A SPECIMEN AND METHOD FOR EVALUATING THE EFFECT OF CLADDING ON THE BEHAVIOR OF SUBCLAD FLAWS*

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ABSTRACT

A specimen that reveals important fracture-related properties of cladding in the presence of a subclad flaw is under development at the Oak Ridge National Laboratory (ORNL). Information developed from testing these specimens, referred to as Jo-Blocks, is being used by the Heavy-Section Steel Technology (HSST) Program in evaluating the behavior of subclad flaws in Pressurized Water Reactors (PWR) pressure vessels during pressurized-thermal-shock (PTS) loading conditions.

The cladding can be idealized as a force that holds an otherwise surface flaw "closed" at the surface, reducing the stress intensity factor along the portion of the crack front in the base material. This closing force is approximately equal to the average stress in the cladding, which for postulated severe PTS transients is at yield, multiplied by the cladding thickness. There is a critical amount of stretching of the cladding that results in through-clad flaw propagation, i.e., cladding failure, thus converting the subclad flaw to a surface flaw.

The Jo-Block specimen consists of two steel (base metal) blocks with ends butted together to form a "crack" and with opposite edges clad so that the crack terminates at the two fusion zones. Testing of Jo-Block specimens reveals as a minimum the "effective yield point" of the cladding, in the presence of a subclad crack, and the critical value of clad stretching (crack opening displacement).

INTRODUCTION

The radiation-induced reduction in inner-wall fracture toughness of Light Water Reactor (LWR) pressure vessels has long been considered as potentially establishing a limit to the useful operating life of commercial nuclear plants. Although normal operating conditions do not result in sufficiently high wall stresses and sufficiently low fracture toughness to cause concern about vessel failures, recognition that accident conditions existed for which there was a high probability of vessel failure prompted extensive investigations for quantifying those factors that might affect vessel life expectancy. The radiation-induced loss of fracture toughness of the vessel material, the presence and size of flaws at the vessel inner wall, the type of flaw, i.e., surface, subclad, shape, etc., and the imposed loading conditions were all identified as being important to the evaluation of vessel integrity [1]. A particular loading condition of concern, and one that has received considerable attention, is the pressurized-thermal-shock (PTS) event. This accident transient causes a combination of pressure and thermal stresses and a reduction in fracture toughness in the inner portion of the wall of the vessel that have the potential to lead to initiation and propagation of existing flaws [2].

In evaluating flaw behavior under PTS conditions, the potential beneficial effects of cladding have only recently received attention [3]. In general, consideration of cladding has been limited to the inclusion of its relatively high thermal resistance and coefficient of thermal expansion which result in a reduction of the "thermal shock" and an increase in thermal stresses at the surface (as compared to an unclad vessel) [4,5]. It has been shown that reduction of the severity of the thermal shock tends to decrease the potential for propagation of subclad flaws but the introduction of high thermal stresses near the surface tends to increase the potential for propagation of surface flaws [3].

A complete evaluation of vessel response to the PTS event requires a valid description of both the base material and the cladding. If the cladding is sufficiently tough, the probability of propagation and the extent of propagation for subclad flaws and the extent of propagation for surface flaws will be less than that for a surface flaw without cladding. The potential benefit of the cladding in the evaluation of the behavior of a subclad flaw, however, depends on (1) the extent of stretching of the cladding above the crack and (2) the crack-mouth opening displacement (CMOD) for failure of the cladding [3]. The greater the amount of stretching of the cladding, the less the benefit. Also, the lower the critical failure load of the cladding, the less the benefit. If the critical failure load of the cladding is less than that of the base material, there will be no benefit at all other than the thermal benefit.

The potential structural benefit of the cladding may be illustrated by considering the stress intensity factor, K_I, for a flaw in a vessel wall. "Benefit" is measured by the decrease in K_I when comparing the subclad to a similar through-clad flaw. Analyses of thermal-shock experiments indicate that, at the times of maximum K_I, the K_I for the deepest point of the subclad flaw was ≈34% less than that for a surface flaw (same geometry and materials properties) [3]. It was also observed that the benefit of the cladding was in direct proportion to the yield strength of the clad material. For example, a 20% reduction in clad yield strength resulted in a cladding benefit of 28% (as compared to 34% above). As an upper bound, i.e., for the case of perfectly elastic cladding, Simonen calculated a 50% benefit for the subclad flaw [6]. These general results were further substantiated by Iskander [7,8] who observed that, for tests of plates with surface flaws, the presence of cladding reduced the potential for crack propagation as compared to unclad plates.

