INVESTIGATIONS ON THE DYNAMIC FRACTURE TOUGHNESS OF HEAVY-SECTION DUCTILE CAST IRON FOR TRANSPORT AND STORAGE CASKS

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ABSTRACT

In consideration of the specific demands required for heavy-section ductile cast iron (DCI) for transport and storage casks the fracture mechanics research programme of BAM is focused on a systematic material characterization under static and dynamic loading conditions with respect to such parameters as microstructure, test temperature, sample size and loading rate.

In the present study, ductile cast iron from an original DCI container with a wide variety of microstructure was investigated in order to determine the materials fracture toughness under dynamic loading conditions in the temperature range from -50 °C to +22 °C using three-point bending specimens with thicknesses of 140 mm and 15 mm, respectively. In contrast to static fracture behavior, the fracture toughness values of thick-walled DCI at higher loading rates show a remarkable reduction with decreasing temperature between +22 °C and -50 °C and a significant shift of the transition range from -40 °C up to +22 °C. On the other hand, the lower bound fracture toughness value used in the design code for transport and storage casks of DCI in Germany was confirmed for dynamic loading conditions by these first investigations using large specimens. Furthermore, at present, BAM works on a research program which comprises systematic investigations of the mechanical and fracture mechanical behavior of heavy section DCI at elevated loading rates.

INTRODUCTION

For more than twenty years ductile cast iron has been used very successfully for spent fuel casks in Germany. During this period the mechanical behavior of hundreds of containers has been investigated. Based on the BAM acceptance criteria for transport and storage containers, material specifications for DCI were established [1-3]. Now, new developments in cask design as well as efforts to extend the application limits require further investigations, especially in the field of fracture mechanical assessment of DCI at elevated loading rates.

The materials toughness of DCI in terms of fracture mechanics characteristics is strongly influenced by microstructural parameters, especially the pearlite content as well as size, morphology and distribution of graphite nodules in the ferritic matrix. Furthermore, it has to be taken into account that in large DCI castings the microstructure is often not homogeneously distributed over the wall thickness.

The International Atomic Energy Agency (IAEA) standard requires that containers certified for transport have to withstand hypothetical accidents, for example, a 9 meter free drop onto an essentially unyielding target at the lowest service temperature of -40 °C without the loss of radioactive contents [4]. Therefore, under these accident conditions, the influence of strain rate at the crack tip on the material behavior has to be considered within design and safety analysis of containers and relevant material characteristics have to be provided.

INVESTIGATED NODULAR CAST IRON MATERIAL

The nodular cast iron investigated in this study was taken from a container which had not totally fullfilled the required material specifications. Due to the cooling conditions in this large casting the microstructure was not homogeneously distributed over the wallthickness. The investigated specimens represent a wide variety of microstructure in terms of pearlite content of the matrix as well as size and distribution of the graphite nodules. Therefore, the mechanical properties vary either, as it can be seen from Figure 1. The materials strength, given by the 0,2 %-offset yield strength, $R_{p0,2}$, seems to be on a comparabel 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.

