Mechanical Properties Used for the Qualification of Transport Casks: Prototype Development and Extension to Serial Production*

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Introduction

A thorough understanding of the mechanical behavior of material in a specific cask is required to properly analyze the structural response of the cask. An appropriate way to establish this understanding is through laboratory testing of cask material. The laboratory testing that was done to support the MOSAIK Drop Test Program is summarized as an example of how mechanical properties can be mapped for a prototype cask. The broad range of measured properties allows the critical aspects of mechanical behavior to be understood. This is necessary for the proper application of fracture mechanics, and focuses on fracture toughness as the inherent materials property which quantifies the fracture resistance of a material. The general fracture mechanics approach and its application to specific cask designs are described elsewhere (Salzbrenner et al. 1990, Sorenson et al. 1992a, Sorenson et al. 1992b). The understanding established by a thorough mapping of the mechanical properties is necessary to apply fracture mechanics to a particular prototype, but it is not sufficient for qualifying serially produced casks. The mechanical behavior of a prototype must be correctly associated with parameters which can be measured on production casks. Since the production casks cannot be destructively tested, measurements are commonly made on sub-size specimens. This may prevent direct measurement of valid design properties. An additional database may then be required to establish the correlation between sub-size specimen measurements and valid design properties. This is illustrated by outlining the additional testing which would be necessary to allow the successful verification of the MOSAIK Drop Test Program to be extended from the prototype to serially produced casks.

Mechanical Property Mapping of the MOSAIK KfK Cask

The MOSAIK KfK is a ferritic ductile iron (DI) cask used to transport and store transuranic waste. The cask was developed by the Gesellschaft für Nuklear-Service (GNS) Company of Germany, and is licensed for use throughout Europe. GNS donated a MOSAIK KfK cask to Sandia for testing purposes. The MOSAIK Drop Test Program was developed to demonstrate the fracture mechanics approach for quantifying the resistance to brittle fracture. The MOSAIK Drop Test Program is described in a companion paper in these proceedings. The MOSAIK KfK is an appropriate vehicle for demonstrating the fracture mechanics approach since it represents a class of alloys that can, under very severe conditions (high loading rate and low temperature), exhibit brittle fracture. A primary objective of the MOSAIK Drop Test Program was to quantify the fracture behavior of the MOSAIK KfK cask.

Figure 1 shows the dimensions of the MOSAIK KfK cask, along with the location of the coring which was removed from the bottom of the cask to provide material for the laboratory mechanical testing. The bottom coring was divided into five separate planes, each approximately 25mm thick. The labeling of these planes is shown in Figure 2 along with photomicrographs that depict the variation in microstructure through the coring. Both quantitative metallographic and chemistry measurements were made on samples taken from each plane. Results are presented in Table 1. The volume fraction of graphite and the average nodule spacing increased from the inner- (Plane 1) to the

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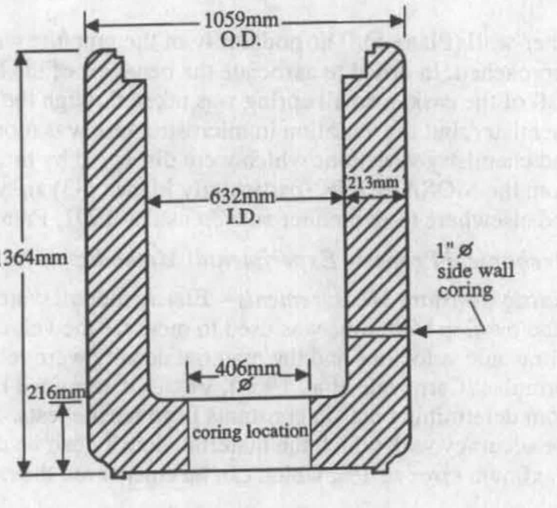
Figure 1. A cross-sectional sketch of the MOSAIK KfK cask, showing the location of the bottom and side corings.