A characteristic feature of flaw behavior for the tests reported by Iskander [7,8] was tunneling of the flaw under the cladding, as is shown in Fig. 1. This type behavior was observed to an even greater extent in the thermal shock tests discussed above [3]. A surface flaw may then become a subclad flaw by propagation under the surrounding cladding. Thus, it appears that incorporation of cladding as a structural element and the consideration of subclad flaw behavior, as compared to consideration of surface flaws alone, can have a significant impact when evaluating the probability of failure of reactor vessels.

Fig. 1. Broken halves of clad plate test specimen showing tunneling of flaw under cladding.

Efforts to quantify the effect of cladding on surface-flaw behavior have included studies of beams [9], plates [6,7,9], and cylinders [3]. Also, a relatively small and simple specimen has been developed, initially under the HSST Program at the Oak Ridge National Laboratory, that provides a relatively inexpensive vehicle to study the fracture related properties of cladding over a subclad flaw. The specimen is fabricated by butting two machined blocks together and cladding over the surface. By careful fixturing and machining of the parent blocks, the interface or "flaw" will have essentially zero width which is representative of a subclad flaw in its initial configuration. The concept of this specimen, some details of its fabrication and utilization, and some preliminary results are the subjects of this paper.

SIMPLE MODEL FOR SUBCLAD FLAW

As discussed above, austenitic cladding has two primary effects: (1) reduction of the severity of the thermal transient due to the relatively low thermal conductivity of the cladding as compared to the base material and (2) introduction of high thermal stresses near the surface due to the greater coefficient of thermal expansion of the cladding. A simple model for inclusion of cladding was proposed by Cheverton and Iskander [11] and Smith [12,13]. This model, which is shown schematically in Fig. 2, replaces the cladding with a crack-mouth closing force that is essentially equal to the stress in the cladding multiplied by the cladding thickness. Note that since the coefficient of expansion of the cladding is greater than that of the base material, the average stress in the cladding during the PTS event is tensile. For the case of a severe PTS transient, and neglecting strain hardening, which is an additional conservatism, the tensile stress is the "yield strength" for the cladding. The resulting closing force causes a reduction in crack-tip opening displacement (CTOD) for the tip of the flaw in the base material, i.e., the contribution of the cladding can be directly calculated as a reduction in the stress intensity factor for the tip of the flaw in the base metal.

If the cladding is breeched, the flaw becomes a surface flaw, and K_I increases accordingly. Cladding failure will occur when the strain over the flaw exceeds the cladding ultimate strain. This ultimate strain can only be properly defined by consideration of the geometric constraint, i.e., strain concentration, and the stress and/or strain state of the cladding. The strain state will reflect prior history of the cladding, i.e., initial shrinkage due to solidification and cooling following deposition, postweld heat treatment (PWHT), hydrostatic testing, etc. It is thus apparent that measurements of clad properties using machined specimens of cladding alone will not provide all the descriptive information required to evaluate subclad-flaw behavior during the PTS event. The Jo-Block specimen described below addresses these technical issues.

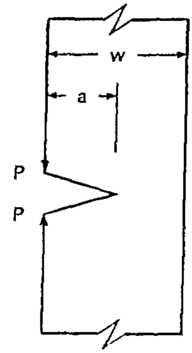

Fig. 2 Crack-mouth closing force associated with tensile stress in cladding over subclad flaw.

DESCRIPTION OF JO-BLOCK SPECIMEN

The Jo-Block specimen was first conceived in the early 1980s under the HSST Program for the purpose of evaluating the fracture properties of cladding over a subclad flaw. The specimen consists of two machined steel blocks with the ends butted together to form a "crack". The name Jo-Block was derived from Johansson blocks, which are precision machined gage blocks used for calibrating instruments, etc. A weldment is prepared where opposite edges of these blocks are clad such that subclad flaw tips are generated where the cladding is laid across the interface between the two blocks. The quality of the butted machined surfaces, the care used in fit-up, and the restraint against distortion during cladding determine the final width of the crack. In practice, essentially zero-width cracks have been obtained. The flaw tip is normally relatively "sharp" having, with careful fit-up, tip radii in the range of 0.02–0.08 mm. However, the shrinkage usually causes additional subsurface crack extension (microcracking) such that the flaw tip is a "true" crack. If further sharpening or additional crack extension is desired, the specimen can be fatigue pre-cracked as would be done with a compact tension specimen. Thus, the final crack configuration resembles a cross-section of the clad/base metal interface region of a two-dimensional subclad flaw in a vessel wall. Since the cladding is applied in the same manner that vessel cladding is applied, the cladding retains many of the characteristics that cladding on a vessel wall would have.

