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DYNAMIC FRACTURE TOUGHNESS BEHAVIOUR OF DUCTILE CAST IRON WITH RESPECT TO STRUCTURAL INTEGRITY ASSESSMENT

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ABSTRACT

Modern structural integrity assessment procedures in the field of nuclear related technology incorporate fracture mechanical concepts. Therefore, they inevitably require the availability of both, loading parameters as well as material characteristics in terms of fracture mechanical quantities. Especially in case of dynamic loading conditions, the methods for the determination of the loading parameters need further improvement and there is a lack of material characteristics as well. In Germany, ductile cast iron (DCI) is used for heavy-sectioned casks for radioactive materials. New developments in cask design and efforts to extend the application limits require further investigations. The present study is part of an ongoing fracture mechanics research programme of BAM which is focused on the systematic mechanical and fracture mechanical material characterisation of DCI materials under dynamic loading conditions. In this study, results of fracture mechanics investigations on ductile cast iron from an original DCI container with a wide variety of microstructure under dynamic loading conditions in the temperature range from -50 °C to +22 °C are presented. Large scale as well as small scale single edge crack bend specimens SE(B) with thicknesses of 140 mm and 15 mm, respectively were tested. Furthermore, it is reported on the results of a finite element simulation of the dynamic large scale fracture mechanics tests. Strength and deformation characteristics were determined in dynamic tensile tests. They are discussed with respect to the influence of pearlite content and test temperature. The material specific experimental difficulties in the determination of reliable dynamic crack initiation toughness values of DCI are outlined.

KEY WORDS: dynamic fracture toughness, ductile cast iron, structural integrity, component, specimen geometry, testing, loading rate, test temperature, microstructure, graphite morphology, crack initiation toughness, analysis procedure, finite element simulation, fracture mechanics

INTRODUCTION

Modern structural integrity assessment procedures in the field of nuclear related technology incorporate fracture mechanical concepts. Therefore, they inevitably require the availability of both, loading parameters as well as material characteristics in terms of fracture mechanical quantities. Especially in case of dynamic loading conditions, the methods for the determination of the loading parameters need further improvement and there is a lack of material characteristics as well. Furthermore, at present, there are no standards available for the determination of dynamic fracture mechanics material characteristics.

In Germany, ductile cast iron (DCI) has been used for heavy-sectioned casks for radioactive materials for more than 20 years. New developments in cask design and efforts to extend the application limits require further investigations and the improvement of the BAM safety assessment concept for nodular cast iron containers [1,2] originally established in the 1980s. The present study is part of an ongoing fracture mechanics research programme of BAM which is focused on the systematic mechanical and fracture mechanical material characterisation of DCI materials under dynamic loading conditions. The variety of excellent experimental facilities for dynamic materials testing at BAM (test stand for shock loading of large structures and specimens, servohydraulic high speed universal testing systems, instrumented drop tower, different Charpy instrumented impact testing machines etc.) combined with extensive experience allow systematic investigations taking influence factors like specimen geometry, loading rate and test temperature into account. With DCI materials, specific microstructural parameters, such as the pearlite content, size, morphology and distribution of graphite nodules in the ferritic matrix have to be considered additionally.

INVESTIGATED DUCTILE CAST IRON MATERIAL AND FRACTURE MECHANICS EXPERIMENTS

Investigated dutile cast iron material

The ductile cast iron investigated in this study, EN-GJS-400-15 according to the German material standardization, was taken from an original cubic waste container which locally had not totally fulfilled the required material specification and was therefore used for research purposes, Fig. 1. As it can be seen from Fig. 1, the thickness of the

SE(B)140 large scale fracture mechanics specimens (140 mm) is in the same range as the wall thickness of the component (160 mm). Due to the cooling conditions in this large casting the microstructure was not homogeneously distributed over the wall thickness. Therefore, the investigated specimens represent a wide variety of microstructure in terms of pearlite content of the matrix (up to 30 %) as well as size and distribution of the graphite nodules. After the tests, the actual microstructure of each SE(B)140 specimen was examined and quantified in whole the ligament area in order to ensure the correlation between microstructure and the fracture mechanics properties determined. Tensile specimens and smaller fracture mechanics specimens were machined from the tested SE(B)140 specimens.

