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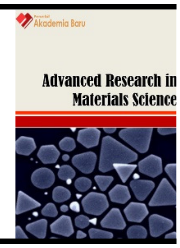

Relationship between Stress Intensity Factor and Fractal Cracks Propagation in AISI 410 Steel

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Mohd Azril Amil[1,*], Muhammad Adil Khattak[2]

[1] Department of Engineering, Faculty of Engineering and Life Sciences, Universiti Selangor, 45600 Bestari Jaya, Selangor, Malaysia
[2] Department of Nuclear Engineering, Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia, 81310 Skudai Johor, Malaysia

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ABSTRACT

This study analyzes the relationship between stress intensity factor and the fractal cracks propagation for AISI 410 Steel. Compact tension specimens were used in the fatigue crack growth test at the applied load ratio, R = 0.1 in accordance with ASTM E647. All tests are performed at room temperature for baseline fatigue crack growth behavior. Results showed that the fatigue crack growth rate behavior displays a threshold growth stage followed by a power-law growth region until final fracture of the specimen. The respective crack propagation were photographed under a 3D Scanning laser machine and measured according to the box counting method to obtain fractal dimensions. The fractal dimension (D) evaluated from crack data through fractal geometry analysis fall within the range of 1.76 -1.88. It is possible to demonstrate a relationship between Stress intensity factor (KIC) and fractal dimension (D) for AISI 410 stainless steel

1. Introduction

In recent years, a great deal of interest has developed in the area of quantitative fractography - the science of relating crack propagation features to material properties or behavior. Investigations into the various modes of failure have produced significant advances in the qualitative and quantitative understanding of how and why fractures develop[1-3].

In order to analyse the irregularity of crack propagation and time-dependent phenomena, various methods such as Fourier analysis and some conventional procedures as stochastic process have been developed and used by many researchers[4, 5] . A concept of fractal proposed by B. B. Mandelbrot [6] is useful to quantify the above irregularity and this has been successfully applied to various fields in both science and technology [7-10]. One of the concepts that has emerged as a potentially useful tool in these efforts is that of fractal geometry.

* *Corresponding author.*
E-mail address: Mohd Azril Amil (azril@unisel.edu.my)

Fractal geometric analysis, when applied to a crack propagation, provides a measure of its irregularity which can be correlated to the plane-strain sress intensity factor, KIC. The present study is intended to suggest best practices and procedures for fractal analysis and demonstrate a relationship between KIC and the fractal dimension for AISI 410 steel.

2. Specimens and Fatigue Crack Propagation Behavior

Material used in this study are AISI 410 steel. The chemical composition of the material was established using Glow Discharge Spectrometry (GDS) machine and is shown in Table 1. The primary alloying elements are chromium (Cr) and carbon (C). AISI 410 martensitic stainless steel have higher amount of carbon and chromium to obtain high strength, high toughness and good corrosion resistance while manganese and nickel contribute to improved toughness of the steel.

Table 1
Chemical composition (in weight percent) of AISI 410 stainless steel

Material	C	Mn	P	S	Si	Cr	Ni	Mo	Al	V	Fe
AISI 410	0.2	0.5	0.02	0.002	0.35	14.20	0.39	0.01	0.003	0.03	Bal.

To obtain the mechanical properties of the respective material as shown in Table 2, tensile test was performed on the dog bone shaped specimen.

Table 2
Mechanical properties of AISI 410 steel at room temperature

Material	Tensile strength (MPa)	Yield strength (MPa)	Elongation (pct.)	Maximum load (kN)
AISI 410	656.04	620.17	30	21.27

2.1 Fatigue Crack Growth Behaviour

Fatigue crack propagation tests were performed by a Instron 100 kN hydraulic servo fatigue testing machine on compact tension type specimen standardized in ASTM [11], [12]. The frequency was fixed to 10Hz, and stress ratios of R＝0.1 was selected. Pre-cracking procedure established an initial crack extension, a_0 = 1.5mm. Crack length measured as specific intervals of load cycles using a digital traveling microscope (20X optical scope). The load cycle and crack length (N,a) data pairs are recorded throughout the fatigue test to the final fracture of the specimen.