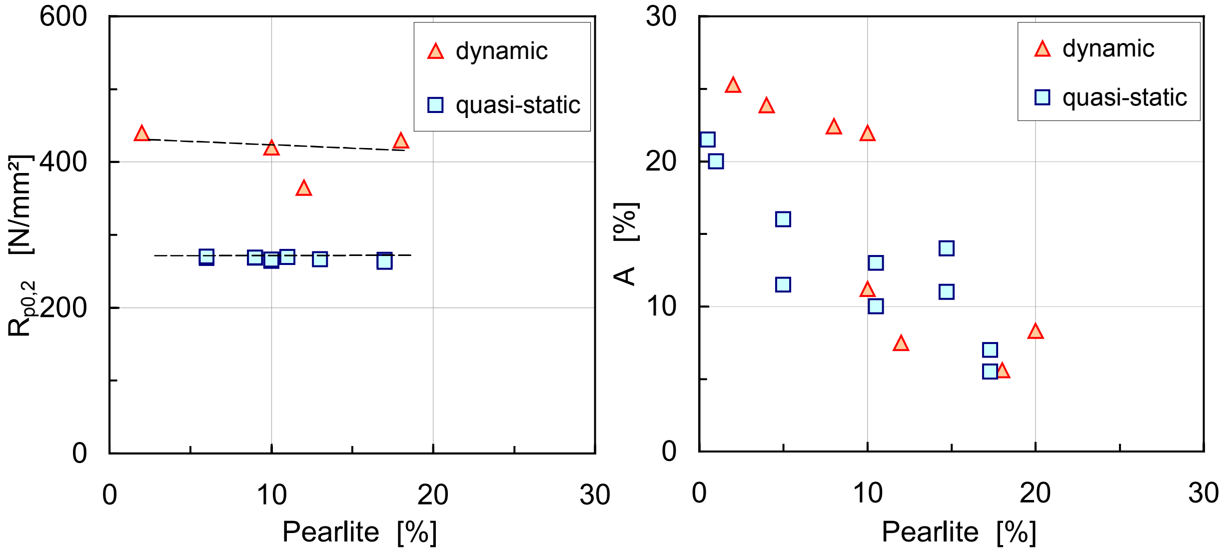
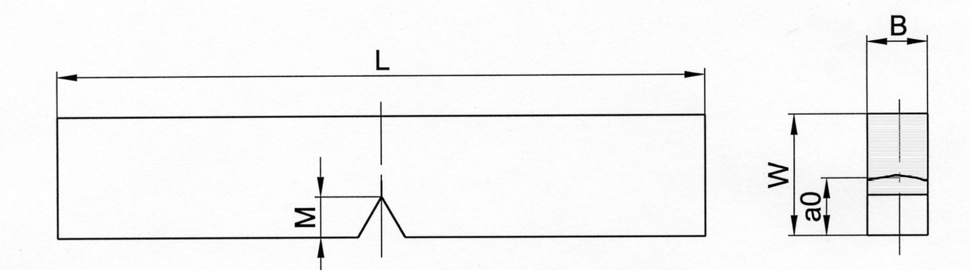


Figure 1, Yield strength, $R_{p0,2}$, and ultimate elongation, A, of DCI as a function of pearlite content at T = 22 °C under quasi-static and dynamic ($\dot{\varepsilon} \approx 1 \cdot 10^2$ s^{-1}) loading conditions, respectively.

EXPERIMENTAL PROCEDURE

The fracture mechanical investigations included the testing of large (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 Figure 2. Prior to testing, all specimens were fatigue precracked providing initial a_0/W ratios of 0.5.

The experimental determination of fracture toughness values using SE(B)140 bend specimens was carried out in a test stand for shock loading, Figure 3. The test stand is operated by a servohydraulic test cylinder of 1000 kN maximum force and 4 m/s maximum speed. In the fracture mechanical tests a maximum force of 700 kN was reached at an impact speed of 2.5 m/s. As shown in Figure 3, the specimens were instrumented with a set of foil strain gauges as well as crack extension sensors in the ligament area. By means of this instrumentation, the crack initiation could reliably be deduced and dynamic fracture toughness values were determined. Within the analysis of the results the requirements of ASTM E 1820 standard [5] for rapid loading K_{Ic} determination were adopted and met so that valid dynamic fracture toughness values K_{Id} were determined. The average stress intensity rate, $\dot{K}$, was about $5\cdot10^4$ MPa√m/s.



