Investigations on the Dynamic Fracture Toughness Behaviour of Nodular Cast Iron

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ABSTRACT: *Fracture mechanics characteristics of nodular cast iron are required for structural safety analysis within the component design and for production control and quality assurance programmes. In consideration of the specific demands required for heavy-section nodular cast iron, the fracture mechanics research programme of BAM is focused on an extensive material characterization under static and dynamic loading conditions with respect to such parameters as microstructure, test temperature, sample size and loading rate. Especially, the fracture toughness behaviour of nodular cast iron is strongly influenced by microstructural parameters like the pearlite content as well as size, morphology and distribution of graphite nodules in the ferritic matrix.*

In the present study, nodular cast iron from an original thick-walled component with a wide variety of microstructural characteristics was investigated in order to determine the fracture toughness characteristics 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. Dynamic crack resistance curves of SE(B)15 specimens were determined in Charpy instrumented impact tests by applying the low-blow multiple specimen technique. The fracture resistance curves are strongly affected by the pearlite content, as increasing pearlite content leads to a lower crack resistance. In comparison to static test results, an increasing loading rate leads to a higher transition temperature so that the change from elastic-plastic to linear-elastic material behaviour in ductile cast iron is observed.

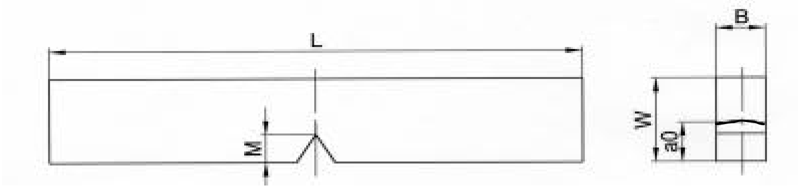
INTRODUCTION

For more than twenty years ductile cast iron has been used very successfully for spent fuel casks in Germany. During this period, the mechanical behaviour 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, 2]. 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.

NODULAR CAST IRON MATERIAL AND FRACTURE MECHANICAL EXPERIMENTS

The nodular cast iron investigated in this study, EN-GJS-400-15 according to the German material standardization, was taken from a container which had not totally fullfilled the required material specification. 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.

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 1. Prior to testing, all specimens were fatigue precracked providing initial a_0/W ratios of 0,5.



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 1. Schematic SE(B) specimen and geometry dimensions

The experimental determination of fracture toughness values using SE(B)140 bend specimens was carried out in a test stand for shock loading, Figure 2. In the fracture mechanical tests a maximum force of 700 kN and 2,5 m/s maximum speed was reached by the servohydraulic test cylinder. The crack initiation was deduced near the crack tip by means of strain gauges (Figure 2), and dynamic fracture toughness values were determined. Within the analysis of the results the requirements of ASTM E 1820 standard [3] for rapid loading K_{Ic} determination were adopted. The average stress intensity rate, $\dot{K}$, was about $5{\cdot}10^4$ MPa√m/s.