Fatigue crack growth behaviour of AISI 410 steel examined in this study is compared in Fig. 1 in terms of normalized crack length, a, versus loading cycles, N. For each test, crack grows initially at slow rate but accelerates as the crack length increases after accumulating larger number of cycles. This is consistent with the increase in stress intensity factor ranges as crack lengthens. Final fracture on each curve is represented by the last point during the fatigue crack growth testing.

Figure 2 shows the fatigue crack growth rate behavior of AISI 410 steel. The fatigue crack growth rate, da/dN is plotted against the applied stress intensity factor range, ΔK. Fatigue crack growth behavior of AISI 410 steel shows a threshold growth stage followed by a power-law growth behavior until final fracture of the specimens. It is confirmed that the fatigue crack propagation behavior is well represented by the following expression [13]

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

$$\Delta K = \frac{\Delta P}{BW^{\frac{1}{2}}} \times f(a) \tag{2}$$

$$f(a) = \frac{(2+\alpha)(0.886+4.64\alpha-13.32\alpha^2+14.72\alpha^3-5.6\alpha^4)}{(1-\alpha)^{\frac{3}{2}}} \tag{3}$$

where $f(\alpha)$is the modification coefficient depending on the specimen configuration of α＝a/W. Furthermore ΔP and a mean the load range and the crack length, respectively. B and W are the specimen thickness and width, and they are B＝13mm and W＝26mm for the present specimens.

