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FRACTURE ANALYSIS OF THE NESC-1 SPINNING CYLINDER EXPERIMENT*

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ABSTRACT

This paper presents finite-element analyses of the cylinder specimen being used in the international Network for Evaluating Steel Components (NESC) large-scale spinning-cylinder project (NESC-1). The objective of the NESC-1 project is to focus on a complete process for assessing the structural integrity of aged reactor pressure vessels. A new cylinder specimen was reconstituted from segments of the previously tested SC-4 and SC-6 specimens because the relatively high fracture toughness of the original specimen might preclude achieving the test objectives. The wall thickness is greater for the reconstituted specimen when compared with the previous specimen geometry (175 vs 150 mm). Also, the initial and coolant temperatures for the proposed thermal shock may be reduced as much as 25°C to increase the probability of achieving cleavage initiation. Analyses were carried out to determine the combined effects of increasing the wall thickness and lowering the initial and coolant temperatures in the experiment. Estimates were made of the change in hoop strain on the clad inner surface directly above a subclad crack due to initiation and axial propagation of the crack. Three-dimensional finite-element models of the clad cylinder were generated with 6:1 and 2:1 semielliptical 70-mm-deep subclad cracks. The cylinder specimen was subjected to thermal-shock and centrifugal loading conditions and analyzed with a thermo-elastic-plastic material model. The analytical results indicate that lowering the initial and coolant temperatures by 25°C will not significantly change the peak driving force, but will shift the stress-intensity factor (K_I) vs temperature curves so that the crack will become critical at an

earlier time in the transient. The peak K_I value occurs at a lower temperature (after the crack becomes critical), which increases the probability of achieving cleavage initiation. Also, the calculated hoop strains for the two crack aspect ratios (simulation of 2:1 crack propagating axially) provide an estimated change in hoop strain in the range of 3 to 4% on the clad inner surface.

INTRODUCTION

In recent years, several international collaborative programs have been initiated to evaluate and exchange knowledge and capabilities in specific disciplines that support vessel and piping integrity assessments. The Network for Evaluating Steel Components (NESC), managed by the Commission of the European Communities, was organized as an international forum to exchange information on processes of structural integrity assessment, to collaborate on specific projects, and to promote the harmonization of international standards.

The initial project proposed by the NESC is designed to study the entire process of structural integrity assessments of aged reactor pressure vessels (RPVs) containing underclad cracks. In this project, important safety assessment issues will be investigated by means of inspection and analysis of a large-scale spinning cylinder with thermal-shock loading (NESC-1). Updated design analyses of the NESC-1 specimen were performed in response to a request from the NESC Project Management. A new cylinder specimen was reconstituted from segments of the previously tested SC-4 and SC-6 specimens. This change was instituted because of concern that the relatively high fracture toughness of the original specimen might preclude achieving the test objectives. However, this change was accompanied by an increase in wall thickness of the specimen from 150 to 175 mm. Also, the initial and coolant temperatures for the proposed thermal shock may be reduced as much as 25°C to increase the probability of achieving cleavage initiation. This paper describes analyses carried out to assist the NESC Task Group on Analysis to

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determine the combined effects of increasing the wall thickness and lowering the initial and coolant temperatures in the experiment. Estimates were made of the change in hoop strain on the clad inner surface directly above a subclad crack due to initiation and axial propagation of the crack. These estimates will be used to determine instrumentation needs for initiation detection.

PROBLEM DEFINITION

The cylinder specimen utilized in the analyses for NESC-1 has a inner diameter of 1045 mm, a wall thickness (including cladding) of 175 mm, clad thickness of 4 mm, and length of 1296 mm. The cylinder was fabricated from A508B class 3 steel with a clad overlay of 308 stainless steel. The best representative material properties (that were obtainable) are given in Table 1. These properties were provided by the NESC Task Group on Analysis; the base metal properties in Table 1 are from the unclad spinning cylinder (SC-4) test performed by AEA Technology, Risley, U. K. (detailed in Ref. 1). The Risley facility has not performed experiments with coolant at the lower temperature (-20°C) used in these analyses. Hence, some material data and stress-strain properties were not available for temperatures less than 27°C .

