ELASTOPLASTIC ANALYSIS OF FUNCTIONALLY GRADED MATERIALS

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Abstract. *It is well known that abrupt transitions in material properties cause problems such as stress concentrations, micro-cracking and delamination, which frequently result in undesired structural failure. In order to solve this problem, a graded layer between two dissimilar materials can be introduced. Generally, the assembly is composed by three layers,the two basic materials layers and the graded layer, such that the material composition varies from* 100 *% of the first material-graded layer interface to* 0 *% first material at graded layer-second material interface. The material properties of the graded layer are modelled by the modified rule of mixtures approximation. Here, the elastoplastic analysis of a tube with two dissimilar materials and a FGM layer between them under internal pressure loading, is presented. The quasi-static deformation process is assumed to be under small strain and the elastic domain defined by von Mises yield criteria. The problem is described by a system consisting of a variational equation that represents the equilibrium of the body and a variational inequality expressing the plastic strain rate evolution. An iterative method for solving this nonlinear system, based on finite element approximation and an incremental-iterative scheme is proposed. The results of some numerical experiments involving the tube with abrupt transition and that one with FGM between the two dissimilar materials are provided.*

Keywords: *Functionally Graded Materials, Elastoplasticity, Incremental-iterative method, Implicit Euler*

1. Introduction

Many structural components encounter service conditions and, hence, required materials performance, which vary with location within the component. In such cases, the use of two dissimilar materials is required and it can cause problems, such as sharp local concentrations of stress, delamination, micro-cracking, and which, frequently result in undesired structural failure, as seen in Cho and Park(2002) and Pitakthapanaphong(2002). The intensity of stress concentrations stress effects due to the large mismatch in material properties can substantially reduced if the microstructure transition is gradually made. Advances in materials synthesis technologies have spurred the development of a new class of materials, called Functionally Graded Materials (FGM), with promising applications in aerospace, transportation, energy, cutting tools, electronics and biomedical engineering. An ideal material combines, for instance, the best properties of metals and ceramic: the toughness, electrical conductivity, and machinability of metals, and the low density, high strength, high stiffness, and temperature resistance of ceramics,Chakraborty(2003). FGM comprise a multi-phase material with volume fractions of the constituents varying gradually in a pre-determinated profile, thus yielding a nonuniform microstructure in the material with continuously graded properties, Jin(2003).

Functionally Graded Materials have the potential to improve the thermomechanical characteristics of a component in several ways, Suresh(1998):

- The magnitude of thermal stresses can be minimized
- The onset of plastic yielding and failure can be delayed for a given thermomechanical loading.
- Severe stress concentrations and singularities at intersections between two edges and interfaces can be suppressed.
- The driving force for crack growth along and across an interface can be reduced by tailoring the interface with gradients in mechanical properties

This paper is concerned with a quasi-static deformation process of an elastic-plastic body, modelled according to infinitesimal flow theory plasticity. For the numerical solution of the boundary value problem the finite element method is applied to approximate the problem in space, and an implicit incremental scheme is adopted to integrate the problem in time. The algorithm is based on Newton-Raphson method associated to Euler implicit method to integrate flow rules. The results in a tube with FGM layer is compared with that one with sharp interfaces.

2. The material effective properties

The developing of a complete understanding of the effective properties of composites is central for graded metal-ceramic composites design. Several models have been proposed, such as the simple rule of mixtures, the modified rule of mixtures and mean-field theories, Suresh(1998), Weissenbek(1997). Thermomechanical analysis of graded structures inevitably call for methods by which the effective properties of the dual phase structures can be determined.

The composition volume fraction functions, V_c and V_m, where the subscripts c and m refer to ceramic and metal, respectively, are defined such that:

$$\mathrm{V}_m(r) = \begin{cases} 1, & \text{if} \quad R_0 \leq r \leq R_1 \\ (\frac{R_2 - r}{R_2 - R_1})^N, & \text{if} \quad R_1 \leq r \leq R_2 \\ 0, & \text{if} \quad R_2 \leq r \leq R_3 \end{cases}$$

where $R_0 \leq r \leq R_1$, $R_1 \leq r \leq R_2$ and $R_2 \leq r \leq R_3$ are respectively, the metal layer, the graded layer and the ceramic layer.

In order to compute the temperature and the overall strain/stress distribution in FGMs, a suitable estimation for properties of the graded layer is necessary, such as the Young's modulus, Poisson's ratio, the thermal conductivity and the coefficient of thermal expansion. The progress in theoretic methods for the overall thermomechanical properties is suggested by Suresh(1998).