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

Figure 2, SE(B) specimen dimensions

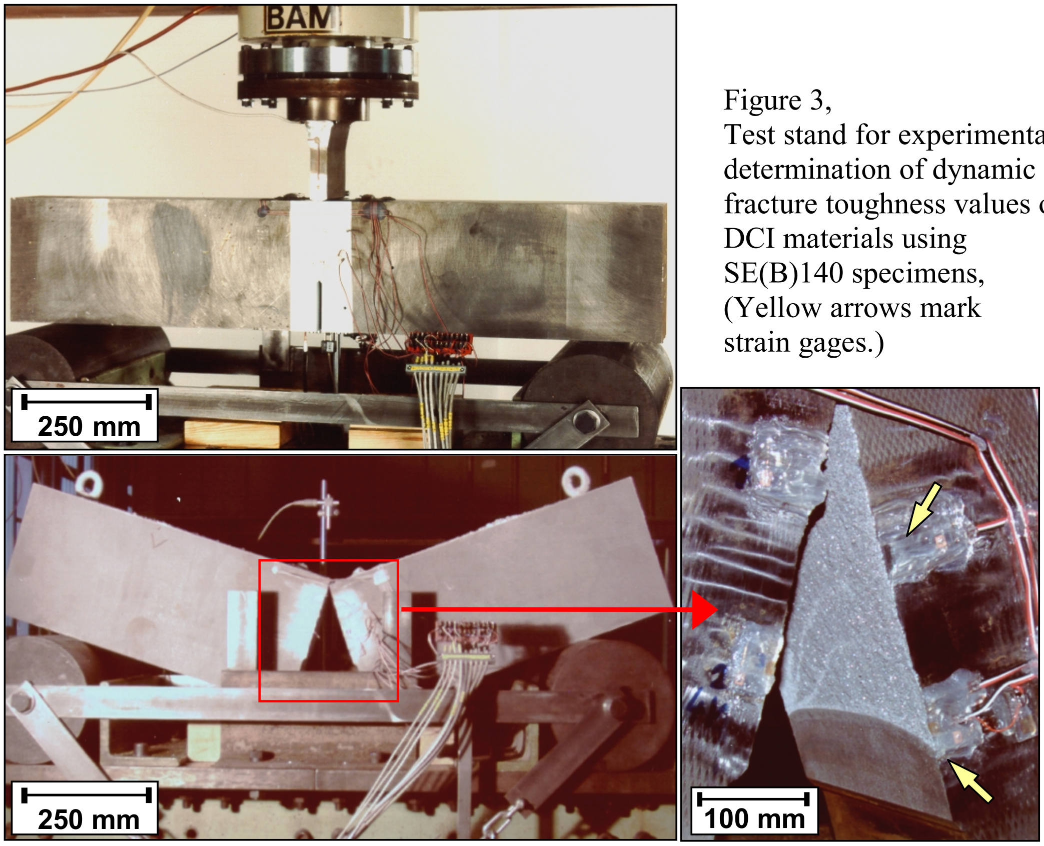


Figure 3,
Test stand for experimental determination of dynamic fracture toughness values of DCI materials using SE(B)140 specimens, (Yellow arrows mark strain gages.)

The experiments for the determination of dynamic crack resistance curves on SE(B)15 specimens were performed with a 750 kJ Charpy impact testing machine using an instrumented 150 J hammer and by practising the low-blow multiple specimen technique, Figure 4. 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. Dynamic crack initiation toughness values J_{Ic} were determined from these dynamic J-R curves based on the regulations of ASTM E 1820 standard.

