# Determination and definition of fracture toughness of dynamically loaded ductile cast iron

H.-P. Winkler[1], R. Hüggenberg[1], A. Ludwig[2], G. Pusch[2], P. Trubitz[2],
[1]*Gesellschaft für Nuklear-Service mbH, Essen, Germany;*
[2]*Technische Universität Bergakademie Freiberg, Freiberg, Germany*
*e-Mail: hans-peter.winkler@gns.de*
*e-Mail: ludwig@ww.tu-freiberg.de*

## 1 Introduction

For a complete review of component safety, special for accident conditions where as a result of rupture load conditions rapid changes of stresses and deformations occur. For that characteristic dynamic fracture material values are necessary to calculate the stress conditions and to determine the margins against brittle fracture.

For the experimental determination of dynamic fracture toughness values the existing guidelines deliver only first approaches, they are orientated on the rule for static tests.

The paper describe a evaluation procedure, that consider the influence of the structure on the behaviour of crack-propagation of ductile cast iron at -40 °C regarding the experimental determination of dynamic R-curves and the definition of physical and technical crack initiation values.

## 2 Test programme

The goal was to determine the dynamic fracture toughness characteristic values at -40 °C as a function of two different sample sizes. After casting three blocks (block dimensions 780 x 250 x 1660 mm) it was possible to provide six sample blanks with the dimensions length: 1360 mm, width: 150 mm, height: 290 mm, from which large samples were prepared (thickness: 140 mm, width: 280 mm, length: 1350 mm), in the following referred as SE(B)140 samples [1].
The small samples (thickness: 10 mm, width: 10 mm, length: 55 mm), in the following referred to as SE(B)10 samples, were prepared from the large samples in the region behind the fracture surfaces (fig. 1). To avoid an anisotropic structure the SE(B) 140 sample blanks had been manufactured by sand casting under controlled conditions. The fatigue cracks had been manufactured in accordance with the requirements of ASTM E 399-97 [2] and ESIS P2-92 [3].

