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Determination of Critical Cavity Growth Parameters for Ductile Rupture Initiation in Piping Material of PHWR

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ABSTRACT - The aim of this work was to investigate the effect of specimen geometry on ductile fracture of a low inclusion content carbon steel SA333 Gr.6 which is used as the material of Primary Heat Transport (PHT) system of Indian PHWR and to determine the critical parameter to characterise the ductile fracture initiation. Uniaxial tensile tests were conducted at room temperature on axisymmetric notched tensile specimens. Geometry effects were studied using specimens with various notch root radii, thus inducing different stress triaxiality levels. Results show that ductility is reduced for specimens with sharp notches. In order to predict rupture initiation, two different types of models are used. The first one is based on critical cavity growth (Rice & Tracey's cavity growth model and Budiansky & coll.'s model). The other model is based on the combined effect of damage and yielding(Tai & Yang's and modified Tai & Yang's model). An in-house Elasto-Plastic finite element code THESIS has been modified and used for the analysis of the notched tensile specimens. It was observed that the critical values of parameters of all the models except Budiansky & coll.'s model are weak functions of stress triaxiality.

KEY WORDS : Ductile rupture, SA 333 Gr.6 steel, Cavity growth model, stress triaxiality, critical parameter.

1. NOMENCLATURE

R_0, V_0 = Initial equivalent radius and volume of microscopic voids respectively.
R, V =Instantaneous equivalent radius and volume of microscopic voids during loading respectively.
n=Strain hardening exponent of the material in the expression $\sigma = c\,\varepsilon^n$.
σ_{ij}=Cauchy's stress tensor, σ_m = Mean hydrostatic stress, σ_{eq}= von-Mises equivalent stress.
ζ=Stress triaxiality ratio=σ_m/σ_{eq}
$\delta\varepsilon_{eq}^p$=Equivalent plastic strain increment.
ε_r = Rupture strain, ν= Poisson's ratio of the material

2. INTRODUCTION

One of the important issues in fracture mechanics research is the existence of geometry effects on fracture toughness property of a material especially when the material of the specimen has very high ductility and fracture toughness. These geometry effects on cracked specimens are clearly observed for numerous materials for which the conventional single parameter approach is not sufficient to characterise the near fully yielded crack tip states. To overcome these difficulties, several approaches on fracture mechanics have been developed. On one hand, fracture is predicted from purely mechanical point of view and is treated in terms of two parameter criteria i.e. J-Q ,J-A_2, J-T and K-T criteria etc. On the other hand, local approaches provide an alternative methodology for fracture analysis of material in which microstructure damage mechanisms are taken into account. The local approach is particularly based on a combination of the following:

(a) The computation of local stress and strain in the severely loaded part of a component or a structure and,

(b) Use of physical fracture models corresponding to various mechanisms; i.e. cleavage, ductile fracture, creep, and so forth to model crack initiation and stable crack growth.

There are basically two routes followed in this local approach. The first one is the "locally coupled model" which is based on a post-processing treatment of elasto-plastic finite element (FEM) results. The main hypothesis of these types of models is that damage does not affect the overall behaviour of the structure. It is also assumed (and also verified) that the onset of the ductile rupture (causing instability of the structure) occurs when a critical value of the given damage parameter is reached. The other type of models, called "fully coupled models", account for the softening effect induced by void growth and coalescence by using yield potentials integrating damage such as those proposed by Gurson (Subsequently modified by Tvergaard and Needleman) and Rousellier etc. In this paper, the first type of approach is used. In this approach, a critical parameter D_c is computed from a conventional relationship such as:

$D_c = \int f(\sigma_m/\sigma_{eq}, \varepsilon_{eq}{}^{pl})\, d\varepsilon_{eq}{}^{pl}$.