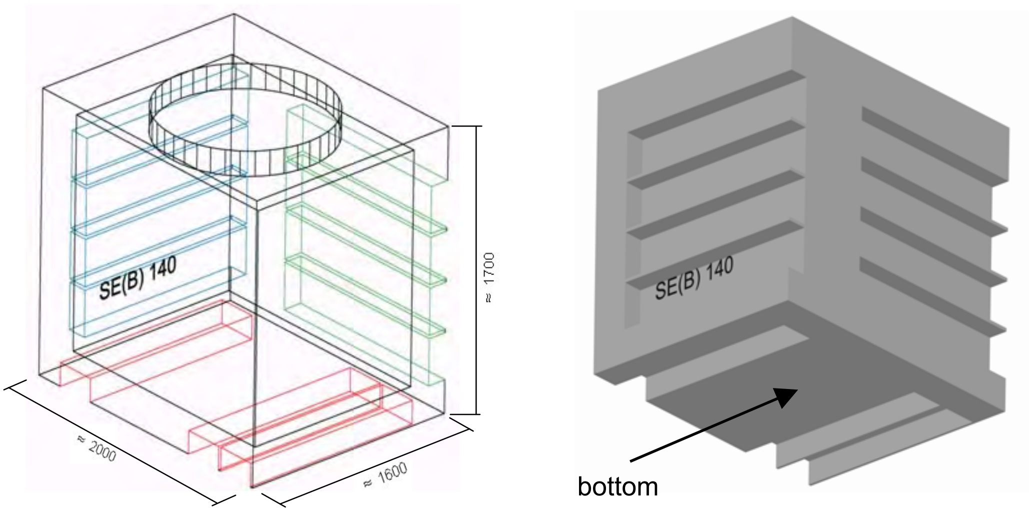


Fig. 1 Specimen cutting from a cubic waste container of ductile cast iron with a wall thickness of 160 mm

The materials strength, given by the 0.2 %-offset yield strength, $R_{p0.2}$, seems to be on a comparable level for pearlite contents not exceeding 20 %. However, an increasing amount of pearlite results in reduced ductility values. As expected, an increase in loading speed leads to higher strength values. Concerning the ductility, the limited available data does not indicate a clear influence of the loading speed.

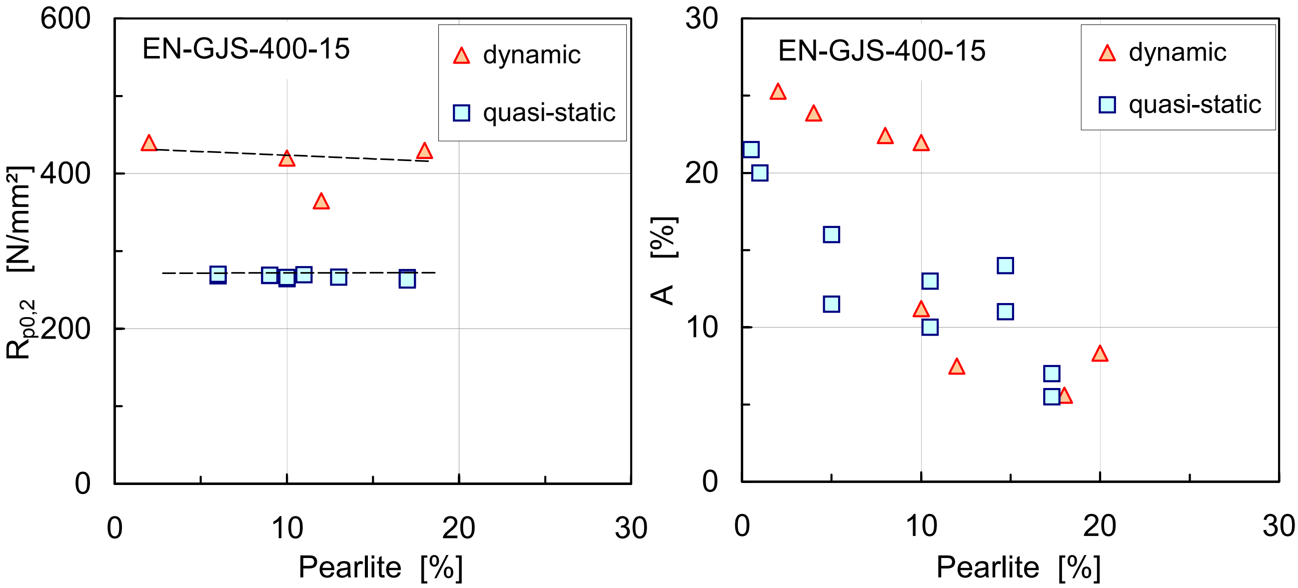
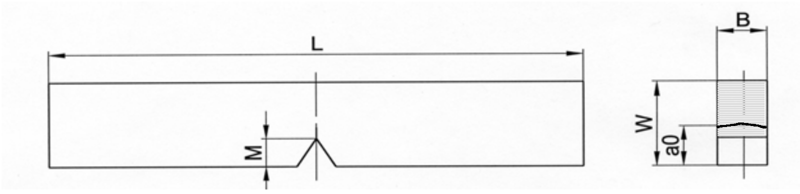