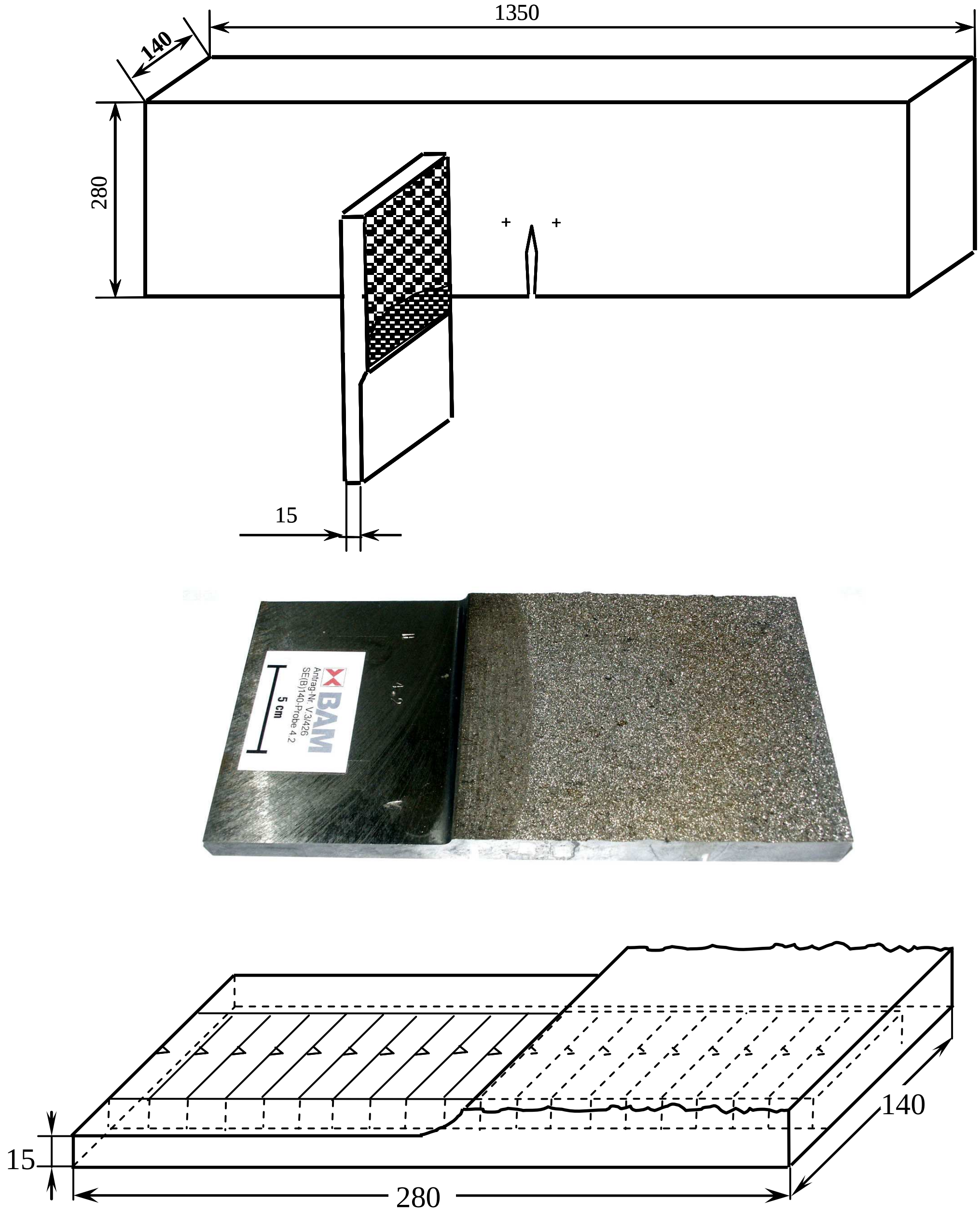
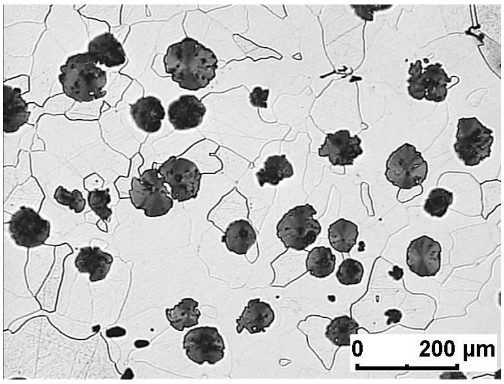



Fig. 1: Sample taking of the SE(B)10 samples (in mm)

## 3 Test material

The examinations were performed on a ferritic ductile cast iron material containing globular graphite (fig. 2).




Microstructure parameters:

Diameter of the graphite nodules $d_G$: 63 µm
Ferrite grain size $d_F$: 62 µm
Particle distance $\lambda$ : 88 µm
Form factor f: 0.71
Number of particles $N_A$: 47 $mm^{-2}$

Fig. 2: Typical microstructure of the test material

The mechanical properties are shown in Table 1.

Table 1: Mechanical characteristics at room temperature

| $R_{p0.2}$ MPa | $R_m$ MPa | $A_5$ % | Z % | E GPa | $\nu$ | HBW 2.5/187.5 |
|---|---|---|---|---|---|---|
| 246 | 362 | 11 | 13 | 172 | 0,28 | 138 |

# 4 Test methodology

## 4.1 Large samples

The loading of the SE(B) 140 samples with fatigue cracking was carried out at -40 °C with the help of a pulse testing machine with a loading rate of $\dot{K} = 5 \cdot 10^4\ \mathrm{MPa}\sqrt{\mathrm{m}}\,\mathrm{s}^{-1}$ [1]. The test preparation, procedure and evaluation are based on ASTM E399-97 [2].