This integral is integrated from ε_0(nucleation strain) to ε_r(rupture strain). It is observed that the generation of material data is simple and its application in complex situations is direct in this type of approach. The present paper deals with the ductile fracture characterisation of the material of primary heat transport (PHT) system of Indian PHWR using four ductile fracture models based on locally coupled type of models. This material exhibits a high degree of ductility and has a high fracture toughness. The task involves the determination of critical cavity growth parameters from the notched tensile tests. First, the tensile properties and the true stress- true strain relationship of the material was determined from simple tension tests. These material properties were used in the numerical simulation of Load vs ΔD(change in diameter) response of the notched tensile specimens. The effect of stress triaxiality (geometry effects) on the fracture strain of the notched tensile specimens was studied by varying the notch root radius. A number of notched tensile specimens were tested and the experimental Load vs ΔD curves were compared with the numerically predicted curves. The curves were found to be in good agreement with the measured values. The rupture strain was determined by measuring the final diameter of the specimens after fracture and analysing their Load vs ΔD curves (Devaux et. al,1987)[1]. It is explained later in detail. The parameters (R/R_o), (V/V_o), (V_D), and (V_{DM}) of the four models (Rice & Tracey's cavity growth model (Rice et. al,1969)[2], Budiansky & Coll.'s model (Budiansky et. al,1982)[3], Tai & Yang's model and modified Tai & Yang's model (Tai et. al,1987)[4]) are determined by integration of the respective integrals of the models. When these parameters attain the critical value over a characteristics length l_c (which is identified as mean inclusion spacing in a material), it represents the phenomena of void coalescence (onset of ductile rupture).

3. THE LOCALLY COUPLED MODELS

3.1. Models Based on Critical Cavity Growth

3.1(a). Rice & Tracey's Model :

Here the damage parameter is considered to be the equivalent cavity radius 'R'. The growth of an isolated void in an infinite block of an elastic and plastic strain hardening material is given by the equation; $\delta R/R = \alpha\, \delta\varepsilon_{eq}^{p} \exp(3\sigma_m/2\sigma_{eq})$, where α is a constant factor and according to Rice & Tracey, for high stress triaxialities, α=0.283. Crack initiation occurs when 'R' reaches its critical value 'R_c'. The effect of void nucleation is not considered here as the nucleation strain is very small for this material and hence the nucleation strain is taken approximately equal to zero.

3.1(b). Budiansky & Coll.'s Model:

The damage parameter is considered to be the volume of voids 'V'. This model gives the equation of growth of an isolated axisymmetric void for a nonlinear elasto-plastic material. The effect of strain hardening exponent 'n' is taken into account by incorporating it in the integral. The dilation rate of a void is given by:

$\frac{\delta v}{v} = \frac{3}{2}\alpha\left[\frac{3}{2}n\left|\frac{\sigma_m}{\sigma_{eq}}\right| + (1+n)(1+0.418n+0.0144\alpha n)\right]^{1/n} . \delta\varepsilon_{eq}^{pl}$ where $\alpha = \mathrm{sign}(\sigma_m)$.

3.2. Models Based on damage & Yielding

3.2(a). Tai & Yang's Model:

Tai & Yang has proposed the following damage criterion for ductile tearing.

$\delta V_D = f(\sigma_m/\sigma_{eq}).\delta\varepsilon_{eq}^{pl}$, where $f(\sigma_m/\sigma_{eq}) = \frac{2}{3}(1+\nu) + 3(1-2\nu) . (\sigma_m/\sigma_{eq})^2$.

3.2(b). Modified Tai & Yang's model:

If the strain hardening exponent of the material 'n' is large, another damage failure criterion is expected to better take into account both strain hardening and plastic strain effects. This is called modified Tai & Yang's model and the parameter V_{DM} is evaluated as follows.

$\delta V_{DM} = f(\sigma_m/\sigma_{eq}).(e_{eq}^{pl})^{2n}. \delta\varepsilon_{eq}^{pl}$, where the function $f(\sigma_m/\sigma_{eq})$ is given by $f(\sigma_m/\sigma_{eq}) = \frac{2}{3}(1+\nu) + 3(1-2\nu) . (\sigma_m/\sigma_{eq})^2$.

In order to apply these models, we need to find out the critical values of these parameters for the given material.

4. MATERIAL OF PHT PIPING

Carbon steel SA333 Gr.6 is used in the PHT system piping (size 16NB) of 220 MW_e Kaiga PHWR. The notched tensile specimens have been machined from a scrap of the PHT piping. The chemical composition of the material is shown in table 2. The material was also studied for the inclusions & second phase particles present in it (Singh et. al,1997)[5]. The details of inclusion type and rating are given in table 3.

