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Application of revised fracture toughness curves in pressure vessel integrity analysis

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ABSTRACT

As plants age and reactor pressure vessels become more embrittled, the impact of conservative analysis methods is becoming increasingly limiting for plant operations and, potentially, for the operating life of the plant. This paper explores the possible use of the Master Curve approach to determining fracture toughness as an alternative to the traditional lower bound reference fracture toughness curve in the ASME Code.

INTRODUCTION

Structural integrity analyses are used to assure the safe operation of nuclear reactor pressure vessels. In the United States, structural integrity analyses are used in setting allowable operating pressure and temperature limits, in demonstrating that pressure vessels can survive pressurized thermal shock conditions, and in determining whether flaws that might be detected during an in service inspection can remain in the vessel during subsequent operation or if they must be repaired. These applications of structural integrity analysis methods differ in some of the specifics of the application -- flaw sizes considered, rigor in the fracture mechanics models, and explicit margins, for example -- but they are all similar in general approach. A measure of the crack driving force, the applied K_I, is compared to a material property known as the fracture toughness.

The U.S. Nuclear Regulatory Commission (USNRC) regulations and regulatory guidance pertaining to reactor pressure vessel integrity involve different levels of conservatism depending on the specific application. The conservatism is manifest in implicit and explicit margins. One of the implicit margins is the fracture toughness curve. For example, in determining operating pressure and temperature limits, it is required that a lower bound fracture toughness curve be used, the so-called K_{IR} curve. However, in pressurized thermal shock analyses and in analyses of flaws detected during in service inspections, the required structural integrity analysis makes use of both the crack initiation curve, the K_{IC} curve, and the crack arrest curve, the K_{Ia} curve. Each of these curves is a lower bound representation of fracture toughness data from several different materials.

The generic fracture toughness curves are indexed to a specific material through the nil-ductility reference temperature, or RT_{NDT}. This parameter is determined in accordance with the ASME Code, Section III, NB-2331, using drop weight and Charpy impact data. The RT_{NDT} is determined as the larger of the drop weight NDT or the temperature at which the material achieves a Charpy energy of 50 ft-lb less 60°F or at which the lateral expansion equals 35 mils (0.035 inches).

The RT_{NDT} is adjusted to account for the effects of neutron irradiation through the procedures outlined in Regulatory Guide 1.99, Radiation Embrittlement of Reactor Vessel Materials. Margins are added to the adjustment to RT_{NDT} to account for data scatter and model uncertainty.

Thus, the material fracture toughness used in these regulatory analyses includes margin from using a lower bound curve, from the definition of the indexing parameter, and from the adjustment used to account for neutron irradiation. These margins are in addition to implicit margins in other parts of the structural integrity analyses, and in addition to the explicit margins.

As plants age and reactor pressure vessels become more embrittled, the impact of these conservative analysis methods is becoming apparent through limits on plant heatup and cooldown rates, and through potential limits on operating life of the pressure vessels. The USNRC has undertaken a broad based review of the fracture analysis methods used in assuring pressure vessel integrity with the objective of providing technically defensible analysis methods, and supporting data, that have identified margins rather than continuing to work with methods that have numerous compounding implicit and explicit margins. While it will not be possible to completely eliminate conservative assumptions in the analyses, the objective is to limit their number and to characterize their impact on the analysis result.

In approaching this effort, one of the major areas of endeavor is the characterization of the material fracture toughness, both in the unirradiated and irradiated conditions. There are several weaknesses in the current approach, starting with the use of the dynamic Charpy impact test results in determining an index parameter for static fracture toughness. Thus, the effort has sought an alternative approach that could provide a more direct assessment of the fracture toughness, potentially eliminating some of the implicit margins in the analysis. The following sections of this paper describe an approach to characterization of fracture toughness in the transition range which is referred to as the "Master Curve" approach and some of the issues that must be resolved before such an approach can be incorporated into regulatory analyses.

THE MASTER CURVE

Predicting the fracture toughness behavior of steels in the ductile, upper shelf region or the full brittle, lower shelf region is a straightforward process due to the generally well-behaved nature of the fracture toughness K_{IC} and J_{IC} in the two regions. In the fracture toughness temperature transition region the toughness on any given volume is unpredictable due to the competition between the ductile and cleavage fracture mechanisms. The traditional way of dealing with such behavior in an engineering sense was to test as many fracture toughness specimens as possible in this region and then determine the lowest bound of all the data and use this bounding value for design purposes. The difficulty with such a procedure is dealing with any change in material condition such as irradiation embrittlement which would require a large fracture toughness testing program for each new condition. The traditional method assumes that the changed fracture toughness transition region can be described by the previously measured region but shifted in temperature by the change in a reference temperature calculated from a drop weight test or from Charpy V notch (CVN) impact toughness curves. This system allows the use of surveillance capsules designed for small CVN specimens rather than large fracture toughness specimens.