Fig. 2 Yield strength, $R_{p0.2}$, and ultimate elongation, A, of DCI as a function of pearlite content at T = 22 °C under quasi-static and dynamic ($\dot{\varepsilon} \approx 1 \cdot 10^2$ s^{-1}) loading conditions, respectively.

Dynamic fracture mechanics experiments

The fracture mechanical investigations included the testing of large scale component like (thickness 140 mm) and small (thickness 15 mm) single edge bend specimens (SE(B)) at elevated loading rates. A schematic outline and characteristic dimensions of the specimens are given in Fig. 3.



Specimen geometry	SE(B)15 specimen	SE(B)140 specimen
Thickness B [mm]	15	140
Width W [mm]	30	280
Length L [mm]	160	1350
Mechanical crack starter notch M [mm]	10	112
Initial crack length a_0 [mm]	15	140
Span S [mm]	120	1120

Fig. 3 Schematic SE(B) specimen and geometry dimensions

Prior to testing, all specimens were fatigue precracked on a 20 MN servohydraulic universal testing machine providing initial crack length ratios of $a_0/W = 0.5$.

The experimental determination of fracture toughness values using SE(B)140 bend specimens was carried out on a test stand for shock loading in dependence on test temperature and microstructure, Fig. 4.

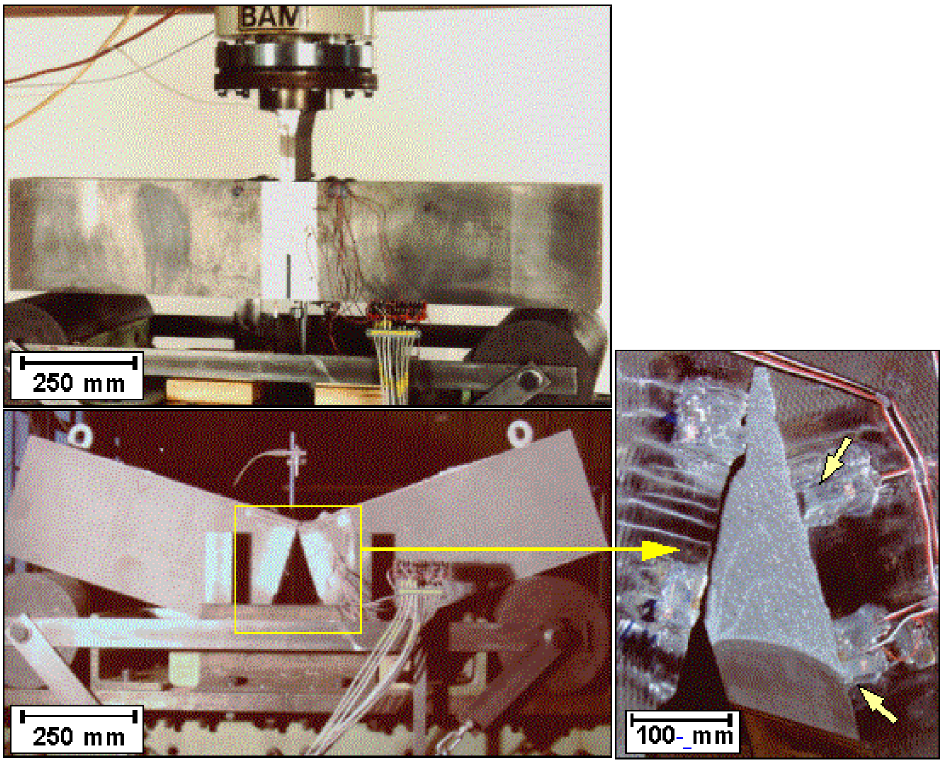


Fig. 4 Test arrangement for experimental determination of dynamic fracture toughness values of DCI materials using large scale SE(B)140 specimens (arrows mark strain gages)

The test stand is operated by a servohydraulic test cylinder of 1000 kN maximum force and 4 m/s maximum speed. In the tests loading speeds of about 2.5 m/s were reached. The measurement of force was realised simultaneously by four strain gages that had been placed on the top side of the specimens near the ligament