5. EXPERIMENTAL DETERMINATION OF MATERIAL PROPERTIES OF PHT PIPING

5.1 Test Specimens

The notched tensile specimens(AER) with nominal diameter of 10mm, minimum diameter of 5mm at the notch portion and different notch root radii 'R' (4.5 mm, 2.7 mm, 1.7 mm, & 1.2 mm respectively) were prepared according to ASTM standard E8M-91 for determining the tensile properties of the material and for studying the effect of notch root radius on the ductile fracture behaviour of the material. The length of the specimens are along longitudinal direction of the pipe. The sketch of the specimens with different notch root radii (R) is shown in Fig.1.

5.2. Notched Tensile Test

The tensile tests have been carried out according to ASTM standard E8M. The tests were conducted using a digitally controlled 100KN INSTRON universal testing machine. The machine was integrated to a sophisticated Image acquisition system for on-line data acquisition of instantaneous diameter of the tensile specimens in the notched portion during the tensile test. The tests were conducted at room temperature and at slow strain rate.

5.3. Determination of true stress strain curve and other material properties.

Based on the data recorded by the image acquisition system, the true strain was calculated using the relation $\varepsilon_{true} = 2 \ln (D_o/D)$ where D_o is the initial diameter of the specimen and D is the instantaneous diameter at the minimum area of cross-section. The true stress was calculated using the relation σ_{true}=Load/A , where A is the instantaneous area corresponding to diameter 'D'. This stress was multiplied with suitable correction factors for taking into account the effect of hydrostatic stress on the true stress of the material (Bridgman's correction). The true stress vs true strain curve after UTS was fitted with a best fit using power law and is given by $\sigma = c^* \varepsilon^n$ for $\varepsilon > 15.1\%$, where 'n' is the strain hardening exponent and c is a constant. The values of c and n are found to be 673.068 and 0.143458 respectively for the material. The other tensile properties are given below in the Table-1.

Table-1 :Tensile Properties of SA333 Gr.6 Steel

Material properties	Yield stress (YS) in MPa	UTS (MPa)	Strain at UTS	%age elongation (ΔL)	%age reduction In area (ΔA)
Measured values	330	511	0.151	37%	82.5%

These material properties are used in the numerical simulation of the notched tensile specimens. The True stress vs True strain curve is shown in the Fig.3.

