EXTENDED DROP TESTING WITH PRECRACKED DCI-CASKS AND EVALUATIONS ON SAFETY AGAINST BRITTLE FRACTURE

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Summary

This paper is a summary of a research study as part of comparable efforts in Japan, France and the USA aimed at developing principles, procedures and material data for the brittle fracture safe design of thickwalled shipping containers made from ductile cast iron (DCI) and other material susceptible - in principle - to nonductile failure. Furthermore, the application of fracture mechanics was to be qualified as an alternative method, relative to the experimental approach applied in previous licensing procedures in Germany and to be demonstrated by subjecting a full-size precracked prototype to drop tests.

Introduction

In previous PATRAM symposia, reports were given on design principles, licensing-test results and acceptance criteria for DCI shipping and storage casks in Germany.

A discussion on different fracture safety philosophies was presented by Wieser 1986 during the PATRAM symposium in Davos, Switzerland.

During PATRAM 89 the status of the application of DCI in Germany was presented (Wieser et al. 1989). Revalidations were granted to German design approvals by several European countries.

A discussion on possible acceptance criteria for potentially brittle structural materials is given in Wieser et al 1991. Pertinacious objections and concerns against the application of structural materials, which, under the specified Type B accident conditions may fail in a brittle manner, as well as the need for optimized package designs, made from such material, initiated a research programme (Contract No. KWA 7905 2 with the Federal Department for Research and Technology (BMFT)) with the following topics:

- Establishment of a reliable database on fracture toughness values for ductile cast iron;
- Safety demonstration with a full-size precracked cask, where the size of the artificial flaw and drop test conditions allow for the performance of sub- and supercritical tests, i.e. the controlled initiation and propagation of a crack;
- International exchange of data and experiences with respect to the application of fracture mechanics and contribution to the internationally agreed acceptance criteria on the brittle fracture safe design of casks.
- Establishment of a design guide on the application of fracture mechanics in Type B licensing procedures;

The study fits well with comparable efforts in France, Japan and the USA.

Establishment of a materials data base for ductile cast iron

The scope of this part of the research study was to describe the basic parameters that are responsible for the mechanical behaviour of DCI and to generate a basic fracture toughness data base. 24 different DI alloys were tested,

- with a pearlite content between 2 and 60 % and constant nodule diameter (Figure 1)
- with an average nodule diameter between 30 and 150 um (Figure 2)

One of the main sequences was CT-300 linear-elastic fracture toughness tests at -40 °C, the lowest service temperature for shipping container under the transport regulations. Five specimens were cooled down to -65 °C and tested at -40 °C. The main results of these tests are:

- valid K_{IC}-values were generated
- K_{IC}-values for licenced DCI were higher than 50 $MPa\sqrt{m}$, the German "lower-bound" value for -40 °C
- K_{IC}-values up to 100 MPa m were found for DCI with a homogenous microstructure and low pearlite content
- At +20 °C the value measured with a CT-300 specimen is higher than values for CT-100 specimen.

The negative influence of pearlite structure can be seen in Figure 3. Cleavage fracture occurs in the pearlite phase and is arrested in ferrite.

Major conclusions, which can be drawn from these investigations are:

- pearlite is the main factor of influence
- below 20 % pearlite, silicon and the graphite structure must be taken into account

- 300-mm thick specimens are necessary to get valid K_{IC}-values at -40 °C
- pearlite content should be below 20 % to avoid cleavage fracture at -40 °C.

The full report on these investigations is presented in Frenz 1991.

Performance of drop test with a precracked cask

The sample used for the test series was a full-size prototype of a shipping cask for vitrified high-level waste (VHLW-cask) with a total mass of 21 280 kg, which, equipped with shock absorbers, had already successfully passed licensing tests (see separate paper by Witt et.al. 1992). Its outer diameter was 1156 mm, wall thickness 260 mm and total length 3455 mm. For the purpose of the tests, an artificial defect with a depth of 121 mm (46,5 % of wall thickness) was machined, located half of the length and perpendicullar to the axis of the cask. The geometry of the defect should allow for the application of devices to measure the crack opening displacement under impact (Figure 4).

