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Pipe and pressure vessel cracking : the role of weld induced residual stresses and creep damage during repair

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ABSTRACT

The effect of residual stresses on surface crack initiation and growth during weld fabrication and weld repair of pipes and pressure vessels is discussed in this paper. A computational model is first briefly summarized and then used to provide the results presented here. First, the development of residual stresses during weld fabrication of a 304 stainless steel pipe is illustrated. Next, the repair of a damaged section of this pipe via weld repair is presented. The three dimensional effects of weld repair geometry is critical for this purpose. It is seen that the weld repair residual stresses are markedly different from the initial fabrication stresses in the region of the repair. The effect of crack initiation and growth in these weld residual stress fields is investigated using the finite element alternating method. Finally, creep damage induced solely by these residual stress fields is studied.

1.0 INTRODUCTION

Most fractures of pressure vessel and piping components occur in or near the regions associated with the welded connections. The residual stresses associated with the original welds can affect the initiation and growth of cracks. The residual stress associated with weld repairs, which are quite different from the original weld fabrication residual stresses, can lead to significantly different crack growth response compared with the original fabrication. Crack initiation often occurs due to corrosion mechanisms induced by the fluid flowing or contained within the vessel. For instance, stress corrosion cracking (SCC) can occur in nuclear piping due to the fluid interacting in a synergistic fashion with tensile stresses induced by the welding process. For thin wall pipes and vessels, the welding process usually leads to tensile residual stresses along the inner surface and compressive stresses at the outer surface. For thick walled pipes and vessels, tensile stresses usually develop at both the inner and outer surfaces with compressive stresses in the center region of the wall thickness. These tensile residual stresses can interact with service loads to enhance SCC and/or fatigue cracking. In addition to SCC crack initiation, creep cracking may be enhanced by these weld induced residual stresses. The purpose of this paper is to summarize recent findings, which investigated the effect of residual stress fields on crack growth in pipes and cylindrical vessels. The effect of weld repairs and creep damage is investigated as well. The material of concern for this study is 304 stainless steel.

The procedure consists of a three-step process. Step1 consists of modeling the residual stress fields induced by the welding process using a shell model so that the three-dimensional effects such as weld torch start/stop effects are accounted for. Step 2 involves extracting the residual stress fields from the shell solution to a three-dimensional finite element grid using a mapping routine. Step 3 consists of using the finite element alternating method with the above described residual stresses as initial conditions to obtain the stress intensity factors at many locations near and in the weldments. The weld process modeling includes three-dimensional effects since weld torch start/stop effects during initial weld fabrication and especially during weld repair cannot be ignored. Finally, the possibilities of developing creep cracks due solely to creep deformations within these residual stress fields is investigated using a continuum creep damage law.

The residual stress predictions were made using a new suite of weld analysis codes developed at Battelle in recent years. The weld thermal analyses were performed using a series of high-speed thermal solution techniques. The structural analyses were performed using ABAQUS with a newly developed user constitutive routine (UMAT) appropriate for weld analysis. It should be noted that the unique features of weld analyses could lead to incorrect predictions if the 'canned' constitutive laws of most general-purpose finite element code libraries are used. Finally, the stress intensity factors were obtained using the finite element alternating method (FEAM). FEAM has emerged as the preferred method for fracture analysis in recent years since the finite element mesh requirements dictate that only the *uncracked* mesh be discretized. The stiffness matrix is reduced only once and is then used for any other crack sizes, locations, etc. desired. The recently developed FEAM-WELD code was used for this purpose. Brief descriptions of both the weld codes and the FEAM-WELD code are provided before showing results.

2.0 WELD PROCESS MODEL AND FINITE ELEMENT ALTERNATING MODEL

To investigate the effect of weld induced residual stresses on crack growth behavior a two part model is required. The weld process model is a two-part model consisting of an uncoupled *thermal model* and *mechanical model.* The fracture model is based on the finite element alternating (FEAM) method. Both of these models are briefly summarized in the following.