6. DETERMINATION OF CRITICAL CAVITY GROWTH PARAMETERS

An in-house elasto-plastic finite element code THESIS has been modified for the analysis of axisymmetric notched tensile specimens. All the four models of local approach to fracture as discussed earlier have been incorporated in the program. Eight noded isoparametric quadrilateral elements have been used in the finite element (FE) mesh. The FE mesh is shown in Fig.2. The FE calculations have been performed using von-Mises yield criteria for plasticity with associated incremental flow rule (Prandtl-Reuss equations). The code is capable of analysing both load controlled as well as displacement controlled problems. In the present analysis, the application of load on the tensile specimens is simulated by a vertical displacement of the nodes at the upper surface of the FE mesh (Displacement control Formulation). Geometric nonlinearity has been considered in the analysis using Updated Lagrangian formulation. The four cavity growth models were implemented in the in-house code and validated against the published results. The Load vs ΔD(change in diameter) curves for all the four notched tensile specimens have been obtained from the analysis using the FEM code and compared with the corresponding curves obtained experimentally. The matching as shown in Fig. 4 was found to be very good. The cavity growth parameters have been obtained as a function of plastic strain for all the specimens and the variation of $\ln(R/R_o)$ with $\varepsilon_p(2\ln(D_o/D))$ is shown in the Fig.5. In the ductile fracture process, the beginning of void coalescence can be related to the first occurrence of a microcrack in the minimum section of the tensile specimen. This occurrence of microcrack is marked by a change of slope in the Load vs ΔD curve. The notch ductility of the specimen is expressed by the value of the true notch diametral strain 'ε_r' at the onset of microfracturing. The bulk values of 'ε_r' measured on the specimens could not be used directly because of a large scatter due to the anisotropy in the tensile properties. The final results to be used for analysis have to be adjusted, considering a correction based on the reduction in area $Z=(S_0-S)/S_0$ (where S_0 is the initial cross-sectional area and S is the area after fracture) measured after fracture, and an analysis of the load-elongation curves. As it was not possible to determine 'ε_r' exactly by examining the experimental Load- ΔD curves of the specimens (shown in Fig.4) in this task, an alternative approach has been followed. For determining the values of 'ε_r', the specimens has been analysed by an in-house code which uses modified Gurson-Tvergaard-Needleman's model in the constitutive relationship. This model uses a yield function where the flow stress of the material depends upon void volume fraction of microscopic voids and the level of hydrostatic stress. The details of the model are given elsewhere (Samal et. al,1998)[6]. This analysis could exactly trace the total experimental Load- ΔD curve. It could also trace the point in the Load- ΔD curve where there is a change in slope due to appearance of microcrack. At this point, the yield surface shrinks to a low value. The strain(ε_r)s corresponding to this point for the notched tensile specimens of notch root radii of 4.5mm, 2.7mm, 1.7mm, & 1.2mm are found to be 78.3%,59.68%,43.5%, & 31.1% respectively. The cavity growth parameters are computed by integrating the expressions of the four models until the applied displacement, for which the strain ε_r is reached in the computation. The value of the parameters at this stage are known as critical cavity growth parameters. These points have been marked with '*' for the different specimens in Fig. 5. The values of these critical parameters $[(R/Ro)_c$, $(V/V_o)_c$, $(V_D)_c$, and $(V_{DM})_c]$ for different AER specimens are plotted in Fig.6 for different models.

7. DISCUSSION

From Fig.6, it was observed that the values of the parameters of Rice & Tracey, Tai & Yang, and modified Tai & Yang's model are approximately constant for notch radius of 1.2 mm to 2.7 mm. However for notch radius of 4.5mm, the values of critical parameters are on higher side for all models except for Rice & Tracey's model. The critical parameter of Budiansky's model shows rapid increase in its value with increase in notch root radius. Hence one can treat Rice & Tracey's critical parameter as a material toughness property. But the critical parameters of other models are dependent on the level of stress triaxiality existing in the component. The average values of the critical parameters are given in Table-4. These critical values can be used to predict crack initiation as well as to study stable crack propagation. The size effects should be taken into account to interpret more closely the variation of the parameters with respect to stress triaxiality. The stable crack propagation can be simulated by using the conditions of node release, a criterion, based on a constant value of the critical parameters. Hence it is observed that a model using Rice & Tracey's critical cavity growth parameter in conjunction with the calculation of stress and strain fields by finite element method can lead to useful results for prediction of ductile crack initiation and stable crack growth.

8. CONCLUSION

A numerical and an experimental program were carried out in order to predict crack initiation and stable crack growth using local fracture criterion for PHT piping material of Indian PHWR. Several notched tensile specimens of different groove radii were tested. The specimens were analysed using an in-house Finite Element code THESIS. The void growth was simulated by using various cavity growth models. The critical values of cavity growth parameters leading to crack initiation were determined by integrating the parameters upto the rupture strain obtained from experiment. The effect of stress triaxiality on the critical values has been studied by taking notched tensile specimens of different groove radii. These local criteria (mainly Rice & Tracey's model) can now be used to model the flawed PHT piping. The anisotropy problems in the material property can be overcome by determining upper and lower bound values of mechanical properties. Finally, it was observed that the piping material of PHT system possesses high toughness. So it is desirable to couple damage parameter (void volume fraction 'f') in the constitutive relation of the material model for predicting ductile crack initiation. Hence fully coupled models which couple damage and plastic flow behaviour (Porous plasticity Models) such as modified Gurson-Tvergaard-Needleman's and Rousselier's model may predict crack initiation and stable crack growth more accurately in comparison to these locally coupled models.

