Methodology to Obtain Semi-Elliptical Cracks in a Nuclear Reactor Pressure Vessel Model

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ABSTRACT

In a PWR nuclear power plant, the reactor pressure vessel (RPV) works like a containment of the reactor core and of the primary system coolant as well. The RPV integrity must be assured during its service life to protect the public as a whole and the environment against the hazard of a significant radiation liberation. One of the critical issues related to the RPV structural integrity is related to the pressurized thermal shock (PTS) event. The RPV steel can have its fracture toughness decreased during its service life due to high temperature and neutron radiation. Extensive research programs have investigated the fracture behavior of heavy-section vessels containing semi-elliptical cracks. In the experimental works with large specimens, like a nuclear reactor vessel model, these semi-elliptical cracks are generally obtained from alternate loading and unloading. This is a long term procedure which involves the use of heavy equipment, like large presses and servo-hydraulic equipment, which becomes a very expensive process.

This work is related to a theoretical-experimental study carried out to evaluate the structural integrity of a RPV model under PTS loading. The RPV model should contain a determined number of axial cracks with well-controlled geometry and localization. Because of the large dimensions of the model, it was necessary to develop a simplified method to obtain these cracks. This paper presents a very simple and cheap methodology to obtain semi-elliptical cracks in large specimens.

Key words: Reactor pressure vessel, Semi-elliptical cracks, Pressurized thermal shock, Structural integrity, Fracture toughness.

INTRODUCTION

A reactor pressure vessel, which contains the nuclear fuel, maintains the coolant in the liquid state at high temperatures and high-pressures during normal operation condition. Thus, it is designed, constructed and inspected according to rigid standards and the maintenance of its structural integrity along its life time is very important (Bass et al, 1999; Mishima et al, 1994).

Since the PTS transient occurred at Rancho Seco Nuclear Power Plant in 1978 (Stalkopf, 1994), this kind of event has been considered as an important safety issue. A PTS involves a transient, in which a rapid cooling causes a thermal shock in the vessel wall, while the pressure is kept constant or it suffers a sudden drop and then the system is pressurized again. The thermal stresses due to the rapid cooling in the vessel wall combined with the stresses due to system pressure result in high tensile stresses, that rise to its maximum value in the internal vessel wall.

At temperatures below the NDT temperature (nil ductility temperature) of the vessel material, the fracture toughness decreases, what in combination with the produced stresses during the PTS could cause the propagation of small cracks eventually present in the vessel wall. Many authors (Jeong et al, 2000) have shown that the high flux of fast neutrons in the reactor core region, achieving the wall vessel, decreases the fracture toughness of the vessel material, thus increasing the probability of crack propagation.

Several methodologies have been developed, from structural analysis and fracture evaluation, in order to determine the safety margins against RPV rupture under a postulated event of PTS. For such analyses, it is necessary to know the mechanical properties, the fracture toughness properties of the material and also the characteristics of the actual defects present on it.

In PTS experiments using RPV models, it is very difficult to manufacture cracks in these models. Many works have presented different alternatives to make semi-elliptical cracks in models for PTS experiments. However, due to the great dimensions of these models, the application of the proposed procedures demand the use of heavy equipment like high load capacity (6.3 MN) servo-hydraulic systems and pumps capable to produce pressures in the range of 2000 bar, what makes these experiments extremely expensive.

The methodology presented here was developed to reduce the cost and to simplify the operations to make cracks in a pressure vessel model utilized in a PTS experiment.

In the following items of this introductory section, the main effects that were taken into account to develop this methodology are described. The methodology itself is presented in Section 2. The obtained results are discussed in Section 3 and the main conclusions are presented in Section 4

LOADING RATE EFFECT

The loading impact causes more severe stresses states than quasi-static loading, affecting significantly the materials properties (Quinan, 1999). It has been demonstrated that many materials present a significant increase in its ultimate tensile strength when submitted to high loading rate, normally up to 7.5 m/sec. At loading rate up to this level, there will be a small change in the ultimate tensile strength.

The yield strength generally increases with the load rate increase. The impact speed effect in the elongation and in the capacity of energy absorption varies according to the kind of material. The behavior of three different materials is illustrated in Figure 3, which shows the elongation curves (a) and the absorbed impact energy (e), related to the impact speed.

