QUALITY ASSURANCE ASPECTS IN USING DUCTILE CAST IRON FOR TRANSPORTATION CASKS

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ABSTRACT

There has been an interest in recent years to assess the suitability of using ductile cast iron (DCI) as the structural containment boundary material for nuclear material transportation casks. This interest is based on the ability to cast to nearly final dimensions and to cast monolithic casks which eliminate welds in the containment boundary. Also, the low material and fabrication costs provide added incentive for evaluating DCI for cask construction.

To date, ferritic materials (including DCI) have not been certified for this application. The principal issue in using ferritic materials is that they can (under certain combined mechanical and environmental conditions) fail in a low energy, brittle type fashion, particularly in the vicinity of a flaw.Also, for thick-walled castings, inevitable variability in material microstructure results in mechanical property variability. To qualify this material for use in transport casks, it is necessary to demonstrate not only that the possibility of brittle fracture is precluded but also that the results are repeatable. That is, the development approach (design,fabrication, and testing) used for a prototype cask for proof tests must be transferable to each production cask.

The applicability of using DCI in transport casks is a part of Sandia's base technology transportation program. The methodology being used in this evaluation is based on fundamental fracture mechanics. This paper will describe the technical issues addressed in the Sandia program and how they relate to quality assurance. Results of experimental work, which relate fracture toughness to material microstructure, will be presented.

INTRODUCTION

Interest in the use of ductile cast iron (DCI) nuclear material transportation casks has increased steadily in the U. S. in recent years.This is due, at least in part, to development efforts in the international cask community. Certified DCI transport casks for spent fuel are in use in Western Europe, and the Japanese have a large development effort underway for developing DCI casks (1).

There are a number of benefits inherent in using DCI. The material is cast to near final cask dimensions which reduces machining efforts/costs. The cask is cast monolithically which eliminates welds in the containment boundary. The monolithic cask wall, which serves both as the structural containment boundary and the gamma shield, also eliminates the need for the "sandwich" type design (gamma shield sandwiched between the containment boundaries) which includes welds and are more difficult to fabricate.Finally, the low material and fabrication costs compare favorably with the traditional sandwich stainless steel cask costs.

There are certain technical issues associated with DCI which must be satisfactorily addressed to certify a DCI cask in the U. S. The principal issue is that a DCI cask can (under certain combined mechanical and environmental conditions) fail in a low energy, brittle type fashion,particularly in the vicinity of a flaw. Fracture mechanics is the engineering approach which can be used to evaluate failure modes in materials subjected to mechanical loadings.

Sandia National Laboratories (SNL) is assessing the applicability of using DCI for cask construction. The assessment is based on a linear-elastic fracture mechanics (LEFM) methodology. A DCI cask can be designed using the LEFM approach to assure ductile behavior (nonbrittle) when subjected to prescribed loading criteria. The methodology includes analysis, materials testing, and nondestructive evaluation (NDE) procedures. This paper gives a brief background on the technical approach and provides a detailed explanation of how quality assurance measures can be employed in production castings to assure conformance to the original fracture mechanics design criteria.

TECHNICAL APPROACH

The linear-elastic fracture mechanics (LEFM) approach is defined mathematically by:

$$K_I = C\sigma\sqrt{\pi a} \qquad (1)$$

where

K_I = stress intensity at the tip of a flaw or material discontinuity (ksi-$\sqrt{in}$)

C = constant = f (flaw orientation and location in the structure)

σ = nominal tensile stress (ksi)

a = flaw depth (in)

Further, a critical state can be described where brittle fracture conditions are imminent:

$$K_{Ic} = C\sigma\sqrt{\pi\, a_c} \qquad (2)$$

where

K_{Ic} = critical stress intensity factor

= static fracture toughness (ksi-$\sqrt{\text{in}}$)

a_c = critical flaw depth (in)

An allowable flaw depth for a specific cask design can be computed by rearranging Eq. (2):

$$a_c = C\left\{\frac{K_{Ic}}{\sigma}\right\}^2 \qquad (3)$$

This equation can be used as a design criterion for establishing flaw rejection limits for specific cask designs. The nominal tensile stress, s, is analytically computed and verified by drop tests. The critical flaw depth,a_c, is a function of the ratio of material fracture toughness to applied tensile stress. The limits of NDE sensitivity must be compatible with the maximum allowable a_c. The NDE inspection procedure must be sensitive and reliable enough to not miss flaws larger than a_c.