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10. REFERENCES

11. Devaux J.C., Mottet,G. et. al, Nuclear engineering and Design,105,pp.131-138, 1987.
12. Rice, J.R. and Tracey, D.M., Journal of Mechanics and Physics of Solids ,17, pp. 201-217, 1969.
13. Budiansky, B., J.W. Hutchinson, & S. Slutsky, Mechanics of Solids- The Rodney Hill 60th anniversary volume, Edited by H.G.Hopkins, amd M. J. Sewell, pp. 13-45, 1982
14. Tai, W.H., & B.Yang, Engineering Fracture Mechanics, vol.27, pp.371-378, 1987
15. Singh, P.K.,et. al, "Tensile and fracture properties of PHT system piping material", BARC External Report No. BARC/ 1997/ E/ 018.
16. Samal, M.K., Dutta, B.K., Kushwaha, H.S., "Modeling of material damage leading to ductile rupture", To appear in the proceedings of 2nd National Conference on Mathematical modeling and Computer Simulation, 6-7 August, IGIDR, Mumbai, INDIA, 1998.

Table 2 : Chemical Composition for SA333 Gr.6 Carbon steel material

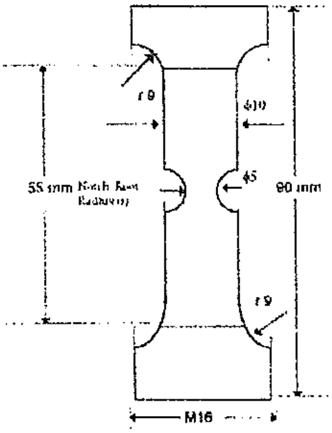
Name of element	C	Mn	Si	P	S	Ni	Cr	Al	Cu	Pb	V	H
%age composition (in weight)	0.14	0.90	0.25	0.016	0.018	525 ppm	805 ppm	<0.1	540 ppm	80 ppm	<100 ppm	<5 ppm

Table 3 : Mettallography Data of the material

Inclusion Type	Sulphide	Alumina	Silicate	Globular Oxide
Inclusion Rating	1 (thin)	1 (thin & thick ~ 15 micron)	1 (thin & thick ~ 10 micron)	1.5 (thick ~ 15 micron)

Table 4: Results from the four local approach models (Critical values of the parameters)

Name of models	Rice & Tracey	Budiansky & Coll.	Tai & Yang	Tai & Yang (Mod.)
Critical Values	$(R/R_o)_c = 2.1$	$(V/V_o)_c = 10.20$	$(V_D)_c = 1.16$	$(V_{DM})_c = 0.76$



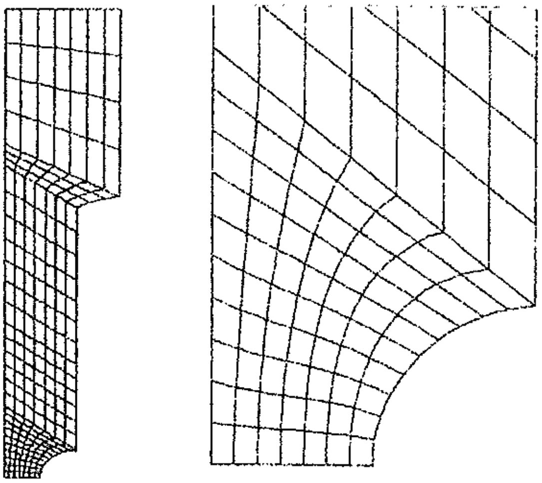


Fig.1 :- Sketch of a Notched Tensile Specimen   Fig.2 :- Finite Element Mesh of the Specimen