For the Young's modulus, Tamura, Tomota and Ozawa proposed the modified rule of mixtures. At the early stage of FGM, the simplest rule of mixtures was widely employed, but this method is occasionally questionable and its accuracy might not be as good as one desires, Cho and Oden(1998).According to this approach, each sub-layer in the graded layer is treated as an isotropic composite for which the uniaxial stress and strain are expressed in terms of the average uniaxial stresses σ_i and ϵ_i ($\imath$ is each constituent material), according to Suresh(1998),Jin(2003),Cho and Ha(2001):

$$\sigma = V_m \sigma_m + V_c \sigma_c \quad \epsilon = V_m \epsilon_m + V_c \epsilon_c \tag{1}$$

This model introduces an additional parameter q, the ratio of stress to strain transfer, as follows:

$$q = \frac{\sigma_c - \sigma_m}{\epsilon_c - \epsilon_m}, \quad 0 < q < \infty \tag{2}$$

For the Young's modulus estimation:

$$E = \frac{[(\frac{q+E_c}{q+E_m})V_m E_m + V_c E_c]}{[(\frac{q+E_c}{q+E_m})V_m + V_c]} \tag{3}$$

Poisson's ratio is defined by the rule of mixtures:

$$\nu = V_m \nu_m + V_c \nu_c \tag{4}$$

Similar to the case of the elastic behavior, the effective plastic response of the composite is assessed by invoking the parameter q. The overall flow strength corresponding the onset of plastic yielding is given by Suresh(1998) and Jin(2003), by:

$$\sigma_y = \sigma_m \left[V_m + \left(\frac{q + E_m}{q + E_c} \right) \frac{E_c}{E_m} (1 - V_m) \right] \tag{5}$$

The strain hardening describing by the uniaxial tangent modulus, is:

$$H = \frac{[(\frac{q+E_c}{q+H_m})V_m H_m + V_c E_c]}{[(\frac{q+E_c}{q+H_m})V_m + V_c]} \tag{6}$$

where H_m is the metal elastoplastic tangent modulus.

Further details on its determination can be seen in Suresh(1998),Cho and Park(2002),Jin(2003),Cho and Oden(1998).

3. Fundamentals of flow theory plasticity

The plastic response of material becomes manifest as soon as a combination of the stress components reaches a characteristic value, governed by a yield function f of the form:

$$f(\sigma, \kappa) = 0 \tag{7}$$

where κ is a scalar valued hardening, depending on strain history. Inelastic strains occur if a stress point is on the yield surface. Stresses states outside the yield contour are not possible, Lubliner(1990) and Sluys(1998).

This leads to a second condition for plastic deformation:

$$\dot{f}(\sigma, \kappa) = 0 \tag{8}$$

Considering the quasi-static plasticity and small deformations hypotesis, the total strain tensor may be splited into an elastic and in a plastic part,Lubliner(1990), Simo(1993):

$$\epsilon = \epsilon^e + \epsilon^p \tag{9}$$

The elastic strain rate is related to the stress rate by the bijective relation:

$$\dot{\sigma} = D_e \dot{\epsilon}_e \tag{10}$$

where D_e is the matrix containing the elastic stiffness moduli.Therefore, the stress-strain relation can be written in a rate form as:

$$\dot{\sigma} = D_e(\dot{\epsilon} - \dot{\epsilon}_p) \tag{11}$$

The plastic strain rate vector is written as the product of a non-negative scalar $\dot{\lambda}$, called consistency factor, and a vector **m**, representing the magnitude and the direction of the plasticity flow, Sluys(1998),Simo and Taylor(1985). The vector **m** is assumed to be gradient of the plastic potential function g_p:

$$\dot{\epsilon}_p = \dot{\lambda}\mathbf{m} \qquad \mathbf{m} = \frac{\partial g_p}{\partial \sigma} \tag{12}$$

In associative flow, the potential function is equal to the yield function *f*, Sluys(1998) and Kuczma(1995). The flow rule relates the rate of change of plastic strain to the rate of change of stress.

The consistency equation can be elaborated as follows and the vector **n** is the gradient of the yield surface:

$$\mathbf{n}\dot{\sigma} + \frac{\partial f}{\partial \kappa}\dot{\kappa} = 0 \qquad \mathbf{n} = \frac{\partial f}{\partial \sigma} \tag{13}$$

The softening modulus is defined as:

$$h = -\frac{1}{\dot{\lambda}}\frac{\partial f}{\partial \kappa}\dot{\kappa} \tag{14}$$

Combining 12,13 and 14:

$$\dot{\lambda} = \frac{\mathbf{n}^T D_e \dot{\epsilon}}{h + \mathbf{n}^T D_e \mathbf{m}} \tag{15}$$

The relation between stress rate and strain rate is gotten, substituting 15 in 11 and 12. The expression between the brackets is called tangent stiffness matrix, denoted by D_i.

$$\dot{\sigma} = \left[D_e - \frac{D_e \mathbf{m}\mathbf{n}^T D_e}{h + \mathbf{n}^T D_e \mathbf{m}}\right]\dot{\epsilon} \qquad D_i = D_e - \frac{D_e \mathbf{m}\mathbf{n}^T D_e}{h + \mathbf{n}^T D_e \mathbf{m}} \tag{16}$$

A yield function is used to distinguish stress points that are in a plastic state from stress points that are in the elastic domain of the stress space. The consistency factor $\dot{\lambda}$ and value of f are constrained by the discrete Kuhn-Tucker conditions:

$$\dot{\lambda} \geq 0, \quad f(\sigma, \kappa) \leq 0, \quad \dot{\lambda} f(\sigma, \kappa) = 0 \tag{17}$$

Thus, the process is termed plastic, if it is accompanied by an increment of plastic strain, otherwise it is elastic.

