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Crack Growth Behavior through Wall Pipes under Impact Load and Hygrothremal Environment

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Abstract

This research concerns study the crack growth in the wall of pipes made of low carbon steel under the impact load and using the effect of hygrothermal (rate of moisture 50% and 50°C temperature). The environmental conditions were controlled using high accuracy digital control with sensors. The pipe have a crack already. The test was performed and on two type of specimens, one have length of 100cm and other have length 50cm. The results were, when the humidity was applied to the pipe, the crack would enhance to growth (i.e. the number of cycles needed to growth the crack will reduce). In addition, when the temperature was increase the number of cycles needed to growth the crack are reduced because the effect of heat on the mechanical properties of the material. In addition, when the test performed on the specimens of length 50cm the number of cycles needed to growth the crack is increase because the effect of bending stress on the pipes.

Keywords: *Cracks, crack initiation, crack growth, hygyothermal, pipes failure.*

1. Introduction

Cracks define as a discontinuity or break which occur in solid (rigid) body and it branded by having an initiation point and by growing from this point to finite size with time. Either leading or not to the separation the original body in two or more parts. Crack growth depended on the loading conditions and environmental conditions. Loading conditions presents the type of load such as static load, dynamic load, load controlled, grip controlled. While Environmental conditions like temperature and corrosive atmosphere influence crack growth. [1]

There are three types of cracks in pipe happen due to several causes associated with their types; first the form of a crack, second its dimension and its function. [2]

1. Longitudinal cracks
2. Lateral cracks
3. Cracks origination at a point

2. The Behavior of Cracks

The behavior of fatigue cracks differs from that of long cracks because of larger sensitivity to the microstructure. A greater size of the plastic zone fit to the crack length, and a minimum fit to crack finish. Advanced have been made in the understanding of the fatigue crack growth process of cracks, and this understanding has been employed in the advance of analytical treatments of short fatigue crack growth. The study of fatigue crack growth behavior is one of the more active areas of research in the field of fatigue. Such cracks are interest not only because their growth can inhabit an important portion of the fatigue life time but also because they can grow at amount much higher or lower than might be expected on the basis on long crack behavior. There are four kinds of cracks fatigue [3]

1. Mechanically cracks (the crack length is less than plastic zone size)

2. Micro structurally (the crack length is less than a critical microstructural)
3. Physically (the crack length is less than at which crack closure if fully developed usually less than 1 mm in length)
4. Chemically (the crack length may be up to 10 mm)

3. Governing Differential Equations

Paris proposed the following equation for the correct crack propagation law

$$\frac{da}{dN} = C(\Delta k)^m \quad \ldots (1)$$

Where C and m are constant and they depended on the material that be used.

This equation seemed to have good correlation with the test data. However, if comparisons are made with the large range of data, such as a higher load ratios and crack growth rates, the correlations is not good. In fact, equation (1) does not seem to be complete. Two effect occur which are not taken into account. One of this variation in the crack growth rate owing to the load ratio, R. the other is the instability of the crack growth when the value of the maximum stress intensity factor approaches to the fracture toughness of the material, K_c, [4]

4. Criteria of Crack Growth

Theoretical and experimental work contains different criteria like crack position, shape of crack, length of crack and crack angle. Moreover, approximation for the study of the crack growing path. Several of this study are created on the stress analysis of the crack tip region. Erdogan and Sih first examined the angled crack. They suggested the MTS criteria basing the stress domain present just before the start of break for guess of the orientation of the initial crack growth. Conferring to the MTS criteria the crack extend in the radial way agreeing to the tangential stress and the crack growth occur then this maximum arrive a ticklish value. Erdogan and Sih's study was created on the presentation of the crack tip stress region in expressions of stress function resulting by Williams [5].

$$\emptyset = r^{3/2} f_1(\theta) + r^2 f_2(\theta) + r^{5/2} f_3(\theta) \quad \ldots (2)$$

For the first term the stress are representation by:

$$\sigma_\theta = \frac{1}{\sqrt[2]{2\pi r}} \cos\frac{1}{2}\theta \left(k_1 \cos^2\frac{\theta}{2} - k_2 \sin\theta\right) \ldots (3)$$

$$\tau_{r\theta} = \frac{1}{2\sqrt{2\pi r}} \cos\frac{1}{2}\theta \, [k_1 \sin\theta + k_2(3\cos\theta - 1) \quad \ldots (4)$$