Wallin at VTT in Finland has performed research for more than 15 years to devise a more direct method of predicting the fracture toughness transition behavior of a steel from a small set of specimens. His work has created what is called the "Master Curve" (MC) approach to predicting fracture toughness in the transition temperature region. The MC approach has several important assumptions:

1) Fracture toughness behavior is controlled by a weakest link mechanism.
2) The weakest link mechanism can be described by a three-parameter Weibull function with a Weibull slope value of four.
3) The shape of the curve of mean Weibull fracture toughness values versus temperature is similar for all pressure vessel steels.
4) A single "Master Curve" can describe the fracture toughness transition behavior of all pressure vessel steels with a simple temperature scale adjustment of the reference temperature (T_0), which is calculated for toughness specimens which have a Weibull mean value of 100 Mpa√m.
5) A T_0 value can be calculated from as few a six fracture toughness specimens.

That the fracture toughness values of a large set of specimens tested at a given temperature is controlled by a weakest link mechanism which can be described by a Weibull function was proposed by Weibull in 1939. [1] The weakest link mechanism for carbon steel has been described micro-mechanically by Ritchie, Knott and Rice (RKR model) in 1973. [2] The use of a three parameter Weibull [3] function with a Weibull slope value of 4 can be supported with a statistical treatment, a micro-mechanical treatment or a fracture toughness treatment as shown by Wallin in 1984. [4] The Weibull behavior and Weibull slope of 4 appears to be easily acceptable to the engineering community with such a history.

The new component of the approach by Wallin is ascertaining the shape of the MC through the application of Weibull statistics on fracture toughness data. The curve defined by equation (1) can be adjusted to a steel with the appropriate T_0. This is directly analogous to the assumption in the traditional method that the fracture toughness transition behavior of pressure vessels steel could be simply adjusted for reference temperature and still describe the appropriate behavior.

$$K_{jc} = 30 + 70 \exp\left\{0.019\,(T - T_0)\right\},\ \text{Mpa}\sqrt{\text{m}} \qquad (1)$$

The application of the MC to new transition toughness data not in the Wallin's original data base by McCabe and co-workers [5] supports the MC approach. McCabe has shown that the testing of as few as six ½ T compact specimens at one temperature can be used to calculate a material specific toughness transition curve. This curve with 95% and 5% confidence limits can encompass all of the traditional fracture toughness data produced for the given weld metal using ½ T to 4T compact specimens. Such anecdotal evidence does support Wallin's claim for the MC. However, showing the similarities of the shape of all pressure vessel steel needs verification via an independent statistical analysis that has yet to be performed. This is especially true for the possible change in the shape of the toughness curve by irradiation. The application of the MC to non-ferrous materials has been attempted with mixed results. [6]

The use of a small number of specimens to calculate the MC reference temperature, T_0, was justified by Wallin [7] with a statistical argument and supporting fracture toughness data which appears to be convincing. The development and verification of the MC for pressure vessel steels has been performed with valid fracture toughness data which required a size of at least ½ T. In order for the MC approach to be applicable for reactor pressure vessel surveillance programs which currently use CVN specimens, the T_0 would need to be calculated using precracked CVN specimens. The fracture toughness value calculated using CVN specimens is often invalid due to the size requirements currently published in ASTM E1737.

The Master Curve is being considered by ASTM to be included as a standard procedure with the provision to accept some fracture values from invalid fracture toughness specimens with a cautionary declaration. The use of invalid fracture toughness data for the calculation of transition toughness behavior which may be used in a possible regulatory issue will be difficult to support without other valid material specific toughness data. The use of invalid fracture toughness specimens in the transition region assumes that the MC approach can account for the possible loss of constraint of those specimens. The MC approach assumes that all variation in toughness resulting from specimens of different sizes can be accounted for by application of weakest link statistics. [8] This approach works well with valid toughness data but will need verification when some invalid data are also included.

The possible use of the MC approach to replace the CVN impact toughness testing for surveillance programs raises the question of dynamic loading effects. The CVN tests are always performed at high loading rate. Should the MC approach have the same requirement? A study published by Wallin and co-workers [9] shows that testing rate affects the apparent changes in MC reference temperate, T_0, due to neutron irradiation. Dynamically tested precracked CVN (PCVN) specimens show a smaller shift in T_0 than statically tested PCVN specimens. Also the study showed that the shift in T_0 from the dynamic results was the same as the shift in the 28 joule level of CVN curves due to irradiation embrittlement.