## 4.2 Small samples

The experimental determination of the dynamic cracking resistance curves of the J-integral concept ($J_d$-$\Delta a$ curves) was carried out on the 20 % side-notched SE(B)10 and precracked samples with fatigue cracking according to the "low-blow" technique using an instrumented pendulum impact tester. Thereby, 6 to 8 samples in the region $2{,}8 \cdot 10^4\ \mathrm{MPa}\sqrt{\mathrm{m}}\,\mathrm{s}^{-1} \le \dot{K} \le 5{,}7 \cdot 10^4\ \mathrm{MPa}\sqrt{\mathrm{m}}\,\mathrm{s}^{-1}$ were loaded, the $J_d$ values were determined via the dynamic force-displacement diagrams and the $\Delta a$ values were determined on the fracture surfaces of the samples. The test was prepared, performed and evaluated according to ESIS P2-92 [3]. However, care must be taken that no stable ductile crack propagation takes place. The results of the raster electron microscopic fracture surface-analysis in fig. 3 show that the $\Delta a$ values for the entire range of the $J_d$-$\Delta a$ curve in the result constitute a stable cleavage crack propagation.

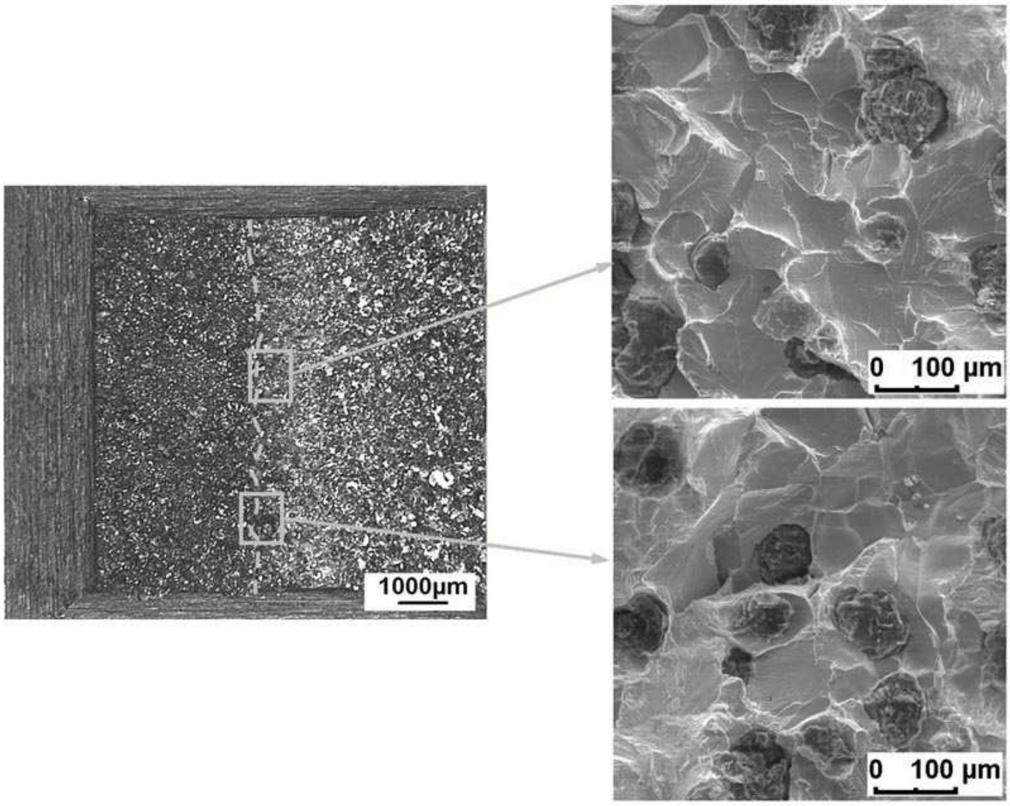



Fig. 3: Cleavage crack propagation on the fracture surface of the SE(B)10 samples at -40 °C

Thereby, it can be assumed that a global unstable crack propagation can be prevented by crack blunting (crack-tip-radius < graphite particle diameter) and energy-dissipative crack arresting (fig. 4).