Erdogan and Sih suggested that the direction of crack growth is given by the condition:

$$\frac{dk_\theta}{d\theta} = 0 \quad \ldots (5)$$

Where:

$$k_\theta = \cos^2\frac{\theta}{2} \left(k_1 \cos\frac{\theta}{2} - 3k_2 \sin\frac{\theta}{2}\right) \quad \ldots (6)$$

$$\cos\frac{\theta}{2}[k_I \sin\theta + k_{II}(3\cos\theta - 1)] = 0 \quad \ldots (7)$$

A better covenant among the theoretical and experimental has been gotten by a personification of the stress region using the first two relations of the Eigen function, equation (2). In addition, by using a lesser but finite radius to detect the maximum assessment of σ_θ and this was exposed by Williams and Ewing. The elastic strain energy dW kept in parallel pipe of volume dV in the dominate Sih expresses region of the strained plate:

$$\frac{dW}{dV} = \frac{1+v}{4E}[k_{1,2}(\sigma_x + \sigma_y)^2 + (\sigma_x - \sigma_y)^2 + 4(\tau_{xy})^2] \quad \ldots (8)$$

$$k_1 = \frac{1-v}{1+v} \quad \text{For plane stress} \quad \ldots (9)$$

$$k_2 = 1 - 2v \quad \text{For plane strain} \quad \ldots (10)$$

Papadopoulos used the elastic strain energy approached to suggest a standard of break, which takings into account the third stress constant Det. (σ_{ij})

$$\text{Det.}(\sigma_{ij}) = \begin{vmatrix} \sigma_x & \sigma_{xy} \\ \sigma_{yx} & \sigma_y \end{vmatrix} \quad \ldots (11)$$

Where:

$$\sigma_{yx} = \sigma_{xy}$$

Conferring to the Det. – criteria the position of crack growth for the mixed mode loading is specified from the state that the determinate of the stress tensor necessity take a maximum rate. In a polar coordinate system, the relations express these conditions mathematically:

$$\left.\frac{\partial \, Det.(\sigma_{ij})}{\partial\theta}\right|_{\theta=\theta^*} = 0, \quad \left.\frac{\partial^2 \, Det.(\sigma_{ij})}{\partial\theta^2}\right|_{\theta=\theta^2} < 0 \quad \ldots (12)$$

The ticklish stress for crack initiation is estimated by:

$$\text{Det.}(\sigma_{ij}) = \text{Det.}(\sigma_{ij})_{cr} \quad \ldots (13)$$

5. Cyclic Load Equations

The equations below are available for transverse crack (α = 90°) with and without internal pulse pressure [6]

$$p = w[1 + \sqrt{\frac{1+2hEA}{wl}}] \quad \ldots (14)$$

$$I = \frac{\pi}{64}(OD^4 - ID^4) \quad \ldots (15)$$

$$\delta = \frac{l^3 p}{48EI} \quad \text{(For simply supported)} \quad \ldots (16)$$

$$\sigma = \frac{MY}{I} \quad \text{(Bending stress)} \quad \ldots (17)$$

$$\sigma_{min} = -\sigma_{max} \quad \ldots (18)$$

$$\beta = \frac{a_j}{r} \quad \dots (19)$$

$$\rho_0 = \frac{a_j}{\sqrt{rt}} \quad \dots (20)$$

$$G_2(\rho_0) = 1 + 0.19\rho_0 + 0.01\rho_0^2 \quad \dots (21)$$

$$C_1 = 1 + \frac{0.7071(1-\beta cot(\beta))}{\left(\frac{\cot(\pi-\beta)}{\sqrt{2}} + \sqrt{2}\cot(\beta)\right)*\beta} \quad \dots (22)$$

$$C_2 = 1 + \frac{0.35355(\beta + \beta cot^2(\beta) - cot(\beta))}{\left(\frac{\cot(\pi-\beta)}{\sqrt{2}} + \cot(\beta)\right)} \quad \dots (23)$$

$$CCF_I = (G_2(\rho_0) * Sin(\beta) * C_2)/(\beta * C_1) \quad \dots (24)$$

$$K_I = \sigma_{app.}\sqrt{\pi a_j} CCF_I = K_{Imax} \quad \dots (25)$$

6. Material Used and Specimens

The material used in this research is Low Carbon Steel (EN 10219 S235JRH). It is a pipe with a circular section thickness about 1.4 mm and a diameter about 75 mm. This research was done on several samples of this article. Some of these samples have a length of 100 cm [7], See Fig. 1 and other have length of 50cm See Fig. 2. The reason for this difference to test the effect of bending on the growth and behavior of the crack. This test was conducted under different environmental conditions to determine the effect of the moisture and heat factors on the growth of the crack.

