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Correlation of fracture parameters during onset of crack in middle tension specimen ☆

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ABSTRACT

The present study addresses the implementation of finite element analysis and the prediction of fracture parameters in a middle tension (MT) specimen that was fabricated using AISI 4140 steel. The correlation of fracture parameters with external loads and crack sizes was investigated. A Finite Element code was developed to simulate the fracture model. The contour integral method was applied in the calculation of stress intensity factor and J-integral in the cracked specimen. The ASTM standard empirical formula was used to calculate the stress intensity factor (SIF) and the numerical predictions were validated. A standard laboratory experiment was also carried out using the MT specimen to calculate the crack growth rate in this specific material. The SIF values were almost linear with external load but it was decreasing as the crack size increases. The crack requires minimum load for crack propagation as the crack size increases. Similarly the J-integral was accelerated with increase in crack size.

1. Introduction

High strength, low alloy (HSLA) steels are widely used for the fabrication of highly loaded structural members of machines, like large diameter ball bearing race. The failure of such components occurs typically by fatigue fracture during its service (Hua, Deng, Han, & Huang, 2013). The understanding of structural components that are susceptible to fail by fracture is indeed a design criterion in the engineering industry to avoid the catastrophic failures. Analyses of such components are complicated because of its complex geometrical shape and size.

Such fracture behaviour of any material can be estimated in a laboratory using ASTM standard test procedures (ASTM International, 2013). Moreover, application of numerical methods like finite element analysis to understand the fracture behaviour is indeed an effective way (Branco & Antunes, 2008; Lei, 2008; Lin & Smith, 1999; Xiao & Dexter, 1998). One of the methods that can be implemented using finite element analysis is a contour integral method. The contour integral method calculates the onset of a crack from the stress intensity factor (SIF). According to the linear elastic fracture mechanics, the stress intensity factor decides the fatigue crack propagation in a structural component (Han, Wang, Yin, & Wang, 2015).

Apart from the SIF, another important fracture parameter is the J-integral which is the representation of the energy release rate at the crack tip opening. Correlation of SIF and J-integral gives an insight to the fatigue crack propagation in the structural component. Research on the prediction of fracture parameters were carried out by many authors. The review of fracture parameters calculation elucidates, various methods in the fracture analysis (Zhu & Joyce, 2012). The relation between J-integral and other parameters were investigated that gave an insight to the importance of this parameter. Also the J-integral can be used in the calculation of stress intensity factor (Barati, Alizadeh, & Mohandesi, 2011; Berto & Lazzarin, 2007; Courtin, Gardin, Bézine, Ben, & Hamouda, 2005; Hedan, Valle, & Cottron, 2011; Kim, Kim, Cho, & Kim, 2004; Livieri, 2008; Vavrik & Jandejsek, 2014; Vukelić & Brnić, 2011).

The finite element implementation of the crack using commercial software was reported in many articles (Lei, 2008; Pathak, Singh, & Singh, 2013; Shi, Chopp, Lua, Sukumar, & Belytschko, 2010; Sukumar & Prévost, 2003). Most of the articles investigated the crack behaviour using compact tension specimens, whereas the middle tension specimens were rarely used for the testing (Kim et al., 2004; Lei, 2008). Fracture parameters for various notch

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configurations like V-notch and U-notch were investigated in the standard specimens (Livieri, 2008). Some researchers were investigated the fracture behaviour in non-standard specimens and real time components using numerical method (Hua et al., 2013; Maligno, Rajaratnam, Leen, & Williams, 2010; Weinzapfel & Sadeghi, 2013).

Based on the literature, it was observed that the prediction of stress intensity factor and J-integral were important in order to understand the fatigue fracture behaviour of a crack. Also the standard specimens and empirical formulae were successfully implemented to validate the numerical simulations. Moreover the correlation of SIF and J-integral was not explicitly analysed in the articles. In this research, finite element model was developed to predict the fracture parameters in the middle tension specimen as per ASTM E647 standard. A standard testing procedure was followed to calculate the crack growth rate and correlated with fracture parameter.