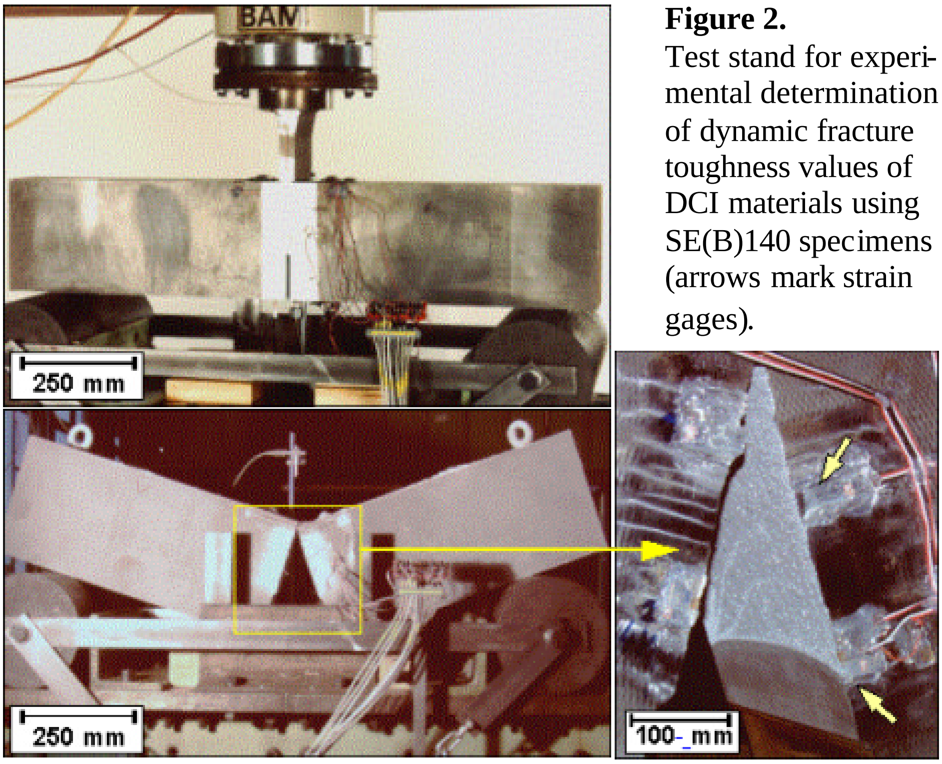


Figure 2.
Test stand for experimental determination of dynamic fracture toughness values of DCI materials using SE(B)140 specimens (arrows mark strain gages).

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. 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_{Id} were determined from these dynamic J-R curves based on the regulations of the ESIS P2 procedure [4].

DISCUSSION OF RESULTS

Dynamic fracture toughness of heavy section DCI

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 3). This material response describes the transition behaviour of dynamic fracture toughness of DCI in dependence on the test temperature. In the 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_{Id} values.

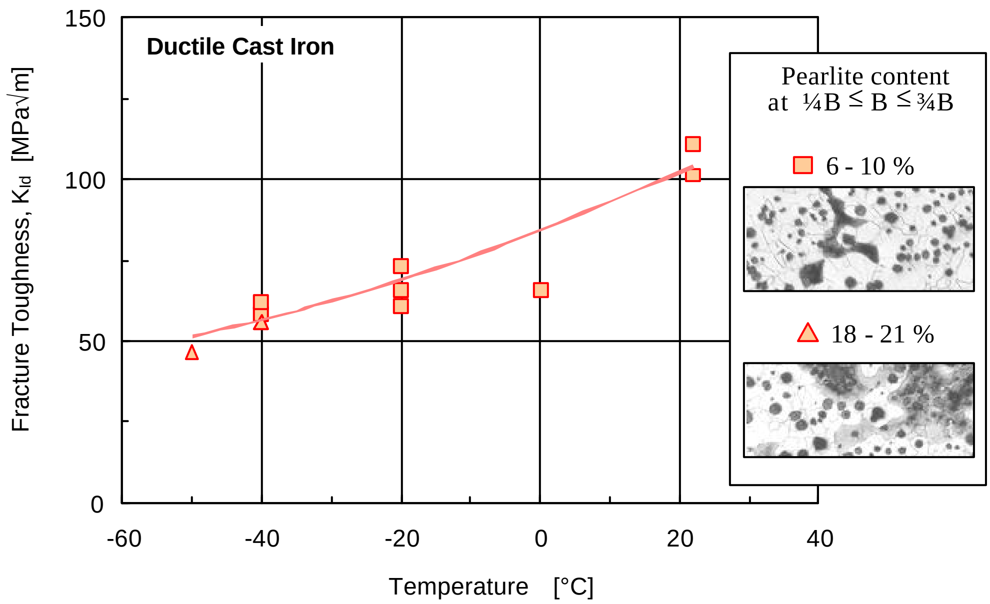


Figure 3. Dynamic fracture toughness of DCI as a function of temperature and pearlite content at test temperatures from –50 °C to +22 °C and loading rate $\dot{K} \approx 5{\cdot}10^4$ MPa√m/s, SE(B)140 specimens.