Fig.1. Two sample of length 100cm.

Fig. 2. Two sample of length 50cm.

7. Manufacturing of The Rig

This device was made of several parts of iron material with different sections according to the required part. Also used the technique of electric arc welding to connect these parts. The parts are cut using the cutting machine. After the cutting, the welding process is carried out to connect them together. However, most parts of this machine have the ability to switch when failure or damage occurs in one of these parts. The rig has the facility of making test for different length of pipes and different fixing conditions to match the requirement for the end fixing. A wooden plate was used to fix the parts of the machine. The dimensions of this plate are (122 cm x 244 cm) and thickness 1.5 cm. This plate has a hole in the middle to facilitate the passage of the hammer lever and to facilitate the examination of the pipe using the camera or naked eye. The dimensions of the parts of each other were developed using a laser device called (level) (see fig.3) that allows the device to see the extent of the separation of these parts or deviation from each other, which adds the possibility of placing the parts with high accuracy. This device enables the possibility of conducting tests on pipes made of iron, carbon steel, aluminum, copper and plastic. The design of this device includes the possibility of changing the height of the hammer to suit the amount of energy necessary and strong with the ability of the metal to withstand the shocks, Also can work on the pipes of different length ranging from 50 cm to 150 cm and different diameters ranging from 2 to 4 inch.

In addition, the researcher or worker on this device can control the environmental conditions to be operated from heat, humidity, and control where it can work in the areas of temperature ranging from 0 °C to 100 °C. Also, control the humidity, where it can work in the humidity ratio ranging from 0% to 100%.

Fig. 3. level device.

8. Material Properties

These properties from DIN EN 10219

1. Chemical composition
   Chemical composition is in percentage by mass. See Table 1**.**
2. Mechanical properties
   These mechanical properties measured at room temperature, See Table 2
3. Physical properties.

Physical properties for this material shown in the Table 3.

Table 1,
Chemical properties of material

Carbon C	Silicon Si	Manganese Mg	Phosphorus P	Sulfur Ag	Nitrogen N
0.17	-	1.4	0.04	0.04	0.009

Table 2,
Mechanical properties of material

Yield strength in N/mm^2 min for nominal wall thickness	235
Tensile strength in N/mm^2 for nominal wall thickness	360-510
Elongation % for nominal wall thickness	24
Impact energy in J at temperature 20°C	27

Table 3,
Physical properties of material

Density at 20°C in kg/dm^3	7.85
Modulus of elasticity kN/mm^2 at 20°C	210
Thermal conductivity at 20°C in w/ m k	54
Spec. thermal capacity at 20°C J/kg k	461
Spec. electrical resistivity at 20°C Ω mm^2/m	0.15

9. Crack Initiation

The crack was created manually by handsaw. Because that the crack is difficult to accomplish using other machines. Where the length of the cut about 24% [8] of the perimeter of the pipe. This percentage was based on previous research, where the length was 56 mm and width of the crack is about 0.7 mm to 0.9 mm. This difference is due to the difference in the thickness of the cutting edge in the saw as well as the hand movement. Other percentages were chosen to indicate the possibility of conducting the search on different lengths of the crack. However, these lengths of (18mm, 25mm, 30mm, and 40mm) took a long time without any continuity in the growth of the crack.

10. Results and Calculations

Table 4**.** and table 5**.** Show the calculations that must be used in this search, then use it in the governing equations, table 6 and table 7**.** To ensure the regular work convicted by equations in point 5**.** Results were obtained by using rig made for testing these specimens. See Fig. 4, the tests were repeated again to ensure a close test result as well as to ensure the correct functioning of the rig. The results are shown in the Fig. 8, Fig. 9, Fig. 10, and Fig. 11.
Outer diameter (OD) =0.075m, inner diameter (ID) =0.0722m, thickness (t) = 0.0014m Yield point= 235 Mpa, modules of elasticity (E) = 210Gpa, high (h) =0.57m, weight of hammer (w) = 6.7Kg

Table 4,
Calculation for 100cm specimens.