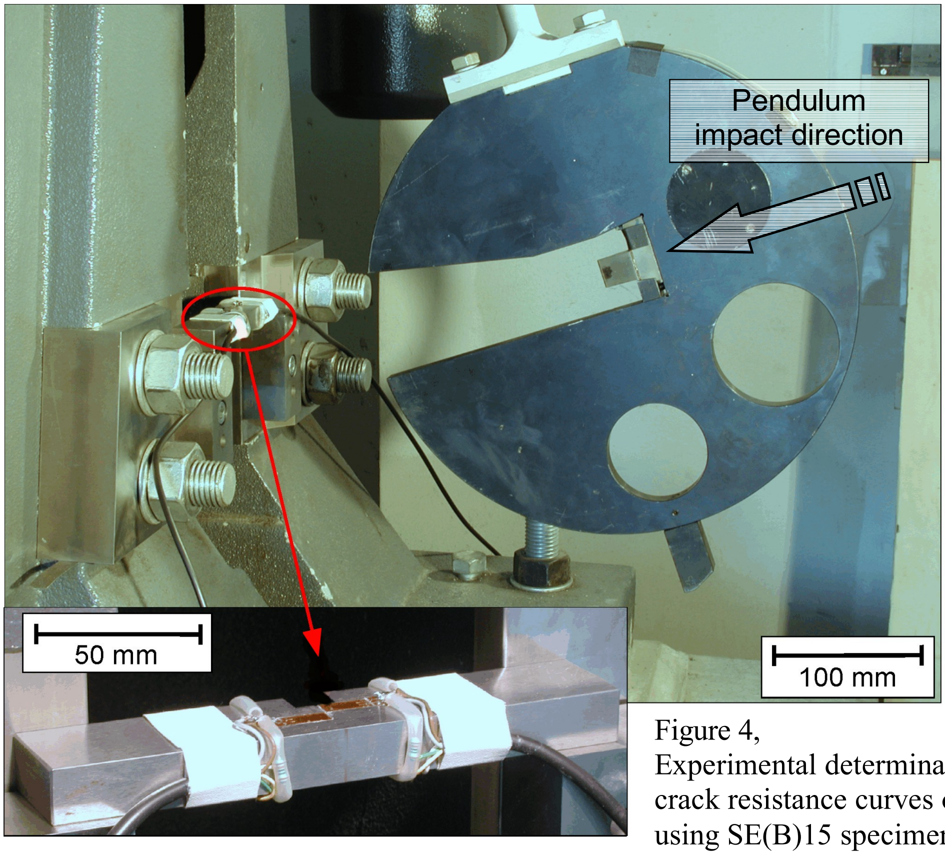


Figure 4,
Experimental determination of dynamic crack resistance curves of DCI materials using SE(B)15 specimens

RESULTS AND DISCUSSION

The fracture toughness values of ductile cast iron at elevated loading rates show a remarkable decrease with decreasing temperature between +22 °C and -50 °C (Figure 5, Table 1). This material response describes the transition behavior 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 behavior gains growing influence. At test temperatures of -40 °C and -50 °C the lower shelf of fracture toughness - characterised by fully linear-elastic material behavior 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.