Five drop tests onto an unyielding target were performed at room temperature in the horizontal impact orientation onto cylindrical rails.

Three accelerometers and ten strain gages were used for instrumentation; additional strain gages were applied to measure the crack opening displacement.

Test numbers, test conditions, deformations and decelerations are summarized in Figure 5.

The first two tests were intended to give better knowledge on the deformation behaviour of the rails and the correlation of drop heights and decelerations in the cask. The artificial defect was upside in the compression zone; these test are of no further interest.

Drop heights and distances between rails for the following three tests were selected as to result in increasing decelerations and stress intensity factors in the cask. According to forerunning calculations, the last test at least should be a critical test, where crack initiation should be provoked.

The test No. 752 was deemed to result in stress intensity factors K_I in the range of the lower bound value for DCI, generally accepted in Germany (30 MPa$\sqrt{m}$); test No. 753 should result in a K_I-factor just at the fracture toughness value of the test sample (K_{IC} = 59 MPa$\sqrt{m}$, established by CT 100 specimen at -100 °C and K_{Ic} = 89 MPa$\sqrt{m}$ at -40 °C).

The evaluation of the stress intensity factors K_I was - as a result of restricted resources and capacities - only possible, so far, by use of fracture mechanics standard models (i. e. flawed bending bar) and by use of the J-Integral established by the crack opening displacement measurements. It proved, that the variations of measured decelerations, failing strain gages attached, in the cavity a general stress level above yield (during the last test) and, above all, the geometry of the big artificial defect caused a considerable margin of interpretation.

Figure 6 shows some results of these evaluations. The last test obviously caused a stress intensity factor above the fracture toughness of the material; so that crack initiation accured.

After the drop testing the flaw surrounding material was manchined out and examined for flaw initiation. Indeed, some smaller cracks were detected which were stopped by the first nodules of the DCI (Figure 7).

Apart from the result of this fracture mechanics assessment, the test series demonstrated again the big margin of safety of shipping containers, made from DCI, under excessive loads far beyond the Type B performance test level, which shall provide an internationally agreed level of safety against transport accidents.

International exchange and cooperation

Starting in June 1987 with an international seminar in Berlin, a process of international exchange and cooperation developed to establish a broader data base and agreed safety and design principles for structural materials of shipping containers with a nonductile failure potential, such as DCI.

Further international seminars were organized in April 1988 in Tokyo, October 1990 in Braunschweig, February 1991 in Albuquerque and November 1991 in Washington.

Major research efforts were sponsored in Japan, USA, France and Germany. The consolidated level of knowledge and experience on one hand and the disagreements among member states on the other hand persuaded the International Atomic Energy Agency (IAEA) to charge a group of consultants with the establishment of a technical document (TECDOC) "Criteria for the brittle fracture safe design of transport packages", whose key part shall become a revised Appendix IX of the IAEA Safety Series No. 37, the Advisory Material on the Regulations for the

Safe Transport of Radioactive Materials. This Appendix IX comprises the principles and acceptance criteria for the brittle fracture safe design of shipping containers. The group has almoast completed its task; the draft of the TECDOC will be submitted to the IAEA in October 1992 for adoption.

German design guide for DCI-containers

A new regulatory guide on the design of thickwalled shipping containers made from DCI is actually prepared in Germany. Its application will become obligatory as an alternative to the previously applied acceptance criteria. The contents will be in line (or even be identical) with the mentioned IAEA TEC DOC.
With this guide, the German authorities responsible for shipping and storage containers for radioactive materials will conclude their efforts with respect to ductile cast iron. This material is then state of the art.

