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An experimental and numerical analysis to correlate variation in ductility to defects and microstructure in ductile cast iron components

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Abstract

This paper describes a statistical test plan to determine tensile properties and fracture properties for ductile cast iron considered for the Swedish nuclear waste canisters and associated analysis. Large variations were found in the ductility between tested canister inserts and between specimens taken from different locations in each insert. A large number of tested tensile specimens were subsequently analysed by fractography and metallography to relate low ductility values to size and type of casting defects. Loss of ductility could be related to slag defects and to a lesser extent to high pearlite content, low nodularity and chunky graphite. Slag defects were modelled by an elasto-plastic fracture mechanics model for penny-shaped slag defects and semi-empirical models for the other defect types. The fracture model was incorporated into a probabilistic scheme to compute distribution of elongation for the inserts and the associated defect size. The computed ductility distribution agrees very well with measured data whereas the computed defect size distribution is underestimated. By including crack growth resistance and various aspect ratios of defects a much better agreement with observed defects can be achieved.
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Keywords: Ductile cast iron; Ductility; Scatter; Nuclear waste canister; Elongation at fracture; Failure probability; Probabilistic fracture mechanics

1. Introduction

The long-term safety of spent nuclear fuel in a deep repository relies on a multi-barrier system with the waste package as the first barrier. Research is ongoing in different countries for the design of such waste packages. The Swedish programme, which is based on a copper over-pack/cast iron insert canister system (referred to as KBS-3 concept) and illustrated in Fig. 1, is perhaps the most advanced in terms of nearness to industrial implementation. These canisters are designed to contain radionuclides for at least 100,000 years at a depth of

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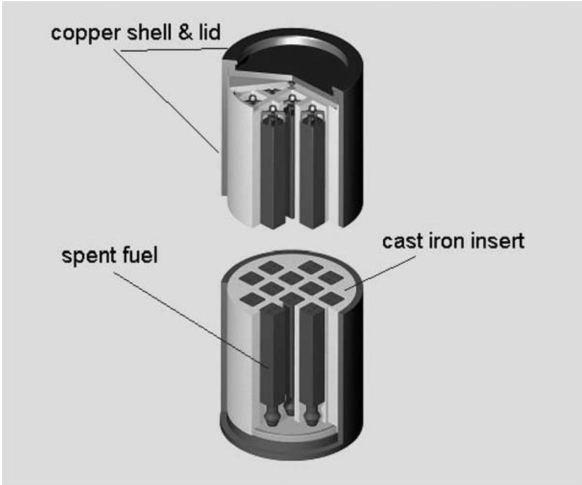

Fig. 1. The Swedish KBS-3 copper/cast iron canister for spent fuel.

500–700 m. In the normal conditions the canister will be subjected to iso-static pressure of 14 MPa from hydrostatic pressure and swelling of the surrounding buffer material. Several ice ages are expected during its service life and the canisters can be subjected to an additional pressure of 30 MPa from a 3 km ice-sheet. The total design pressure is therefore 44 MPa [1]. Although the canisters are globally loaded in compression large tensile stresses appear close to the fuel channels. The current status of the KBS-3 programme can be found in the most recent R&D plan for the Swedish Nuclear Waste Agency (SKB) [2]. A more detailed summary of the canister design can be found in [3,4].

Ductile cast iron has been selected as the load-bearing component in the KBS-3 inserts and must fulfill strength and ductility requirements. It is a cast ferrous material in which the free graphite is present in a graphical form. Fig. 2 shows a typical microstructure with the graphite modules in ferrite and pearlite matrix. Pearlite increases the strength but reduces ductility. The properties of ductile cast iron is strongly affected by the graphite nodules, in particular the roundness (referred to as nodularity) but also the number of graphite per area unit and the volume fraction. In addition the carbide content should be controlled to avoid detrimental effects on the fracture toughness. Magnesium is added to attain high nodularity but it may result in slag defects when it reacts with oxygen and other products such as silica. The casting process must be such that a sufficiently homogenous and flawless structure is obtained in the entire volume within precise geometry requirements. It is difficult to control the microstructure for complex geometries and material properties may have a relatively large scatter. Tensile tests of cast iron inserts that have been produced as part of the KBS-3 development showed relatively low overall ductility, but more importantly, the scatter was quite large

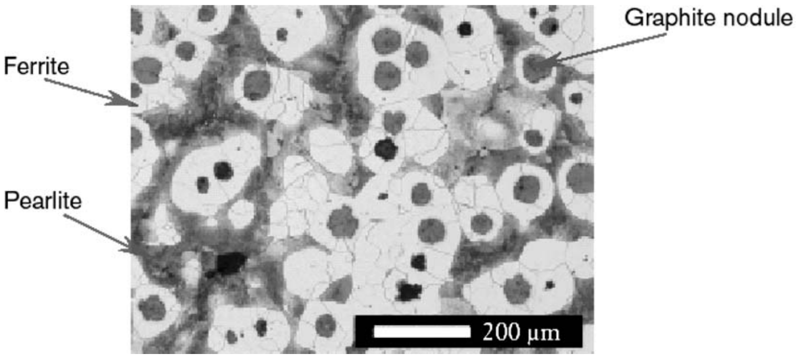

Fig. 2. Ductile cast iron illustrating graphite nodules in ferrite and pearlite matrix.

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