area. Prior to the tests, all strain gages had been calibrated statically. In order to minimise dynamic effects, an optimised damping layer made of technical rubber was placed between the tup and the specimen. Furthermore, the displacement of the specimen was measured in the load line. As shown in Fig. 4, the specimens were additionally instrumented with a set of foil strain gages as well as crack extension sensors in the ligament area. By means of this instrumentation, the crack initiation could reliably be deduced. The analysis of the results was performed by adoption of the formulae and validity requirements for static K_I calculation according to ASTM E 1820 [3]. The requirements of ASTM E 1820 for rapid loading K_{Ic} determination were met and average stress intensity rates, $\dot{K}$, of about $5 \cdot 10^4$ MPa√m/s were deduced. Dynamic fracture toughness values, K_{Id}, were determined by use of the force values in the moment of crack initiation.

The experiments for the determination of dynamic crack resistance curves on SE(B)15 specimens were performed with a 750 J Charpy impact testing machine using an instrumented 150 J hammer and by practising the low-blow multiple specimen technique, Fig. 5.

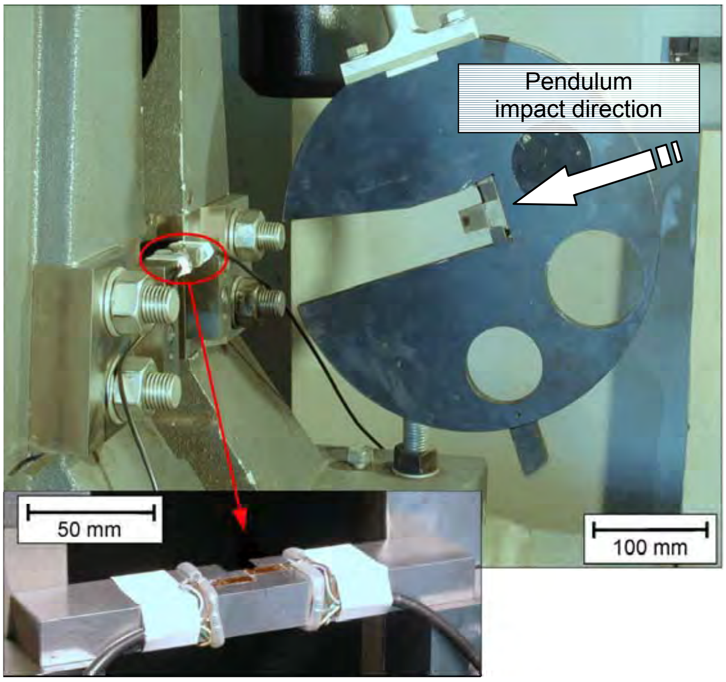


Fig. 5 Experimental determination of dynamic crack resistance curves of DCI materials by low-blow technique using SE(B)15 specimens

Within these configuration impact speeds in the range of 1 to 2 m/s were realised. By analysis of the registered force-deflection curves dynamic crack resistance curves were deduced by application of the J-integral concept and dynamic crack initiation toughness values were determined based on the regulations of ASTM E 1820 as well as ESIS P2 [4].