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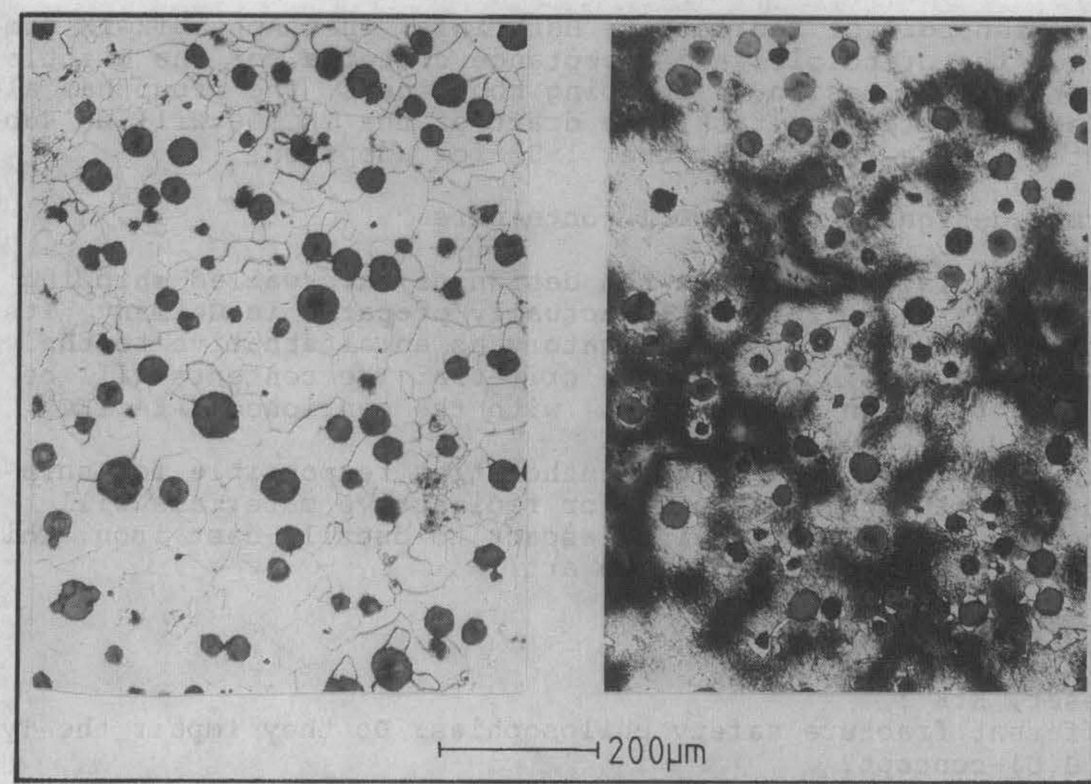