2.1 Weld Process Model

An uncoupled thermal and mechanical numerical model is used to predict residual stresses induced by welding. This is a two part model consisting of: (i) a *temperature model* which is used to predict the temperature versus time histories at every material point in the structure of interest and (ii) a *mechanical model* which uses the temperature versus time histories from (i) to predict the residual stress state induced by the weld process.

The developments of the analytical thermal models are based upon classical solutions for a heat source moving in an infinite solid. A number of steady state and transient solutions have been developed for this purpose over the years. These solutions are applicable for the infinite body problem. The finite body solutions (i.e. for structures consisting of plates and shells) are obtained from series expansions of the basic solutions. This physically amounts to reflecting heat sources above and below the plate surfaces to force insulated boundary conditions or convective and/or radiation losses at the boundaries. Mathematically, this amounts to expanding the infinite body solutions in a Fourier series. The theoretical development of the thermal solution code (called the thermal weld analysis code – TWAC) is detailed in Reference [1]. The accuracy of these methods are verified via comparisons with experimental data and full scale finite element and finite difference solutions. Details of the model development and verification are provided in References [1,2].

The ABAQUS (Reference [3]) finite element code is used to perform the mechanical analyses for prediction of weld induced residual stresses and distortions. Unfortunately, there are many unique features associated with the welding process that cannot be correctly nor efficiently modeled using ABAQUS (or other general-purpose finite element packages). In particular, the material models (or constitutive laws) available in ABAQUS cannot account for some of the unique features associated with the welding process including material annealing caused by melting/remelting as different weld passes are deposited, material phase changes, and thermal cycling, among others. Moreover, the procedures required to model the weld process using ABAQUS are quite awkward. For instance, when modeling the weld process using the finite element method, the weld metal ahead of the current arc position has not been deposited as yet. To correctly account for this effect using ABAQUS one must use a tedious element birth option. This procedure is tedious in terms of manpower requirements and is computer intensive. As such, an ABAQUS UMAT subroutine was developed to account for constitutive model effects that are unique to the weld process. Detailed summaries of these subroutine models are provided in References [4, 5]. Material grind out is accounted for using the UMAT constitutive routine as well by reducing the stiffness of 'removed' elements and eliminating their history (a similar procedure is used to permit material annealing as additional weld passes are deposited and remelting occurs with conventional welding). The shell solution procedure is detailed in a companion paper within this conference (Reference [6]).

2.2 *Fracture Model*

Once the residual stresses induced by the weld and/or weld repairs are established the stress intensity factors must be obtained. For this purpose, the finite element alternating method (FEAM) is used.

The finite element alternating method (FEAM) is the state of the art method for obtaining stress intensity factors for three-dimensional surface crack problems and for two dimensional problems. The method has recently been extended to handle two-and-three-dimensional elastic-plastic and creep problems where the J-Integral and other fracture parameters may be evaluated for both stationary and growing cracks. The major advantage of the method is that a finite element mesh of *the uncracked geometry* is all that is needed to obtain stress intensity factors or the J-Integral, displacements, stresses, etc. More importantly, the same mesh can be used to obtain solutions for many different crack sizes and for multiple cracks. Because the finite element stiffness matrix only needs to be reduced once regardless of the crack size, crack location, crack orientation, crack number (mixed mode conditions can be handled as well), etc., the method is extremely efficient. The FEAM methods have been verified for many different crack problems, loading conditions, etc. A more detailed description of the FEAM method as used for obtaining K in residual stress fields is provided in References [2,4,5] and References cited therein.

