Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

STATISTICAL ANALYSIS OF DYNAMIC FRACTURE TOUGHNESS DATA OF TWO DCI LARGE SCALE SPECIMEN TEST SERIES

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ABSTRACT

Advanced codes and guidelines for the assessment of component safety include fracture mechanics concepts in many cases. Regarding this, extreme loading situations such as accidental conditions are of special interest within the design and proof of safety process. Dynamic (high-rate) loading causes fast changes of the stress and strain states in the material. Therefore, the determination of appropriate corresponding fracture mechanics material properties is an experimental challenge but at the same time it is an essential prerequisite for the practical applicability of the codes. The material in focus here is ductile cast iron (DCI). One major field of application of DCI is the production of casks for radioactive materials.

At first the present paper deals with a BAM test series of dynamic fracture toughness tests in 2006. A series of 6 large scale SE(B)140 specimens of DCI was tested at -40 °C and loading rates of $dK/dt \approx 5 \cdot 10^4$ MPa√m/s. If the validity criteria of the static test standard ASTM E 399 are formally applied here, all data can be regarded as valid dynamic fracture toughness values K_{Id}.

The statistical analysis of the data was based on a two parameter Weibull distribution function. The data was completed by 4 results of a identical BAM test series in 1998/1999. Weibull analyses of three samples covering different pearlite contents (≤ 4 %, ≤ 9 %, ≤ 20 %) were performed and characteristics of the distribution functions and two-sided confidence intervals were calculated.

All investigated samples could be properly described by the applied Weibull distribution function. The calculated characteristics show that K_{Id} of DCI decreases with increasing pearlite content. These results are valuable since a statistical analysis of the dynamic fracture toughness of DCI depending on microstructure has been performed for the first time. This is especially important with respect to the production process of heavy-walled DCI castings where small amounts of pearlite are normally tolerated. Nevertheless, the presented results are still based on relative small sample sizes and therefore of preliminary nature. The statistics should be improved

by further analyses taking more specimens and especially more ones with higher amounts of pearlite into account.

INTRODUCTION

Advanced codes and guidelines for the assessment of component safety [1-3] include fracture mechanics concepts in many cases. Regarding this, extreme loading situations such as accidental conditions are of special interest within the design and proof of safety process. Dynamic (high-rate) loading causes fast changes of the stress and strain states in the material. Therefore, the determination of appropriate corresponding fracture mechanics material properties is an experimental challenge but at the same time it is an essential prerequisite for the practical applicability of the codes. Within this context the present paper deals with the experimental determination and statistical analysis of dynamic fracture toughness values of Ductile Cast Iron (DCI). One major field of application of DCI in Germany is the production of casks for transport and storage of radioactive materials.

MATERIAL

It is reported on a series of dynamic fracture toughness tests at 6 SE(B)140 large scale specimens of ductile cast iron (DCI) [4]. The mechanical properties of the material under investigation are shown in Table 1. The specimens 3 and 4, 5 and 6 as well as 7 and 8 were machined in pairs from ingots of a thickness of 150 mm. All ingots come from the same melting charge.

Table 1. Static mechanical properties of the DCI material at ambient temperature

Specimen	$R_{p0.2}$ in MPa	R_m in MPa	A in %
3 and 4	245	361	14
5 and 6	243	359	12
7 and 8	244	362	12

The mean pearlite volume fraction in the materials under investigation is shown in Table 2. In order to improve the statistical analysis, the data of the present investigation was completed by the results of 4 SE(B)140 large scale specimens of a BAM test series on DCI in 1998/1999 which was run under the same testing conditions [5], Table 2.

Table 2. Mean volume fraction of pearlite in the DCI materials tested in this test series and in a BAM test series in 1998/1999

Specimen	Mean volume fraction of pearlite in %	Comment
3 and 4	2	BAM test series in 2006 [4]
5 and 6	4	
7 and 8	4	
8	7	BAM test series in 1998/1999 [5]
9	9	
7	18	
1	20	

EXPERIMENTAL DETERMINATION OF DYNAMIC FRACTURE TOUGHNESS BY LARGE SCALE SPECIMEN TESTING

The test conditions for the determination of dynamic fracture toughness by testing of SE(B)140 large scale specimens are listed in Table 3.