The general procedure used to fabricate the Jo-Block specimen was as follows: Machined pressure vessel steel (ASTM A533) blocks were arranged as shown in Fig. 2. The assembly was initially held together using clamping blocks (one piece) that were welded to the parent blocks. These clamping blocks maintained alignment, provided restraint against distortion, and served as run-off tabs during cladding. The assembly was alternately clad on opposite sides with the specified cladding material and procedure and then subjected to a postweld heat treatment (PWHT). Blanks were next cut from the width direction of the assembly as is shown in Fig. 3. Final machining of these blanks yielded a Jo-Block specimen, the configuration of which is shown in Fig. 4. The closeness of fit of the parent blocks can be seen in Fig. 5 which reveals details of the block interface and clad overlay for a machined Jo-Block specimen.

The Jo-Block specimen, as shown in Fig. 4, is basically a tensile bar that simulates the basic geometry, deformation, and failure behavior features of cladding over a subclad flaw in a vessel wall. From this specimen, the effective yield stress and the rupture strain of the cladding and the CTOD beneath the cladding can be determined. A simple tensile-type test (load vs axial displacement), in conjunction with posttest cross-section measurements, provides the

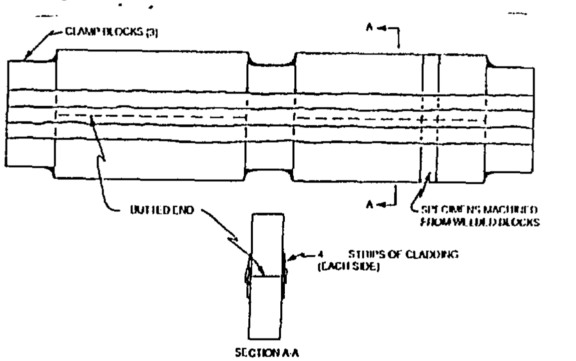

Fig. 3. Weldment of type used to fabricate Jo-block specimens.

necessary information to calculate the effective yield strength of the cladding. The amount of clad surface stretching directly over the flaw tip can be measured using conventional foil-type strain gages or surface extensometers. Conventional clip gages are used to measure CTOD and CMOD at the specimen midplane as is done in a compact tension test. These basic materials and fracture measurements provide the information to evaluate the incremental change in K_I for a subclad flaw.

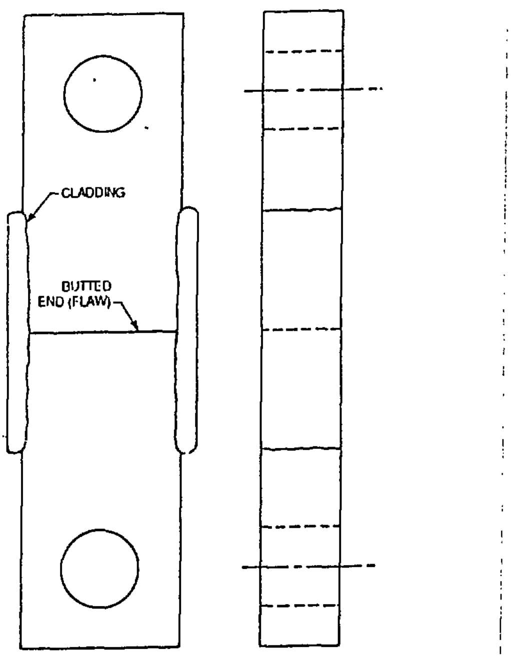

Fig. 4. Jo-Block specimen developed to measure fracture properties of cladding over a subclad flaw.

An additional piece of information that may be obtained from this specimen is the initial, average through-clad residual thermal stress (stress in cladding at test temperature and with no external loading applied). As discussed above, the residual stress in the cladding will be tensile due to the larger coefficient of thermal expansion of the clad material vs the base metal if the test temperature is not excessive. The mating surfaces of the two blocks will not begin to separate until the external load just balances the residual thermal tensile stress in the cladding. This point in loading is evidenced by a detectable change in slope of the load-displacement curve.

