Predicting Crack Arrest in Reactor Pressure Vessels

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ABSTRACT

The pressurized thermal shock issue has provided increased motivation for the development of an accurate crack arrest prediction methodology. The currently accepted procedure for predicting crack arrest is incorporated within the ASME Code; it is based on static linear elastic fracture mechanics principles, with a crack being presumed to arrest when the crack tip stress intensity K_I^{ST} falls below the arrest toughness value K_{Ia}. Motivated by recent Combustion Engineering results, this paper describes research, based on the use of the reflectionless stress intensity factor procedure, which shows that the ASME Code static procedure is overly conservative when it is applied to the arrest of a deep crack in the wall of a reactor pressure vessel.

INTRODUCTION

Pressurized thermal shock (PTS) is a limiting condition on water-cooled nuclear reactor pressure vessel integrity, and may occur during a severe system transient. It requires the following conditions: (1) high re-pressurization following severe overcooling of the inner surface of the vessel wall, (2) significant degradation of the vessel material toughness due to radiation embrittlement, (3) the presence of a critical-size defect in the vessel wall. In order to assure the integrity of a vessel during a PTS event, the United States NRC established the PTS rule (U.S. NRC 1985). This rule defines the vessel material RT_{NDT} (nil-ductility reference temperature) below which the PTS risk is considered to be acceptable. The PTS rule also prescibes the way in which the projected RT_{NDT} is to be calculated, the basis being U.S. NRC Regulatory Guide 1.99 Rev 2, 1988, which is used to predict radiation embrittlement levels; this guide has upgraded and expanded the calculative procedures that are acceptable to the NRC. If the Revision 2 procedures are applied in conjunction with the PTS screening criteria, the increase in the predicted end-of-life RT_{NDT} causes some plants with high nickel content welds to exceed the PTS screening criteria limit prior to the expiration of their 40-year operating licences (Griesbach, Norris and Server 1988). The Revision 2 procedures, which are intended to be conservative, are being imposed against a background of existing potentially large margins of conservatism, which are associated with the basis of the PTS rule that was used to establish the screening criteria. Some areas have been identified where there are potential margins (Griesbach, Norris and Server 1988), and one such area is crack arrest predictions.

A recent coordinated analytical and experimental programme conducted by Combustion Engineering (1987) has demonstrated that the currently accepted ASME Code (1975) static crack arrest procedure is overly conservative when it is applied to the arrest of a deep crack in the thickness of a reactor vessel. The Combustion Engineering study has highlighted the importance of the bending deformation associated with the final deformed state analysis for a deep crack in a solid of finite thickness, and the effect of this bending on the difference between K_I^{ST} and the actual crack tip stress intensity at arrest. As a follow-on to the CE work, this paper describes the results of research based on the use of the reflectionless stress intensity factor procedure for predicting crack arrest. The results provide further underpinning for the view that the ASME Code procedure predictions can be overly conservative.

REVIEW OF COMBUSTION ENGINEERING RESULTS

The objective of the Combustion Engineering programme was to determine the response of pre-cracked laboratory specimens of unirradiated reactor pressure grade material to simulated PTS conditions. The moment modified compact tension (MMCT) test specimen is loaded separately by a set of moment arms to simulate pressure type loadings, and a split wedge to simulate thermal shock type loadings. The specimen is unirradiated but is chilled at the initial pre-crack end, and heated at the crack arrest end to produce an increasing toughness gradient in the material along the crack path. With the aid of this specimen it was possible to demonstrate crack arrest in an increasing K_I^{ST} field, which is a characteristic of the PTS situation. A dynamic analaysis showed that the stress intensity factor K_I^{ST} at arrest, as computed by traditional static LEFM techniques, does not describe the instantaneous crack tip conditions at crack arrest. The analysis results, using the crack velocity data as input, show that the crack, following the onset of crack extension, propagates into the specimen so fast that the bulk of the specimen does not have time to respond to the crack's presence. Detailed observations (Kobayashi and Giovanola 1989) of the fracture surfaces showed that crack propagation proceeded by a cleavage mechanism with crack arrest occurring before there was any significant crack tip blunting. Because the bulk of the specimen does not have time to respond to the crack's presence prior to arrest, the instantaneous K_I at arrest is much lower than the K_I^{ST} which is computed via an analysis based on the final deformed static state of the cracked specimen.