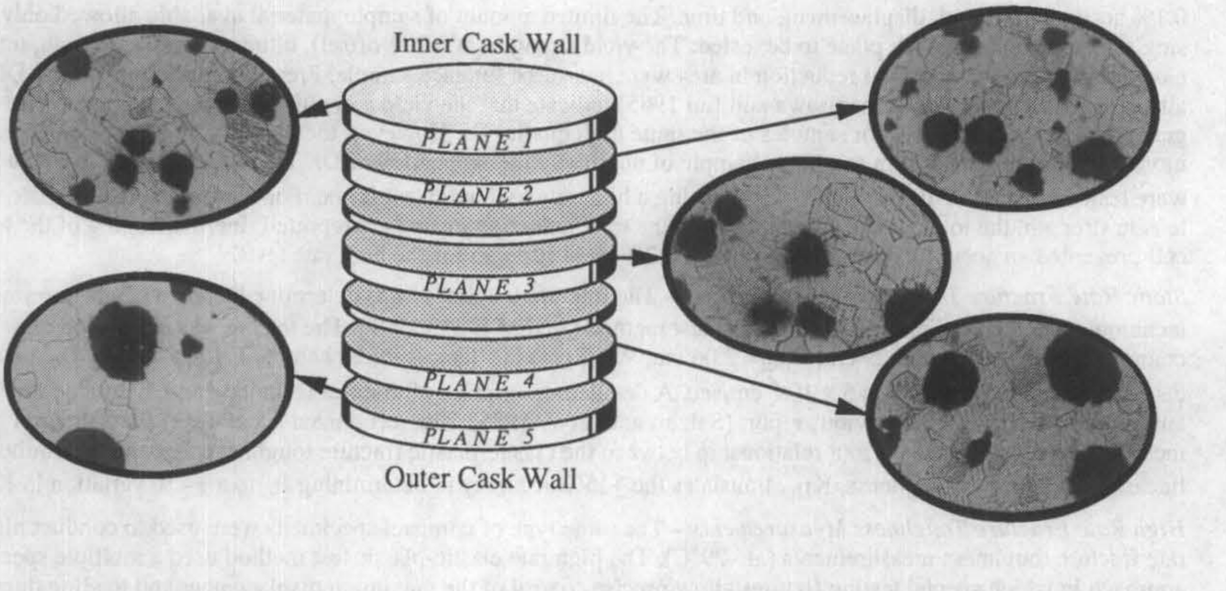


Figure 2. An exploded view sketch of the bottom coring from the MOSAIK KfK cask showing the plane locations and their mircostructure (mag. ~100X) relative to the inner and outer cask surfaces.

Table 1. Microstructural and compositional measurements for Planes 1 through 5 of the bottom coring of the MOSAIK KfK Cask.

Sample Location	Graphite Vol. Frac. (%)	Pearlite Vol. Frac. (%)	Nodule Count (#/mm^2)	Nodule Spacing (mm)	Nodule Type	Ferrite Grain Size (mm)	C (wt. %)	Si (wt. %)	Ni (wt. %)	S (wt. %)
Plane 1	10.5	0	123	0.045	100% type I	0.030	3.56	1.72	0.06	0.006
Plane 2	13.8	0	122	0.045	100% type I	0.029				
Plane 3	10.8	3	74	0.058	100% type I	0.029	3.39	1.74	0.05	0.005
Plane 4	18.4	3	41	0.079	90% type I*	0.034				
Plane 5	18.0	5	48	0.073	75% type I*	0.037	3.32	1.70	0.06	0.005

* The balance is type II — see ASTM A 495 for description of nodule type.

outer-wall (Plane 5). The nodularity of the graphite was found to be somewhat degraded as the outer surface was approached. In orded to associate the behavior of the large bottom coring to the behavior of the material in the side wall of the cask, a small coring was taken through the wall (see Figure 1). The side wall coring displayed a similar chemistry, but the variation in microstructure was more limited. Planes 1 through 3 encompass the microstructural and chemistry variations which were displayed by the side wall coring. The chemistry and microstructure of the DI from the MOSAIK KfK (particularly Planes 1-3) are very similar the other DI alloys that have been tested at Sandia and elsewhere (Salzbrenner and Crenshaw 1991, Frenz 1992, CRIEPI Report 1988).