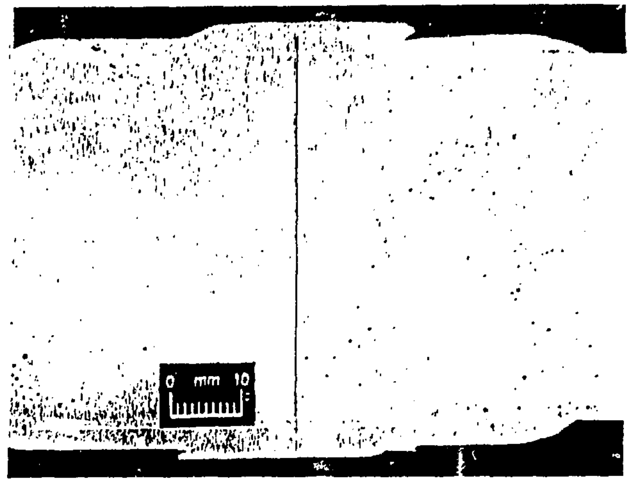

Fig. 5. Jo-Block specimen showing "crack" between parent blocks and clad overlay.

It is worthwhile to note that the reliability of the residual stress information is somewhat dependent upon the fit-up of the blocks during specimen fabrication. If care is not taken to assure that the "crack" is tight, then free contraction of the cladding will occur, and the residual stress measured will be less than would occur in a vessel. It is also interesting to note that the thickness of the base material is not overly important in determining the final residual stress state. Thus, when the thermal histories are considered, the cladding on a Jo-Block specimen or a vessel wall will have nearly the same residual stress. This is important when testing at different temperatures since the relevant residual stress state will be automatically carried with the specimen.

There is one final feature of the Jo-Block specimen that assumes importance for PTS evaluations. The specimen is small enough that it can be irradiated. Thus, material conditions prototypic of PTS conditions can be simulated for testing.

FINITE-ELEMENT-ANALYSIS MODEL OF JO-BLOCK SPECIMEN

The ORMGEN/ADINA/ORVIRT fracture analysis system was used to perform some preliminary investigations of Jo-Block behavior. ORMGEN [14] is an automatic mesh generator that will generate two-dimensional (2-D) or three-dimensional (3-D) finite-element models of cracked structures and creates files that are formatted properly for input to ADINA [15], the structural analysis code. ORVIRT [16] is a post-processor for the ADINA stress analysis results and calculates the fracture parameters. The strategy is to surround the crack front with a core of special wedge-shaped crack-tip elements as shown in Fig. 6 and to model the remainder of the structure with conventional 8-node isoparametric brick elements for 2-D models or 20-node isoparametric brick elements for 3-D models. The special crack-tip elements model the appropriate singularity in the stress field. The nodes that initially share the same location at the tip (Fig. 6*a*) will separate with increasing load to allow for "blunting" of the crack (Fig. 6*b*). Crack-tip blunting applies basically to ductile deformation behavior whereas other techniques are required for a description of ductile tearing. Some preliminary effort to model ductile tearing was performed whereby successive nodes were released at appropriate stress levels to idealize the crack growth process into the cladding. The disadvantage of this procedure was that the crack quickly grew out of the region of refined mesh with associated decrease in sensitivity when calculating fracture parameters. However, this method did provide a better description of the Jo-Block deformation response as compared to use of crack tip blunting alone.

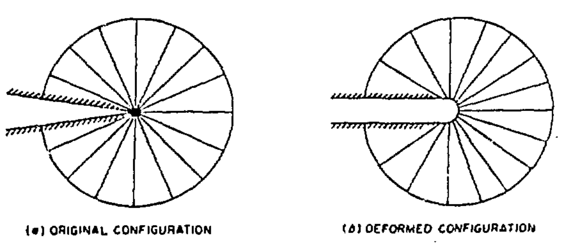

Fig. 6. Collapsed prism elements appropriate for analysis of subclad flaw crack tip.

For preliminary analyses, a deformation-plasticity-material model utilizing a multilinear, temperature-independent, stress-strain curve was employed for the cladding. Since the stresses in the base material are below yield, only a linear elastic model was required for the base material.