Table 3. Test conditions for the determination of dynamic fracture toughness by testing of SE(B)140 large scale specimens

Parameter	Implementation
Specimen geometry	SE(B)140 (140 x 280 x 1350 mm) (see Figure 1)
Initial flaw	Fatigue crack with $a_0/W \approx 0.5$
Measurement of force	Strain gages on the specimen
Measurement of displacement	Optical extensometer
Detection of crack initiation	Crack extension sensors in the ligament
Test system	Servo-hydraulic impact test system (max. force 1000 kN, max. velocity of piston 8.5 m/s) (see Figure 3)
Test arrangement	Three point bending
Test temperature	-40 °C
Loading rate	$dK/dt \approx 5 \cdot 10^4$ MPa$\sqrt{m}$/s

The fatigue precracking was performed according to ASTM E 399 [6] and all strain gages for the measurement of force were statically calibrated before the tests, Figure 2. Stress intensity factors K_I were calculated from the force values at initiation of instable fracture in the dynamic fracture mechanics tests. All K_I values meet the validity criteria of the static test standard ASTM E 399. Therefore, they can be regarded as valid K_{Id} values independent from specimen size.

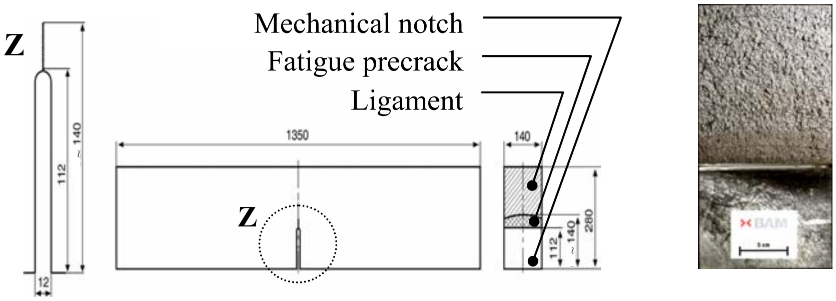

Figure 1. SE(B)140 specimen with $a_0/W \approx 0.5$, at right: fracture surface after the test

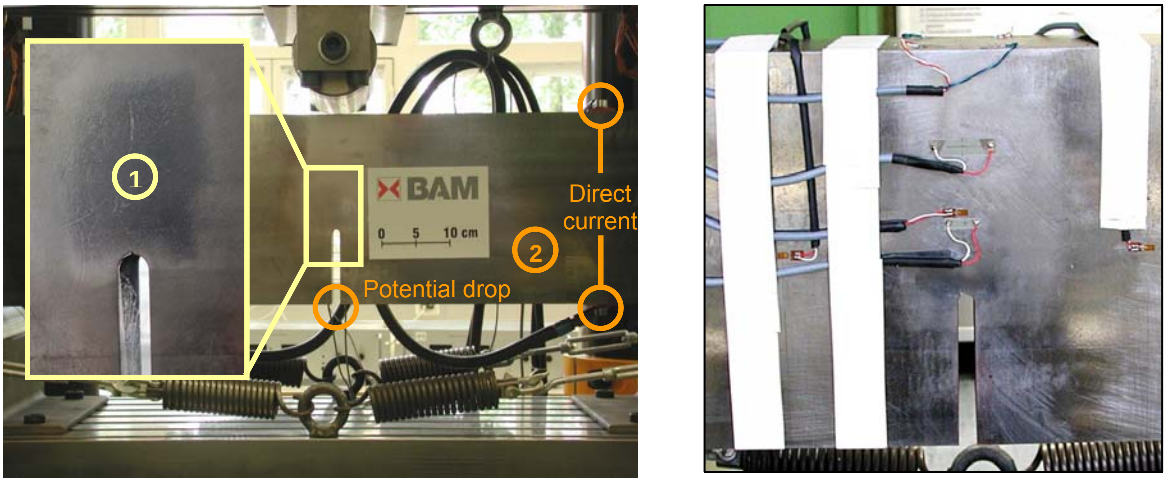

Figure 2. At left: Fatigue precracking in a 4 MN test system with control of crack extension by optical surveillance (1) and DC potential drop technique (2); At right: SE(B)140 specimen with strain gage instrumentation and crack extension sensors

Figure 3. Servo-hydraulic impact test system mounted for dynamic fracture toughness tests with SE(B)140 specimens

DYNAMIC FRACTURE TOUGHNESS VALUES

Table 4 contains all dynamic fracture toughness data determined for the investigated DCI material at -40 °C and a loading rate of dK/dt ≈ $5 \cdot 10^4$ MPa√m/s. The data are listed in ascending order for the statistical analysis.