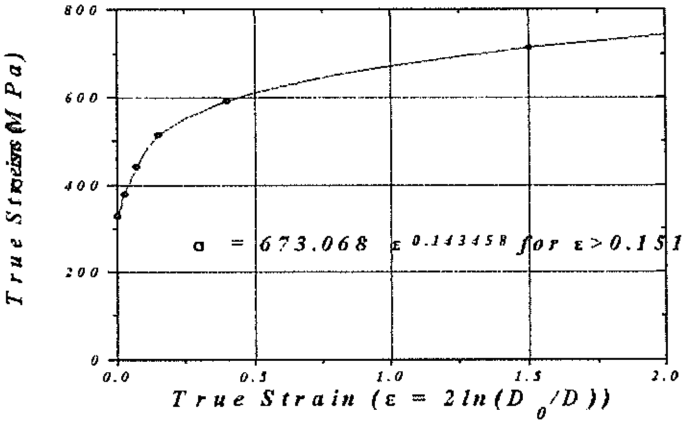
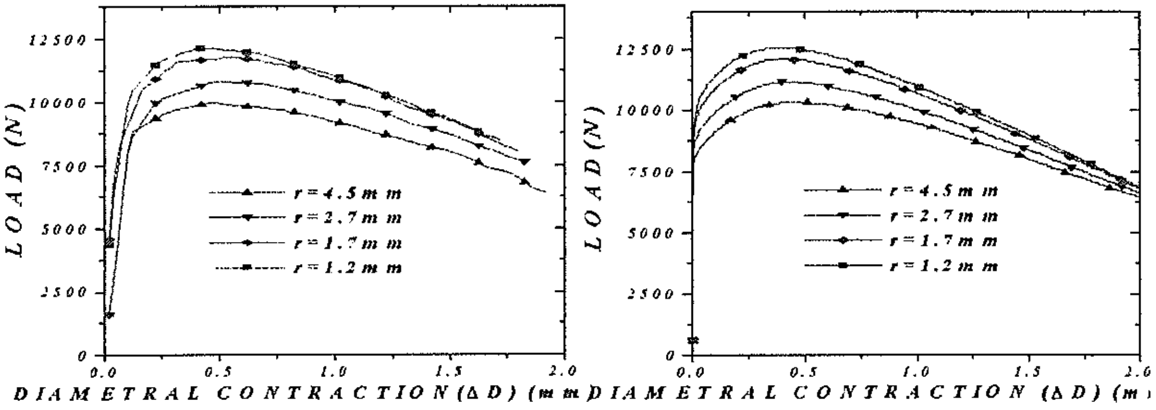