Figure 1 Variations of pearlite contents

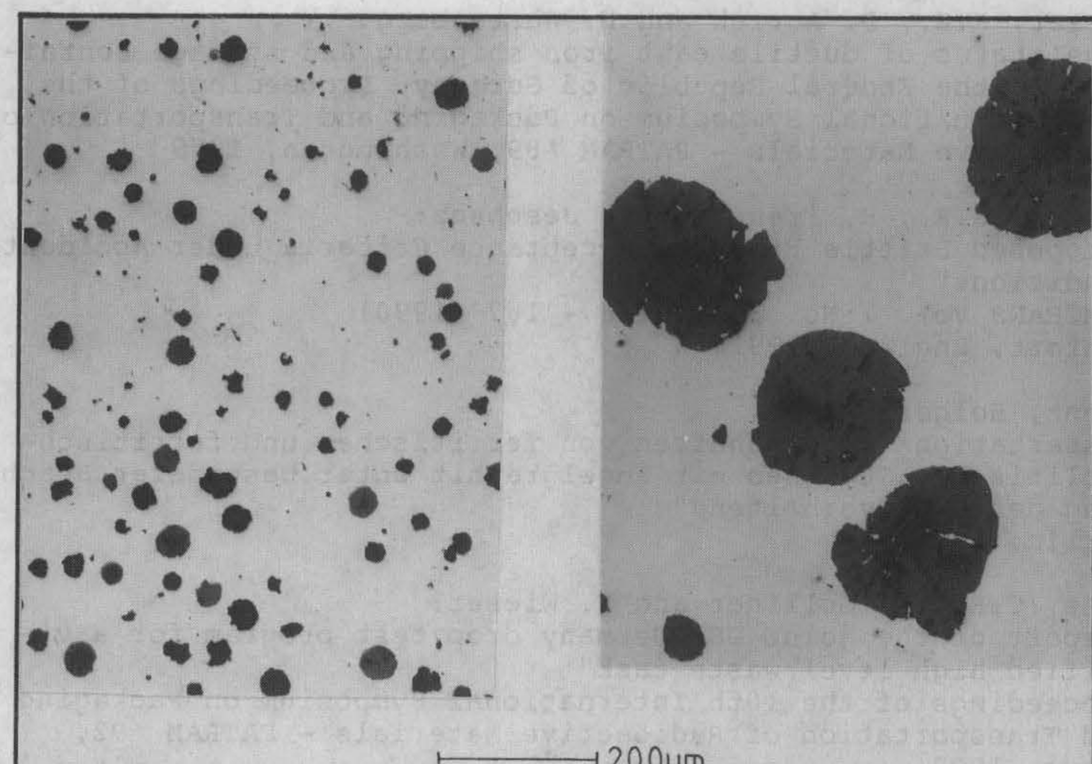

Figure 2 Variations of nodule diameters

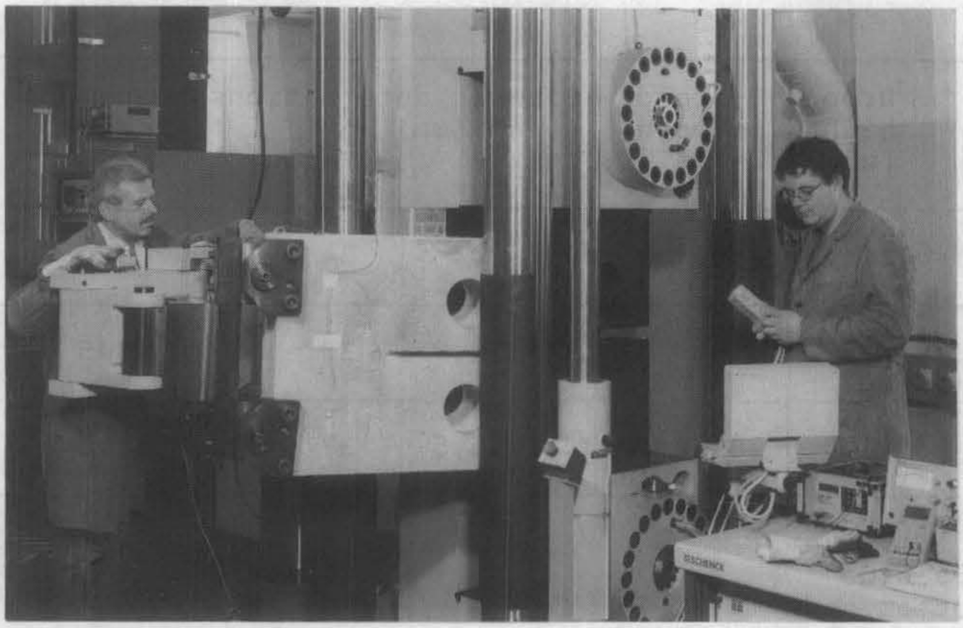