Mechanical Property Experimental Methods:

Elastic Constant Measurements – Elastic moduli were determined from ultrasonic velocity measurements. A pulse echo overlap technique was used to measure the velocity of 5 MHz shear and longitudinal waves (Papadakis 1967). Ultrasonic velocities and the material density were related to polycrystalline elastic moduli through standard formulas (Carnevale et al. 1964). Values determined by this method are not subject to the gross errors that can result from determining elastic constants from tensile tests. The absolute accuracy of this method is generally limited by the accuracy with which the material density can be determined. For this work, the density was measured with a maximum error of 1%, which can be considered the overall accuracy of the elastic moduli measurements.

Tensile Measurements – Tensile tests were conducted at strain rates of 10^{-3} and 1 sec^{-1} on a conventional servohydraulic test frame in accord with standardized testing procedures (ASTM E 8 1991). Standard round tensile specimens with a gage length of 2.5 cm were used. All testing was performed at –29°C to match the hypothetical accident conditions specified by U.S. regulations (10CFR71 1984). The test equipment was calibrated to within 0.1% accuracy for load, displacement, and time. The limited amount of sample material available allowed only single specimens from each plane to be tested. The yield strength (at 0.2 % offset), ultimate tensile strength, total elongation to failure, and total reduction in area were measured for each sample. Previous studies on similar DI alloys (Salzbrenner 1986, Yanagisawa and Lui 1985) indicate that the yield and ultimate tensile strengths will generally vary less than 1% for samples of the same high quality DI. However, the ductility may vary considerably more, often up to $\pm$10% from sample to sample of nominally the same alloy of DI. Two specimens from Plane 3 were tested at a rate of 10^2 sec^{-1} (at –29°C) using a high rate hydraulic test frame. For these tests, the ultimate tensile strength, the total tensile elongation, and the total reduction in area are reported. Inertial ringing of the load cell prevented an accurate determination of the 0.2% yield strength for the high rate tests.

Static Rate Fracture Toughness Measurements – The fracture toughness was determined using a single specimen J_{Ic} technique which complies with the standard test method (ASTM E 813 1991). The testing was conducted on compact specimens (B_G=2.29 cm, B_{net}= 2.06 cm, W= 5 cm) in a temperature chamber held at –29°C. The load line displacement rate was fixed at 5 x 10^{-4} cm/sec. A detailed description of thie test technique and the method of analysis can be found in a previous report (Salzbrenner et al. 1985). The recognized accuracy of the J-integral method is $\pm$15%. The square root relationship between the elastic-plastic fracture toughness, J_{Ic}, and the equivalent linear elastic fracture toughness, K_{JIc}, translates the $\pm$15% accuracy in determining J_{Ic} to a $\pm$4 % variation in K_{JIc}.

High Rate Fracture Toughness Measurements – The same type of compact specimens were used to conduct high rate fracture toughness measurements (at –29°C). The high rate elastic-plastic test method used a multiple specimen approach in which special testing fixtures allow precise control of the maximum displacement and loading duration. The test technique and the analysis of test results are based on the same principals used for static-rate testing. The fixturing was coupled with a high rate hydraulic frame in which the actuator rate was maintained at 125 cm/sec. This actuator rate delivers a stress intensity rate of approximately 10^5 MPa-√m /sec (depending on the specific sample material and crack length). The laboratory testing rate exceeds the loading rate of the cask flaw caused by a 9 m drop. Further details on the high rate testing technique can be found elsewhere (Salzbrenner and Crenshaw 1990b). This high rate test method also allows the plain strain fracture toughness to be determined when samples behave in a suitably linear-elastic fashion. Since the same test set-up (fixturing, instrumentation,...) is used regardless of specimen behavior, no pretest assumptions need be made concerning whether the specimen will behave in a brittle fashion or in an elastic-plastic manner.