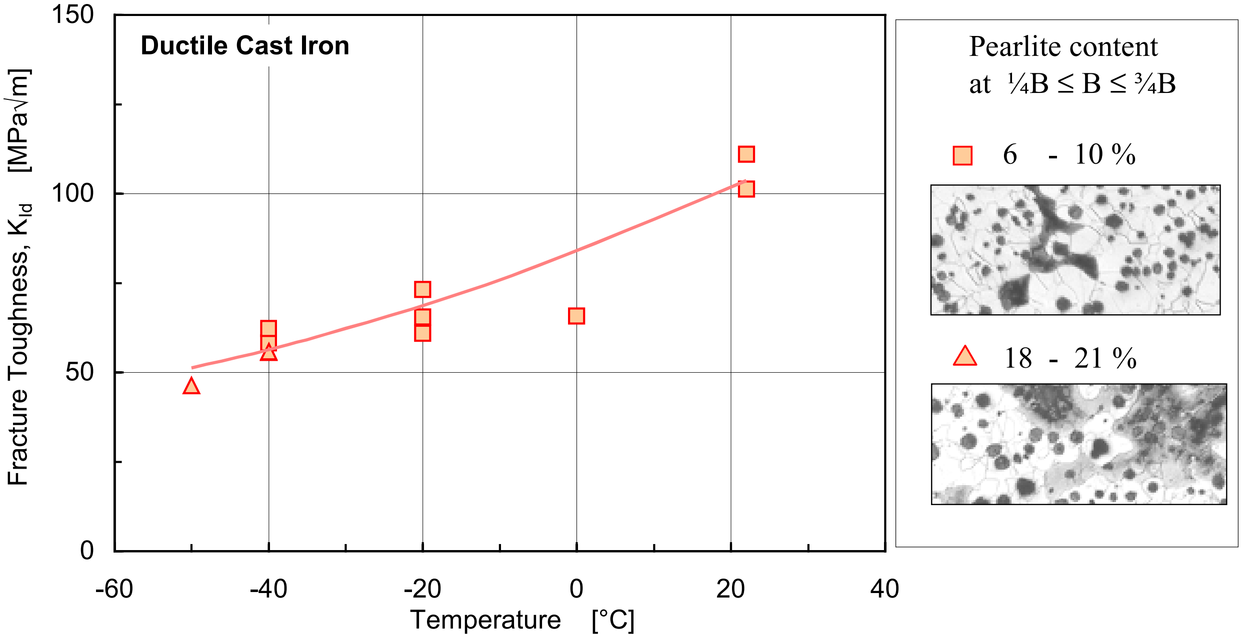


Figure 5, Dynamic fracture toughness of DCI as a function of temperature and pearlite content at test temperatures from –50 °C to +22 °C and loading rate $\dot{K} \approx 5\cdot10^4$ MPa√m/s, SE(B)140 specimens.

Table 1, Fracture mechanics values of DCI under impact loading conditions, SE(B)140 specimens, loading rate $\dot{K} \approx 5\cdot10^4$ MPa√m/s.

Temperature T [°C]	Pearlite content ± s [%] at ¼B ≤ B ≤ ¾B	Dynamic fracture toughness 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

At static loading conditions, the transition region where ductile fracture changes to brittle fracture is supposed to be between -80 °C and -100 °C for small specimens [6], and for larger thicknesses between -40 °C and -80 °C as pictured in Figure 6. In Figure 6, the results of the present investigations show that in comparison to quasi-static loading conditions the transition range is shifted to higher temperatures between about -40 °C and +22 °C due to the elevated loading rates. The levels of fracture toughness values in the lower and upper shelf are nearly equal to those of static loading conditions. Nevertheless, there should be a certain increase in thoughness in the upper shelf region as a result of increased material strength in the case of dynamic loading.