Figure 3 Testing of CT-300 DCI specimen by BAM

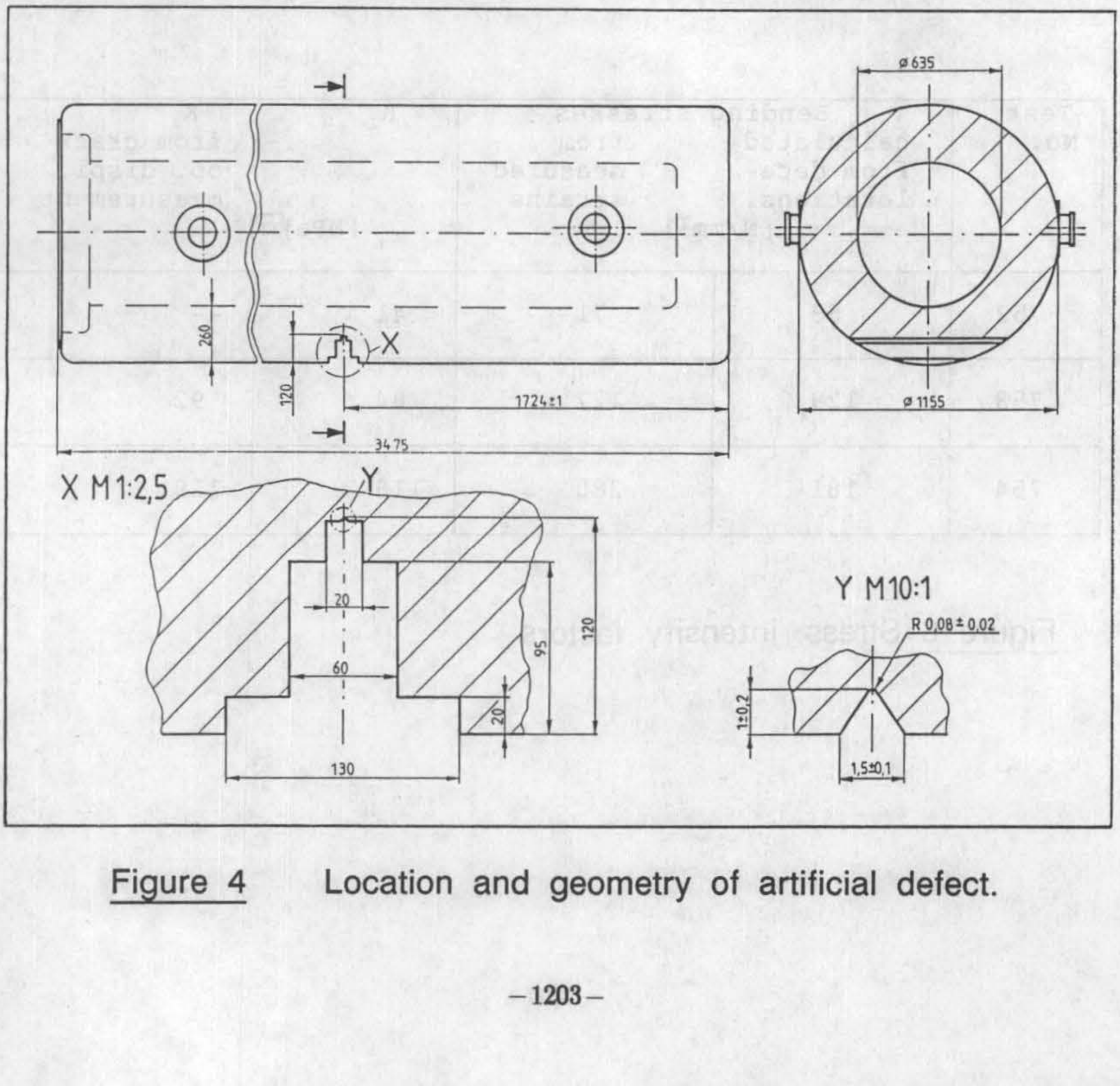

Figure 4 Location and geometry of artificial defect.