JO-BLOCK EXPERIMENTAL RESULTS

Preliminary testing of the Jo-Blocks was performed as part of the test-procedures development effort, and the results presented in this paper pertain to this effort only. An extensive testing program has been conducted, but the results are not available for publication.

A typical instrumentation layout for a Jo-Block test is shown in Fig. 7. Brackets for conventional clip gages allow measurement of CTOD, and strain gages measure cladding surface deformation. For the set of test specimens discussed in this paper, the strain gages and the centerline clip-gages were not used, but two additional clip gages were mounted on the back surface of the specimen. The four clip-gages were mounted in line with the clad/base metal interface to measure COD at the initial crack tip. The specimens were tested at both room temperature and at −129°C (−200°F). The servohydraulic test machine loading rate was in the range typically used for tensile testing.

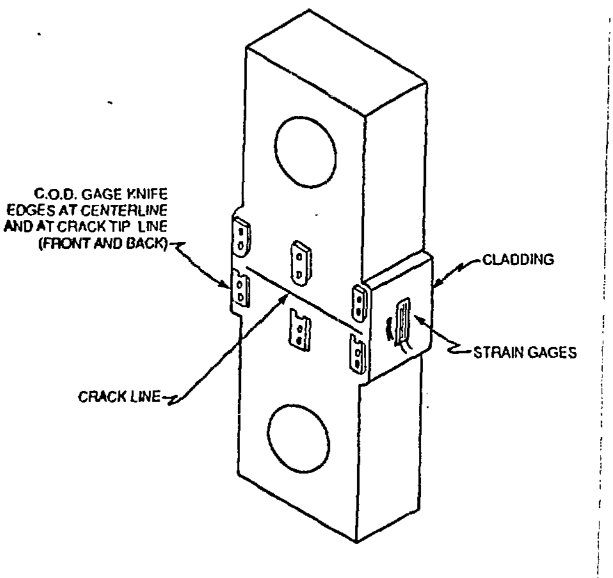

Fig. 7. Typical location of COD and strain gages on Jo-Block specimens.

A typical plot of front-surface clip-gage readings versus load is shown in Fig. 8. Figure 9 is an enlarged view of the initial part of this loading curve, which shows three distinct regions of behavior. The first of these, which extends up to a load of approximately 25 kN (≈6 kips) is the linear elastic response of the entire specimen (base metal and cladding) and is due to the pre-load caused by the

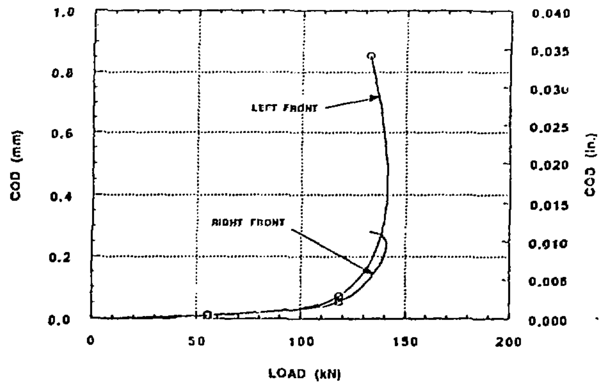

Fig. 8. Measured crack-tip COD for developmental Jo-block specimen A tested at room temperature.

cladding residual thermal stress. This is indicated as the "Elastic Bar" line in Fig. 9. The second region is the near linear elastic behavior of the cladding acting alone. Nonlinear response of the cladding initiates at approximately 80 kN (≈18 kips). The last region is the fully non-linear plastic behavior of the cladding. For the cladding, taking the deviation from non-linear behavior as the "yield" point, and based on a clad cross sectional area of 245 mm^2, an effective clad yield stress for this configuration of 327 MPa (47 ksi) would be obtained. The maximum load for this test was 141 kN (31.7 kips) for an engineering ultimate strength of 576 MPa (83.5 ksi). A crack-tip opening displacement of greater than 0.8 mm (0.032 in.) was achieved at failure of the cladding.

