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An updated correlation for crack-arrest fracture toughness for nuclear reactor pressure vessel steels☆

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Abstract

An updated and statistically-rigorous correlation is provided for crack-arrest toughness values versus normalized temperature for light-water nuclear reactor pressure vessel (RPV) steels. The database used in this effort is larger than applied heretofore and includes results from tests of laboratory-size specimens and from tests of large-scale specimens, which contain features prototypical of operating RPVs. The mathematical methodology used is based on a lognormal distribution, with its parameters calculated by *orthogonal distance regression*. This correlation was developed as one of several items updated for use in the US Nuclear Regulatory Commission's extensive program to evaluate and potentially revise its rule for ensuring structural integrity of operating RPVs when subjected to pressurized thermal-shock transients.

Keywords: Fracture mechanics; Crack arrest; Nuclear reactor; Pressure vessel; Ferritic steels; Lognormal distribution

1. Introduction

This paper documents results from one of several efforts that have been conducted by Oak Ridge National Laboratory (ORNL) to establish best-available technologies for use in an updated version (version control code 04.1) of the probabilistic fracture-mechanics computer code FAVOR [1] (Fracture Analysis of Vessels—Oak Ridge). That version of the FAVOR code and the embedded technologies are key elements of the US Nuclear Regulatory Commission's (NRC) comprehensive assessment to determine if sufficient technical advances have been made in recent years to warrant making changes to existing rules for regulating US nuclear reactor pressure vessels (RPVs) when exposed to pressurized thermal-shock (PTS) conditions. Refs. [1–3] include considerations of the various technologies being addressed in the NRC's PTS assessment project.

The technologies embedded in the 'current version' of FAVOR [1] include rigorously-developed fracture-initiation (K_{Ic}) and crack-arrest toughness (K_{Ia}) versus temperature correlations which are discussed in Williams et al. [4]. The 'updated' crack-arrest toughness versus temperature correlation presented herein is based on an extension of the data set applied in Williams et al. [4]. The paragraphs below first tabulate the groups of data which make up that extended crack-arrest toughness (K_{Ia}) database. Those data groups include: (1) the laboratory-scale-specimen data that have been used in the past to develop K_{Ia} correlations [4,5] and (2) data from experiments that used large-scale specimens. The specific large-scale experiments were those conducted by ORNL as part of the Heavy-Section Steel Technology (HSST) program.

There were three series of large-scale experiments that generated the crack-arrest toughness (K_{Ia}) data that were used in this study. Many of those data points were for temperature and loading conditions that could not be obtained from tests of small laboratory specimens. The large-scale specimens were large cylinders, pressure vessels, and thick plates. The test materials included two prototypic RPV steels (A508, class 2 and A 533 grade B

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class 1) and a ferritic steel that simulated degraded RPV steel. While the authors recognize that crack-arrest data have been obtained from large-scale tests at other laboratories worldwide, those results were not included in this exercise because of uncertainties concerning how consistent the test materials and test techniques were with those used by the HSST Program or with the conditions that may exist in US RPVs.

The extended K_{Ia} data set included several results where the temperatures were higher than that where the steel exhibits onset of Charpy upper-shelf behaviour. Data from the tests that used large-plate specimens were interpreted by both static and dynamic analyses. The dynamic analyses included inelastic modeling of material behaviour during the rapid propagation of cracks.

This paper then summarizes the mathematical techniques employed in this study to develop an 'updated' K_{Ia} versus normalized temperature statistical correlation. Both the 'current' lognormal model based on the data set applied in Williams et al. [4] and the 'updated' model reported herein are included as options in the probabilistic fracture-mechanics computer code FAVOR (v04.1) [1–3].

2. Updated crack-arrest database

2.1. Summary of contributing K_{Ia} data sources

The HSST program at ORNL has been active for more than 30 years in generating, modeling, and recording crack-arrest toughness data. The database used by Williams et al. [4] to generate a mathematically rigorous K_{Ia} versus normalized temperature statistical model incorporated the available data that had been accumulated over the years from tests of laboratory-size crack-arrest specimens. Those data are documented in Refs. [5–8]. The range of those data was limited because tests that use the relatively small compact crack-arrest (CCA) specimens, such as those specified by ASTM Standard E 1221, [9], are not capable of producing K_{Ia} values above about 200 MPa $\sqrt{m}$. (Some background information to the ASTM specimen and its capabilities is given in Ref. [10].)

Concurrently, the HSST program also conducted over those years a variety of large-scale fracture experiments to further develop and validate fracture-analysis methods for predicting initiation and arrest of crack propagation behaviour for thick-sections of RPV steels. The objectives of many of those experiments included generation of fracture data for metal temperatures higher than could be obtained from smaller laboratory specimens. Specifically, the relevant HSST large-scale fracture experiments included sixteen wide-plate experiments (WPEs), four thermal-shock experiments (TSEs), and two pressurized thermal-shock experiments (PTSEs).

Table 1 provides a summary description of the extended K_{Ia} database when the large-specimen results are combined with the CCA specimen data used by Williams et al. [4] to develop a mathematically rigorous K_{Ia} versus normalized temperature statistical model. Data groups 1–4 in that table identify the data that were used to construct the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code curve and the additional data used by Williams et al. [4]. Data groups 5–10 list the large-scale specimen test data. The number of data points and temperature range are given for each data group. Sections 2.2–2.4 provide descriptions and tabulations of the data obtained from each of the three types of HSST large-scale tests.

Table 1
Summary of the extended K_{Ia} database

Data group no.	Data group application	Type and source of RPV steel	Data references	Specimen type used	T_{arrest} range (°C)	$(T_{arrest}-RT_{NDT})$ range (°C)	No. data points
1	ASME curve[a]	A533B HSST plate 02	[5]	CCA[b]	−101 to 49	−83 to 67	50
2	NRC PTS re-evaluation[c]	HSST weld 72W	[8]	CCA	−61 to 5	−38 to 28	32
3	NRC PTS re-evaluation[c]	HSST weld 73W	[8]	CCA	−61 to 15	−27 to 49	25
4	NRC PTS re-evaluation[c]	Midland Weld 12J	[8,10]	CCA	−20 to 10	−20 to 10	4
5	Updated extension	A533B Cl 1 HSST plate 13A	[11–13]	Wide plate	29–92	52–115	15
6	Updated extension	2 1/4 Cr–1Mo HSST plate	[13–15]	Wide plate	61–162	1–102	39
7	Updated extension	A533B CE plate	[13,16]	Wide plate	36–60	71–95	4
8	Updated extension	A508 Cl. 2 (PTSE-1)	[17–18]	Pressurized vessel	163–179	72–88	2
9	Updated extension	2 1/4 Cr–1Mo (PTSE-2)	[19]	Pressurized vessel	131–163	56–88	3
10	Updated extension	A508 Cl. 2 (TSE 4-6)	[20–22]	Thermally-shocked cyl.	22–131	−35 to 57	10

[a] See Ref. [5].
[b] Compact crack-arrest specimen (CCA).
[c] See Williams et al. [4].