Other Measurements – The Charpy "V" notch impact (CVN) behavior (as a function of temperature from (–130 to +100°C) was also measured. These results are not included herein due to space limitations and because such values are useful only as qualitative indicators of material behavior. Charpy values are not inherent materials properties and cannot be used to quantify the mechanical performance. The Charpy test results are available elsewhere (Salzbrenner and Crenshaw 1990a).

Experimental Results:

Elastic Constants – There was a small, but distinct variation in the Young's and shear moduli in moving from Plane 1 toward Plane 5. This is shown graphically in Figure 3. This decrease is most probably caused by the increase in

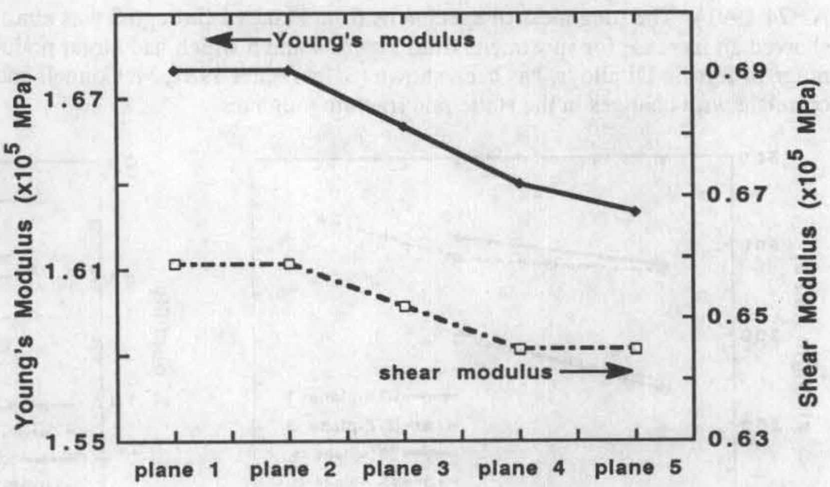


Figure 3. The variation of elastic moduli (derived from ultrasonic velocity measurements) with location for the bottom coring of the MOSAIK KfK cask.

the volume fraction of graphite in the bottom coring from the inner- to the outer-wall. There is, however, little practical engineering significance to the small variation, and the elastic constants are essentially constant through the bottom coring.

Tensile Properties – The results from the tensile measurements (at 10^{-3} sec^{-1}) exhibit little change in strength as a function of sample location (see Figure 4a). There is however a general decrease in tensile ductility from the inner to the outer wall (Figure 4b). Similar results were found for the tests conducted at the higher strain rate of 1 sec^{-1}. Previous work (Salzbrenner 1986) demonstrated that the strength of ferritic DI is controlled primarily by material composition. Since the compositional measurements (Table 1) show little variation through the coring, the tensile results are in agreement with the previous study. The decrease in tensile ductility with increasing coarseness of the microstructure is consistent with results from another study (Frenz 1992). While this correlation may hold for a limited range of composition and variation in microstructure, it is not universally true for the broadest range of composition and microstructure available for DI (Salzbrenner 1986).

