Pergamon

J. Mech. Phys. Solids, Vol. 46, No. 10, pp. 1997–2016, 1998

Printed in Great Britain
0022–5096/98 $—see front matter

PII: S0022–5096(98)00035–0

DYNAMIC CRACK INITIATION IN DUCTILE STEELS

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(*Received* 20 *December* 1997; *in revised form* 13 *February* 1998)

ABSTRACT

The goal of the work presented here is to study dynamic crack initiation in ductile steels (Ni–Cr steel and 304 stainless steel) at different loading rates and to establish appropriate dynamic failure criteria. A variety of infrared and visible optical methods and high-speed photography are used in this study. Precracked steel specimens are subjected to dynamic three-point bend loading by impacting them in a drop weight tower. During the dynamic deformation and fracture initiation process the time history of the transient temperature in the vicinity of the crack tip is recorded experimentally using a high-speed infrared detector. The dynamic temperature trace in conjunction with the HRR solution is used to determine the time history of the dynamic J-integral $J^d(t)$, and to establish the dynamic fracture initiation toughness, J^d_c. The measurements made using high-speed thermography are validated through comparison with determination of $J^d(t)$ by dynamic optical measurements of the crack tip opening displacement (CTOD). Finally, the micromechanisms of fracture initiation are investigated by studying the fracture surface using scanning electron microscopy. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: A. fracture toughness, dynamic fracture, B. elastic–plastic material, C. electron microscopy

1. INTRODUCTION

To aid in the design and vulnerability analysis of impact loaded structures and energy systems (e.g., pressure vessels, pipelines and reactors), it is necessary to quantify the mechanical behavior and failure modes of materials used in such systems under carefully controlled conditions. Because of design constraints and safety issues, these energy systems are typically fabricated with corrosion resistant and highly ductile metallic alloys such as stainless and Ni–Cr steels. Yet, relatively little is known regarding dynamic crack initiation and growth in such ductile metals. A major stumbling block in this area is the measurement of relevant fracture parameters, such as the J-integral, under a combination of large scale yielding conditions and dynamic loading. Considerable effort has been made towards the analytical and computational characterization of fracture parameters in highly ductile metals (Hutchinson, 1968; Rice and Rosengren, 1968; Needleman and Tvergaard, 1987; Nakamura and Parks, 1990; Narasimhan and Rosakis, 1990; Duffy and Chi, 1992; Cho *et al*., 1993). Recently, several researchers have presented detailed analyses of ductile fracture using higher order expansions of the deformation fields within the plastic zone (Li and

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Wang, 1986; Sharma and Aravas, 1991; O'Dowd and Shih, 1991, 1992; Yang *et al.*, 1993).

To date relatively little experimental work has been done on determining fracture parameters, such as $J^d(t)$, for ductile fracture under dynamic loading conditions. Limited cases exist where careful choice of specimen geometry and loading histories allow for the measurement of J^d based on the use of dynamic boundary value measurements interpreted on the basis of quasi-static formulae for J (Costin *et al.*, 1977). Also, Douglas and Suh (1988) and Sharpe *et al.* (1988) have developed an alternate method based on comparing a dynamic finite element analysis with experimental observations to provide the critical value of CTOD (crack tip opening displacement) and thus the critical value of J, corresponding to crack initiation. The only direct measurements of the dynamic value of the J-integral, $J^d(t)$, have been made using the optical technique of caustics in conjunction with high-speed photography (Rosakis *et al.*, 1988; Zehnder *et al.*, 1990). However, even this approach employs a procedure using calibration of J vs the caustic diameter, D, under quasi-static loading conditions and then extends the same to dynamic loading conditions. Hence, this technique is limited to rate-insensitive materials and requires calibration for all combinations of specimen material and specimen geometry.

The current study introduces a technique for measurement of temperature variation in the vicinity of the dynamically loaded crack tip using a high speed infrared detector to determine the time history of the dynamic value of the J-integral, $J^d(t)$. The dynamic temperature trace is also employed to establish the dynamic fracture initiation toughness, $J^d(t_c) = J_i^d$, where t_c is the time of fracture initiation. The measurements made using high-speed thermography are validated through comparison with determination of $J^d(t)$ by dynamic optical measurements of the crack tip opening displacement (CTOD). Both these techniques provide a direct measurement of the time history of the dynamic J-integral and are not restricted by specimen geometry, rate of loading, or rate-sensitivity of the material.

2. EXPERIMENTAL SETUP

In this investigation high-speed infrared measurements of temperature and optical measurements of crack tip opening displacements were employed to study dynamic crack initiation in precracked ductile steel specimens. In the former, the temperature increase ahead of the crack tip during dynamic deformation is measured and is related to the dynamic J-integral. In the latter, the dynamic J-integral is estimated by relating it to the measured crack opening displacement history.

2.1. *Specimen configuration, loading arrangement and material properties*

The experiments employed edge cracked specimens in a three point bend configuration. The specimens were fabricated out of 2.3Ni–1.3Cr steel (will be referred to as Ni–Cr steel here onwards) and 304 stainless steel, whose compositions are listed