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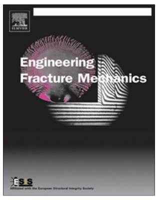

Investigation of cleavage fracture under dynamic loading conditions: Part II numerical analysis

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ABSTRACT

Part I of this study was an extensive fractographic investigation that covered the topics local crack arrest, and cleavage fracture-inducing mechanisms under dynamic loading situations. Also, it produced data regarding the origin of cleavage fracture. Now, this data is used for the numerical part of this study. First, the development of temperature and strain rate increase at the origin of cleavage fracture is conducted, and linked to discrepancies regarding experiments and the Master Curve concept in a phenomenological way. Then, cleavage fracture controlling mechanical field variables at the origin of fracture are analyzed, whereas very similar conditions regarding crack initiation and propagation are found when compared to quasi-static data. The influence of wave phenomena is examined as well. Finally, micromechanical simulations showed that a local temperature increase at the particle–matrix interface does not influence fracture behavior either, and that conclusively, the actual physical mechanism of cleavage fracture initiation (crack initiation and instability) takes place under the same conditions at elevated loading rates as under quasi-static conditions. Ultimately, the mechanisms responsible for the shortcomings of the Master Curve concept under dynamic loading conditions are identified, and current local approach concepts need to be adjusted to consider local crack arrest to be reliable.

1. Introduction

In part I of this study a total of six additional mechanisms was introduced that could potentially impact cleavage fracture behavior under dynamic loading conditions. The mechanisms are

1. temperature increase,
2. strain rate increase,
3. wave phenomena/inertia,
4. local crack arrest,
5. different fracture-inducing mechanisms (i.e. different particle types),
6. local temperature increase at the particle-matrix interface.

Part I consisted of a thorough fractographic examination, and investigating mechanisms 4 and 5. Also, the exact origin of cleavage fracture was documented which is used for this part of this study. Part I proved the strong relevance of local crack arrest for dynamic loading conditions. A general correlation of the probability for crack arrest with fracture toughness was

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Nomenclature

a	short semi axis of ellipse
b	long semi axis of ellipse
a_0	initial crack length
d_{eq}	diameter of a circle of equivalent area
h	local stress triaxiality
K_I	stress intensity factor
K_{Ic}	fracture toughness
K_{Icd}	dynamic fracture toughness (elastic)
K_{IR}	ASME lower boundary curve
K_J	stress intensity factor (small scale yielding)
$K_{J,1T}$	size corrected stress intensity factor (small scale yielding)
K_{Jcd}	dynamic fracture toughness
$K_{Jcd,1T}$	size corrected dynamic fracture toughness
$K_{Jcd,1T\_50\%}$	median fracture toughness curve with 50% failure probability
x_{cl}	distance of origin of fracture from crack tip
R_m	Tensile Strength
W	specimen height
ε_e^{pl}	accumulated plastic equivalent strain
ε_{matrix}	matrix strain
$d\varepsilon/dt$	strain rate
μ	friction coefficient
σ_I	maximum principal stress
$\sigma_{I,matrix}$	maximum principal stress of matrix
σ_p	particle stress
ASME	American Society of Mechanical Engineers
CMOD	crack mouth opening displacement
FEM	Finite-Element Method
MC	Master Curve
SE(B)	single edge-notched (bending)

witnessed for all examined crack tip loading rates from 10^3 to 10^5 MPa $\sqrt{}$m/s. Important in this context is the fact that also the very low crack tip loading rates appear to trigger this mechanism as well, which matches the presented discrepancies between Master Curve (MC) and dynamic fracture mechanics experiments [1–4]. This also proves that current local approach concepts do not have the physical fundament to guarantee reliable assessment in terms of cleavage fracture at elevated loading rates. In addition, different primary cleavage fracture inducing mechanisms, such as detachment of MnS, were proven to be non-existent. Carbide fracture at grain boundaries was identified to be prevailing, which is identical with observations made under quasi-static test conditions.

This part II involves a subsequent numerical investigation to analyze mechanisms 1, 2, 3 and 6. First, the local change in temperature and strain rate at the fractographically obtained origins of cleavage is calculated numerically to discuss the relevance and impact of mechanism 1 and 2 regarding cleavage fracture. Since temperature and strain rate control toughness on a phenomenological level, an analysis of these mechanisms is important for the understanding dynamic fracture in a phenomenological sense. Furthermore, a thorough study of the cleavage fracture controlling mechanical field variables at the origin of fracture is conducted and compared to results from quasi-static investigations, whereas an influence of mechanism 3 is also studied at this level as well. The mechanical field variables inherently conceive the changes in temperature and strain rate, and are the variables which are used for local approach assessment. Finally, a micromechanical approach – involving particle simulations – is applied to examine mechanism 6. Also, the resulting particle stresses upon load are examined too, and compared to similar investigations conducted for quasi-static conditions.

2. Numerical simulations

2.1. Model and material properties

The 3D Finite-Element Method (FEM) model of the SE(B)40-20 specimen used for numerical analysis is displayed in Fig. 1, whereas the specimen's symmetries were used according to the image as well. For reasons of numerical stability a crack front with a radius of 5 μm was used with the aid of fully-integrated 8-node volume elements with a linear displacement function. A mean initial crack length a_0 was determined from fractographic examinations. Displacement-controlled load of the striker was applied according to average experimental CMOD-time courses of the respective loading rates, due to