Fig.3 True Stress(σ) vs True Strain(ε) Curve of the material



(Experimental Load-ΔD curve)   *(Numerical Load-ΔD curve)*

Fig.4 Load vs dimetral contraction(ΔD) curve for notched tensile specimens

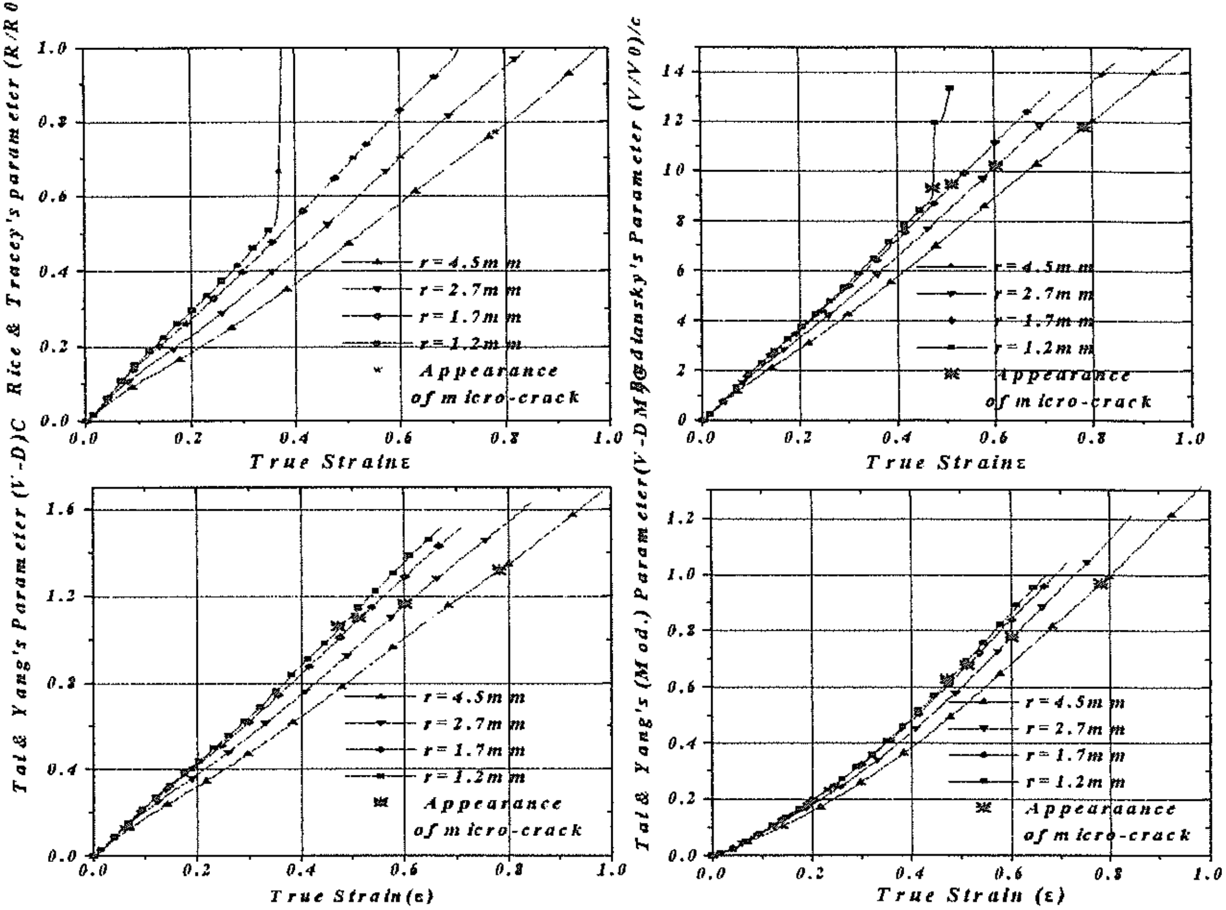


Fig. 5:-Curves showing variation of parameters i.e. Rice & Tracey's, Budiansky's, Tai & Yang' and Tai & Yang's (Modified) with respect to true strain for four notched tensile specimens with different notch root radii(r)

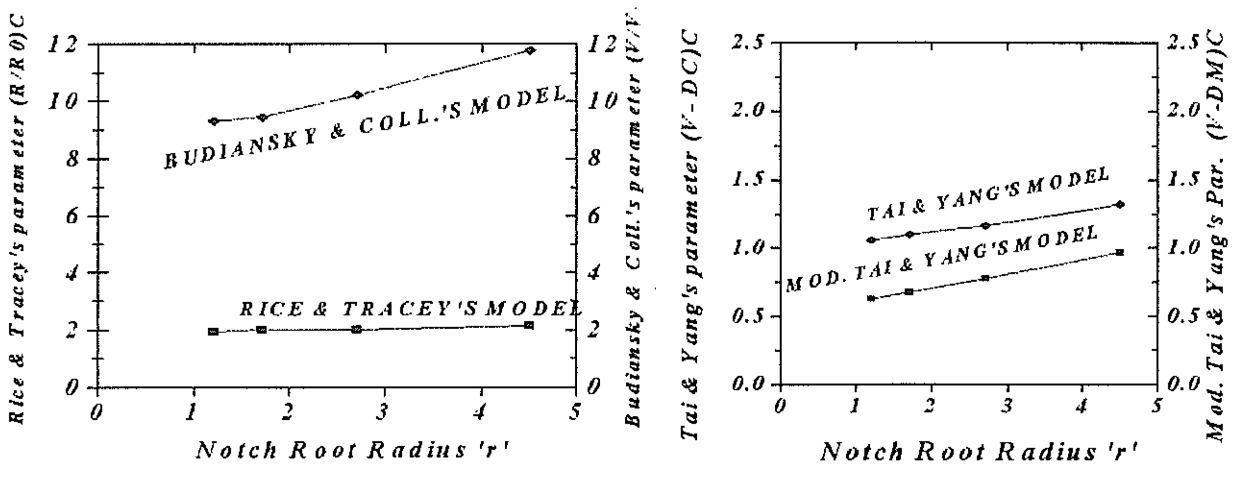


Fig.6 Variation of Critical Parameters of the four Models with notch root radius 'r' of Tensile Specimens