Comparison of dynamic and static fracture toughness behaviour

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, and for larger thicknesses between -40 °C and -80 °C [5] as pictured in Figure 4. In Figure 4, 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. Nevertheless, there should be a certain increase in toughness in the upper shelf region as a result of increased material strength in the case of dynamic loading.

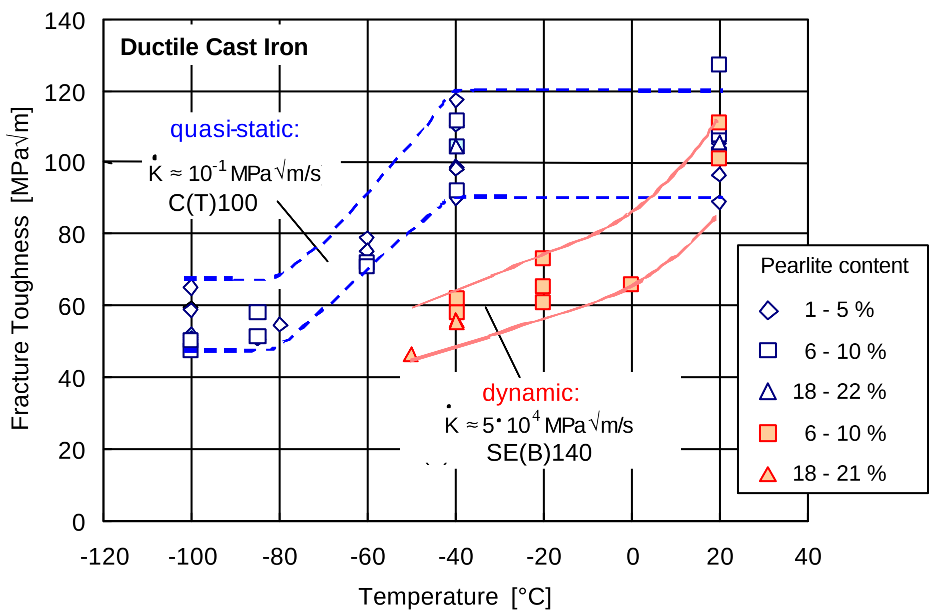


Figure 4. Fracture toughness behaviour of ductile cast iron as a function of test temperature and loading rate, C(T)100 and SE(B)140 specimens.

Fracture resistance of SE(B)15 specimens under impact loading

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 1, 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. Figure 5 and Table 1 show 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 6 for ferritic DCI (Table 1).