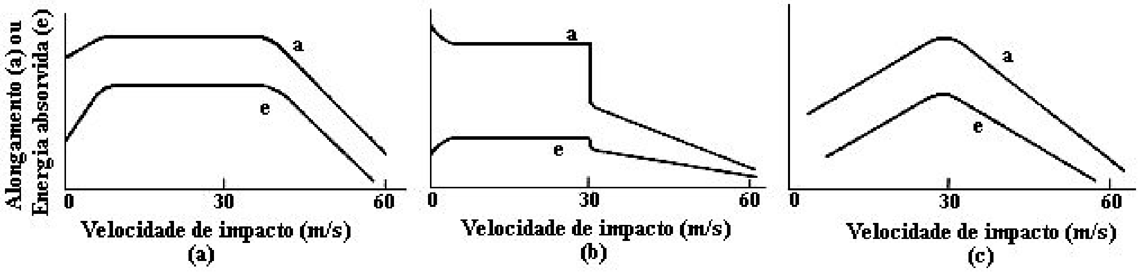

Figure 3- Elongation variation (a) and absorbed impact energy variation (e) related to the impact speed, for three different materials: (a) annealed steel ASTM 1020 , (b) spheroidic steel ASTM 1045 , (c) cold rolled steel ASTM 1020 [6]

TEMPERATURE EFFECT

Low alloy steels, low carbon steels and many other metals with body centered cubic structure (bcc), are subjected to absorbed impact energy reduction due to the temperature reduction (Quinan, 1999). This change is accompanied by the transition of a fracture surface of a fibrous aspect (ductile fracture) into crystalline surface (brittle fracture).

The temperature at transition range is called ductile-brittle transition temperature. The transition temperature curves (Figure 2) are used to determine the temperature above which the brittle fracture will never occur at elastic stresses level. The smaller the transition temperature is, the greater the material fracture toughness.

If the curve presents an accentuated drop, there will be three distinct regions: upper shelf, transition zone and lower shelf. When the transition zone extends over a wider temperature range, there will not be a well-defined temperature transition. At temperatures below the transition region, the ferritic steels present nil ductility, that is, they behave in a typical brittle manner and their fracture occurs by cleavage.

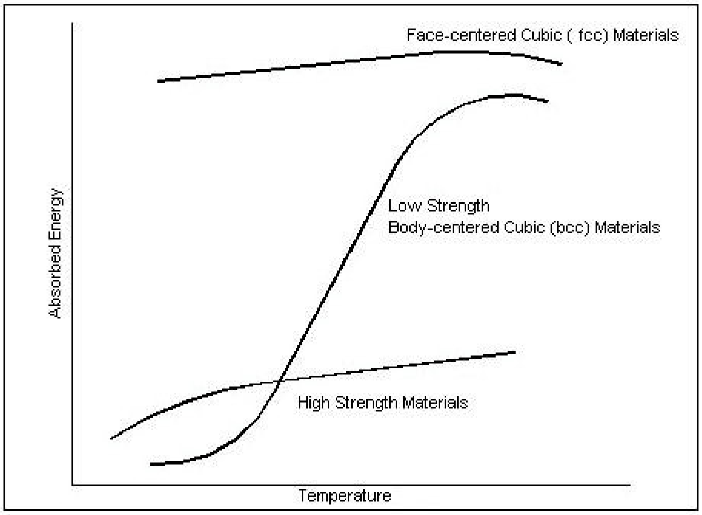

Figure 2 – Ductile-brittle transition curves

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NOCTH EFFECT

The stress distribution in a body containing a discontinuity is not uniform in the discontinuity region, and the stresses will be larger in this region than the average stress on the most distant points of the body (Vida Gomes, 1999). If the stress ahead of the notch tip achieves the material yield strength, there will be a localized plastic strain that will alleviate the elastic stress, limiting it to the material yield strength level[5]. Considering a brittle material, there will be a large stress concentration, because there will not be enough plastic strain to relieve them. However, the greatest notch effect is the creation of a triaxial stress state. Considering a thin plate with a notch submitted to stress σ (less than the yield strength - σ_{ys}) according to Figure 1-a, it can be seen that as it goes far from the notch, σ_y decreases causing a plastic strain gradient ahead of the notch tip. So it produces an elastic stress σ_x that decreases with the increase of the distance from the notch tip. Considering that there is stress only when there is restriction, and that on plate surface the stress is null (there is no restriction), one can affirm that the stress in Z direction (σ_z) is negligible and there is a plane stress state ($\sigma_z = \tau_{xz} = \tau_{yz} = 0$). On a thick plate (thickness relatively big if compared to the notch dimensions), the stress in Z direction can not be neglected and, thus, there will be a plane strain state or triaxial stress state (Figure 1-b and Figure 1-c).