Based on the experimental results, Combustion Engineering developed a simplified procedure CECA (Combustion-EPRI-Crack-Analysis) to predict crack arrest. It was argued that the conditions at the crack tip during crack extension can be approximated by a static analysis of the loading conditions at initiation, considering the specimen to be restrained from subsequent response. This restraint is represented in the MMCT specimen by the prevention of motion, in the direction of crack extension, along a line remote from the crack, i.e. the back face of the specimen; in other words the back surface is prevented from bending during crack propagation. The arrest predictions obtained by the CECA procedure are in approximate accord with the dynamic analyses of the MMCT tests, i.e. the static stress intensity K_I^{CE} obtained via the CE procedure is approximately equal to the instantaneous K_I at arrest. Most importantly $K_I^{CE} << K_I^{ST}$ with long crack jump lengths; this is because the significant amount of bending that occurs after the arrest of a deep crack in a finite thickness specimen gives rise to a high K_I^{ST} value.

Combustion Engineering then performed an analysis of cracks in vessels in order to evaluate the relevance of the MMCT test results to vessel integrity evaluation. The results showed a similar pattern, and they therefore argued that the CECA procedure could be applied to vessels; the vessel analysis showed that the actual K_I at crack arrest is approximately equal to K_I^{CE}, and is appreciably lower than K_I^{ST} with a deep crack. Consequently, the static (K_I^{ST}) procedure in the ASME Code is conservative in its prediction of the arrest of a deep crack in a reactor vessel.

THE REFLECTIONLESS STRESS INTENSITY FACTOR PROCEDURE AND ITS APPLICATION

If it is assumed that as a crack propagates, wave reflections do not reach the crack tip, then the crack tip equation of motion can be written in the form (Freund 1972, Eshelby 1969, Rose 1976)

$$K_I^{DYN} = f_I\ (\dot{a})\ K_I^* \left\{ \equiv \sqrt{\frac{2}{\pi}} \int_0^{\epsilon} \frac{p(\lambda)d\lambda}{\sqrt{\epsilon-\lambda}} \right\} = K_{ID}(\dot{a}) \quad (1)$$

where K_I^{DYN} is the dynamic crack tip stress intensity and f_I $(\dot{a})$ is a known function of the crack tip velocity $\dot{a}$ with f_I $(\dot{a}) \to 1$ as $\dot{a} \to 0$. K_I^*, which is referred to as the reflectionless stress intensity factor, is given by relation (1), with ϵ being the crack extension and $p(\lambda)$ the tensile stress ahead of the crack tip when it is in its original position at time $t = 0$. It is important to appreciate that the derivation of equation (1) is based on an exact dynamic analysis which gives the deformation field in the immediate vicinity of a crack tip, with the material which has not experienced the effect of waves emitted from the tip retaining the same deformation field as it had at the onset of crack propagation; there is compatibility at the boundary between the two regions of material.