3.0 ORIGINAL WELD CASE

The case considered first is that of a cylinder or pipe with a circumferential girth-butt weld deposited. The material is stainless steel and the weld parameters, temperature dependent material and physical properties, etc., are typical of those for stainless steel (see References [7]). The axial direction residual stresses are illustrated in Figure 1. These stresses were produced via a shell solution and the stresses mapped to this 3D solid element mesh. The shell solution procedure is summarized in a companion SMIRT-97 paper (Reference [6]). Only one quarter of the pipe was modeled due to symmetry. However, note the significant variation of the residual stresses as a function of circumferential location around the pipe, especially near the vicinity of the weld start/stop position. The usual type of axisymmetric analyses cannot account for this effect since the entire weld is modeled as being laid at once in such an analysis. With the present analysis procedure, the true circumferential movement of the weld torch as it traverses the circumference of the pipe is accounted for.

Note that the stresses are nearly uniform over a large circumferential portion of the pipe except at the weld torch start/stop position. The effect of weld torch start/stop effects on weld residual stresses and the corresponding crack development response can be quite important, and this issue will be covered in another forthcoming paper. A blow-up of the region near the centerline of the pipe, again for axial direction stresses, is illustrated in the right part of Figure 1. The residual stresses are nearly independent of circumferential direction in this region. Also, observe that the residual stresses are rather large (near the room temperature yield stress for 304 stainless steel) and they are tensile at the pipe inner surface and compressive at the pipe outer surface. As seen in Figure 1, the axial residual stresses range from –240 Mpa at the outer surface to 182 Mpa along the inner surface in the region of the pipe centerline. This suggests that circumferential cracks could develop at the pipe inner surface due to corrosion and/or fatigue considerations. Indeed, such cracking long been a concern in the nuclear industry, as circumferential cracks often develop in and near pipe welds that have not been stress relieved.

Consider now the introduction of circumferential surface cracks developing at the pipe inner surface. Both stress corrosion crack growth and fatigue crack growth can be correlated (in an engineering sense) using the stress intensity factor, K. For this case, service loads are neglected and the stress intensity factors due to the residual stresses alone are calculated using the FEAM method. The inset in Figure 2 illustrates the crack location and definition. As discussed earlier, this one mesh is used to obtain K for many different crack sizes (note that axial cracks can be considered as well, or cracks at any angle although these results are not presented here). The residual stresses serve as input to FEAM as initial stresses.

Consider the case of a crack with a major elliptic axis length of c = 8 mm, with the crack depth, a, varying. For this case the mean pipe diameter was 398 mm and the wall thickness was 16 mm. Figure 2 illustrates the variation of K with elliptic crack angle. For the small crack depth (a = 5 mm), the maximum value is at the deepest portion of the crack. However, as the crack becomes deeper (while keeping the crack length, c, constant at c = 8mm) the maximum K value begins to approach the surface (at elliptic crack angles near 0 and 180 degrees) while the value of K at the deepest point of the crack becomes small. If K governs stress corrosion cracking and/or fatigue cracking, this suggests that very long surface cracks could develop before the crack breaks through the pipe wall to become a through-wall crack. Indeed, in the field, very large surface cracks are often found (see Reference [8] and the many References cited therein).

4.0 WELD REPAIR CASE

Weld repairs are often made to pipes to repair damaged or cracked locations. Consider the case of a repair weld made by grinding out a circumferential section of the weld and heat affected zone region (to a depth of about 2/3 of the pipe wall thickness) and back filling with additional weld metal. The analysis procedure for modeling the grind out of the damaged region from the pipe and the corresponding redeposition of the repair weld passes is completely described in Reference [6].

This analysis was again performed using the shell analysis procedure and the resulting stresses were mapped to the 3D model. This 3D model is subsequently used to perform the

FEAM analysis to obtain stress intensity factors. A blow-up of the axial residual stress state in the region of the weld repair, after this process is complete, is illustrated in Figure 3. Observe that the axial residual stresses are tensile through the entire pipe wall (compare to Figure 1 where the through wall stresses varies from compression at the outer surface to tension along the inner surface). The residual stress state away the weld repair is nearly identical to that of the original weld (i.e. similar to Figure 1). Hence, the weld repair significantly alters the residual stress state in the near vicinity of the weld repair only.