Finite element simulation of the dynamic large scale fracture mechanics tests

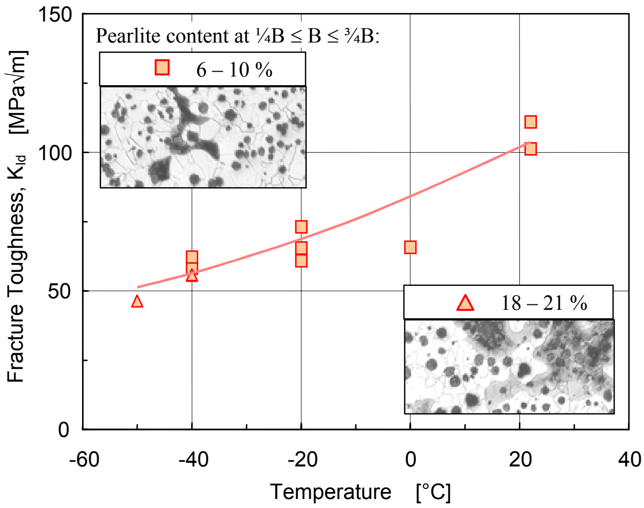
Due to the lack of introduced standard procedures for dynamic fracture mechanics investigations the analysis of the large scale bending tests had been performed by adoption of the available static formulae for fracture toughness calculation. In order to validate this procedure, numerical analysis of the dynamic large scale fracture mechanics tests has been performed and contrasted with the experimental data [5].

The stress intensity factor was determined by analysis of the dynamic J-integral along different integration contours around the crack tip taking dynamic effects into account. To simulate the experimental boundary conditions as exactly as possible different 2d- and 3d-models as well as different ways of load input were investigated. The results show that the analysis of the dynamic large scale fracture mechanics tests and the determination of dynamic K_{Id} material characteristics based on static formulae provides correct data. It is pointed out that this applies for loading conditions in the range of the experimentally realised loading speeds and damping of the tup touch down. The numerically and experimentally determined K_{Id} values show good agreement, especially in the range of crack initiation. Furthermore, the numerically determined loading rate in terms of $\dot{K}$ closely equals the experimentally measured loading rate dK/dt. For further details it is referred to reference [5].

DISCUSSION OF RESULTS

Dynamic fracture toughness of heavy sectioned DCI

The dynamic fracture toughness values K_{Id} of ductile cast iron show a remarkable decrease with decreasing temperature in the investigated range between +22 °C and -50 °C, Fig. 6. This material response describes the transition behaviour of dynamic fracture toughness of DCI in dependence on the test temperature. In the upper transition range of fracture toughness towards ambient temperature elastic-plastic material behaviour gains growing influence. At test temperatures of -40 °C and -50 °C the lower shelf of fracture toughness - characterised by fully linear-elastic material behaviour and brittle fracture - is almost reached. It should be stressed that in the investigated temperature range all fracture mechanics characteristics of the SE(B)140 specimen met the requirements for valid K_{Ic} or K_{Id} values, respectively.



T [°C]	Pearlite content ± s [%] at ¼B ≤ B ≤ ¾B	K_{Id} [MPa√m]
-50	21 ± 6.0	46
-40	21 ± 6.6	56
	18 ± 10.6	56
	9 ± 3.3	62
	7 ± 3.0	58
-20	8 ± 3.7	61
	8 ± 3.6	73
	8 ± 3.3	65
0	9 ± 3.7	66
22	10 ± 4.8	111
	6 ± 3.6	101

Fig. 6 Dynamic fracture toughness of DCI as function of temperature and pearlite content, loading rate $\dot{K} \approx 5 \cdot 10^4$ MPa√m/s, SE(B)140 specimens

Comparison of dynamic and static fracture toughness behaviour of DCI

As pictured in Fig. 7, at quasi-static loading conditions, the transition region where ductile fracture changes to brittle fracture is for C(T)100 specimens approximately between -40 °C and -80 °C [6]. In Fig. 7, the results of the present investigations on SE(B)140 specimens show that in comparison to quasi-static loading conditions the transition range is shifted to higher temperatures between about -40 °C and ambient temperature due to the elevated loading rates. Nevertheless, there should be a certain increase in toughness in the upper shelf region which was not in the focus of the present investigations as a result of increased material strength in the case of dynamic loading.