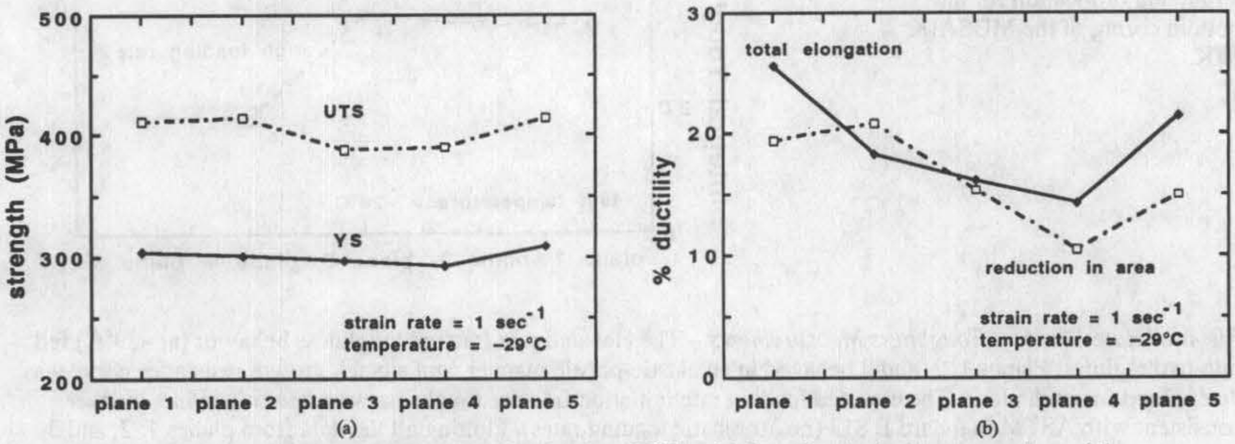


Figure 4. The variation in the tensile behavior (at –29°C) with location in the bottom coring of the MOSAIK KfK cask: (a) strength and (b) ductility).

The strength was found to exhibit a moderate increase with increased strain rate. This trend is shown in Figure 5 for Planes 1 and 3 (the other planes behave in a similar fashion). An increase in strength with increased strain rate is commonly observed for many alloys (Hertzberg 1976). The tensile ductility generally decreases with increased strain rate (see Figure 5). A decrease in ductility with increased strain rate has been observed in other ferrous alloys (Nakamura et al. 1968).

Static Rate Fracture Toughness Measurements – The static rate J_{Ic} measurement results are plotted in Figure 6 as a function of position. The static rate fracture toughness of all the DI in the MOSAIK KfK cask exceeds the minimum properties expected from material meeting the newly approved ASTM specification for a nuclear grade DI (ASTM

A 874 1991). The toughness of specimens from Planes 1 through 3 was almost constant. The toughness then showed an increase for specimens from Planes 4 and 5 which had larger nodule spacing. Nodule spacing, in a broad range of ferritic DI alloys, has been shown (Salzbrenner 1987, McConnell and Lombrozo 1987) to statistically correlate with changes in the static rate fracture toughness.

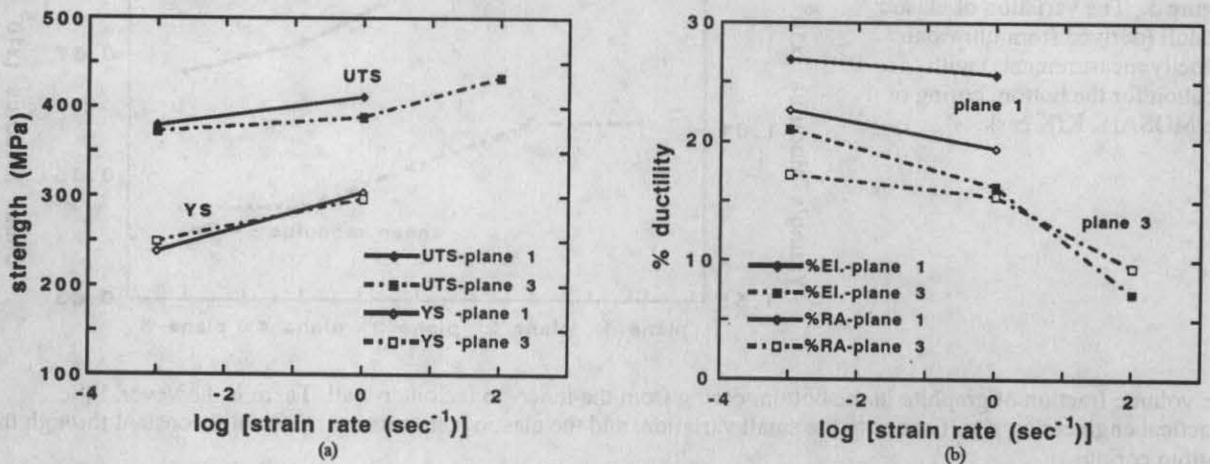


Figure 5. The variation in tensile behavior (at –29°C) with strain rate for material from the bottom coring of the MOSAIK KfK: (a) strength and (b) ductility.