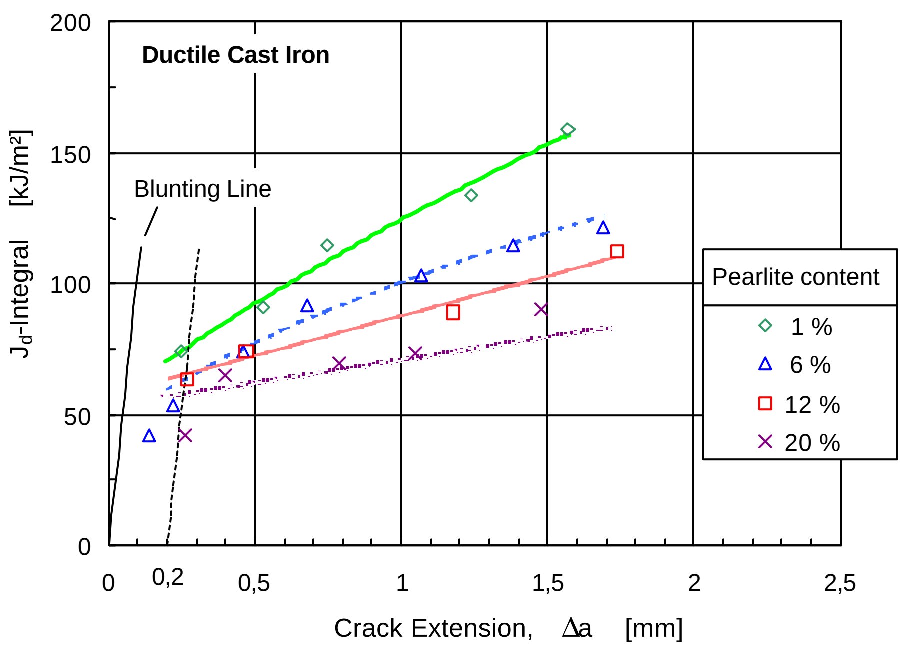


Figure 5. Crack resistance behaviour of DCI under impact loading conditions as a function of pearlite content at ambient temperature: Low-blow test with $v_0 \approx 1$ m/s, SE(B)15 specimens, regression according to ESIS P2.

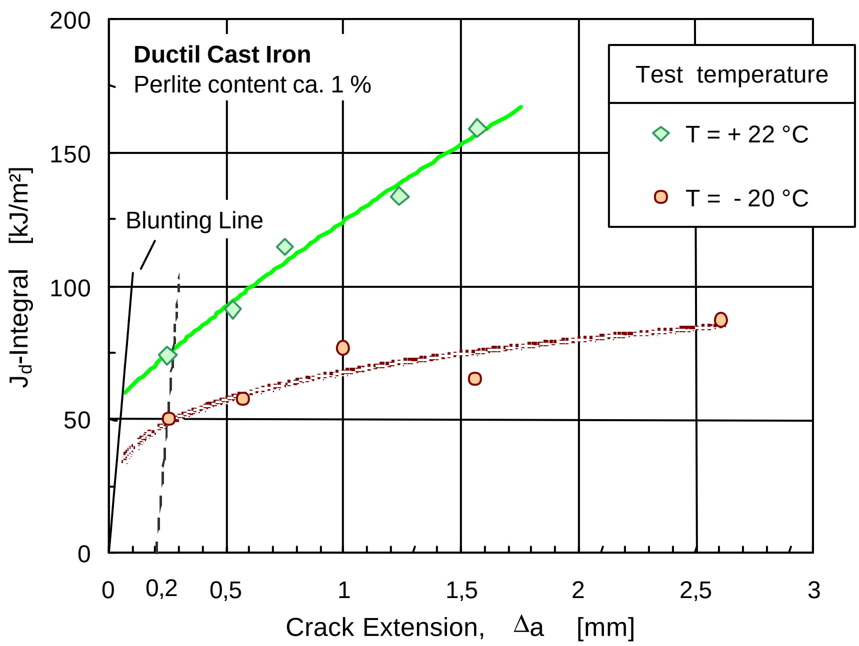


Figure 6. Crack resistance behaviour of ferritic DCI under impact loading conditions as a function of test temperature: Low-blow test with $v_0 \approx 1$ m/s, SE(B)15 specimens, regression acc. to ESIS P2.

Table 1. Dynamic crack initiation toughness values of DCI SE(B)15 specimens as a function of test temperature and pearlite content, low-blow test with $v_0 \approx 1$ m/s, acc. to ESIS P2.

J_{Id} [kJ/m²]	Influence of ***test temperature*** (pearlite content ≈1 %)		Influence of ***pearlite content*** (at 22 °C)			
	+22 °C	***-20 °C***	***1 %***	***6 %***	***12 %***	***20 %***
$J_{d0,2}$	71	46	71	59	63	57
$J_{d0,2BL}$	76	49	76	63	65	58

SUMMARY AND CONCLUSIONS

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 behaviour 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 [1] was confirmed by the first investigations of larger SE(B) 140 specimens 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 behaviour. At present, BAM works on a research programme which comprises systematic investigations of the mechanical and fracture mechanical behaviour 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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