Effective length is 1 m			
Load applied N	**Moment of inertia m^4**	**Deflection m**	**Bending stress Mpa**
2279.3	$0.22 * 10^{-6}$	0.0103	1949.1

Table 5,
Calculations for 50cm specimens

Effective length is 0.5 m			
Load applied N	**Moment of inertia m^4**	**Deflection m**	**Bending stress Mpa**
2223.2	$0.22 * 10^{-6}$	0.0018	1378.1

Table 6,
Calculation using cyclic load equations for 100cm specimens

Type of test	k1		k2		Slop (m)	
	LHS	RHS	LHS	RHS	LHS	RHS
without	$1.8*10^8$	$1.8*10^8$	$1.87*10^8$	$1.87*10^8$	6.91	8.4
hygrothermal	$1.3*10^9$	$1.3*10^9$	$1.34*10^9$	$1.38*10^9$	6.02	2.4

Table 7,
Calculation using cyclic load equations for 50cm specimens

Type of test	k1		k2		Slop (m)	
	LHS	RHS	LHS	RHS	LHS	RHS
without	$1.33*10^8$	$1.33*10^8$	$1.35*10^8$	$1.35*10^8$	2	7.6
hygrothermal	$9.22*10^8$	$9.5*10^8$	$9.28*10^8$	$9.7*10^8$	3.9	7

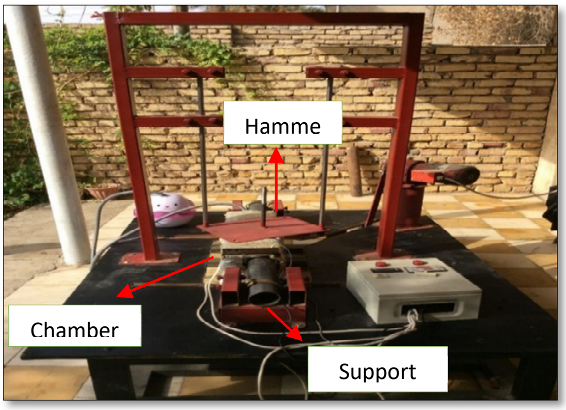

Fig. 4. The rig used in this research.

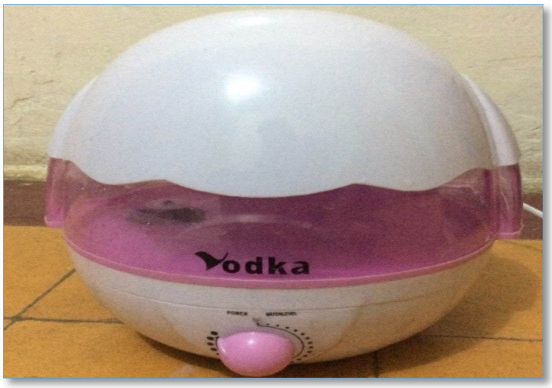

Fig. 5. Humidifier device.

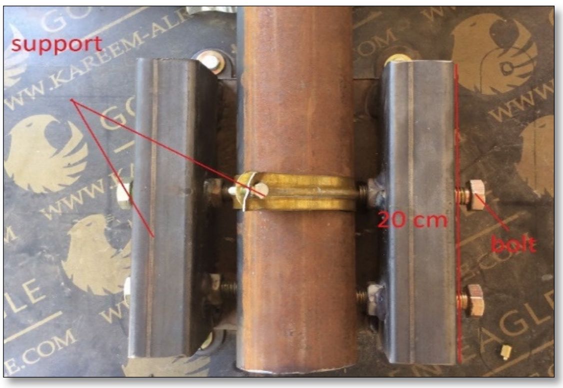

Fig. 6. Support.

Fig.7. Close up photo show the crack and crack growth.

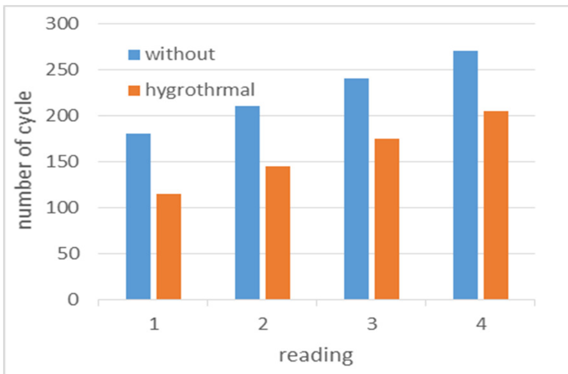

Fig. 8. Show number of cycle of 100cm specimens.

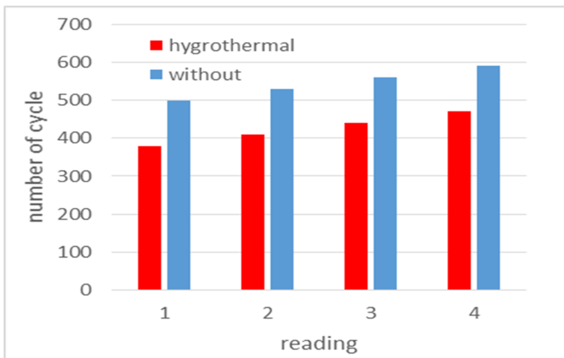

Fig. 9. Show number of cycle of 50cm specimen.