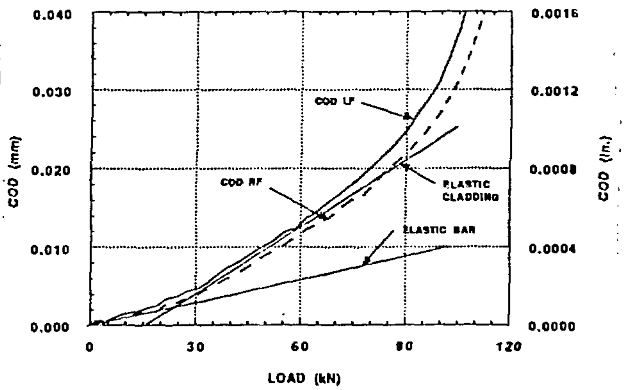

Fig. 9. Low load COD behavior for developmental Jo-block specimen A.

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Specimen failure was characteristically as shown in Fig. 10, i.e., only one ligament of cladding failed. When yielding occurs in one clad surface as shown in Fig. 8, there is little further increase in load. The yielded surface becomes the "weak link" and continues to stretch up to failure of the cladding. Since there is little additional load increase, axial deformation and CTOD of the opposite surface essentially stop. The amount of CTOD shown in Fig. 10 is not that measured at failure of the cladding. Due to compliance of the specimen and load train, additional CTOD occurs after cladding failure resulting in the "bent" configuration shown in Fig. 10.

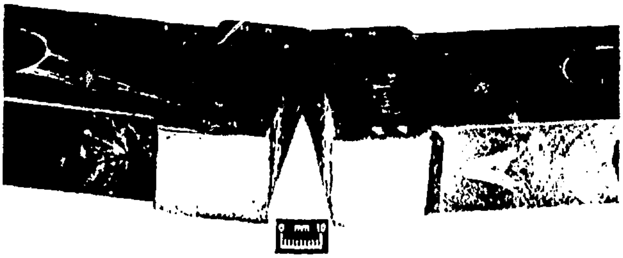

Fig. 10. Characteristic failure of Jo-Block specimens used to study fracture properties of cladding.

Preliminary finite-element analyses of these specimens using the procedures described previously tended to underpredict the amount of axial displacement. This is consistent with the results observed in analyzing the thermal shock tests reported in Ref 2. Two areas which may account for this are residual stress and ductile tearing. The analyses performed did not include either of these mechanisms. Inclusion of residual thermal stress would provide a prior history including prior plasticity in the cladding. This potentially could alter the response of the cladding under external load. Ductile tearing would result in reduction in load carrying area at a much greater rate than for plastic instability alone. Both of these mechanisms, which are being investigated further, may provide insight into the lack of agreement between the analyses and the experimentally observed behavior.

Using this particular case as an example of subclad flaw behavior during a PTS event, the "yield point" in the cladding would provide a crack-mouth force of approximately 80-kN per unit surface length of the flaw. For a 13-mm-deep surface flaw, this is equivalent to a ΔK_I value of 41 $MPa\sqrt{m}$ (37 $ksi\sqrt{in.}$). Since such a surface flaw would normally develop a K_I in the range of 110 $MPa\sqrt{m}$ (100 $ksi\sqrt{in.}$) during a PTS transient, it is apparent that the cladding would provide a significant reduction in the K_I at the deepest point of the crack tip, and a substantial cladding "benefit" would result.

SUMMARY AND CONCLUSIONS

It has been shown [3] that subclad flaws have a smaller potential for propagation than through-clad (surface) flaws, but the extent of potential benefit of cladding depends on two factors: (1) the fracture resistance of the cladding and (2) the amount of stretching of the cladding over the subclad flaw. If the cladding fails at some load less than the critical load for propagation of an otherwise similar through-clad flaw, no structural benefit of the cladding exists. Also, as the cladding continues to stretch, the potential benefit, as measured by a reduction in K_I at the tip of the flaw in the base metal, decreases. It is thus important to be able to measure fracture parameters of cladding over a subclad flaw, particularly the effective "yield" strength and the effective "uniform" elongation.

Oak Ridge National Laboratory has developed a laboratory specimen, the Jo-Block specimen, that has the capability to provide these two pieces of data. In addition, it was observed that, with careful fabrication, the Jo-Block would yield a measure of the membrane component of residual thermal stress in the cladding.

The preliminary tests indicate a high potential for this type of specimen to develop an understanding of cladding behavior over a subclad flaw. The primary advantages for development of a data base using this specimen include (1) small laboratory scale specimen size rather than large scale, complex components and (2) direct measurement of clad behavior as compared to deducing cladding effects from more complex experiments. ORNL is continuing to develop and use the data gathering and analytical potential inherent in the Jo-Block specimen.

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