A plot of the stress intensity factors as functions of elliptic angle are shown in Figure 4. Again, the residual stresses from the repair weld analysis serve as input for this FEAM analysis. Observe that the K values (for fixed c = 8 mm, and varying crack depth, a) are maximum at the deepest point of the crack (elliptic angle 90 degrees) for the small depth cracks. However, as the crack depth increases, K doesn't fall as rapidly at the deepest point of the crack, and increase as rapidly near the surfaces compared with the original weld case see Figure 2). This clearly suggests a weld repair may lead to much more aggressive through-wall crack growth compared with circumferential growth. Hence, the case of weld repairs to piping systems needs to be investigated further.

5.0 CREEP DAMAGE IN WELD REPAIR

There are some components in power generation equipment that experience very low levels of routine service loads (such as very low operating pressures). For such components that operate at high temperatures where creep damage could develop, it is interesting to observe whether creep cracks can nucleate from the weld residual stress fields alone. The main concern for such a scenario is that, once cracks develop, an upset condition (such as earthquake response, etc.) may cause system failure (loss of coolant, etc.) at the locations where the creep cracks have developed.

It is often argued that creep straining in secondary stress fields (such as residual stress fields near welds) will not lead to crack nucleation. The reason that cracks will not nucleate under such 'displacement type' load situations, the argument goes, is because creep straining relaxes the residual stresses fast enough so that creep cracks have no chance to nucleate. However, if the residual stresses are large enough and creep strain development rapid enough (at the operating temperature) one cannot rule out the possibility that creep cracks may initiate. Such a possibility is investigated in the following.

Consider the residual stress state in the repair weld illustrated in Figure 3. Recall that Figure 3 represents the axial residual stresses in the region of the weld repair. The axial stress over the entire half pipe away from the weld repair region is very close to that shown in the upper left portion of Figure 1. The creep damage development is considered using the following three step process.

- The temperature is raised to 700 C. This alters the residual stress state illustrated in Figures 1 and 3 since the material properties change as a function of temperature.
- Creep straining is considered using a simple secondary creep model.
- The creep damage is integrated throughout the entire creep straining history using a continuum creep damage nucleation law.

The material parameters for the simple Norton (power law) creep law considered here (i.e. $\dot{\epsilon}^c = A\sigma^n$) are A = 3.08E-18 and n = 6.7 for stress in Mpa and time in hours.(at 700 C). The creep damage law is a modification of the classical creep damage laws of the type discussed in by

Lemaitre and Chaboche in Reference [9]. The functional form for the creep crack nucleation law is:

$$D = \sum \Delta D = \sum \frac{\Delta \overline{\varepsilon^{c}}}{\varepsilon_{funi}} \cdot \exp\left\{ p \cdot \left(\frac{\sigma_{I}}{\overline{\sigma}} - 1 \right) \cdot \exp\left(\left(\frac{q}{2} \right) \left(3 \frac{\sigma_{P}}{\overline{\sigma}} - 1 \right) \right) \right\}$$

In Equation 1, ϵ_{funi} is the materials uniaxial creep ductility, $\Delta\epsilon^{c}$ is the equivalent creep strain increment, σ_I is maximum principle stress, $\overline{\sigma}$ is equivalent stress, σ_P is the hydrostatic stress, and p and q are material constants which are taken as p = 0.15 and q = 1.25 here (from measurements for 304 stainless steel at 700 C). The damage, D, is 0 for no damage and is 1 for crack nucleation. Figure 5 illustrates the damage in the pipe for creep damage developing after 2000 hours of creep. Over the 2000 hours the residual stresses have relaxed significantly, with the maximum value of axial stress about 25 Mpa. Figure 5 shows that no creep cracks are expected to develop for this case. The creep damage is plotted separately for the inner and outer shell surfaces, respectively. The maximum creep damage predicted is only 0.08 which is much less that 1.0 required for creep cracks to nucleate.