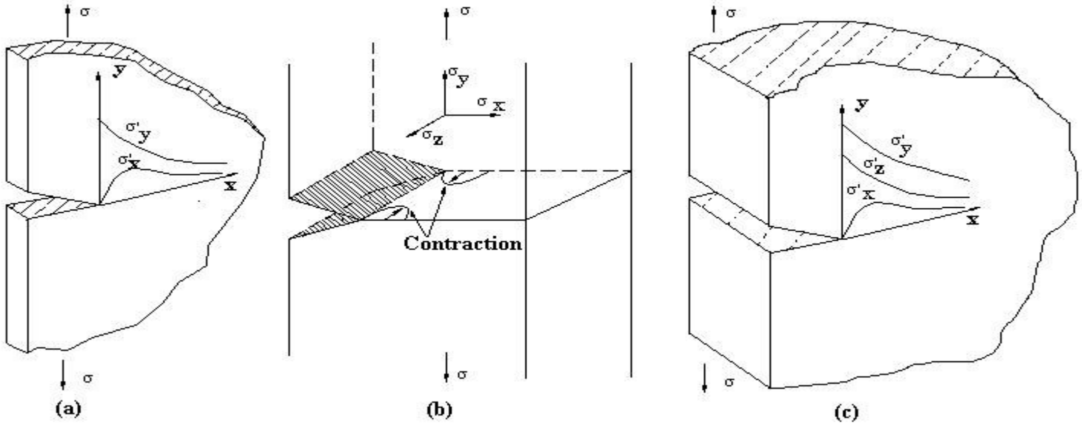


Figure 1 – Stress States
(a)- Plane stress state; (b) and (c) – Plane strain state

Near the notch tip, where σ_y is bigger, there is an elastic contraction (due the Poisson's ratio). As the stress doesn't act in the notch area, the stress will be concentrated in front of the notch. So, tensile stress (σ_z) will appear on the contracted area, while the notch area maintains its original dimensions. As reported previously, the plate surfaces are not stressed externally and, consequently, σ_z will be maximum in the plate center. In the same way, the tensile stresses in X direction are established, due to the contraction restriction in this direction. These stresses raise the σ_y value in order to occur the yielding that can be explained considering the Tresca criterion for the yielding. By this criterion, $\sigma_y = \sigma_1 - \sigma_3$ or $\sigma_y = \sigma'_y - \sigma'_z$. If the body doesn't have a notch ($\sigma_z = 0$), $\sigma_y = \sigma'_y - 0$, what means that the yielding will occur when the stress σ'_y is equals to the material yield stress. If the body has a notch, σ'_y must be bigger so such yielding can occur.

When a localized yielding occurs, on the notch tip, there is a plastic strain with constant volume (the Poisson's ratio assumes the value $\upsilon = 0{,}5$ instead of the elastic value $\upsilon = 0{,}3$) and a consequent increase of σ_x which has its maximum value in the elastic-plastic interface. With the stress increasing, the plastic zone moves itself to the interior until the entire notch region becomes plastic, causing the collapse. The general yielding stress for a notched body is greater than the stress for an uniaxial yielding, due to the triaxial stresses in the notch that makes difficult an yielded expansion zone.

MATERIALS AND METHODS

The RPV model material and the specimens were built with steel ASTM 8620, hot-forged, in the "as received" state. Based on the fact that a state of triaxial stresses, just like the one that exists in a notch, high loading rates and low temperatures decrease sensibly the fracture toughness of the ferritic steels, it was developed a methodology to obtain cracks, as described below:

Machining a semi-elliptical notch in the desired region

In Figure 4, it is shown the notch, which is obtained by machining using a circular saw with thickness of 1.6 mm. To obtain a sharper notch, a second circular saw with thickness of 0.4 mm is used to the desired depth.

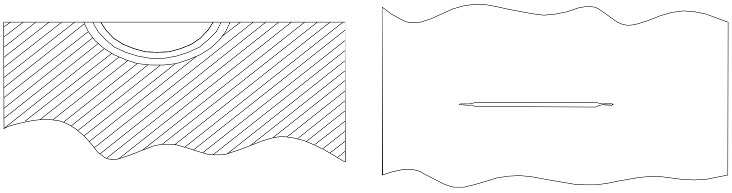


Figure 4 - Longitudinal- section of the notch region

In Figure 5, it is shown a notch machining equipment positioned over the vessel model.

Figure 5 - Notch machining on the vessel model wall

Execution of the weld beads on both sides of the notch

After the notch machining, two longitudinal weld beads are made on both sides of the notch, according to Figure 6.

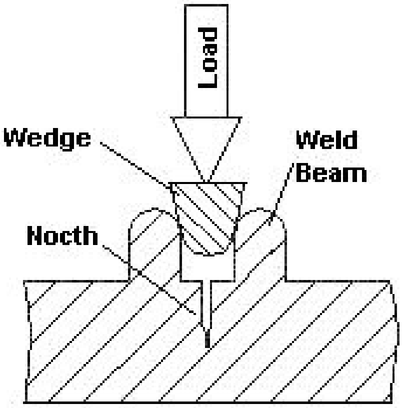


Figure 6 - Cross-section of the notch region and loading direction

These weld beads are 17mm high and their aim is transforming the impact load in tensile effort that will open the notch, consequently, causing the cracking growth. In Figure 7-a, it is shown, schematically, the notch and the weld beads on the vessel model wall. In Figure 7-b, it is shown a lateral view of the weld beads after machining of their edges.

