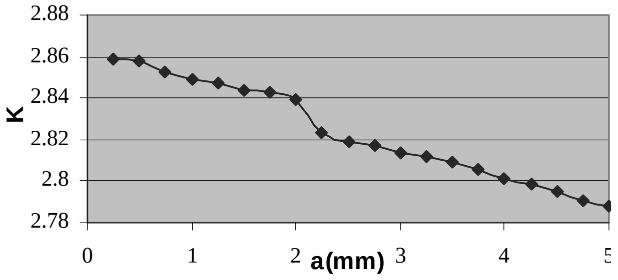


Fig. 13. Variations of K coefficiant with the length of cracks at critical section and four cracks

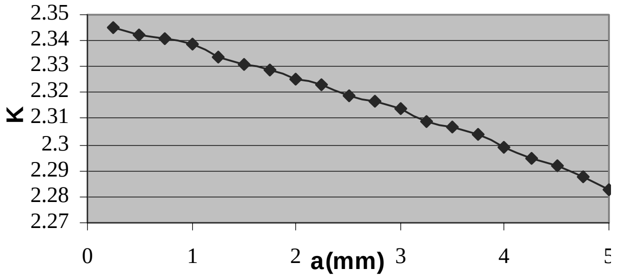


Fig. 14. Variations of K coefficiant with the length of cracks at critical section and twenty five cracks

According to the fatigue values, these parameters are variable and their amounts decrease with the length of the cracks. But these variations are very small, so that, they can be assumed to be constant. The average of these amounts is used in calculations.

Figure 15 shows the comparison between K coefficient variations with the length of the cracks in various conditions.

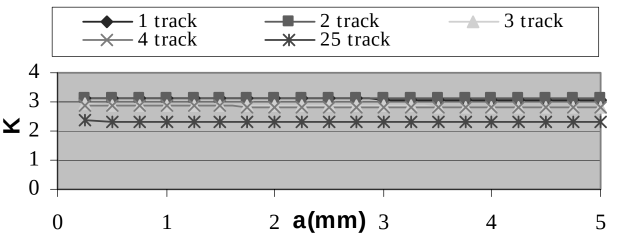


Fig. 15. K coefficient variations with the length of the cracks in several conditions

5. Conclusions

- Cannon's life is related to the explosion pressure, geometrical shape of the model, fracture toughness and the material of the cannon barrel.
- Stress intensity on the inner surface of the cannon barrel is a function of the initial crack numbers. At the less number of the cracks, the amount of the stress intensity is also less and according to the Paris Formula, the cannon's life will be much more too. The physically expression of this mater is that, the growing of the cracks directly depends on the stress intensity on the crack tip and if the amount of this stress is small, then, the crack will reach to its critical condition late.
- Dimensionless coefficient K is a function of the geometrical shape of the model and the crack. The amount of this coefficient decreases with the number of the cracks.
- When the number of the cracks is more than two then, the interaction between the cracks causes the improvement of the cannon's barrel life. Therefore, the critical condition is when the number of the cracks is two.

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