6.0 CONCLUSIONS

The results presented here indicate that crack growth behavior in original fabrication welds may be quite different from the crack growth behavior that occurs in a weld repair. It appears that long cracks will tend to develop in the original fabrication welds before the crack grows through the pipe wall while more rapid through-wall crack growth is expected in the repair welds. An important issue not addressed here is the behavior of crack growth near the start/stop positions of the weld torch. This issue is currently being analyzed and will be reported in the near future.

For the case of a repair weld considered here, it appears that creep cracks are not caused solely by the weld repair residual stresses alone for the conditions considered here. However, only secondary creep straining was considered here and primary creep may affect these results. Moreover, the creep constitutive constants and damage parameters were obtained for virgin 304 stainless steel only. The properties may be different for the weld metal. However, creep cracks may be possible for other initial weld conditions or for different repair procedures and should be investigated in the future. Moreover, weld residual stresses may combine with service loads to reduce creep ductility.

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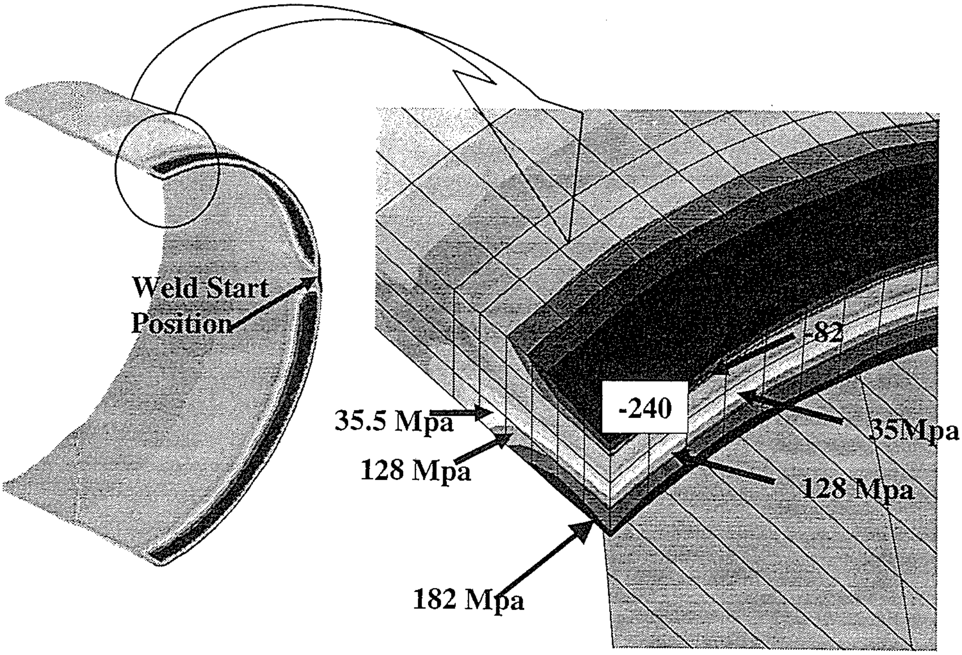