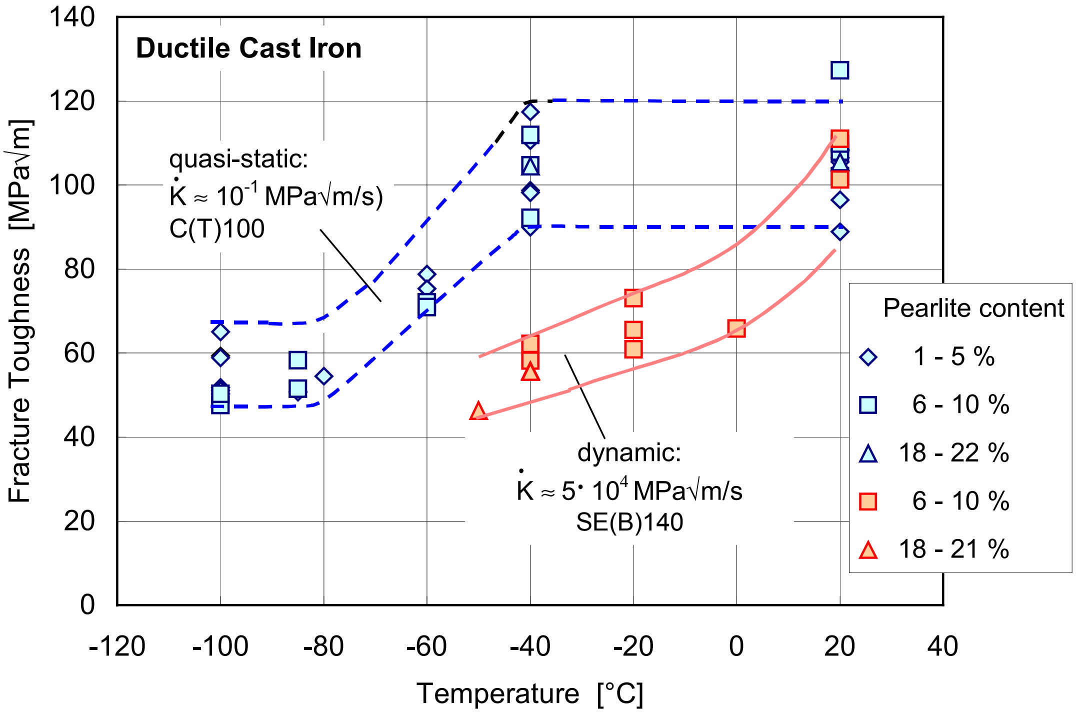
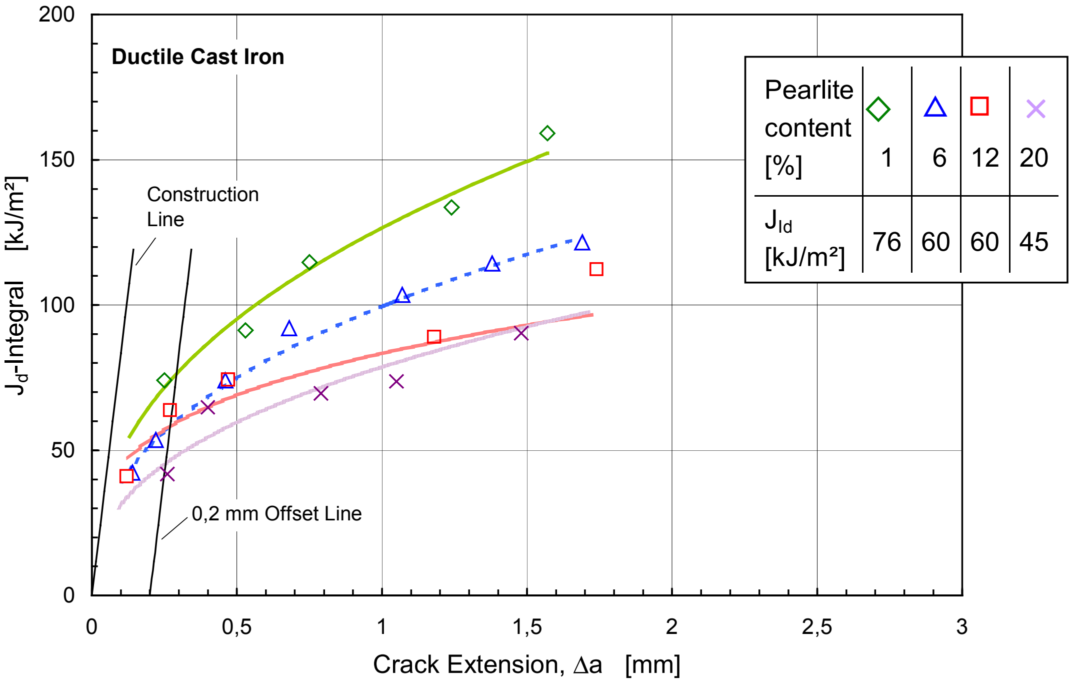


Figure 6, Fracture toughness behavior of ductile cast iron as a function of test temperature and loading rate (specimen dimensions and loading rate are noted in the figure), [2, 3].

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 samples taken directly from the container without totally destroying the component. Therefore, smaller bend type specimens of SE(B)15 geometry, Figure 2, were investigated in the present study.

Due to the elastic-plastic fracture behaviour of these specimens dynamic crack resistance curves could be determined and crack initiation toughness values J_{Id} could be deduced. If required, these data can be converted to toughness values in terms of fracture toughness, K, according to ASTM E 1820, for instance. Figure 7 shows that both, the crack initiation values, J_{Id}, as well as the fracture resistance curves, J_d-Δa, 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 as indicated in Figure 8 for ferritic DCI.