Dynamic fracture toughness behaviour of DCI investigated by testing of SE(B)15 specimens

Fracture mechanics characteristics of DCI are required for structural safety analysis within the container design and - with respect to the relevant material specification in case of irregularities of the cast iron quality - for production control and quality assurance programs. In the latter case, the fracture mechanical evaluation procedure is restricted to the results of relatively small specimens which can be machined from drilling cores taken directly from the container without totally destroying the component. Therefore, smaller bend type specimens of SE(B)15 geometry, Fig. 3, were investigated in the present study too.

Due to the elastic-plastic fracture behaviour of these specimens dynamic crack resistance curves could be determined and dynamic crack initiation toughness values were deduced. Fig. 8 and Table 1 show that both, the dynamic crack initiation toughness values as well as the level of the dynamic crack resistance curves are strongly affected by the pearlite content. Increasing pearlite content leads to lower crack resistance. The same way, a decrease of the test temperature results in lower fracture toughness such as example indicated in Fig. 9 and Table 1 for ferritic DCI (0 % pearlite).

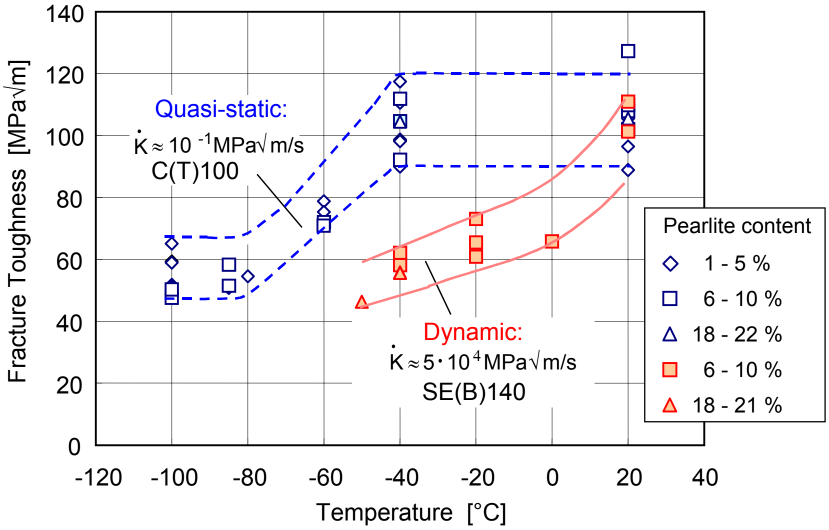


Fig. 7 Fracture toughness behaviour of DCI as a function of test temperature and loading rate, C(T)100 and SE(B)140 specimens