The distinctive issue in assuring that production DCI casks satisfy Eq.(3) is to assure that a minimum fracture toughness, K_{Ic}, is maintained throughout the casting. The casting process produces inherent material variability and, hence, material property variability through the thickness ofthe cask. Therefore, a link is needed between material physical properties and fracture toughness in order to characterize fracture toughness as a function of material properties. In this manner an understanding of how the fracture toughness will vary through the thickness of a production casting is attained.

DEVELOPMENT OF A QA APPROACH

A series of reports (2,3,4) document experimental work to establish material property correlations to mechanical properties. Reference 2 evaluates the relationship of compositional and microstructural properties to tensile properties (strength and ductility). Results of the study indicate that tensile strengths (yield and ultimate) correlate well with the nickel and silicon content. There was no apparent correlation between tensile strength and microstructure. Further, there was no simple relationship between ductility and composition or microstructure. This suggests that the mechanisms controlling tensile strength and ductility are at least partially decoupled.

Reference 3 evaluates the relationship between fracture toughness and physical material properties. Results of the study indicate that there is agood linear correlation between graphite nodule spacing and fracture toughness for the material tested. The material tested in both Refs. 2 and 3 was mainly ferritic (low pearlite) with Types I and II (highly spherical) graphite nodules as defined in ASTM A247. Figure 1 shows the linear relationship between 2-D graphite nodule spacing and fracture toughness as measured by ASTM E813.

Reference 4 compiled a large body of DCI properties from numerous sources and evaluated compositional and microstructural properties with respect to mechanical properties. The results in (4) agreed well with those in (2) and (3). Tensile properties do not correlate well to microstructure;whereas, fracture toughness does correlate to microstructure (graphite nodule spacing). The results of the SNL test program were corroborated by a large body of material data. Figure 2 shows the nodule spacing-to-fracture toughness relationship for the large database. The SNL data from Fig. 1 is included in this figure. There is more scatter in Fig. 2 than in Fig. 1. This is most likely due to not taking the micrographs from the same location in the casting as the fracture toughness test specimen. The SNL micrographs were taken from the fractured test specimen. Regardless of the scatter there is a clear lower bound with a minimum static fracture toughness of 50 ksi-$\sqrt{\text{in}}$(55 MPa-$\sqrt{\text{m}}$). This relation is restricted to ferritic DCI with high nodularity.

Reference 4 evaluated the relationship of numerous physical parameters to fracture toughness. Figure 3 shows the relationship between graphite nodularity and fracture toughness. A nodule shape of Type II or higher has a significant detrimental effect on fracture toughness; Types I and II, in general, exhibited high fracture toughness ($>$ 50 ksi-$\sqrt{\text{in}}$).

Previous research (5,6) has shown that an excessive amount of carbide in the form of pearlite has a significant effect on fracture toughness.Therefore, the metal matrix should be mainly ferritic ($>$ 80 percent).

Based on these results, specific recommendations can be made to provide DCI castings with an improved static fracture toughness:

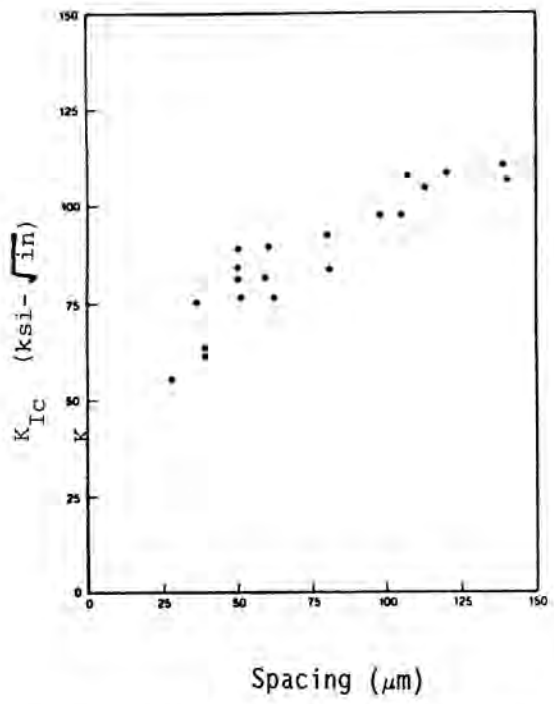

Fig. 1. Graphite Nodule Spacing Vs. Fracture Toughness - Sandia Data (Ref. 4).