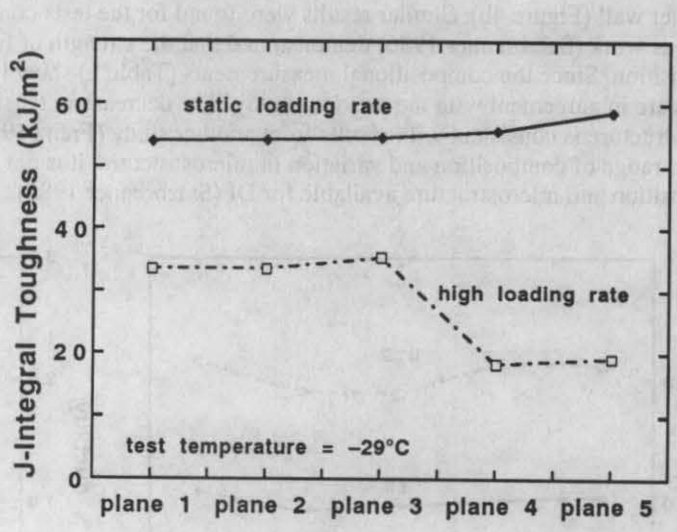


Figure 6. The fracture toughness as a function of location for the bottom coring of the MOSAIK KfK.

Elevated Rate Fracture Toughness Measurements – The elevated rate fracture toughness behavior (at –29°C) fell into two regimes. Planes 1, 2, and 3 behaved in an elastic-plastic manner, and a crack growth resistance curve was determined for each plane. The elevated loading rate initiation fracture toughness was determined in a manner consistent with ASTM Standard E 813 (i.e., for static loading rates). Plotting all the data from planes 1, 2, and 3 together produced a single crack growth resistance curve (shown in Salzbrenner and Crenshaw 1990b). The elevated rate initiation toughness for Planes 1 through 3 can thus be described as constant, as it was for the static rate testing. The value for the initiation toughness decreases from an average of 54.4 kJ/m^2 for static rate, to 33.1 for elevated rate. The reason for this decrease is not readily apparent, since scanning electron microscopic examinations of the fracture surfaces shows ductile tearing to dominate at both rates.

Fracture toughness specimens taken from Planes 4 and 5 behaved in a linear-elastic fashion when tested at high rate (at –29°C). The tests were analyzed as plane strain fracture toughness tests (governed by ASTM E 399 1991). Although requirements concerning linearity were met, the samples did not possess the minimum dimensions specified in the standard. The initiation values for the specimens from Planes 4 and 5 are used only as estimates of the true elevated loading rate fracture toughness for DI material from those planes. When compared to the results from Planes 1-3 the toughness of Planes 4 and 5 showed a substantial decrease (see Figure 6). Examination of fracture surfaces of samples from Planes 4 and 5 showed extensive cleavage (i.e., low energy) fracture.

Selection of Properties for Finite Element Model

Mechanical measurements encompassing all microstructures and compositions present in the cask provide the foundation for selecting the values for the material model for finite element analyses. The proper application of finite element analyses allow the mechanical response to be quantified. Systematic measurements determine if large variations, and/or unexpected discontinuities in the mechanical properties are present. When the variations are small, the selection of the representative mechanical properties is straightforward, and a simple (homogeneous) material model can be used. When the measurements indicate the presence of large variations, a more complicated material model may be needed to properly predict the mechanical response of the overall cask. The measurements on the prototype MOSAIK KfK are used to illustrate which mechanical properties are required for finite element analyses and provides an example of how values for each can be selected.