Fig. 1. Axial Residual Stresses From Original Weld

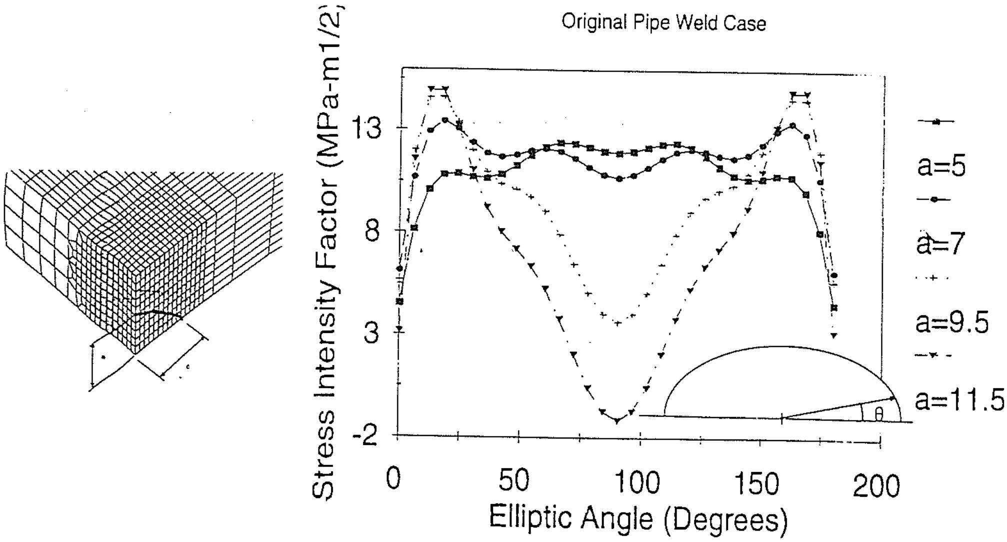

Fig. 2. Stress Intensity Factors for Original Weld

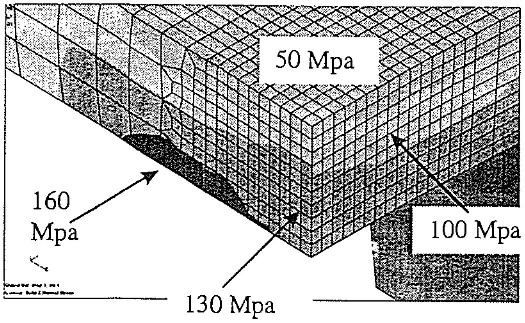