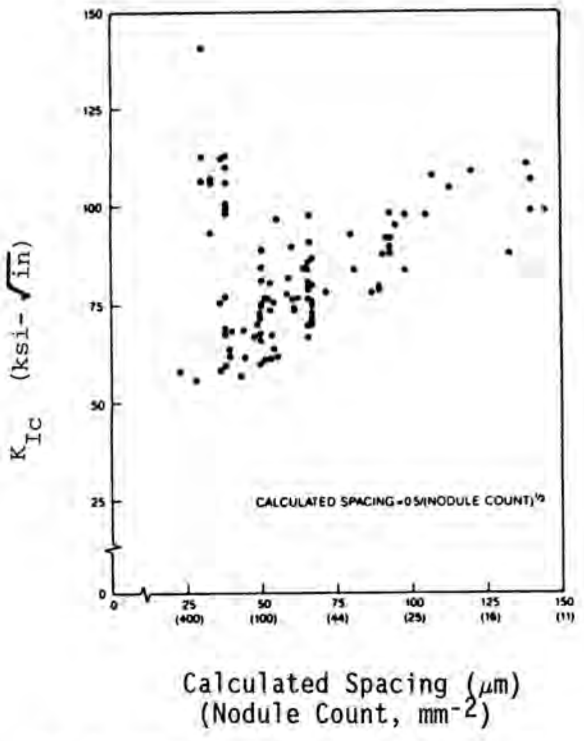

Fig. 2. Graphite Nodule Spacing Vs. Fracture Toughness - Combined Data From Numerous Sources (Ref. 4).

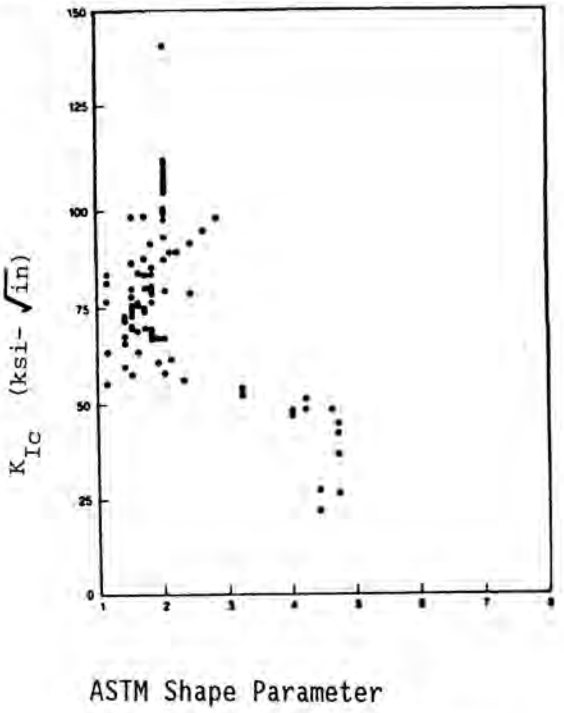

Fig. 3. Graphite Nodularity Vs. Fracture Toughness (Ref. 4).

- The metal matrix should be mainly ferritic with no massive carbides.
- The graphite nodules should be ASTM A247 Type I or II.

In addition, with the above two conditions met, static fracture toughness can be accurately estimated by measuring the graphite nodule spacing. Figure 4 shows a thick-wall casting and the variability in microstructure through the thickness of the cask wall. Using the relationship between graphite nodule spacing, static fracture toughness can be accurately estimated in production castings without performing rigorous fracture toughness tests. This provides a method for evaluating fracture toughness in production castings (and, thus,assures a minimum fracture toughness) by taking micrographs at specific locations.

