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Materials Science and Engineering A 486 (2008) 562–571

MATERIALS SCIENCE & ENGINEERING A

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Acoustic emissions during fracture toughness tests of steels exhibiting varying ductility

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Received 1 April 2007; received in revised form 15 September 2007; accepted 19 September 2007

Abstract

This investigation is primarily aimed at examining steels with varying ductility using characteristics of acoustic emission (AE). Four steels (AISI 1060, AISI 1080, SA333 grade 6 and AISI 304LN) were selected and their structure property relations were characterized using standard metallographic examinations, hardness and tensile properties. Fracture toughness of these steels was determined as per the guidelines of ASTM standard E1820 with simultaneous recording of AE signals. The results of these investigations have been used to demonstrate that: (a) nature of the variation of AE cumulative counts with time is different for linear and non-linear load–displacement plots, (b) synergistic analysis of the rate of change of cumulative energy, cumulative counts and intensity of AE signals provide the point of crack initiation in a material, and (c) fracture toughness of a material estimated using AE parameters is lower compared to that obtained by ASTM standard procedure.

Keywords: Acoustic emission; Fracture toughness; AISI 1060 steel; AISI 1080 steel; SA333 steel; AISI 304LN steel

1. Introduction

A large number of international standards on determining fracture toughness of structural materials are currently available. These standards suggest procedures for estimating fracture resistance of materials using analysis of load–displacement plots. Acoustic emission (AE), on the other hand, is capable of indicating directly the crack initiation point during loading of a specimen. For exploiting this potential of AE, several investigators [1–5] have carried out conventional fracture toughness tests in liaison with AE technique; but so far no generalized guideline has emerged out from this type of 'combined' experiments. The major aim of this investigation is to examine results related to fracture toughness values of a few steels estimated by these 'combined type' experiments in order to suggest a guideline.

Attempts to estimate fracture toughness values from the characteristics of acoustic emission signals are a few in number. But almost each of these has different approaches. Arii et al. [1], in an early work, monitored the variation of total AE counts with crack opening displacement (COD). They concluded that the point of crack initiation in C–Mn steels corresponds to the significant change in slope of total AE counts versus COD curve. Clark et al. [2] have indicated that the first appearance of high-amplitude AE signal during fracture toughness tests of A533B pressure vessel steel can be attributed to the crack initiation process, which involves rapid shear linkage of growing voids. Khan et al. [3] have obtained the point of crack initiation from the sudden change in slope of total AE energy (E_{AE}) versus J curve. Blanchette et al. [4] have studied the acoustic emission behaviour during fracture toughness tests on 7075–T651–aluminium alloy. These researchers have concluded that the point of crack initiation in a material corresponds to the sudden change in the slope of log N (total counts) versus K (stress intensity factor) curve. In another instance, Camerini et al. [5] measured the crack tip opening displacement (CTOD) for specimens of C–Mn structural steels, while simultaneously monitoring the acoustic emission signals. They observed two distinct peaks in the variation of total AE events with time. The first peak was attributed to the point of crack initiation whereas the second peak was attributed to the final fracture. Mashino et al. [6] have observed AE events corresponding to the generation of microcracks during fracture

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doi:10.1016/j.msea.2007.09.036

toughness tests of Ti–8Al–1Mo–1V alloy using characterization of the mechanisms from information related to AE events. Long et al. [7] have synergistically monitored AE signals during the fracture toughness tests of modified 9Cr–1Mo steel. They observed that load determined by AE spectrum analyses is lower than that estimated during conventional fracture toughness tests. In addition to the above mentioned reports [1–7], a few investigations [8,9] are found directed on notched tensile specimens in which the relationship between stress intensity factor and total AE counts have been examined with reference to the variation in thickness and chemistry of the materials.

The above reports [1–7] do not provide any recommendation towards guideline for detecting the point of crack initiation using AE signals generated during fracture toughness tests. In the present investigation time domain AE analyses have been made synergistically with standard fracture toughness tests (as per the guidelines of ASTM E1820) in order to detect the point of crack initiation in four different steels. The steels were selected on the basis of their varying ductility. The estimation of crack initiation resistance of the selected steels is based on cross examination of AE characteristics like variation of cumulative counts, cumulative energy and peak amplitude versus time against the recorded data of ‘load versus time’ as obtained from the fracture tests.