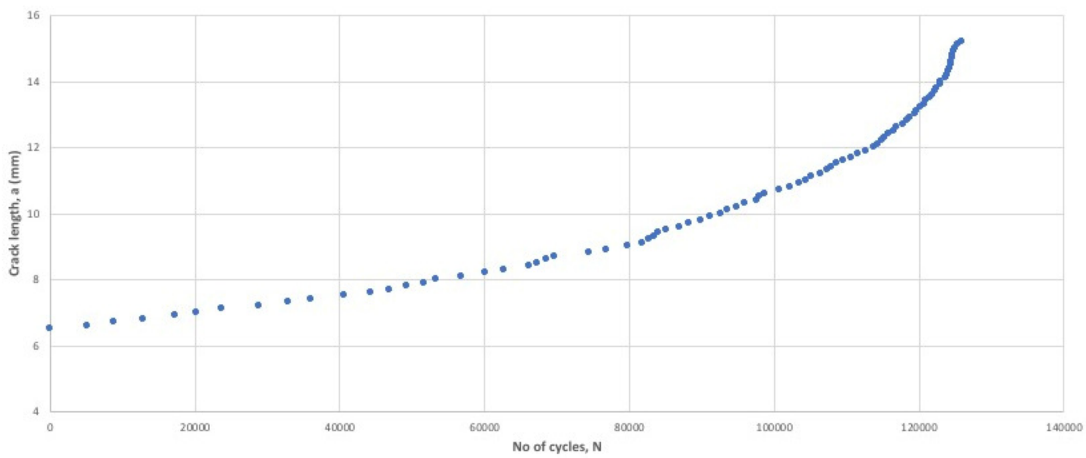

Fig. 1. Fatigue Crack Growth Behavior Test – AISI 410

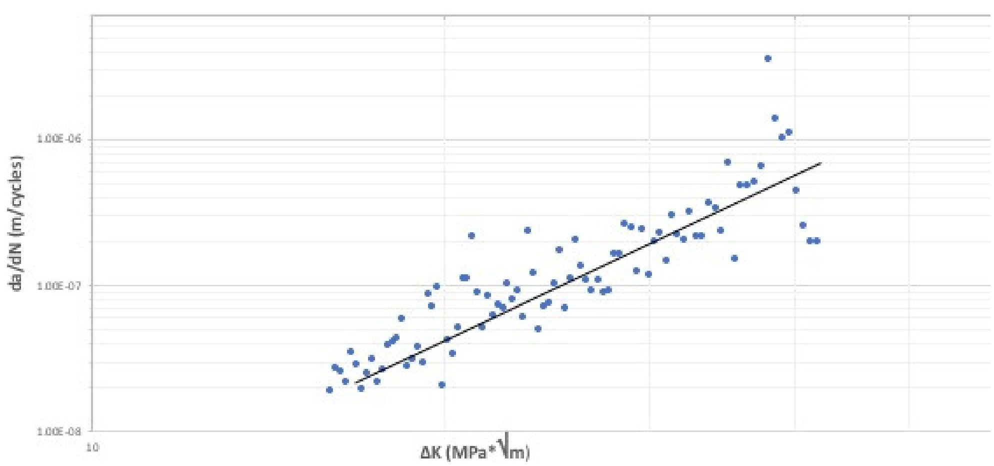

Fig.2. Relationships between stress intensity factor range ΔK and crack growth rate da/dN

2.2 Fractal Analysis

Fatigue fractal propagation were observed by means of a system explained in other paper [14] whereas the fatigue crack propagation was observed by an 3D laser microscope with the resolution of ×100. Based on the crack propagation behavior thus observed in Figure 1, relationships between the stress intensity factor range ΔK and the crack growth rate da/dN are plotted as shown in Figure 2. It should be noted that only one specimen was assigned to each series of the fatigue crack propagation test. In this figure, each solid line is determined as to provide the least squares for the respective data points. Figure 3 shows the crack propagation results of the experiment.

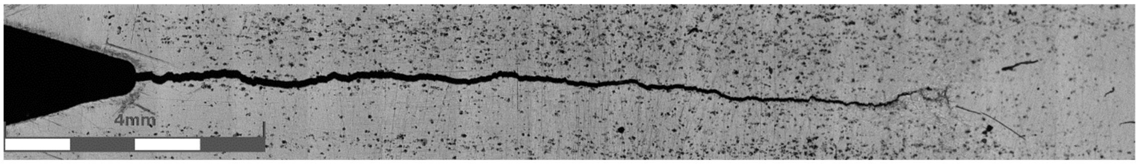

Fig. 3. Crack propagation under 100x digital microscope

In this study, Minkowski-Bouligand Method or more recognised as Box Counting Method is employed to compute the fractal dimensions. The method is done by assigning the smallest number of boxes to cover the entire image surface at each selected scale as required and obtained more accurate estimation of fractal dimension. For the ease of counting, MATLAB algorithm are used in this project to calculates the covered area of crack. Area fall in the box, are counted. This method/steps had been widely used by past researchers [15–19].

3. Fractal Evaluation Results and Discussions

From MATLAB algorithm, values for Fractal Dimension, F_D are obtained. Then, the Fractal Dimension, F_D in regards of stress intensity factor range ΔK were plotted as shown in Figure 3. Few fractal window sizes been chosen and tested. Theoretically, if we assumed that the crack is fractal, then the fractal dimension of each box sizes should have similar value of Fractal Dimension, F_D.

