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Materials Science and Engineering A 454–455 (2007) 467–471

MATERIALS SCIENCE & ENGINEERING A

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Surface crack fracture toughness and HRR fields of ultra-high strength steel

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Received 19 May 2006; received in revised form 8 November 2006; accepted 13 December 2006

Abstract

In present, due to continuous increasing of the fracture toughness and continuous reduction of steel plate thickness for ultra-high strength steel used in the aerospace solid rocket motor, it is difficult to measure its fracture toughness of surface crack using the linear elastic fracture mechanics method. In this paper, the tensile test was used to achieve the conditional load when the surface crack initiation occurred. Then, the finite element method (FEM) was conducted to calculate the ductile fracture toughness J_{IC} under the conditional load. Lastly, the surface crack fracture toughness, K_{Ie}, can be computed from J_{IC} based on the fracture mechanics method. In addition, the analysis on validity of J-integral showed that K_{Ie} converted from J_{IC} was able to evaluate the fracture toughness of ultra-high strength steel. These are important technical parameters for design of aerospace solid rocket motor.

Keywords: Solid rocket motor; Ultra-high strength steel; Surface crack; Fracture toughness; FEM; J-dominant zone

1. Introduction

In present, the thin-walled structure of ultra-high strength steel was widely used in the aerospace vehicles motor with the development of aerospace technology. However, the brittle fracture accidents often occurred. The studies showed that most of the accidents were resulted from surface crack propagation. Therefore, the surface crack fracture toughness (K_{Ie}) was a critical target in the evaluation for this ultra-high strength steel.

31Si2MnCrMoVE steel is ultra-high strength steel which was specially developed for manufacturing solid rocket motor shell. The content of inclusions decreased and controlling for the chemical constitution became precise in the steel with development of the smelting technology, as well as the harmful elements can be strictly restricted. Therefore, the fracture toughness have been continuously increased, correspondingly, the steel plate thickness can be reduced. However, the increasing of fracture toughness and reduction of plate thickness resulted in the difficulty of measuring its surface crack fracture toughness because the very small ligament sizes of specimens could not satisfy the validity criterion. So, the linear elastic fracture mechanics cannot be used to evaluate the fracture toughness of thin ultra-high strength steel, but the ductile fracture toughness (J_{IC}) of thin thickness ultra-high strength steel can be evaluated using the elasto-plastic fracture mechanics. Thaulow et al. [1] and Zhang and co-workers [2] had studied the fracture resistance and the application of constraint correction in evaluating toughness of high strength steel. Beremin [3] and Toyoda and Minami had already studied the toughness of high strength steel based on the local approach for a long time [4–7]. Dotta and Ruggieri [8] and Croavero and Ruggieri [9] had studied the fracture behavior and the ductile crack extension in a high strength pipeline steel. However, in present, the papers with respect to the fracture toughness of ultra-high strength steel were very rare.

In this paper, the surface crack fracture toughness specimens had been fabricated using steel plate of original thickness. The fracture mechanics test and finite element method (FEM) had been conducted to calculate the J-integral in the vicinity of the crack tip under the conditional load in the condition that the conditional fracture toughness (K_{IQ}) cannot satisfy the validity criterion. The computed J-integral was hoped to be used as the ductile fracture toughness of the material. However, the validity of J-integral must be analyzed before the J_{IC} can be used as the fracture parameter. So, the conservation of Loop J-integration

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doi:10.1016/j.msea.2006.12.045

Table 1
Chemical compositions %

C	Si	Mn	Cr	Ni	Mo	V	P	S
0.29	1.66	0.85	1.10	0.25	0.44	0.091	0.01	0.002

and the *J*-dominant characteristic of ultra-high strength steel surface crack were studied.

2. Fracture toughness test

The test chose the ultra-high strength steel plate (31Si2MnCrMoVE) with 5 mm thickness. The chemical compositions and mechanical properties of 31Si2MnCrMoVE steel were listed in Tables 1 and 2, respectively. This test used the uniaxial tension specimens with surface pre-crack. The configuration of tension specimen was showed in Fig. 1, and the dimension of each specimen was $2L \times 2W \times B$ in length, width and thickness, respectively. The number of tension specimens was five, and all specimens were abstracted from the steel plate along the rolling direction of the steel plate.