REGULATORY APPLICATION

The NRC has permitted application of the MC approach in a very limited manner for welds with a low Charpy upper shelf energy. In that application it was concluded that determination of initial RT_{NDT} via the CVN procedure of NB-2331 of Section III of the ASME Code was not appropriate. The alternate approach was to demonstrate that T_{NDT} was actually more appropriate for the determination of RT_{NDT}. To make this demonstration, the MC approach was used, with both static and dynamic fracture toughness data, to show that the resulting fracture toughness transition curve, with a lower RT_{NDT}, was still bounded by the ASME fracture toughness curves. In this manner, it was demonstrated that the initial RT_{NDT} value could be lowered from 0°F to -26°F. This limited application of the MC approach was justified by the: (1) the relatively large amount of fracture toughness data for the material in question; (2) the use of 1T fracture toughness specimens and; (3) the availability of dynamic fracture toughness data.

CODES AND STANDARDS ACTIVITIES

The NRC has encouraged interested licensees and Owners Groups to seek resolution of the technical issues related to application of the MC technology with Codes and Standards Committees on a consensus basis. NRC and its' contractors are also involved with supporting these processes. In this regard, it is appropriate to note that several activities are underway that, when completed, will provide a sound basis for using the MC technology. As mentioned earlier, ASTM is currently balloting the MC Standard for approval. NRC is supporting the development of a technical basis document for the MC standard which should be completed in 1997. Additionally, the ASME Pressure Vessel Research Committee (PVRC) has formed a Task group to provide recommendations to ASME on the implementation of the MC technology into the Code. The PVRC group serves as a focal point for presentation and discussion of data and analyses related to implementation of MC technology. The group is coordinating an MC testing round-robin and is developing a basis document containing guidelines on applications of the MC technology. Finally, the ASME has also formed a MC Task Group under the Section XI Subgroup on Evaluation Standards. The short term goal of the Task group is to develop an alternative to determination of initial RT_{NDT} using fracture toughness specimens and the MC approach.

ISSUES FOR FUTURE APPLICATION

Broader applications of this technology, including application to irradiated materials, will require resolution of a number of issues, including: (1) testing performed on the appropriate material (e.g., the actual limiting weld, plate, etc. or an appropriately qualified surrogate); (2) adequate constraint conditions for the specimens tested; (3) dynamic loading effects where appropriate (e.g., use of MC technology for determination of RT_{NDT}) and; (4) effects of irradiation on the shape of the master curve. Most of these issues can be resolved by appropriate testing programs and test methods. However, the issue of testing the appropriate material is a key consideration for many U.S. plants.

As knowledge about the factors controlling neutron irradiation has improved, the identification of the limiting material in any given pressure vessel may change. In fact, this has proven to be a problem for some U.S. plants, where the limiting material, determined based on the current understanding of embrittlement, may not have been included in the material surveillance program. In some cases, "similar" materials and welds have been included. However, there are no proven guidelines for determining what would constitute a credible "surrogate" material that could be tested in lieu of testing the actual limiting material from a reactor pressure vessel. For example, are welds made using the same heat of weld wire, flux lot, and post weld heat treatment sufficiently similar in mechanical properties that they can be used interchangeably in determining T_o? Testing of such "similar" welds has revealed significant variability in the nil ductility temperature. Additionally, test results from welds removed from a canceled plant in the U.S. have revealed scatter in the Charpy transition temperature on the order of 100°F. [10] This variability in properties for the same weld, and similar instances of variability in properties for other welds, strongly suggests that identifying acceptable surrogate materials is a matter that requires careful consideration before the MC technology can be confidently applied for U.S. reactor pressure vessels.

SUMMARY

As plants age and reactor pressure vessels become more embrittled, the impact of these conservative analysis methods is becoming apparent through limits on plant heatup and cooldown rates, and through potential limits on operating life of the pressure vessels. The USNRC has undertaken a broad based review of the fracture analysis methods used in assuring pressure vessel integrity with the objective of providing technically defensible analysis methods, and supporting data, that have identified margins rather than continuing to work with methods that have numerous compounding implicit and explicit margins.

A major aspect of this endeavor is the characterization of the material fracture toughness, both in the unirradiated and irradiated conditions. There are several weaknesses in the current approach, starting with the use of the dynamic Charpy impact test results in determining an index parameter for static fracture toughness. Thus, the effort has sought an alternative approach that could provide a more direct assessment of the fracture toughness, potentially eliminating some of the implicit margins in the analysis. The Master Curve approach is promising in this regard, however significant technical, process and regulatory issues remain to be adequately addressed before full implementation of such an approach can be endorsed by NRC:

(1) Fracture toughness characterization performed on the actual material in question or an appropriately qualified "surrogate."
(2) Fracture toughness characterization performed on specimens with adequate constraint and at appropriate loading rates.
(3) Quantification of the effects of irradiation on the shape of the master curve.
(4) Development and finalization of consensus Codes and Standards (ASTM, PVRC and ASME).
(5) Revisions to USNRC rules and regulations governing RPV integrity.

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