TABLE 1. MATERIAL PROPERTIES FOR NESC-1 SCOPING ANALYSES

Material Property	A508 Base Forging	308 Stainless Steel Clad
Thermal Conduct. (k)	33.92 W/m $\cdot$ K	15.30 W/m $\cdot$ K
Specific Heat (c_p)	541 J/kg $\cdot$ K	495 J/kg $\cdot$ K
Density (ρ)	7787 kg/m 3	7920 kg/m 3
Young's Modulus (E)	212.35 GPa @ 0°C 189.10 GPa @ 350°C	200.00 GPa @ 20°C 178.00 GPa @ 288°C
Coefficient Thermal Expan. (α)	1.186E-05 $^{\circ}\text{C}^{-1}$ @ 0°C 1.340E-05 $^{\circ}\text{C}^{-1}$ @ 350°C	1.389E-05 $^{\circ}\text{C}^{-1}$ @ 20°C 1.850E-05 $^{\circ}\text{C}^{-1}$ @ 288°C
Poisson's Ratio (ν)	0.28	0.30
Yield Stress (σ_y)	504.3 MPa @ 20°C 467.6 MPa @ 150°C 338.7 MPa @ 350°C	280.0 MPa @ 27°C 205.0 MPa @ 288°C
Heat transfer coefficient : 22,000 W/m 2 $\cdot$ K (inner surface)		

Analyses were carried out for two inner surface subclad cracks with a crack depth of 70 mm and aspect ratios (crack length to crack depth) of 6:1 and 2:1. The assumed loading conditions consisted of the cylinder being heated to a temperature of 295°C , spun at increasing speed (maximum acceleration is 180 rpm/min) about its axial centerline up to a maximum speed of 2500 rpm, and then thermally-shocked on the inner surface with coolant at -20°C to achieve cleavage crack initiation. The analytical results are compared with material fracture toughness data taken from Ref. 1 to predict whether the crack will initiate. Figure 1 shows toughness plotted against temperature for the upper and lower bounds of the compact

tension (CT) specimen data and for the SC-4 test result. The toughness data for SC-4 are shown as a straight line due to the uncertainty in temperature at the crack tip at initiation [1].

FIG.1 FRACTURE TOUGHNESS DATA FOR SMALL-SCALE CT SPECIMENS AND SC-4.

FRACTURE ANALYSIS

Heat Conduction Model

The calculation of the temperature distribution in the NESC-1 cylinder was performed with the ABAQUS [2] finite-element program [a nuclear quality assurance certified (NQA-1) code] and an axisymmetric model. The model consists of 21 nodes and 10 axisymmetric one-dimensional (1-D) conduction elements with convection boundary conditions. The geometry, material properties, and loading conditions were summarized in the previous section. Figure 2 shows the calculated temperature distribution in the cylinder wall for different time steps.

FIG. 2 RADIAL TEMPERATURE DISTRIBUTION IN THE CYLINDER WALL CALCULATED BY ABAQUS.

3-D Finite-Element Analyses

Subclad semielliptical axial cracks at the inner surface having aspect ratios of 6:1 and 2:1 and a crack depth of 70 mm were evaluated in this study. The 3-D finite-element model of the cylinder was generated with the ORMGEM [3] mesh-generating program. From symmetry conditions, only one-fourth of the cylinder (180° model) is included in the model (Fig. 3). Both models consist of 9399 nodes and 1938 twenty-noded isoparametric elements. Detailed plots of the crack-tip region of the 6:1 and 2:1 subclad cracks are also shown in Figs. 3 and 4.