Since f_I $(\dot{a}) \to 1$ as $\dot{a} \to 0$, crack arrest occurs when $K_I^* = K_{ID}$ $(\dot{a} \to 0) = K_{ID}$ say, and consequently if the arrest toughness K_{Ia} is equated with K_{ID}, crack arrest occurs when $K_I^* = K_{Ia}$. For the special case where a semi-infinite crack propagates in an unbounded solid due to the effect of time-independent loads, it can be shown (Freund 1972) that $K_I^* = K_I^{ST}$, and then crack arrest occurs when $K_I^{ST} = K_{Ia}$. This particular result, albeit for a highly idealised situation, has been viewed as providing a measure of theoretical underpinning for the ASME Code static crack arrest procedure. Relation (1) also shows that $K_I^* = K_I^{ST}$ for small crack propagation distances. In both these cases, wave reflection effects clearly do not play a role, but the question arises as to whether such effects can be ignored in a PTS event with a reactor pressure vessel. It has been argued (Marston, Smith and Stahlkopf 1979, 1980) that any crack propagating in a PTS event will be propagating perpendicular to the outer vessel wall and, unlike the case of, for example, the rectangular double cantilever beam test, the crack tip will not experience wave reflections from surfaces parallel to the crack. Furthermore, the results from the Combustion Engineering MMCT experiments would seem to support the view that the effect of waves reflected from the vessel surfaces during a propagation event can also be ignored.

It is against this background that the reflectionless stress intensity factor procedure has been used (Smith 1990, Smith and Griesbach 1990) to analyse the problem of the arrest of a deep crack in a finite thickness solid, thus simulating in a simplified way crack arrest in a PTS event. The model analysed is shown in Figure 1; a plate of finite thickness w, but of infinite dimensions in the other directions, is subject to a tensile stress σ (this simulating the pressure loading); a crack of initial depth a_o extends to a depth a. The objective of the analysis is to determine, for this crack of depth a, the reflectionless stress intensity factor K_I^*, the stress intensity factor K_I^{ST} which allows the plate to assume its static state and K_I^{CE}, the stress intensity factor obtained by preventing any transverse movement of the plate's right-hand surface once the loading has been applied prior to crack extension, i.e. by using the CECA procedure. The analytical details have been presented elsewhere (Smith 1990, Smith and Griesbach 1990), the analysis simplifying considerably if the initial crack is infinitesimally small, i.e. a_o is allowed to tend to zero. The results for the three stress intensity factors are shown in Figure 2. The important conclusions arising from an inspection of these results are, firstly, that K_I^{CE} is markedly less than K_I^{ST} for propagation deep into the plate thickness, a conclusion that is in accord with the conclusions from the Combustion Engineering investigation. Secondly, K_I^* is also markedly less than K_I^{ST} for large crack propagation distances, while there is not a marked difference between K_I^* and K_I^{CE}. Broadly similar conclusions have also been obtained (Smith and Griesbach 1990, Smith and Griesbach 1991) for the more general case where the plate is loaded by a tensile stress σ together with a bending moment M, these simulating respectively the pressure induced hoop stress and the thermal loadings in a pressure vessel subjected to a hypothetical PTS event.

DISCUSSION

The results that have emerged from the recent Combustion Engineering programme, together with this paper's results based on the application of the reflectionless stress intensity factor procedure, lead to the conclusion that when a crack arrests deep in the thickness of a reactor vessel, there is a large safety margin if the arrested crack depth is determined via the ASME Code K_{Ia} procedure, which is based on the determination of K_I^{ST}, the LEFM static stress intensity factor relevant to the final deformed steady state. This is because K_I^{CE} and K_I^* are both markedly less than K_I^{ST}, the reason for this difference being that the final deformed steady state involves a significant amount of bending, which is responsible for a large K_I^{ST} value. This fact was not appreciated in earlier work (Melville 1977, Smith 1985) when K_I^* was compared with K_I^{ST}, since the analyses did not allow for the bending deformation that is characteristic of a deep crack in a finite thickness solid (a similar state of affairs arises with regard to the case of small a/w in the present paper's model – see the results in Figure 2).