Table 4. Dynamic fracture toughness data of DCI at -40 °C and dK/dt ≈ $5 \cdot 10^4$ MPa√m/s

Specimen	Mean volume fraction of pearlite in %	Dynamic fracture toughness K_{Id} in MPa√m	Comment
1	20	56	BAM test series in 1998/1999 [5]
7	18	56	
8	7	58	
9	9	62	
8	4	64	BAM test series in 2006 [4]
3	2	67	
4	2	71	
7	4	71	
5	4	75	
6	4	79	

STATISTICAL ANALYSIS

It is common practice to describe the scatter of toughness data of ferritic materials in the toughness transition region by Weibull distribution functions as for instance within the Master curve concept covered by ASTM E 1921 [7]. In the present paper a two parameter Weibull distribution function was used for the statistical analysis of K_{Id} data as it is applied in the ASME Code Case N-670 [8]. All data in Table 4 was regarded as one common data base and sorted into three samples covering different pearlite contents (≤ 4 %, ≤ 9 %, ≤ 20 %), Table 5. Weibull analyses were performed then and characteristics of the distribution functions and two-sided confidence intervals were calculated.

Table 5. Samples of dynamic fracture toughness values

Sample size	**Dynamic Fracture Toughness K_{Id} in MPa√m**	**Sample size**	**Dynamic Fracture Toughness K_{Id} in MPa√m**	**Sample size**	**Dynamic Fracture Toughness K_{Id} in MPa√m**
N = 6 P ≤ 4 %	64	N = 8 P ≤ 9 %	58	N = 10 P ≤ 20 %	56
	67		62		56
	71		64		58
	71		67		62
	75		71		64
	79		71		67
			75		71
			79		71
					75
					79

The Weibull analyses were performed by use of a Maximum-Likelihood estimator based on [9]. Equations 1 to 3 show the formulation of the two parameter Weibull distribution function and the characteristics determined.

Cumulative frequency function
$$P_f\left(K_{Id}\right) = 1-\exp\left[-\left(\frac{K_{Id}}{\beta}\right)^m\right] \qquad (1)$$

Expectation
$$E = \beta\cdot\Gamma\left(1+\frac{1}{m}\right) \qquad (2)$$

Variance
$$Var = \beta^2\left\{\Gamma\left(1+\frac{2}{m}\right)-\left[\Gamma\left(1+\frac{1}{m}\right)\right]^2\right\} \qquad (3)$$

The estimated values of the Weibull exponent m provided by this method are not un-biased. Therefore, the m values were multiplied by tabulated correction factors b according to equation (4) in order to emend the systematic difference.

Unbiased estimated value of the Weibull exponent:
$$m_{korr} = m\cdot b \qquad (4)$$

RESULTS OF THE STATISTICAL ANALYSES

Figure 4 shows the Weibull plots of the investigated samples with N = 6, N = 8 and N = 10. Table 6 provides the corresponding distribution parameters.

As it can be seen from Figure 4 all investigated samples can be described well by the applied two parameter Weibull distribution function. Generally it holds that single runaways at high or low probabilities of failure are only of lower importance when an overall distinctive tendency for linearity exists as it is the case here.