The process of preparing the surface pre-crack was as follows:

Firstly, the tension specimens were fabricated using the 31Si2MnCrMoVE steel in the annealed condition.

Secondly, a surface indentation in the center of the specimen was formed using a special knife with 1.2 mm width and 0.05–0.10 mm thickness. The indentation pressure was controlled in 0.18–0.22 kN, and the indentation depth was in 0.10–0.20 mm.

Table 2
Mechanical properties of 31Si2MnCrMoVE

Proof strength, non-proportional extension, $R_{P0.2}$ (MPa)	1323.0
Tensile strength, R_{m} (MPa)	1643.0
Percentage elongation after fracture, *A*	9.5

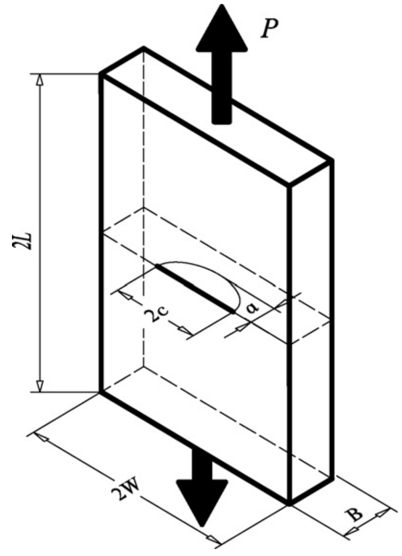

Fig. 1. Surface cracked specimen subjected to tension.

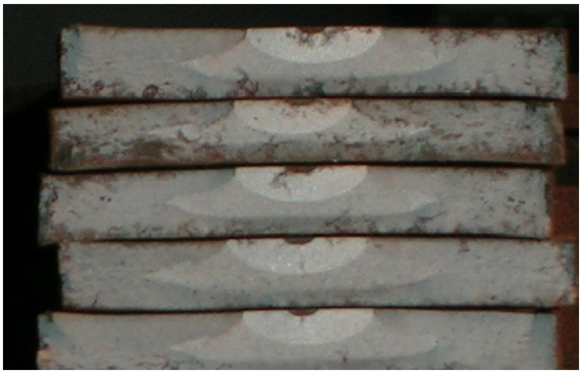

Fig. 2. Fracture appearance of surface crack.

Thirdly, the specimens were heated in a salt-bath furnace. The furnace temperature was 930 °C, and the specimens were maintained 10 min under that temperature. Then the specimens were treated oil quenching (the temperature of oil was the room-temperature). When the furnace temperature reduced to the 300 °C, the specimens were put into the furnace again and were maintained 2 h. After the specimens were cooled in the air, the oxides on the specimen surface were grinded off.

Lastly, the surface fatigue pre-crack was created on a 20 kN high frequency fatigue experiment machine using three point bend test. The crack length ($2c$), and crack depth (a) were controlled so that both a/B and a/c were in the range of 0.45–0.55. The crack depth a can be estimated by the following equation through observing the crack length:

$$\frac{a}{B} + \frac{a}{c} = 1 \qquad (1)$$

The tension test was on a MTS880 material test machine. An extensometer was used to measure the crack opening displacement. The loading speed was approximately 1.0 mm/min. The load-crack opening displacement curve (*P*–*V* curve) was recorded in the test. The test ended until the specimen fractured. Then, a 50× toolmaker's microscope was used to measure the crack depth and crack length. Fig. 2 showed the appearance of fracture of the surface crack observed.

In Fig. 3, the heavy line was the *P*–*V* curve, and line OA was the initial tangent line. The rate of slope of the line OD was 15% lower than that of the line OA. The load at the point F which was the crossing point between the *P*–*V* curve and OD was defined as the conditional load (P_{Q}), and the P_{Q} corresponded to the conditional initiation of crack [10]. $P_{\max}$ was the maximum load in the *P*–*V* curve.

3. Test results and analysis

3.1. Conditional fracture toughness

In this paper, the Newman–Raju expression [11] was chosen to compute the stress intensity factor (K_{I}) of surface crack because of its good precision and small dispersibility. The expression of the conditional fracture toughness (K_{IQ}) was as