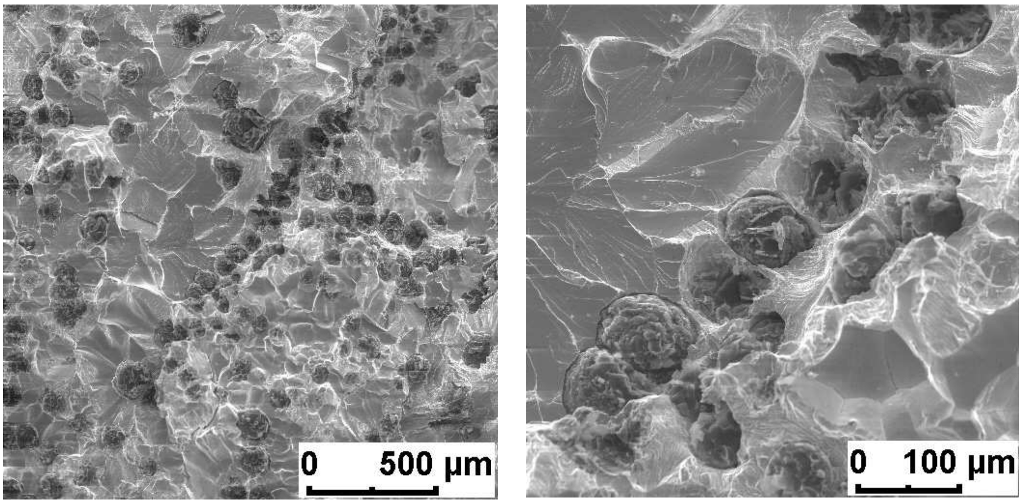



Fig. 4: Crack arresting at a graphite barrier

Since no stretch zone appears with this material-specific crack propagation, the definition of physical crack initiation values according to [3] in analogy to static loading is not possible. The applied procedure for recording and evaluating dynamic crack resistance curves of ferritic ductile cast iron materials can be described as follows (fig. 5):

1. Calculation and determination of the data points $J_d$ and $\Delta a$ according to ESIS P2-92

2. Determination of the dynamic crack initiation value $J_{di/\Delta a=0}$ at $\Delta a$ = 0 mm at the intersection of the linearly extrapolated $J_d$-$\Delta a$ values by using the datas in the range 0.1 mm ≤ $\Delta a$ ≤ 0.5 mm.
In accordance with [3] $\Delta a_{max}$ = 0.5mm results of $\Delta a_{max} \leq 0{,}1$ (W-a) with W = sample width and a = crack length.

3. Determination of a dynamic crack initiation value $J_{d0,2}$. according to $\Delta a$ = 0.2 mm.

4. Conversion of the $J_d$ values to $K_{Id}(J)$ values according to

$$K_{Id}(J) = \left[\frac{J_d \cdot E}{1-\nu^2}\right]^{1/2} \quad (1)$$

Fig. 5 shows furthermore that any processes damaging the microstructure, such as detachment of the graphite particles from the ferritic matrix or crack propagation between the particles, have an order of magnitude corresponding to the respective microstructural parameters.