Test No.	Drop hight [m]	Distance between rails [mm]	Plastic deformations [mm] Cask LS	Cask BS	Rails LS	Rails BS	Decelerations [m/s^{-2}]
752	2,4	2595	3,8	44	24	24	300
753	3,5	3165	5,4	4,9	30	27	345
754	14,0	2895	4,2	5,5	37	37	600

LS = Lid side
BS = Bottom side

Figure 5: Drop test conditions and results with precracked VHLW-container

Test No.	Bending stresses calculated from decelerations [N/mm²]	Bending stresses from measured strains [N/mm²]	K_I [MPa$\sqrt{m}$]	K_J from crack op. displ. measurement [MPa$\sqrt{m}$]
752	63	71	41	--
753	129	127	84	92
754	181	280	118	119

Figure 6 Stress intensity factors

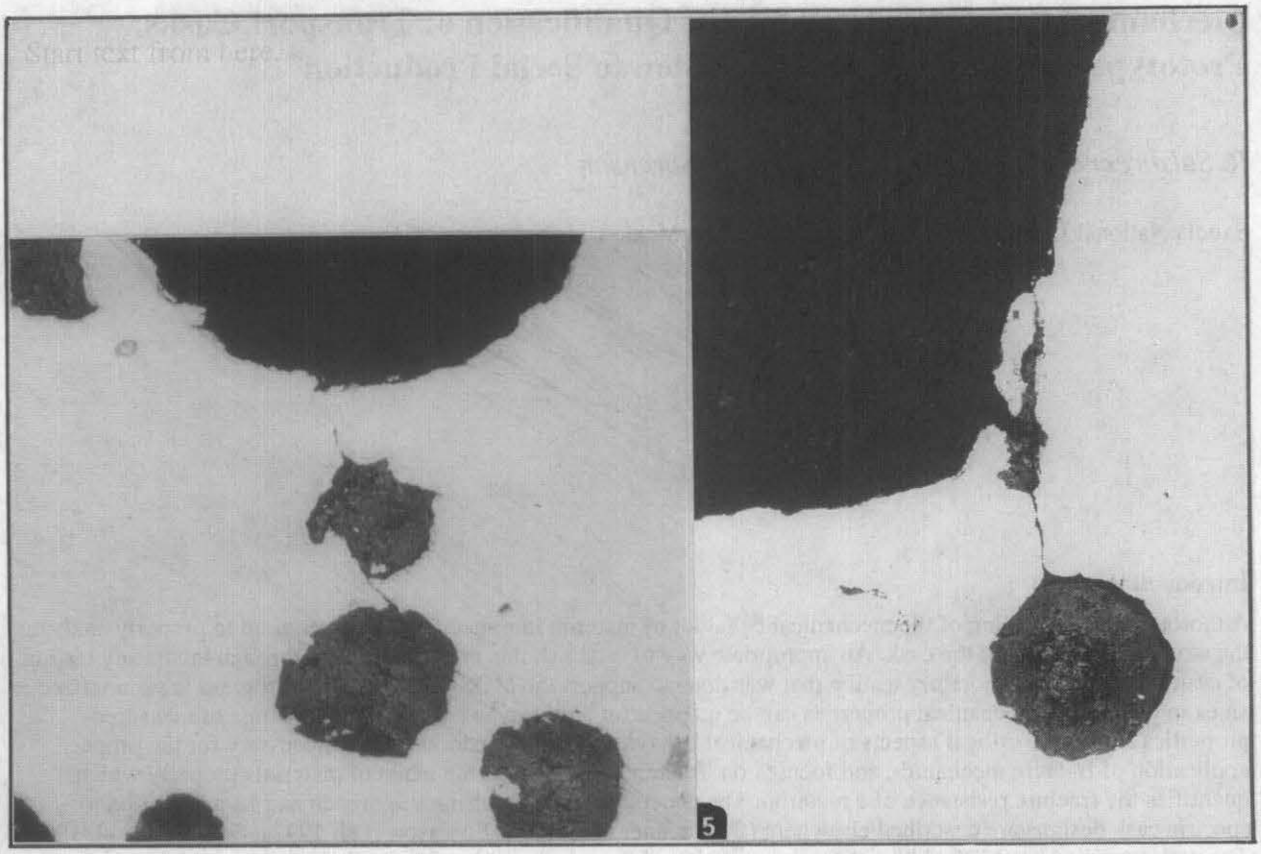

Figure 7 Initiated cracks after the drop test series starting from the flawtip (left) and groove edge (right).