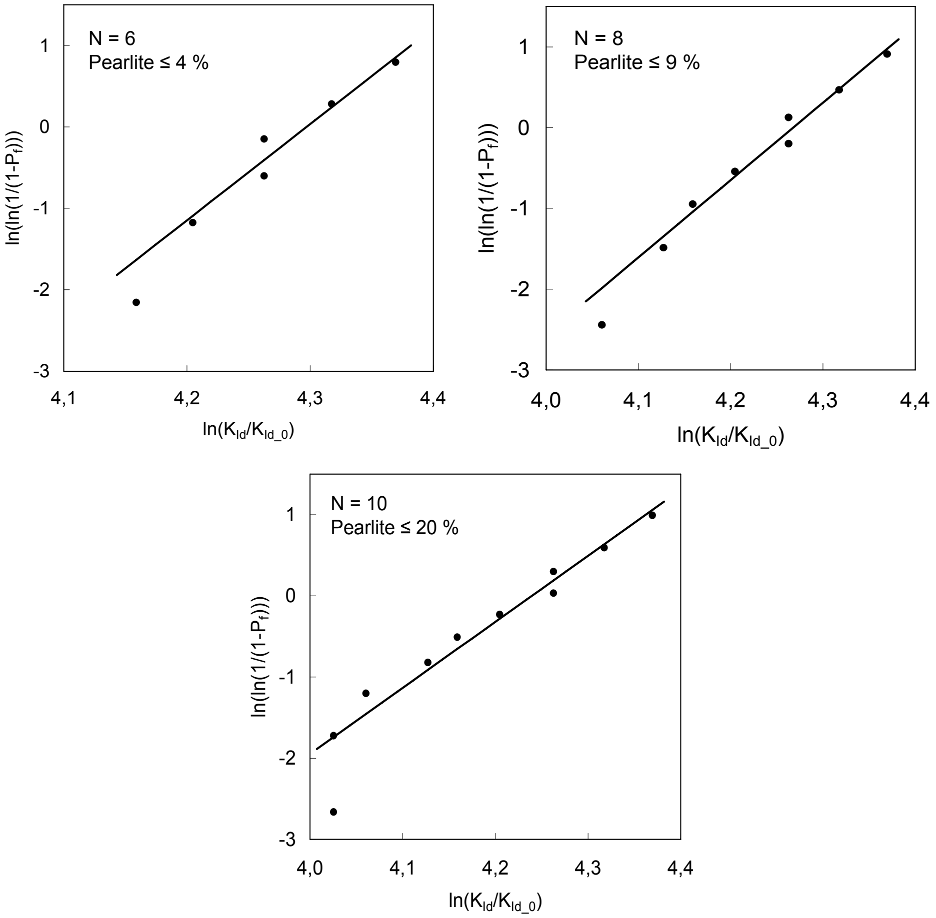

Figure 4. Weibull plots of the investigated samples with N = 6, N = 8 and N = 10
(K_{Id_0} is a quantity with a value of 1 MPa√m in order to make K_{Id}/K_{Id_0} non-dimensional)

Table 7 provides a summary of calculated characteristics of the Weibull distributions of the investigated samples. As it can be seen from Table 7, the expectation of the dynamic fracture toughness K_{Id} decreases with increasing volume fraction of pearlite. The ASME Code Case N-670 [8] requires to use the expectation of K_{Id} reduced by the triple standard deviation (right column in Table 7) for purposes of component safety analyses. This way the scatter of K_{Id} due to material inhomogeneities as well as the measurement can be taken into account adequately.

Table 6. Parameters of the Weibull distribution

Sample	Mean volume fraction of pearlite in %	ß	m	m_{korr}
N = 6	≤ 4	73.49	15.69	11.80
N = 8	≤ 9	71.36	11.68	9.58
N = 10	≤ 20	69.36	9.47	8.13

CONCLUSIONS

The assessment of the present results of the Weibull analyses should take into account that the sample size is relatively small and the count of results for higher volume fractions of pearlite is underrepresented in the samples with N = 8 and N = 10. From the component safety point of view a more detailed statistical analysis of DCI K_{Id} data is necessary which has to be performed systematically in dependence on microstructural material parameters. But this is currently not possible based on the limited available experimental data. An improved statistical analysis needs enlarged samples containing more results of parallel specimens especially for higher volume fractions of pearlite. Nevertheless, the analysis procedure demonstrated here can be regarded as a useful tool to provide at least preliminary results for the distribution of the dynamic fracture toughness K_{Id} of DCI with a pearlite volume fraction up to 20 % at -40 °C.

Table 7. Characteristics of the Weibull distribution

Sample	Mean volume fraction of pearlite in %	Expectation E in MPa√m	Variance in MPa²m	Standard deviation S in MPa√m	E - 3·S in MPa√m
N = 6	≤ 4	70	52.4	7.2	48
N = 8	≤ 9	68	72.1	8.5	42
N = 10	≤ 20	65	91.2	9.6	37

The results are valuable since a statistical analysis of the dynamic fracture toughness of DCI has been performed for the first time in dependence on the microstructure. This is especially important with respect to the production process of heavy-walled DCI castings where small amounts of pearlite are normally tolerated.

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