(a) (b)

Figure 7 - (a) notch and weld beads in the vessel wall, (b)- lateral view sight of the weld beads after machining.
Drop weight system

In Figure 8-a, it is shown the drop weight system positioned over the pressure vessel model. The system was designed to provide sufficient impact energy to the desired crack growth, in the test temperature. In Figure 8-b, it is shown a view of weight positioned over the notch region. The impact energy is estimated using simplified fracture mechanics formulation and the material fracture properties for crack initiation and crack arrest.


(a) (b)

Figure 8- (a)- Drop weight system mounted over the RPV model, (b)- view of the weight positioned over the notch

Cooling the notch region with liquid nitrogen

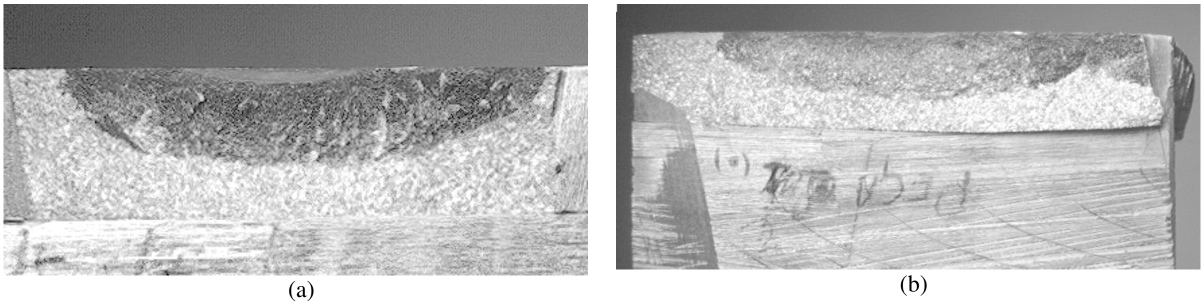
For cooling the notch region at temperatures below the ductile-brittle transition range, it was used liquid nitrogen that was fed manually during a certain cooling time. The temperature was controlled by thermocouples on the internal surface of the pressure vessel

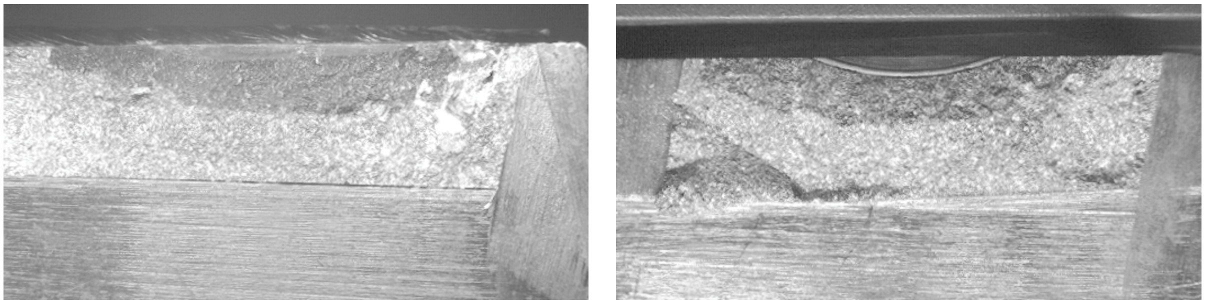
Impact loading and crack growth

When the notch region reaches the desired temperature, the weight drops under the wedge that is previously positioned between the weld beads. The wedge is compressed against the weld beads, which imposes tensile loads, thus causing the creation of a crack ahead of the notch tip.

RESULTS AND DISCUSSION

In Figure 9 (a, b, c and d), it is shown the fracture surfaces obtained by this methodology, where the dark regions are the crack surfaces. It can be observed that the cracks have semi-elliptical boundaries. There were no significant changes in the cracks planes relative to the notch planes.


(a) (b)



(c) (d)

Figure 9 - Fracture surfaces on specimens

CONCLUSIONS

The results obtained from the specimens show the viability of this methodology. Specific investigation can be done to precisely define a relationship between the temperature and the load impact in order to obtain a crack in the desirable depth and length in each case. With regard to the notch depth, it was observed that it had no influence in the dimensions of the crack obtained.

This methodology has been applied to make surface axial cracks in the RPV model to be used in the PTS experiment already mentioned.

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