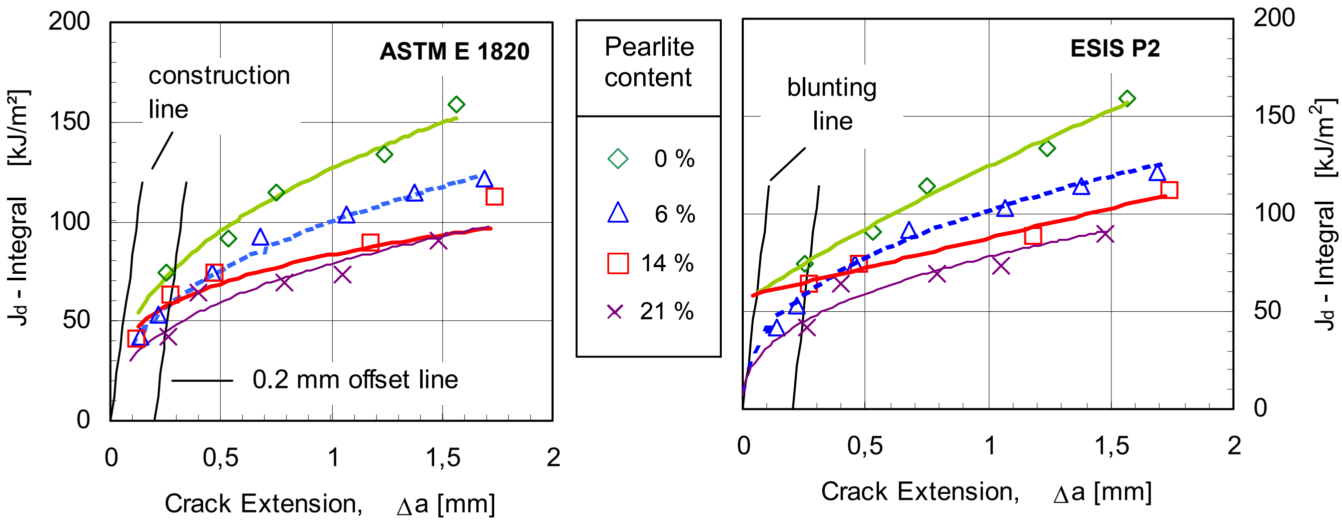


Fig. 8 Crack resistance behaviour of DCI at ambient temperature under impact loading conditions (low-blow test with $v_0 \approx 1$ m/s) as a function of pearlite content; analysis according to ASTM and ESIS P2, resp.; SE(B)15 specimens

Table 1. Dynamic crack initiation toughness values of DCI as a function of pearlite content, analysis standard and test temperature; low-blow test with $v_0 \approx 1$ m/s, SE(B)15 specimens

Test temperature		Ambient temperature				- 20 [°C]
Microstructure		Pearlite content [%] 0	6	14	21	Pearlite content 0 %
ESIS P2	J_{dBL} [kJ/m²]	59 (103)*)	22 (63)	58 (102)	14 (49)	29 (72)
	$J_{d0.2}$ [kJ/m²]	70 (112)	53 (98)	63 (106)	41 (83)	46 (91)
	$J_{d0.2BL}$ [kJ/m²]	76 (117)	59 (103)	64 (107)	44 (86)	48 (93)
ASTM E 1820	J_{Id} [kJ/m²]	70 (112)	54 (99)	56 (100)	43 (88)	49 (94)

*) The numbers in brackets are the dynamic fracture toughness values in terms of dynamic stress intensity K_J in MPa√m as they result from formal conversion of the dynamic J-values provided plane stress state.

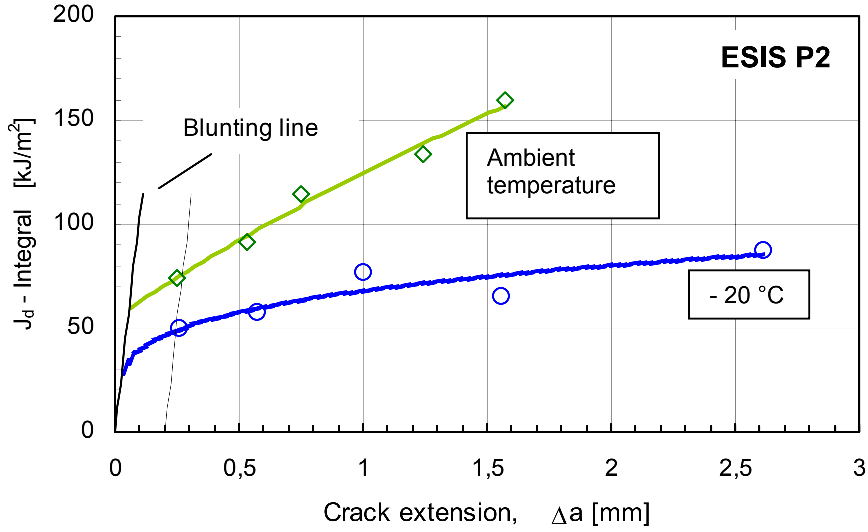


Fig. 9 Influence of test temperature on the crack resistance behaviour of ferritic DCI (0 % pearlite) under impact loading conditions (low-blow test with $v_0 \approx 1$ m/s); analysis according to ESIS P2, SE(B)15 specimens

A comparison of the results of the large scale SE(B)140 tests with the SE(B)15 specimen results can be undertaken for the ambient temperature test condition, Fig. 6 and Fig. 7 as well as Table 1. It has to be underlined that at present there is only very limited data available. But it seems that both specimen geometries lead to comparable results in terms of dynamic fracture toughness.