2. Experimental details

2.1. Materials and microstructures

Four different steels have been used in this study :(a) AISI 1060 steel, (b) AISI 1080 steel, (c) SA333 grade-6 steel, and (d) AISI 304LN steel. The chemical compositions of all these steels are shown in Table 1. The first two steels are used in the construction of railway wheels and rails, respectively. The steels SA333 and AISI 304LN are materials used for the construction of primary heat transport (PHT), system of pressurized heavy water reactor (PHWR) and advanced heavy water reactor (AHWR), respectively. Rectangular blocks of approximately 15 mm × 10 mm × 10 mm were cut from the as received sample blanks for microstructural study. The samples were ground up to 1000 grade emery paper, were polished up to 0.25 μm diamond paste and were then etched to reveal the microstructures. The first three steels were etched using 2% Nital whereas the stainless steel was etched using aqua regia. The examinations of all the microstructures were carried out using an optical microscope. A few representative photographs were taken during these examinations. The average austenite grain size in AISI 304LN steel and the average ferrite grain size in SA333 steel were determined using linear intercept method following ASTM standard E112-03 [10].

2.2. Mechanical properties

Cylindrical tensile specimens of 6 mm diameter and 30 mm gauge length were fabricated from the as received blanks of the steels. Each specimen was loaded till fracture in an Instron machine (model: 8562) at a nominal strain rate of $0.001\,\mathrm{s}^{-1}$. Vickers hardness measurements were carried out using a load of 10 kgf. At least five readings were taken to estimate the average hardness value for each material.

2.3. Fracture toughness test coupled with acoustic emission monitoring

Compact tension [$C(T)$] specimens are used to determine fracture toughness of AISI 1060 ($B = 30$ mm), AISI 304LN ($B = 20$ mm) and SA333 steels ($B = 25$ mm) whereas single edge notch bend [SE(B)] specimens are used to estimate the fracture toughness of AISI 1080 steel ($B = 25$ mm); thickness of the specimens (B) are referred with each steel grade in parenthesis. The specimens were fatigue pre-cracked to achieve $a/W \approx 0.5$ following the ASTM standard E647-03 [11]. The pre-cracking was carried out on a computer controlled servo hydraulic Instron machine (model: 8502) coupled to a commercial software. All pre-cracking experiments were carried out at a stress ratio of $R = 0.1$ using a frequency of 15 Hz.

Plain strain fracture toughness tests (K_{IC}) were carried out for the AISI 1080 and AISI 1060 steels using fatigue pre-cracked SE(B) and $C(T)$ specimens, respectively. All these tests were performed on a servo-electric Instron machine (model 8562) using a crosshead velocity of 0.003 mm/s at room temperature till the maximum load bearing capacity of a specimen is reached. A clip gauge (with a travel of 10 mm) was attached to the mouth of each specimen during the fracture toughness tests to monitor the crack mouth opening displacement (CMOD). The load–CMOD data for each of the specimens was recorded for subsequent analysis for estimating their fracture toughness values. These tests were carried out following the guidelines suggested in ASTM standard E399-03 [12]. Unlike the determination of fracture toughness of AISI 1060 and AISI 1080 steels, the measurements of fracture toughness for AISI 304LN and SA333 steels were made using J integral tests. The J integral tests were performed on fatigue pre-cracked $C(T)$ specimens by single specimen unloading compliance technique following ASTM

Table 1
Chemical composition of the investigated steels (in wt%)

Steels	C	Si	Mn	P	S	Cr	Ni	Fe
AISI 1080	0.76	0.2	1.21	0.015	0.012	0.033	–	Bal.
AISI 1060	0.63	0.27	0.83	0.012	0.086	0.033	0.012	Bal.
SA333	0.18	0.25	0.90	0.02	0.02	–	–	Bal.
AISI 304LN[a]	0.03	0.54	1.80	0.028	0.014	18.55	9.50	Bal.

[a] Contains 0.1% nitrogen.