14th International Symposium on the Packaging and
Transportation of Radioactive Materials (PATRAM 2004),
Berlin, Germany, September 20-24, 2004

Paper # 111

DYNAMIC FRACTURE TOUGHNESS DATA FOR CASTOR® CASKS

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1 Introduction

For the use of cast iron with spherical graphite for heavy-sectioned casks for transportation and storage of radioactive materials a complete failure assessment including fracture mechanical analysis is necessary. The casks require an elaborate fracture mechanics design based on fracture mechanics evaluation [1]. The extension of the existing code [2] with respect to dynamic loading takes account new developments to extend the field of applications. It also includes new criteria to design these casks against operating and accident loadings [3] to [7].

A fundamental requirement for the realisation of this standard and the calculation of admissible crack lengths of stresses under dynamic loads is the availability of fracture mechanical data.

The paper presents -as a part of a large test-program- first results of dynamic fracture-toughness-investigations depending on structure and temperature. The test-program will incorporate investigations on more then 2500 specimens. The investigations that will be done include static and dynamic fracture mechanic tests, dynamic tensile and pressure-tests on different formed specimens. The temperatures and other test conditions follows the IAEA-regulations ant the real service conditions. The test-program will be realised in partnership with different institutes.

This first results of pre-tests are determined on specimens of ductile cast iron of grade GJS-400. The material is comparable to the ductile cast iron in accordance with GNB-specification. In the next step specimens from the drill hole bars will be included in the investigations. This tests had been done to determine the orientation for the following main test-program.

Investigations of the resistance to dynamic loading of ductile cast iron at the institute of material technology at the TU Bergakademie Freiberg [8] to [11] show a significant reduction in comparison to static loading. In these tests dynamic crack initiation for the J-integral and CTOD-concepts (multiple specimen low-blow technique) were used. They also revealed the influence of low temperatures and of different microstructures. Orientation tests using different single specimen methods [12], as opposed to multiple specimens methods, did not show reliable results. Therefore more investigations will be done to improve the rational approach of the single specimen method.

This paper deals with the preliminary results of an extensive research program to determine dynamic fracture toughness as functions of temperature and microstructure. The influence of the dynamic loading rate is verified by comparison to the fracture toughness properties under static loading.

2 Materials to be tested

Specimens were taken from cored samples of a transportation cask (diameter of core 38 mm, length 1600 mm. Microstructure resp. microstructure parameters of the 2 different material states are shown in table 1.

Table 1: Microstructure of the tested materials

Micro-structure parameter	Volume share of graphite	Mean distance between graphite particles	Shape factor of graphite particles	Mean size of graphite particles	Matrix
	V_G [%]	λ [µm]	f	d_G [µm]	
GJS-400 Series no. 9	10	89	0,74	55	ferritic, 3 – 6 % Perlite
GJS-400 Series no. 6	13	87	0,76	51	ferritic, 17– 18 % Perlite

3 Mechanical properties

The mechanical properties of the static tensile test are shown in table 2.

Both the evaluation of the strength properties as well as the determination of the fracture toughness properties under dynamic loading require the experimental determination of the strength properties under elevated loading rates and different temperatures [13].

Table 2: Mechanical properties of the tensile test

	$R_{p0,2}$ [MPa]	R_m [MPa]	A_5 [%]	Z [%]	$E^{1)}$ [GPa]
GJS-400 Series no. 9	254	385	12	17	172
GJS-400 Series no. 6	250	396	13	12	173

1) Determined by ultrasonic measurements

The tensile tests started with quasi-static loading conditions. They encompassed loading rates up to $d\ /dt = 0,5\ s^{-1}$ and temperatures from -80°C to +200°C. The specimens with diameters of d_0 = 6 mm were tested on an universal testing machine (ZWICK 1476). Elongations were measured with a clamp-type strain gage. The tests were evaluated according to DIN EN 10.002 [14].

Impact-tensile tests were performed with a rotation impact testing machine at speeds of up to 30 m/s ($\approx 1.500\ s^{-1}$) at room temperature on specimens with d_0 = 4 mm **(Fig. 1)**. They were evaluated in accordance to ESIS P7-00 [15]. Forces were measured using a Hopkinson bar and deformations both with strain gages directly applied over the gage lenght and indirectly by double integration of the force-over-time signal.