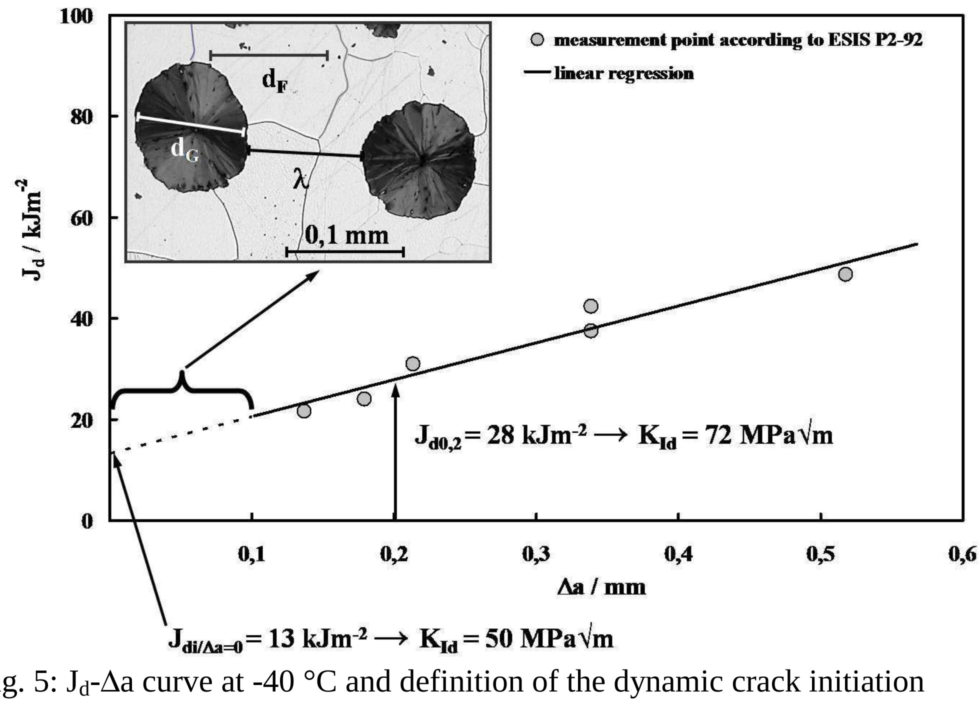



Fig. 5: $J_d$-$\Delta a$ curve at -40 °C and definition of the dynamic crack initiation values

# 5 Test results and discussion

The dynamic fracture toughness values of the K and J integral concept determined with the small and large samples and the conversion according to equation (1) are shown in Table 2. Gray marked data are measured values, the other data are the converted values from measured data by using aq. (1).

Table 2: Dynamic fracture toughness values at -40 °C

| Sample No. | SE(B)140 samples | | SE(B)10 samples | | | |
|---|---|---|---|---|---|---|
| | $K_{Id}$ MPa $\sqrt{m}$ | $J_d(K_{Id})$ kJm $^{-2}$ | $J_{di/\Delta a=0}$ kJm $^{-2}$ | $K_{Id}$ ($J_{di/\Delta a=0}$) MPa $\sqrt{m}$ | $J_{d0,2}$ kJm $^{-2}$ | $K_{Id}$ ($J_{d0,2}$) MPa $\sqrt{m}$ |
| 1 | 67 | 24 | 13 | 50 | 28 | 72 |
| 2 | 71 | 27 | 17 | 56 | 31 | 76 |
| 3 | 75 | 30 | 16 | 56 | 37 | 83 |
| 4 | 79 | 33 | 17 | 56 | 32 | 77 |
| 5 | 71 | 27 | 19 | 59 | 27 | 71 |
| 6 | 64 | 22 | 24 | 66 | 34 | 79 |

The dynamic 0.2 % elongation limit was determined according to BS 7448-3 [4] via the corresponding strain rate at -40 °C with $R_{dp0.2}$ = 378 MPa. Therewith, the $K_{Id}$ values determined with the SE(B)140 samples
fulfil the thickness criterion

$$B \geq 2{,}5\left(\frac{K_{Id}}{R_{dp0,2}}\right)^2 \qquad (2)$$

and thus can be transferred to the component. The extended combined measuring uncertainty (test and measuring technology) can be specified too, resulting in $75\,\mathrm{MPa}\sqrt{\mathrm{m}} \pm 4{,}5\,\mathrm{MPa}\sqrt{\mathrm{m}}$ for sample No. 3 as example.

The scatter of the $K_{Id}$ values in the range from $64\,\mathrm{MPa}\sqrt{\mathrm{m}}$ to $79\,\mathrm{MPa}\sqrt{\mathrm{m}}$ in a material-specific way and can be explained by the heterogeneity of the casting microstructure. This also applies for the dynamic toughness parameter values determined for the SE(B)10 samples with characteristic $J_d$-$\Delta a$ curves according to fig. 5.

The influence of the microstructure here becomes evident via the averaged random sampling of the six $J_d$-$\Delta a$ curves (fig. 6). The figure shows all single data-points of all small samples prepared from the large samples 1 to 6 (see fig 1).