The cylinder was analyzed with the ABAQUS [2] finite-element program, which employs a domain integral method for the computation of the J-integral. The stress-intensity factor

(K_I) was calculated from the J-integral using the following plane-strain relation:

$$K = \sqrt{(JE/(1-\nu^2))} \quad (1)$$

where $E = 189.1$ GPa and $\nu = 0.28$. The thermo-elastic-plastic analyses were performed using the material properties in Table 1 and the stress-plastic strain curves depicted in Fig. 5. At transient temperatures below the range for which material data are available, the measured properties are used that correspond to lower bound temperatures of the data set. The temperatures through the wall for each time step were obtained from the heat conduction analysis and were applied to the cylinder by interpolation. The "stress-free" temperature was taken as the initial temperature of the cylinder (residual stress effects were ignored).

(A)

(B)

FIG. 3 3-D FINITE-ELEMENT MODEL OF THE CLAD CYLINDER (NESC-1) WITH A 70-mm-DEEP SUBCLAD CRACK AND 6:1 ASPECT RATIO: (A) CYLINDER; (B) CRACK-TIP REGION.

FIG. 4 CRACK-TIP REGION OF THE CLAD CYLINDER (NESC-1) WITH A 70-mm-DEEP SUBCLAD CRACK AND 2:1 ASPECT RATIO.

FIG. 5 MULTILINEAR REPRESENTATIONS OF THE STRESS-PLASTIC STRAIN BEHAVIOR FOR A508B BASE FORGING AND 308 STAINLESS STEEL CLAD.

K_I Evaluation. In performing the 3-D analyses, K_I was calculated at nodal positions along the crack front. Values are plotted as functions of time and angle in Fig. 6 for the 6:1 and 2:1 subclad cracks. In Fig. 7, K_I values are plotted as a function of time for positions 5, 7, 9, and 17 around the crack front (see Fig. 3 for these locations). The peak K_I value is near the clad/base interface (position 7) at a time of 366 s.

(A)

(B)

FIG. 6 K_I VALUES INCREASE NEAR THE CLAD/BASE INTERFACE DUE TO THE THERMAL STRESSES: (A) 6:1 CRACK; (B) 2:1 CRACK.

In Fig. 8, values of K_I for the same positions around the crack front are plotted as a function of temperature and compared with the fracture toughness values from Fig. 1 and previous analytical results [4]. The analytical results indicate that lowering the initial and coolant temperatures by 25°C will not significantly change the peak driving force, but will shift the K_I vs temperature curves extensively. In Fig. 9, the K_I values near the interface for the old and new analysis models are compared with postulated fracture toughness curves for SC-4 (curves A, B, and C). These postulated toughness curves were constructed to better illustrate the influence of lowering

(A)

(B)

FIG. 7 THE HIGHEST K_I VALUE IS NEAR THE CLAD/BASE INTERFACE AT A TIME OF 366 s: (A) 6:1 CRACK; (B) 2:1 CRACK.

the initial and coolant temperatures on initiation. The curves span the range of uncertainty in the crack-tip temperature at cleavage initiation during the SC-4 experiment (achieved at $K_I \approx 175$ MPa√m), but otherwise are not based on measured data. The crack becomes critical ($K_I/K_{Ic} > 1$ beyond postulated toughness curve C) at an earlier time in the transient using the new model and $\dot{K}$ remains positive for all three postulated toughness curves. Also, the peak K_I value occurs at a lower temperature (after the crack becomes critical), which increases the probability of achieving cleavage initiation for a 70-mm-deep subclad crack. The importance of $\dot{K}$ being positive is highlighted by results from the PTSE-1A pressurized-thermal shock test [5], shown in Fig. 10, for which warm prestressing inhibited propagation of an otherwise critical crack ($K_I/K_{Ic} > 2$). In Fig. 11, the K_I values for the 2:1 crack are shown to be lower than the 6:1 crack (peak K_I value decreases by 8%) but the crack is still predicted to initiate.

FIG. 8 COMPARISON OF K_I VALUES WITH MATERIAL TOUGHNESS FOR 70-MM-DEEP 6:1 SUBCLAD CRACKS.