Elastic response is fully characterized by utilizing two elastic moduli of the material. The measured variation of the elastic constants (derived from ultrasonic velocity measurements through the bottom coring) is small and will have a negligible effect on the mechanical response of the cask. The average values for both the Young's modulus and Poisson's ratio were calculated and used in the material model.

The yield strength (as determined by tensile testing) is used as the engineering definition of the beginning of plastic deformation. Tensile testing as a function of strain rate, shows that the strain rate sensitivity is not large, and will not have a major effect on the analyses of 9m drops. The strain rate of 1 sec^{-1} provides the best overall match for the loading rate of the 9m drop test. Since the variation (through the coring) of the yield strength is small, the average of the five measured responses is a good estimation of the beginning of plastic deformation.

The plastic response of a material is characterized with a power law hardening material model (Stone et al. 1990). The stress-strain behavior of a tensile specimen furnishes the required information for this model. The stress-strain response of all specimens (particularly from planes 1 through 3) was similar and average values were used to determine the parameters for the power law hardening model. The largest variation in the tensile behavior through the coring was found in the tensile ductility (i.e., the engineering strain to failure). Such a variation could properly be accounted for in a FE material model through ductile failure criteria. For the transport casks under consideration here, such an inclusion is moot. This is due to the elastic design "rules" that are applied to transport casks in general, and to the MOSAIK KfK cask in particular. Specifically, only elastic deformations are allowed for all design loading conditions (including accident conditions). The through-section stresses which result from applied loads are below the yield strength of the structural material. The 9m drop of the MOSAIK KfK produced a maximum tensile stress at mid-span, of approximately 210 MPa (Sorenson 1988), and this is substantially below the yield strength of the cask. Plastic deformation occurs only in localized volumes in the vicinity of the artificially introduced flaws, or underneath the steel supports. (Details of the drop test conditions, including the steel end supports to enhance the tensile stresses in the vicinity of the artificial flaw are available in Sorenson et al. 1992b.) Since global plastic deformation does not occur for even the severe (hypothetical) accident condition of the 9m drop (onto an unyielding target), a failure criterion related to the ductility of the material is unnecessary, and the tensile ductility is not used in the finite element analyses.

The variation in the high rate fracture toughness (and the uncertainty in its measurement) is greater than that in the modulus or tensile measurements. Nonetheless, the measured values can be used to provide a reasonable estimation for finite element analyses. The appropriateness of the value chosen is ultimately validated by the full scale drop tests of the prototype cask. Measured values of the fracture toughness were effectively invariant for both static and elevated loading rate tests conducted on samples from Planes 1 through 3. The microstructure from Planes 1-3 closely matches the entire variation seen in the side wall, and it therefore is appropriate to estimate the toughness in the vicinity of the flaw in the sidewall as the average of the values from Planes 1-3. Since the rate of the laboratory fracture toughness tests was only slightly higher than that caused by the drop test, the best estimate of the fracture toughness is the average of the high rate measurements on specimens from Planes 1 through 3 (i.e., 33.1 kJ/m^2).

The finite element analysis of the response of the cask to a 9m drop is verified by the full scale testing. The elastic response of the cask is measured by appropriately placed accelerometers and strain gages, and is compared to the values calculated by the finite element analysis. Examination of the data and the cask after the drop confirm that through-wall (global) plastic deformation did not occur. Although the cask is designed to preclude failure occurring by tensile overload, the resistance to cracking (by ductile tearing and/or brittle cleavage) must also be demonstrated. An important purpose of the drop test of a prototype cask is to verify the accuracy of the fracture mechanics method used to predict the fracture behavior. The drop test confirms both the calculational methodology and the laboratory methods of determing the fracture toughness of the material. For the MOSAIK KfK example, the applied J-integral from the 9m drop was calculated by finite element analysis and compared to the (average) value determined by the laboratory measurements. The magnitude of the applied J-integral from the drop test was intentionally enhanced by the coincidence of the artificial flaw and the maximum tensile stress. The J-integral value of the fracture toughness from the laboratory measurements was used as the global failure parameter. When the applied J-integral was less than the measured fracture toughness, the analysis predicted that crack extension from the artificial flaw would not occur. When the value of the applied J-integral exceeded the elevated rate fracture toughness, the analysis predicted that at least some crack extension would occur. The results from the MOSAIK Drop Test Program (Sorenson et al. 1992b) demonstrated i) the correctness of the finite element analysis, ii) the validity of using the J-integral as the failure parameter, and iii) the accuracy of the fracture toughness determined by the laboratory testing.