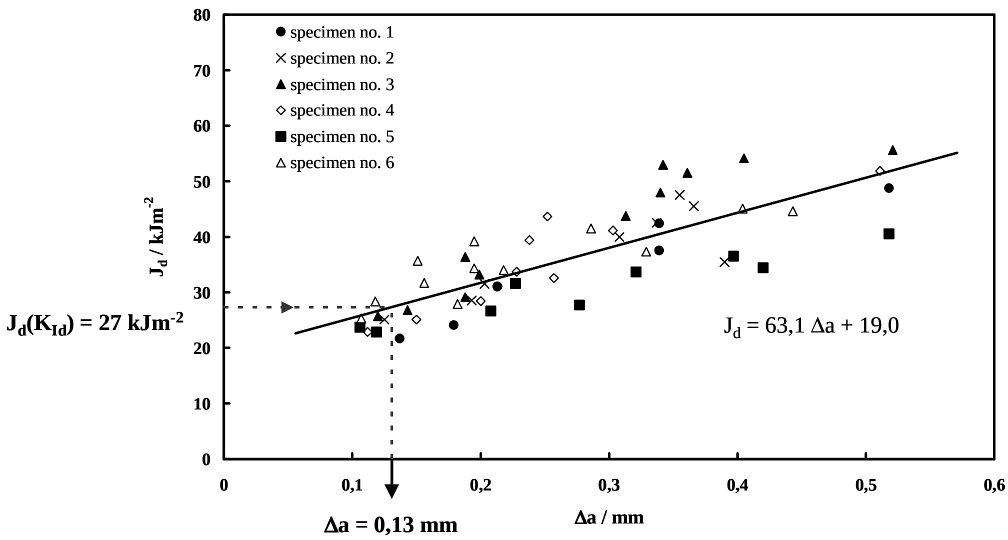



Fig. 6: Classification of the average value $J_d(K_{Id})$ of the SE(B)140 samples in the averaged random sample of the $J_d$-Δa curve of the SE(B)10 samples (-40 °C)

For the average value of the SE(B)140 samples of $K_{Id} = 71 \mathrm{MPa}\sqrt{\mathrm{m}}$ or $J_d(K_{Id})$ = 27 kJm$^{-2}$ follows for classification in the averaged random sample of the Jd-Δa curves a corresponding stable crack propagation for Δa = 0.13 mm (fig. 6). This explains the large extent of agreement of the $J_d(K_{Id})$ values or the $K_{Id}$ values of the SE(B)140 sample with the $J_{d0.2}$ and $K_{Id}(J_{d0.2})$ values determined in agreement with ESIS P2-92 at Δa = 0.2 mm. The dynamic crack initiation values at Δa = 0 mm determined outside of ESIS P2-92 are more conservative, as expected.

## 6 Prospects to the future

Methods for the experimental determination of dynamic fracture toughness values on small specimens via recording of dynamic crack resistance curves can be realised using existing standards [3], [5] or standard drafts [6]. The observed stable cleavage crack extension of ferritic ductile cast iron material demands alternative definitions of physical crack initiation values. Finally this procedure is going to be published as a guideline of VDG (Association of German Foundry Experts). Further investigations are focussed on the transferability of these specific values to samples and components of different thickness. Also the comparison to values measured by single specimen procedures will be done.

## 7 References


[1] W. Baer, Statistische Auswertung dynamischer Bruchmechanikversuche an Großproben aus ferritischem Gusseisen mit Kugelgraphit, 39. Tagung des DVM-Arbeitskreises Bruchvorgänge, Dresden, 13.-14.02.2007, Tagungsband, 319-328

[2] ASTM E 399-97, Standard Test Method for Plane-Strain Toughness of Metallic Materials, ASTM,1997

[3] ESIS P2-92, Procedure for determining the fracture behaviour of metallic materials, European Structural Integrity Society, Delft, 1992

[4] BS 7448-3, Fracture mechanics toughness tests, Part 3: Method for determination of fracture toughness of metallic materials at rates of increase in stress intensity fracture greater than 3 MPam0,5s-1, March 2003

[5] ISO 12135: Metallic materials – Unified method of test for the determination of quasistatic fracture toughness. December 2002

[6] ESIS TC5(2006), Proposed standard methods for instrumented pre-cracked Charpy impact testing of steel, Draft 26, March 2006. (eingereicht bei ISO)