The conclusion that the ASME Code K_{Ia} procedure is conservative in its crack arrest predictions is particularly important with regard to the impact of Regulatory Guide 1.99 Revision 2 (1988) procedures for determining the effects of radiation embrittlement in the context of the PTS screening criteria that are used by the United States NRC. The margin of conservatism will of course depend on the actual thermal and pressure loadings in the assumed PTS event, and also upon the arrest toughness gradient. It is important to assess the impact of using a more accurate crack arrest predictive methodology (K_I^* or K_I^{CE}) in the context of the conservatism of the screening criteria limits in the PTS rule. Such an assessment is seen as an integral part of a more wide-ranging assessment of areas where there are potential margins of conservatism associated with the calculational procedures that have been used to establish the screening criteria. Areas, other than crack arrest predictions, where there might be large margins have been identified (Griesbach, Norris and Server 1988) and include flaw size and shape characterisation, residual stress assumptions, effect of cladding and the effect of warm pre-stress.

The question arises as to which methodology should be considered as an alternative to the K_I^{ST} approach. The K_I^{CE} procedure, which evolved directly from the Combustion Engineering programme, does recognize, in a general sense, that the deformation pattern well away from the crack tip is unchanged during the propagation event. However, it does not go as far as the K_I^* procedure, which is based on a dynamic propagation theory, and accounts in a quantitative way for differences in the behaviour of material which has, and has not, experienced the effect of waves emitted from the moving crack tip. Furthermore, the K_I^* procedure is easier to apply, in that it only requires (see relation (1)) a knowledge of the stress distribution ahead of the crack at the onset of crack extension. However, whether the K_I^{CE} or the K_I^* procedure is used (a detailed comparison of their physical bases has been presented by Smith and Griesbach 1990), the difference between their predictions are not likely to be large (see the results in Fig. 2).

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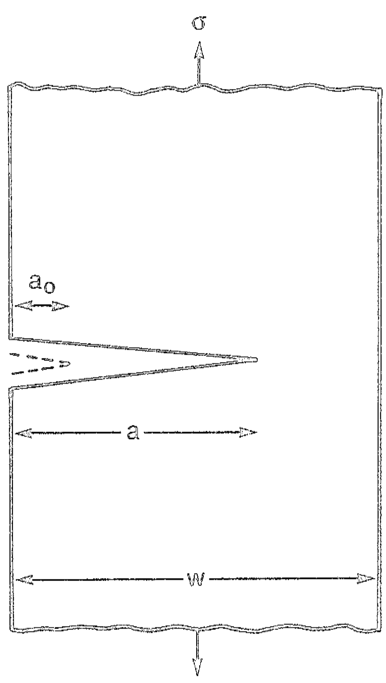

FIG. 1
The model of a cracked plate subjected to a tensile stress.

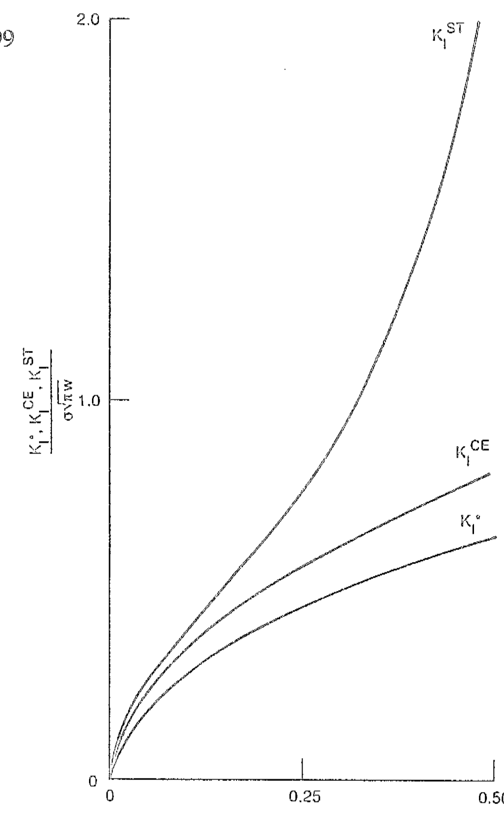

FIG. 2
The various stress intensity factors.