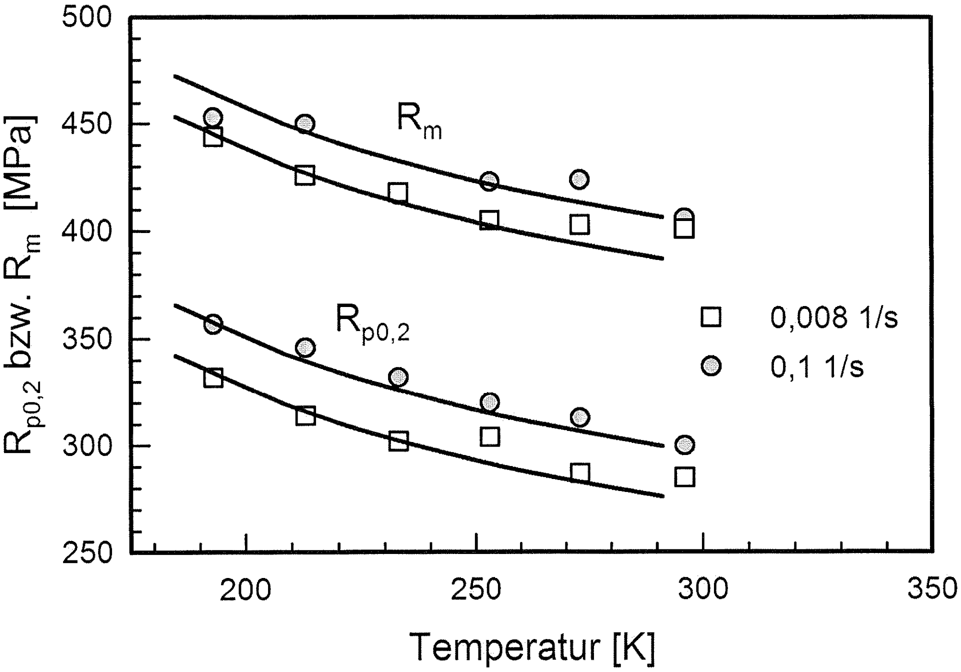

Fig. 1 $Rp_{0,2}$ and R_m as function of $\dot{\varepsilon}$ and temperature

This standard method for the instrumented Charpy-Test [16] that is modified for dynamic tension tests, provided results in very good accordance with the experimental strain measurements up to the loss of the strain gage signal and permitted the analysis over the complete range of deformations. The transferability of the strains computed in this manner is also supported by the fact that the initial slope of the stress strain diagram corresponds to the elastic modulus and that the elongation to rupture measured on the specimen correspond sufficiently well with the elongation to rupture gained from the stress strain diagram.

As to be expected tensile strength and elastic limit $R_{p0,2}$ increase under higher loading rates and lower temperatures, which is in accordance with results reported in [8, 9, 18].

The analytic description for this correlation, that has been successfully applied for structural steels [19], is also valid for cast iron materials and is possible by using the Arrhenius-equation.

$$R_{eL} = \sigma_i + \sigma_0^* \cdot \left[1 - \frac{k \cdot T \cdot \ln(\dot{\varepsilon}_0 / \dot{\varepsilon})}{\Delta G_0}\right]^m \quad (1)$$

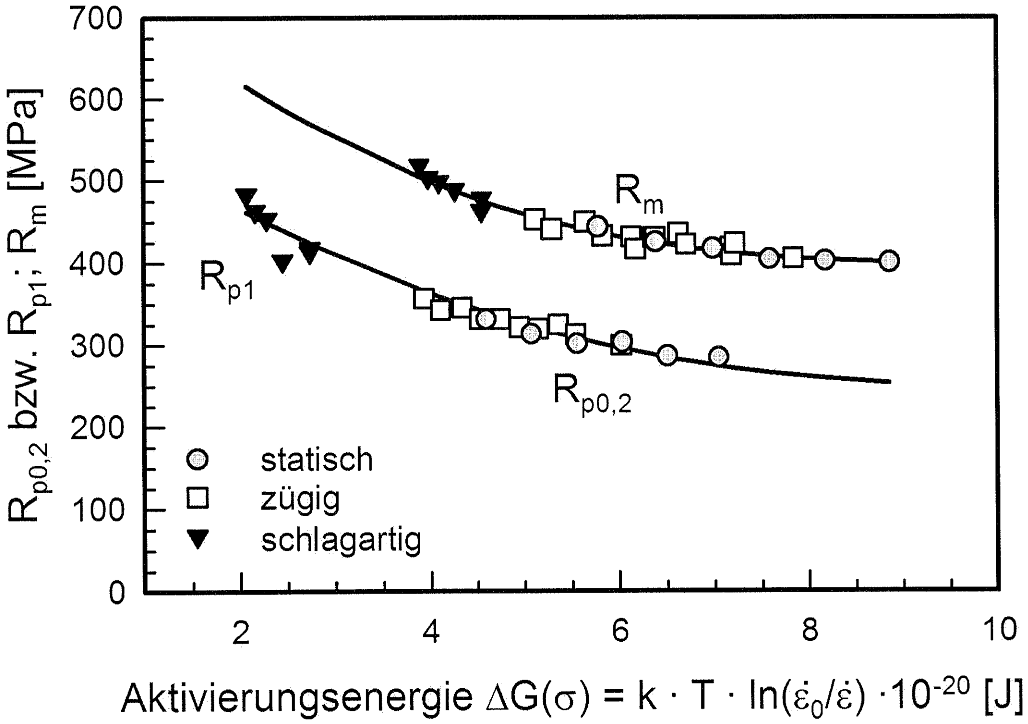

Fig. 2: Strength properties of GJS-400 (series no. 6) as a function of the activating energy G( )

For the GJS-400 (series no. 6) it follows that the elastic limit $R_{p0,2}$ as well as the R_{p1} limit and formally the tensile strength R_m can be computed for the investigated range of temperatures and strain rates as functions of the temperatures and strain rates **(Fig. 2)**. Equation (1) is applied by inputting the numerical values given in table 3 for the portions σ_i and σ_0^* of the thermally activated plastic stress, the activation energy ΔG_0, $\dot{\varepsilon}_0$ and m. Verification of the parameters in Eq. (1) will be further investigated on GJS-400 with varying microstructures.