Fig. 3. Repair Weld Axial Residual Stresses

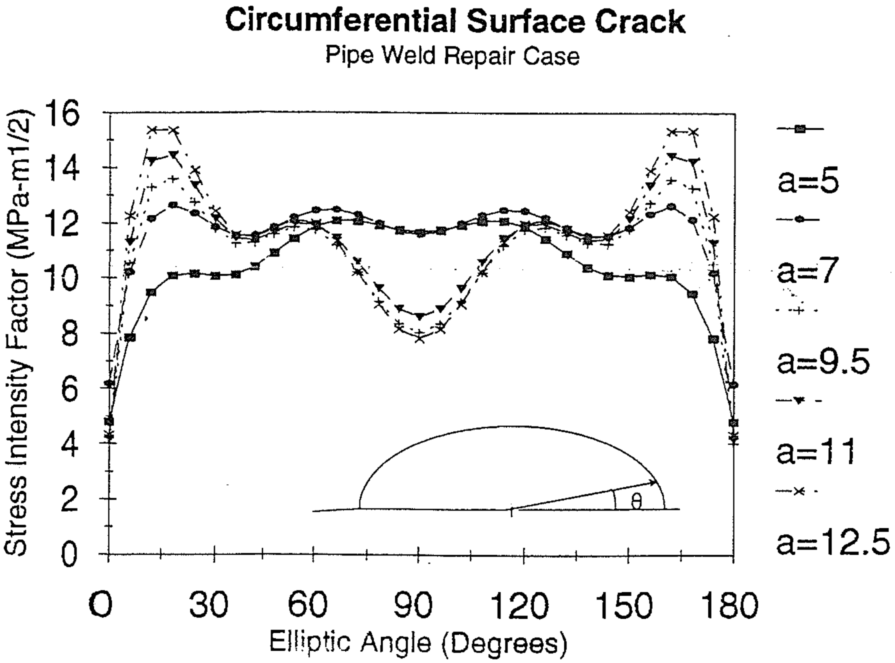

Fig. 4. Stress Intensity Factors for Repair Weld

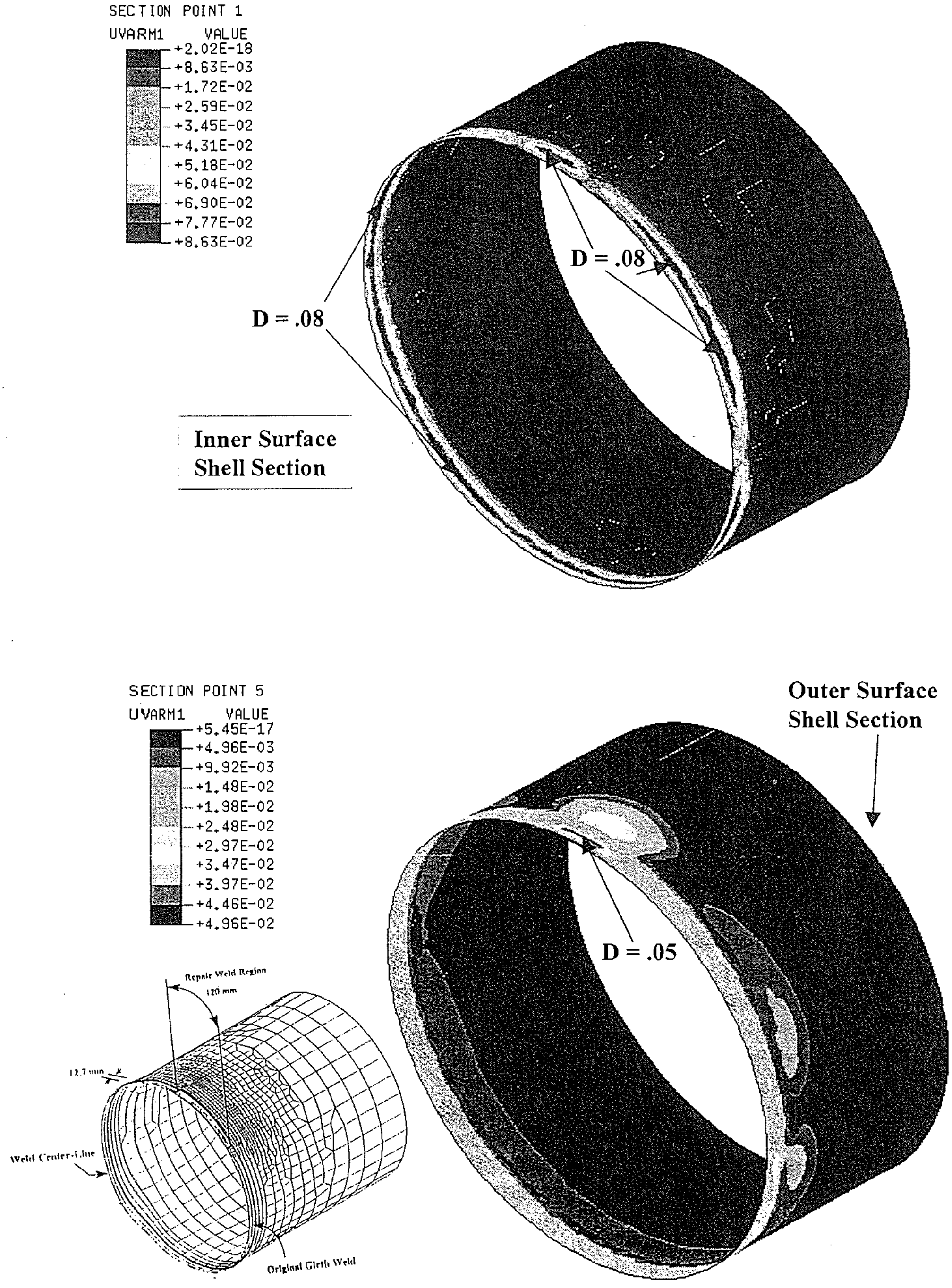

Fig. 5. Creep Damage Accumulation for Repair Weld