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Investigation of cleavage fracture under dynamic loading conditions: Part I fractographic analysis

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A R T I C L E I N F O

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A B S T R A C T

The fracture toughness of ferritic steels under dynamic loading conditions on the one hand shows decreasing values with elevated loading rates but on the other hand the shape of the temperature dependent fracture toughness curve has turned out to be different from the static Master Curve according to ASTM E 1921. This difference is often explained by adiabatic heating in the crack tip region, yet it is not clear if there are other additional mechanisms under dynamic loading conditions that contribute to these changes. This work is dedicated to systematically identifying and quantifying additional mechanisms regarding cleavage fracture under dynamic loading conditions. In part I of this study an extensive fractographic analysis of the fracture surfaces was conducted for various crack tip loading rates and testing temperatures. The primary fracture-inducing mechanism was found to be identical to the dominant one under quasi-static conditions (carbide cracking). Yet, the dynamic loading conditions appear to change the origin of fracture, promote local crack arrest, and cause multiple fracture initiation sites that lead to global failure. These results also question the reliability of current local approach concepts if used to assess fracture probability at elevated loading rates. The fractographic results are used in, and complemented by, part II of this study which deals with the numerical analysis of other additional mechanisms such as inertia.

1. Introduction

Brittle failure must be compellingly ruled out in safety-relevant nuclear components such as reactor pressure vessels. The failure of these ferritic-bainitic steels is usually conducted by macroscopic assessment methods in a deterministic or probabilistic manner. Examples for deterministic concepts are given by the ASME-Codes [1–3], while the prominent method in terms of a probabilistic assessment is known as the Master Curve (MC) concept, standardized in ASTM E 1921 [4]. Deterministic concepts assume non-failure if a load parameter like the stress intensity factor K_I remains below a certain material-specific value, i.e. critical fracture toughness K_{Ic}, under dynamic conditions referred to as dynamic fracture toughness K_{Icd}. However, the great practicality and simplicity of this method is confronted with widespread experimental results showing that brittle failure is always associated with a large scatter in results, which is explained by the statistical distribution of potentially cleavage-inducing brittle particles within the material [5]. In this context, macroscopic probabilistic methods such as the MC concept have improved cleavage fracture assessment meaningfully, due to the fact that they respect the nature of cleavage fracture by assessing a probability of failure. This concept solely uses the obtained experimental fracture toughness values, and describes a material's temperature-dependent probability towards brittle failure by using a statistical

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Nomenclature

a_0	initial crack length
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
T_0	Master Curve reference temperature
W	specimen height
ε_e^{pl}	accumulated plastic equivalent strain
$d\varepsilon/dt$	strain rate
σ_I	maximum principal stress
ASME	American Society of Mechanical Engineers
DCG	ductile crack growth
IWM	Fraunhofer Institute for Mechanics of Materials IWM
MC	Master Curve
SE(B)	single edge-notched (bending)

formalism. It assumes a similar progression of all curves for all ferritc-bainitic materials and their conditions, whereas a sole parameter T_0 (MC reference temperature) can be used to classify a materials resistance towards brittle failure. T_0 is defined as the temperature at which the median fracture toughness curve $K_{Jcd,1T\_50\%}$ has a fracture toughness of 100 MPa $\sqrt{m}$. Moreover, more brittle material conditions coincide with a MC shifted towards higher temperatures, and vice versa (more information available in ASTM E 1921 [4]).

Since the reactor catastrophe in Fukushima in 2011 the German competence pool for nuclear technology is especially concerned with the safety assessment of nuclear components subjected to explosions, air plane crashes, earth quakes, etc. [6]. In connection with falling debris onto the reactor pressure vessel the material's behavior at elevated loading rates must be understood and characterized. Eventually, the MC concept is technically allowed to be used to assess brittle failure at elevated loading rates, or in other words dynamic loading conditions. However, recent experimental data from various sources states that the achieved dynamic fracture toughness values K_{Jcd} do not match the calculated shape of the MC, especially for higher temperatures or higher dynamic fracture toughness values. An example of this is shown in Fig. 1 from Reichert et al. [7], while very similar observations have been made by Mayer et al. [8] or Böhme et al. [9]. Fig. 1 shows fracture toughness values of three test series at −20, 0, and +20 °C at an elevated crack tip loading rate of $4 \cdot 10^5$ MPa $\sqrt{m}$/s (rather fast), whereas the dynamic embrittlement, represented by the T_0-shift from quasi-static conditions, is correctly conceived by the MC concept. The dashed line indicates the calculated median facture toughness $K_{Jcd,1T\_50\%}$ for all test series together (multi-temperature method), while reference temperatures for the three individual test series are depicted next to the fracture points with the experimental median value (large white diamonds). It is apparent that the multi-temperature method does not match the experimental results, and that the individual T_0-reference temperatures are very different from the one obtained by the multi-temperature method (−10 °C). Noteworthy at this point is that the test series with lower fracture toughness values at −20 °C does not necessarily produce lower values than expected, but that the median $K_{Jcd,1T\_50\%}$ curve is constructed from all test series, being a best fit for the entire temperature range.

The mentioned discrepancies are often explained by the presence of adiabatic heating at the crack tip due to the short testing times (Zehnder and Rosakis [10]). Schindler and Kalkhof [11] proposed an adjustment of the MC concept by changing the exponent that controls the shape of the curve, which has been pursued and adapted by Reichert et al. [7], Mayer et al. [8], and Böhme et al. [9], unitarily proving this procedure to be accurate. Furthermore, these discrepancies are also observed for rather slow crack tip loading rates of $4 \cdot 10^3$ MPa $\sqrt{m}$/s [7], which only correspond to a nominal test velocity of about 0.025 m/s for the specific specimen geometry used in Reichert et al. [7] (SE(B)40-20).

On the other hand, there exist more complex *local* probabilistic methods to assess cleavage fracture, also known as *local approach*, which numerically calculate global failure of a structure or specimen by direct assessment of local mechanical field values (stresses and strains) in the vicinity of the crack tip. In other words, probability of cleavage fracture is assessed by consideration of real micromechanical processes at the origin of cleavage initiation. Some examples of these local approaches are published by Beremin et al. [12], Faleskog et al. [13], or more recently by Hohe et al. [14], all with similar backgrounds, yet the levels of complexity vary. For ferritic-bainitic steels in the brittle-ductile transition area literature (Knott [15], or