2. Experimental method

2.1. Choice of material

AISI 4140 steel has superior mechanical characteristics and has high resistance to corrosion as compared to conventional carbon steels. The chemical composition of AISI 4140 steel is given in Table 1. Due to its superior properties, it is widely used in the fabrication of angular contact ball bearing which is employed with highly loaded machine components. It has Yield and ultimate tensile strength of 660 MPa and 1000 MPa respectively. Though it has better strength, to improve the wear resistance of the surface, it will undergo surface hardening processes. Thus, in many practical applications the hardness along its thickness varies and not a constant parameter. The typical Young's modulus of this material is 2×10^5 N/mm^2 and Poisson ratio is 0.3.

2.2. Middle tension specimen

The middle tension (MT) specimen employs a pre-crack at its centre and the specimen can be loaded with tension-tension or tension-compression loading condition. It allows fatigue loading under both positive and negative ratio (R). The thickness (B) and width (W) of specimen are independent parameters which depend on the buckling and through thickness crack curvature consideration. The dimensions of the MT specimen were chosen based on the ASTM-E647 standard. The sample of 0.005 m thickness was used with initial crack length of 0.0045 m and the analysis was carried till the crack length reaches 0.0095 m. The notch along with the pre-crack was created using electrical discharge machining using a wire diameter less than 0.25 mm. The machined notch shall be aligned with the centreline of the specimen and the length of the specimen can be adjusted to the specimen fabrication conditions.

2.3. Experimental setup

The fatigue machine which is used in this experiment is shown in Fig. 1. The test was carried out using the above mentioned MT specimen. This experiment was carried out in open atmospheric condition whereas the temperature and corrosive environment significantly affect the SIF and crack growth rate. The crack size was measured based on the number of fatigue cycles and the rate of crack growth was calculated.

The crack growth rates are the function of SIF range K which is calculated using linear elastic stress analysis. The peak SIF

Table 1
Chemical composition of 4140 steel.

Component	C	Mn	Si	S	P	Cr	Mo	Fe
wt%	0.394	0.671	0.247	0.031	0.020	0.984	0.210	Balance

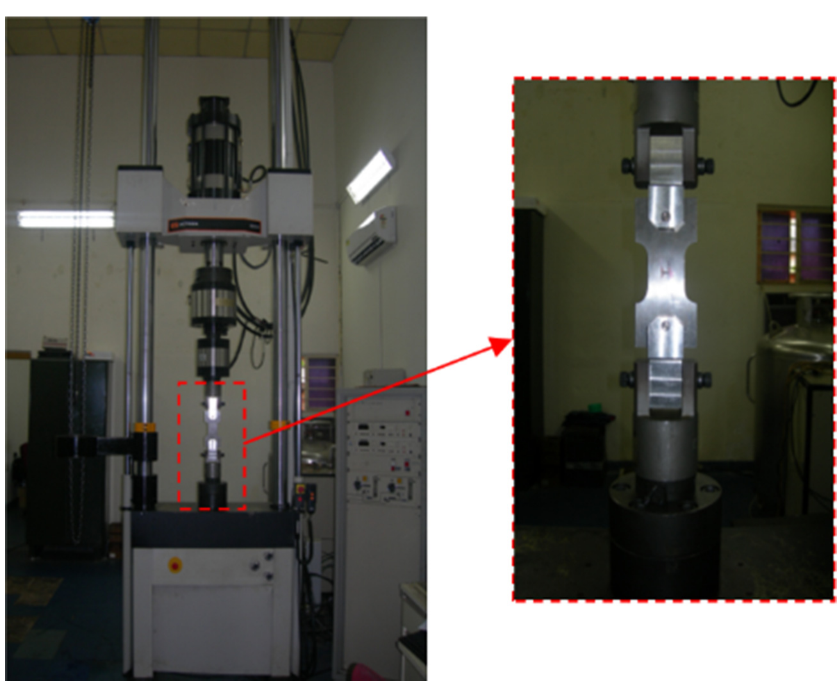

Fig. 1. Experimental setup.