Figur 7, Crack resistance behavior of DCI under impact loading conditions as a function of pearlite content at ambient temperature: Low-blow test with $v_0 \approx 1$ m/s, SE(B)15 specimens, regression according to ASTM E 1820 (definition of J_{Id} similar to J_{Ic} at static loading).

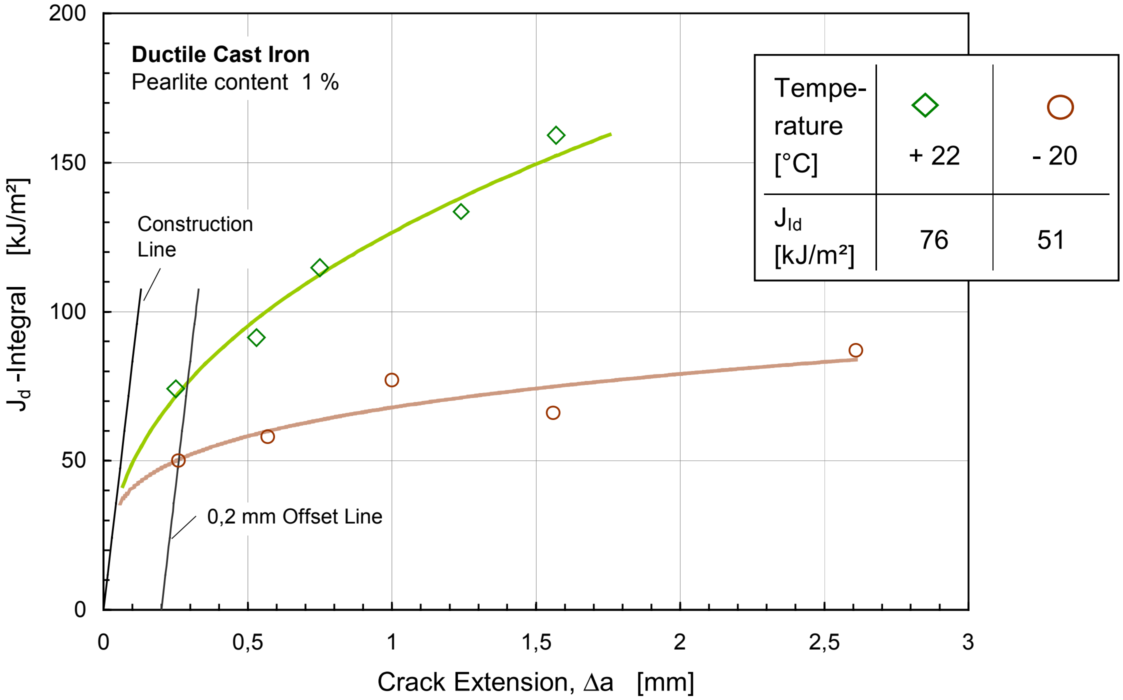


Figure 8, Crack resistance behavior of ferritic DCI under impact loading conditions as a function of test temperature: Low-blow test with $v_0 \approx 1$ m/s, SE(B)15 specimens, regression according to ASTM E 1820 (definition of J_{Id} similar to J_{Ic} at static loading).

SUMMARY AND OUTLOOK

In comparsion 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 behavior in ductile cast iron. The lower bound fracture toughness value of 50 MPa√m used for DCI in the design code for transport and storage casks in Germany was confirmed by the first investigations at elevated loading rates.

However, further research work requires the determination of dynamic fracture toughness values especially on small-size specimens and a statistical assessment procedure according to the materials behavior. At present, BAM works on a research programme which comprises systematic investigations of the mechanical and fracture mechanical behavior of heavy section DCI at elevated loading rates taking parameters into account like variation of microstructure, test temperature, sample and component size and loading rate.

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