General aspects of dynamic R-curve testing and analysis with DCI materials

Due to the lack of introduced test standards for dynamic loading conditions the analysis of the present investigations was performed by formal adoption of the regulations of the relevant standards for static testing and elevated loading rates. As can be seen from Fig. 8 and Table 1, different test standards systematically provide specific differences in terms of the dynamic fracture toughness values deduced independent from test temperature or microstructure. Basically, ASTM and ESIS use different procedures and mathematical functions for curve fitting of the crack resistance curves. But within both procedures the availability of sufficient data points in the blunting range and at small amounts of stable crack growth as well as their proper spacing is essential to qualify the R-curve in that range where the characteristics are deduced later although the analysis procedures take these first J_d–Δa data points only very limited into account, Fig. 8. Keeping this background in mind it has to be mentioned that the relative low level of fracture toughness of DCI and its heterogeneous microstructure often cause experimental difficulties in the crack initiation region in case of multiple specimen technique. Therefore, the relevant experimental tools and techniques are currently improved. Furthermore, the blunting line determined by the ESIS recommendations is steeper (more conservative) than the ASTM definition. Within the ASTM framework only one single parameter for crack initiation toughness, J_{Id}, is determined in the intersection of the 0.2 mm offset line with the crack resistance curve. This parameter already includes certain amounts of stable crack growth and it therefore denotes a technical measure of crack initiation toughness. It is approximately in the same order of magnitude as the technical crack initiation toughness parameter of ESIS, $J_{d0.2BL}$, defined in the intersection of the 0.2 mm offset line of the ESIS blunting line with the crack resistance curve, Table 1.

On the other hand, material specific difficulties especially in dynamic fracture mechanics testing of DCI materials can be identified: typical high roughness of the fracture surface due to the microstructure leading to highly difficult conditions in identifying and quantifying amounts of crack growth as well as a nearly non-measurable stretched-zone so that this parameter is not available for the definition of physical crack initiation toughness values as it is known from static loading and other materials.

Within the assessment of component safety exclusion of crack initiation is basically required [7]. Furthermore, only physical crack initiation toughness parameters (like J_{dBL}) which describe the materials toughness at the very beginning of stable crack growth are regarded as independent from specimen size and therefore transferable to components. So, the problem of how to determine a dynamic crack initiation toughness parameter from dynamic crack resistance curves which incorporates both, description of physical crack initiation as well as a reliable basis of experimental data is essential and difficult. At present, it still has to be discussed carefully which characteristics should be used for safety assessment: the more reliable but technical dynamic crack initiation toughness characteristics like J_{Id} or physical crack initiation toughness characteristics like J_{dBL}. The latter should be the correct values in the physical sense and they are more conservative but include a higher experimental uncertainty. More experimental and numerical investigations are needed on this item.

SUMMARY AND OUTLOOK

In comparison to static test results an increasing loading rate is predominantly responsible for a higher transition temperature and the change from elastic-plastic to linear-elastic material behaviour in DCI. The lower bound static fracture toughness value of 50 MPa√m used for DCI in the design code for transport and storage casks in Germany was confirmed by first investigations at dynamic loading rates.

At present, BAM is working on a research programme which comprises systematic investigations of the mechanical and fracture mechanical behaviour of heavy section DCI at dynamic rates taking parameters into account like variation of microstructure, test temperature, sample and component size and loading rate. Furthermore, experimental and analysis aspects like qualification of single specimen techniques for dynamic testing of DCI or statistical data treatment are in the focus of these investigations.

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