FIG. 11 COMPARISON OF K_I VALUES WITH MATERIAL TOUGHNESS FOR 70-MM-DEEP 6:1 AND 2:1 SUBCLAD CRACKS.

FIG. 9 COMPARISON OF K_I VALUES FOR 70-MM-DEEP 6:1 SUBCLAD CRACKS WITH POSTULATED MATERIAL TOUGHNESS CURVES.

FIG. 10 COMPARISON OF K_I VALUES FOR PTSE-1A WITH MATERIAL TOUGHNESS CURVE.

Comparison of Principal Strains. In the SC-4 experiment, a 40-mm-deep semicircular axial inner-surface crack initiated near the surface and propagated in cleavage axially to become a 6:1 crack (approximately) of the same depth. Analysis of the 2:1 subclad crack indicates that the crack will initiate near the clad/base interface (see Fig. 11). If the 2:1 subclad crack is assumed to initiate and propagate axially to become a 6:1 crack, then estimates of the change in hoop strain at the clad inner surface directly above the propagating crack can be made. The principal strains for the 6:1 and 2:1 subclad cracks at a time of 366 s are shown in Figs. 12 and 13, respectively. The strain in the hoop direction for the 6:1 crack has a peak value of 3.2% near the end of the crack. The hoop strain for the 2:1 crack has a smaller peak value of 2.3% and then drops to 0.13% at 173 mm from the center of the crack (near the location of the peak hoop strain in the 6:1 crack). Thus a strain gage in this location (173 mm) on

FIG. 12 PRINCIPAL STRAINS FOR A 6:1 70-MM-DEEP SUBCLAD CRACK AT A TIME OF 366 s.

FIG. 13 PRINCIPAL STRAINS FOR A 2:1 70-MM-DEEP SUBCLAD CRACK AT A TIME OF 366 s.

the inner surface is projected to measure a change in hoop strain of about 3%.

A large strain finite-element analysis was performed on the cylinder with the 6:1 crack to determine the effect on the hoop strain. The principal strains are shown in Fig. 14. The K_I values at the time of 366 s changed less than 0.4% from the small strain analysis, but the peak hoop strain increased from 3.2 to 4.1%. Assuming that the hoop strain in the 2:1 crack would increase by about the same amount in a large strain analysis, the change in hoop strain (as measured by the strain gage) is projected to be about 4%.

FIG. 14 PRINCIPAL STRAINS FOR A 6:1 70-MM-DEEP SUBCLAD CRACK AT A TIME OF 366 s (LARGE STRAIN ANALYSIS).

SUMMARY AND CONCLUSIONS

Thermo-elastic-plastic analyses of 6:1 and 2:1 subclad inner surface cracks indicate that the K_I vs temperature curves can be shifted by lowering the initial and coolant temperatures by

25°C in the experiment, which results in the crack becoming critical at an earlier time in the transient. The peak K_I value occurs at a lower temperature (after the crack becomes critical), which increases the probability of achieving cleavage initiation for a 6:1 or 2:1 70-mm-deep subclad crack.

Estimates of the change in hoop strain on the clad inner surface were made, assuming that a 2:1 subclad crack will initiate and propagate axially to become a 6:1 crack. Small and large strain analyses indicate that a strain gage located on the inner surface near the peak strain of the 6:1 crack would measure a change in hoop strain in the range of 3 to 4%. A set of strain gages placed on the cylinder inner surface over a span of 70 to 210 mm from the crack center could provide strain-field measurements to determine crack propagation during the experiment.

These analyses have been based on material properties and boundary conditions (i.e. stress-plastic strain curves and heat transfer coefficient) measured at temperatures higher than the lowest values achieved during the computed thermal transient. Subsequent analyses will be performed when new material properties become available for the lower temperatures.

The actual specimen will contain multiple deep cracks located at 90° intervals around the circumference of the cylinder. Future work will include three-dimensional finite-element analyses to determine the extent of interaction between multiple cracks in the cylinder.

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