A complementary effort, which has been underway for the past two years,is the development of an ASTM Material Specification for DCI. A Draft Specification, ASTM A874, "Specification for Ferritic Ductile Iron Castings for Nuclear Material Transport Containers Suitable for Low Temperature Service" has been written. The material specification provides for a basis of material quality by specifying limits on composition, microstructure, and mechanical properties. The establishment of limits on microstructure and minimum static fracture toughness is based on the results in Ref. 4. Table I shows the basic material properties required by ASTM A874 (draft). Supplying a DCI casting which meets the limits specified in ASTM A874 will assure a minimum static fracture toughness of 50 ksi-$\sqrt{in}$.

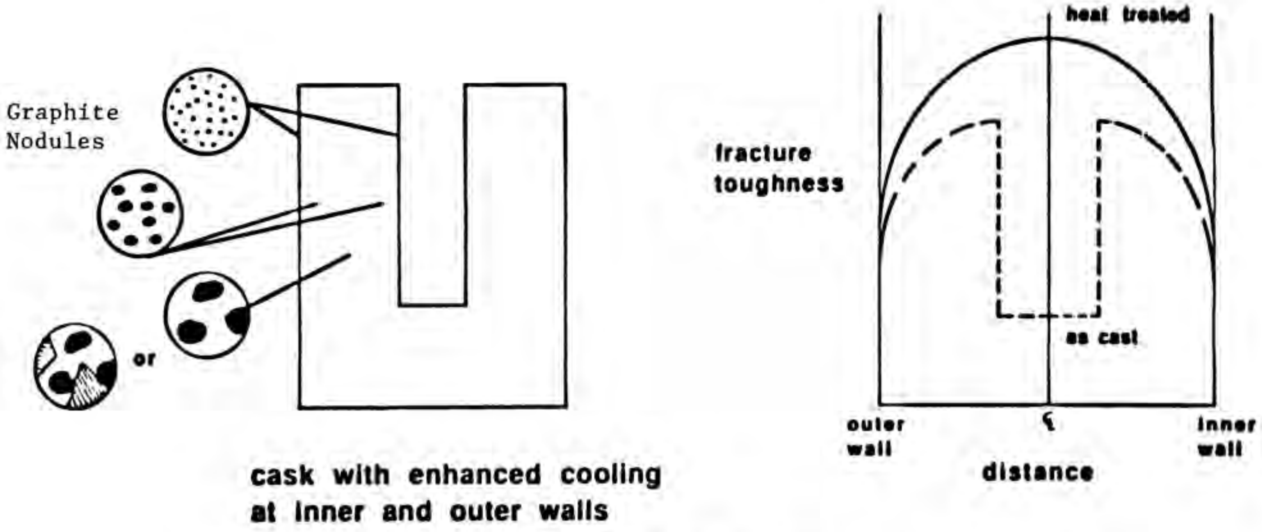

Fig. 4. Schematic Presentation of the Variation of Microstructure and Fracture Toughness Through a DCI Cask Wall.

TABLE I

ASTM A874 Draft Specification Material Properties

Mechanical Properties

• Ultimate Strength	45 ksi (300 MPa)
• Yield Stress	30 ksi (200 MPa)
• Elongation	12%
• Static Fracture Toughness	50 ksi - √in (55 MPa - √m)

Microstructure

- Essentially Ferritic Structure With No Massive Carbides
- > 90% Types I and II Graphite Nodules
- < 275/mm^2 Graphite Nodule Count

Composition

	MIN	MAX
• Carbon	3.0 -	3.8%
• Silicon	1.2 -	2.0%
• Nickel	-	1.0%
• Phosphorous	-	.03%

CONCLUSION

A method has been developed to assure production DCI casks meet a minimum standard of material quality. First, the draft specification provides a baseline of material quality. This assures the cask developer and the regulator that minimum material properties throughout the casting are met. In particular, the material standard requires a minimum static fracture toughness of 50 ksi-$\sqrt{\text{in}}$.

Second, a procedure has been established for estimating fracture toughness at discrete points in the castings. By using the microstructure-to-fracture toughness correlation, the change in fracture toughness can be associated with the inevitable change in material microstructure through the thickness of the cask wall. This provides a practical alternative to performing rigorous fracture toughness testing, which is technically complex and requires a significant amount of material.

REFERENCES

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