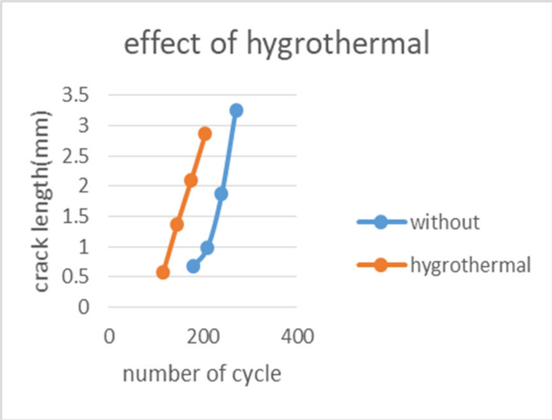

Fig. 10. Effect of hygrothermal on crack growth for 100cm specimens.

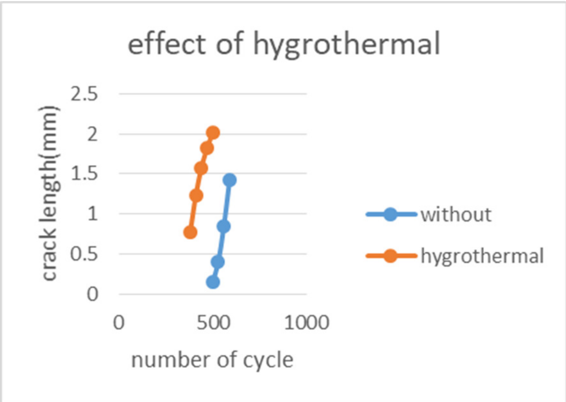

Fig.11. Effect of hygrothermal on crack growth for 50cm specimens.

11. Conclusion

The purpose of this study is to determine the extent to which the crack is able to grow when shedding and how long it takes to grow these cracks. Some things need to be discussed to know what changes are made to these cracks and to make things better.

1- The number of cycle needed to growth the crack are reduced due to the effect of humidity because the formation of oxides on the fracture surface.

2- The number of cycle needed to growth the crack in the specimens of length 50cm are increase because the effect of bending stress in the pipes.

3- The number of cycles needed to growth the crack are reduced because the effect of heat on the mechanical properties of the material that helps to increase the ductility.

Notations

LEFM	linear elastic fracture mechanics
MTS	multi-tasking staff
da/dN	crack growth per cycle, m/cycle
r,θ	polar coordinate, dimensionless
k_1 , k_2	stress intensity factor, Mpa$\sqrt{m}$
E	young modulus, Gpa

Greek Letters

π	mathematical constant, dimensionless
ν	poison ratio, dimensionless
δ	deflection, m
θ	angle of crack propagation, degree
$\tau_{r\theta}$	shear stress in cylindrical coordinate, Mpa
σ_x , σ_y , τ_{xy}	component of stress tensor, Mpa
σ_θ	circumferential stress near crack tip, Mpa
β	non dimensional factor, unit less

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نمو الصدوع وتصرفها خلال جدران الانابيب المعرضة لأحمال صدمية ومحيط حار ورطب

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الخلاصة

يتناول هذا البحث دراسة نمو الصدع في جدار الانابيب المصنوعة من الفولاذ منخفض الكربون تحت تأثير حمل الصدمة واستخدام تأثير الحرارة (٥٠ درجة مئوية) والرطوبة بنسبة (٥٠%). تم التحكم في الظروف البيئية باستخدام جهاز تحكم عالي الدقة مع أجهزة الاستشعار. الانابيب تحتوي على صدع مسبق، واجري الاختبار على نوعين من النماذج أحدها ذو طول ١٠٠سم والأخر ذو طول ٥٠سم. عند اجراء الاختبار فأن النتائج كانت، عند تطبيق الرطوبة فأن عدد الدورات اللازمة لنمو الصدع سوف تقل. كذلك عند تطبيق الحرارة فأن عدد الدورات اللازم لنمو الشق سوف يقل بسبب تأثير درجة الحرارة على الخواص الميكانيكية للمعدن فضلا عن ذلك فعند اجراء الاختبار على النماذج ذات الطول ٥٠سم فأن عدد الدورات اللازم لنمو الشق سوف يزداد نتيجة لتأثير اجهاد الانحناء على الانابيب .