Table 3: Parameter describing the strength properties according to the thermally activated plastic flow model

	Property	σ_i [MPa]	σ_0^* [MPa]	ΔG_0 [eV]	$\dot{\varepsilon}_0$ [s^{-1}]	m
GJS-400	Rp0,2 resp Rp1	250	359	0,65	2.1E5	2,4
	Rm	400	420		1.7E7	3,0

4 Fracture mechanics properties

The static properties of the J-integral concept at ambient temperature and at -40°C were determined using the single specimen method on 20% side notched SENB-specimens (10 x 20 x 120 mm). The determination of the physical crack initiation strength J_i was done at the intersection of blunting line and J_R-curve.

The dynamic properties of the J-integral concepts were determined at ambient temperature and at -40°C on unnotched SENB-specimens (10 x 10 x 55 mm) applying the multiple-specimen method (low blow method) with the help of an instrumented pendulum impact testing machine . The determination of the dynamic crack initiation toughness from the intersection of the J_{dR}-curve with the blunting line was performed after testing and evaluation according to ESIS-P2 [20]. The juxtaposition of the properties **(Fig. 3)** reveals the significant influence of the loading rate and the temperature on the resistance to crack initiation under dynamic loading.

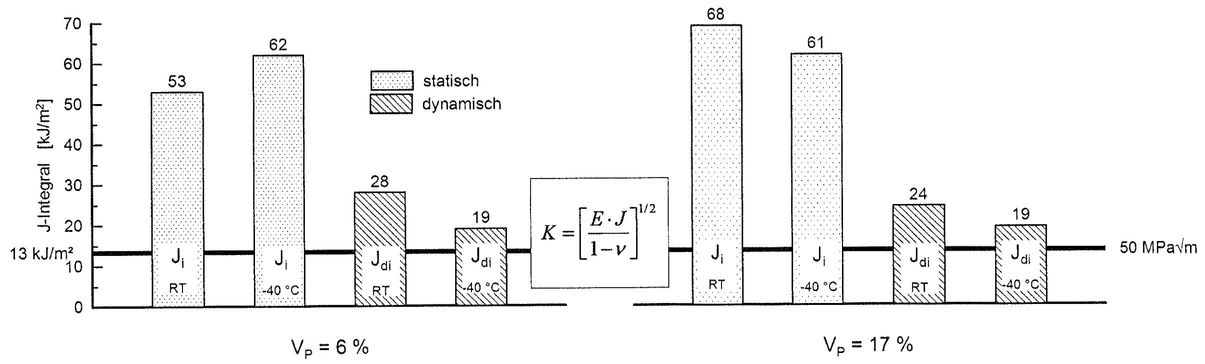

Fig. 3: Static and dynamic crack initiation values for GJS-400

Fig. 3 leads to the conclusion that the lower bound of 50 MPa√m that according to [2] must be guaranteed for the static loading rate is also valid for dynamic loading. This can be explained by the relatively big size of the graphite particles and by the ductile ferritic matrix whose perlite content is still sufficiently small. This finding is in accordance with investigations on large specimens taken from casks and dynamically tested between ambient temperatures and –40°C [3]. It should be noted that under dynamic loading the transition from ductile to linear elastic fracture is in the range from –40°C to + 22°C and that the lower bound value may be well be smaller at –40°C [8] [21]. Further investigations arfe necessary to study the important influence of the microstructure (Perlite content, Graphite morphology).

5. Conclusions

The experimental determination of dynamic fracture toughness values by the multiple specimen method permits the characterisation of the resistance to crack initiation of ductile iron materials depending on microstructure and temperature. The particular problems, with respect to precision and reproducbility, arising from the heterogeneous microstructure must be kept in mind. Among others this concerns the irregular crack propagation front that can be countered by using notched specimens. Another challenge is the exact determination of the small Δa values near the origin of the J_{dR} curve that might be solved by producing a second fatigue crack front after the dynamic loading in combination with the oxidation of the crack surface. For the determination of the dynamic crack initiation values by intersecting the blunting line with the J_{dR} curve values for dynamic strength must be experimentally determined as function of the microstructure. The single specimen methods are the favorites for a rational determination of dynamic material properties. First results for the application of the key curve method are in good agreement with the J_{dR} curve of the low blow method near the origin of the dynamic crack resistance curves which is where crack initiation values are determined. In the further it can be stated a lower course of the J_{dR} curve measured by the key curve method, whose interpretation is the goal of ongoing reasearch. These also serve to check possible correlations between dynamic crack initiation values and the characteristic microstructure parameters (shape and distance of graphite particles) and the characteristic values of the elastic-plastic stress strain curve that could already be shown for the case with static loading [22].

6 Literature

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