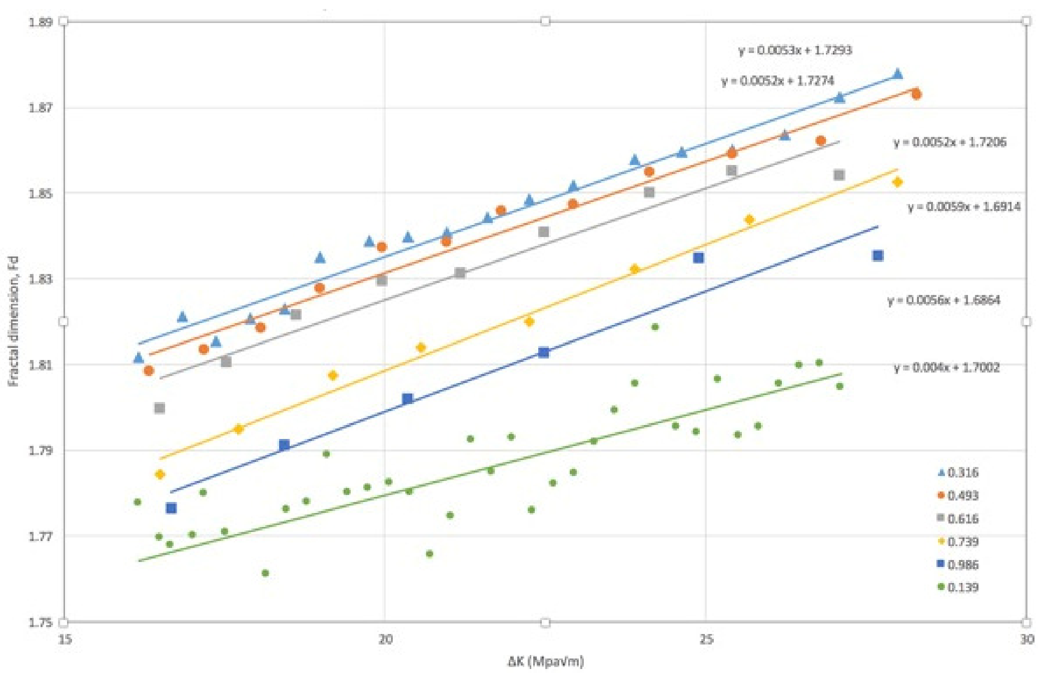

Fig. 4. Comparison between different window sizes for F_D and ΔK

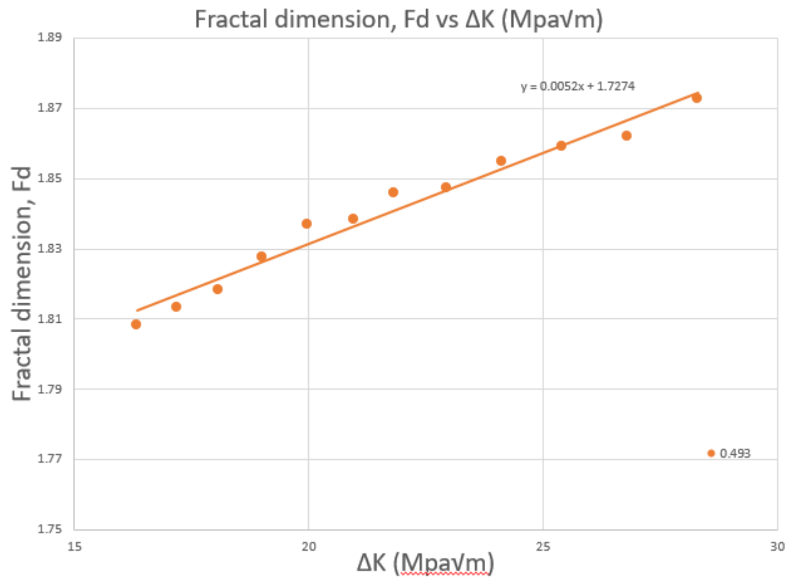

Fig. 4. Relationship between Stress Intensity Factor and Fractal Cracks Propagation in AISI 410 Steel

However, there is some deviation in the slope when the different window sizes been used, especially when the window sizes are too small such as 0.139. The window size of 0.493 was chosen as the Fractal Dimension, F_D model due to the constant slope value compared to other window sizes. The chosen plot is shown in Figure 4. It shown that the value of the fractal dimension is 1.76 – 1.88 and comply the results that must be under the value of 2.0.

4. Conclusions

The results of this study provide the basis for forming the following conclusions:
1) The fractal dimension was measured on AISI 410 Steel to provide a range of values based on Fatigue Crack growth test data. This is one of the few studies that examines one material to study the relation between Stress Intensity Factor and Fractal Cracks Propagation in AISI 410 Steel
2) The low crack growth rate region is characterized by crack growth bridging process. At higher stress intensity factor range, the crack growth rate, da/dN increases with increasing applied ΔK.
3) Fractal dimension and each index of crack propagation nature were successfully connected to the stress intensity factor range ΔK giving the key parameter in the fracture mechanics approach.

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