Extension to Serially Produced Casks

The work described above demonstrates the applicibality of the general qualification method. The detailed measurement of the mechanical properties as a function of location within a cask provides a foundation for understanding the mechanical response of the cask during normal and accident conditions. The drop testing of the prototype cask verifies the analysis and the mechanical property testing. A benchmark is thus established which allows other casks of the same material, specification, geometry, etc., to be qualified. Although the foregoing process of detailed mechanical property measurement and the prototype drop testing may be necessary (to establish the benchmark), it is not sufficient to qualify serially produced casks. Critical properties of each serial cask must be appropriately linked back to the prototype. Critical properties must meet or exceed minimum values for every cask which is to be qualified.

In the current example, the fracture toughness is the critical property that must be shown to be above a minimum value in each production cask. This might be done by measuring the fracture toughness directly on samples from representative material from each cask. The material for such measurements could be obtained from corings, prolongations, and/or test blocks that have been shown (by the mapping process) to incorporate the minimum toughness material found in the cask. When values from such specimens exceed the minimum acceptable value, the individual cask is acceptable. This procedure is very clear in concept, but may present difficulties in application. As an example, the determination of the fracture toughness on the relatively small specimens which might be available from corings may not produce a valid value. An additional database may need to be created which allows parameters which can be measured on small specimens to be statistically correlated to valid design properties. The results of mechanical measurements on subsize specimens such as a notched round bar (Arai 1992) may be shown to correlate to the fracture toughness of much larger specimens. As an alternative, the relationship between valid fracture toughness (on large specimens) and the microstructure/composition of the material may established, and allow straightforward chemistry and metallographic measurements to qualify the material. A relationship of this type has been shown for the static rate elastic-plastic fracture toughness of ferritic ductile irons (Salzbrenner 1987). This type of understanding must be extended to elevated loading rate fracture toughness (at low temperatures) in order to be applied to quality assurance of production casks.

Summary

The qualification process that should be sufficient for qualification of a specific cask (material/geometry combination) has been examined. The prototype cask should be tested to determine its overall variation in microstructure, chemistry, and mechanical properties. This prototype may also be subjected to "proof testing" to demonstrate the validity of the design analysis (including the mechanical properties used in the analysis). The complete mechanical property mapping does not necessarily have to precede the proof testing (i.e., portions of the cask which experience only low (elastic) loads during the drop test are suitable for mechanical test specimens). The behavior of the prototype cask and the production casks are linked by assuring that each cask possesses at least the minimum level of one or more critical mechanical properties. This may be done by measuring the properties of interest directly, or by relying on a secondary measurement (such as subsize mechanical test results or microstructure/compositional measurements) which has been statistically correlated to the critical properties. The database required to show the correlation between the secondary measurement and the valid design property may be established by tests on the material from the prototype cask. The production controls (e.g., on the casting process, feed materials, ...) must be demonstrated as being adequate to assure that a uniform product is produced. The testing of coring (or test block or prolongation) samples can only be viewed as providing a valid link to the benchmark results provided by the prototype cask if the process used to create follow-on casks remains essentially similar. The MOSAIK Test Program has demonstrated the qualification method through the benchmarking stage. The MOSAIK program did not establish a means for qualifying serial production casks through, for example, a correlation between small specimen parameters and valid design fracture toughness properties. Such a correlation would require additional experimental work.

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