The hardening parameter κ is dependent on the strain history. The evolution of this parameter is postulated to be equal to:

$$\dot{\kappa} = \sqrt{2/3(\dot{\epsilon}_p)^T \dot{\epsilon}_p} \tag{18}$$

4. Numerical formulations

From the Virtual Power Principle, the weak form of the equilibrium is obtained. According to it:

$$\langle \sigma, \dot{\epsilon}^* \rangle = \langle p, v^* \rangle \tag{19}$$

where ϵ^* is the virtual deformation field and v^* represents the virtual velocity field.

In a time t, the equilibrium must be satisfied. Thus:

$$\int_V \sigma^t \dot{\epsilon}^* dV = \int_V p^t v^* dV \tag{20}$$

In a time $t + \Delta t$:

$$\sigma^{t+\Delta t} = \sigma^t + \int_t^{t+\Delta t} \dot{\sigma} d\tau \tag{21}$$

The equilibrium must be satisfied in a time $t + \Delta t$ and substituting 16, 21 in 20:

$$\int_V \int_t^{t+\Delta t} D_i \dot{\epsilon} \dot{\epsilon}^* d\tau dV + \int_V \sigma^t \dot{\epsilon}^* = \int_V p^{t+\Delta t} v^* dV \tag{22}$$

5. Discretization of boundary value problem

The equilibrium equation represented by 22 can be solved by the Finite Element Method. More details about the Finite Element Method can be found in Bathe(1996) and Reddy(1984). The body can be divided into a finite number of elements and for each element the displacement field **u** can be interpolated by:

$$\mathbf{u} = Na \tag{23}$$

where *L* contains the interpolation polynomials and *a* the nodal displacements.

From kinematics:

$$\epsilon = L\mathbf{u} \qquad \epsilon = Ba \qquad B = LN \tag{24}$$

The incremental nodal displacement vector is defined as follows:

$$\Delta a = a^{t+\Delta t} - a^t = \int_t^{t+\Delta t} \dot{a} d\tau \tag{25}$$

Finally, the equilibrium equation can be written as:

$$\int_V B^T D_i^t B \Delta a dV = \int_V N^T p^{t+\Delta t} dV - \int_V B^T \sigma^t dV \tag{26}$$

Introducing some notations for the tangential stiffness matrix, the external load vector and the internal force vector.

$$K^{\,t} = \int_V B^T D_i^t B dV \qquad f_e^{t+\Delta t} = \int_V H^T p^{t+\Delta t} dV \qquad f_i^t = \int_V B^T \sigma^t dV \tag{27}$$

Then, Eq. 26 can be rewritten:

$$K^t \Delta a = f_e^{t+\Delta t} - f_i^t \tag{28}$$

As soon as the integration points reach the plastic state, the material properties change. In order to associate each integration point property, represented by tangent stiffness matrix D_i, to a tangential stiffness matrix in Finite Element Method, an interpolation is proposed.

$$D = \sum_{j=1}^{nnoel} D_i(j) \phi_j \tag{29}$$

In order to compute the tangential stiffness matrix K^t, the tangent stiffness matrix represented by Eq.29 is applied.

6. Solution algorithm

For the solution of the discrete problem, the incremental-iterative Newton-Raphson solution method is proposed. The use of so-called return mapping algorithms provide an effective and robust integration scheme of the rate constitutive equations, Simo and Taylor(1985). Geometrically, the return mapping algorithm amounts to finding the closest distance of a point to a (convex) set. The implicit Euler is applied in order to solve this problem.

6.1 Incremental-iterative solution techniques

The solution starts dividing the total external load into a small loading steps.At the beginning of each step the difference between external loads and internal forces should be zero.Any unbalance that has been left behind at the end of the previous loading step will be carried along in all subsequent loading steps.

In a pure incremental method there is a gradual departure of the numerical solution from the true solution. It can be prevented by adding equilibrium iterations within each loading step, as seen in Sluys(1998). For explanation of the method, the superscript will be used for the iteration number and no longer for the time step:

$$K^{\,t} = K^0 \qquad\qquad f_i^t = f_i^0 \tag{30}$$

At the beginning of the step, the loading $f_e^{t+\Delta t} = f_e$ is fixed during iteration. For example, a first estimate for the displacement increment Δa is made through:

$$\Delta a^1 = [K^0]^{-1}[f_e - f_i^0] \tag{31}$$

The superscript 0 of the internal force vector relates to the fact that this vector is calculated using the stresses at the beginning of the loading step $\sigma^t = \sigma^0$. The internal and unbalance forces:

$$f_{\,i}^{\,j+1} = \int_V B^T \sigma^{j+1} dV \qquad\qquad r^{j+1} = f_e - f_i^{j+1} \tag{32}$$

Every iteration the total displacement increment within the step is computed and on basis of this, the total strain increment and the total stress increment are computed. The new stresses are found as the sum of the stresses at the beginning of the step and the total stress increment.

This procedure is repeated until the convergence is reached. The most demanding criterion is the force norm, based on L_2 norm of the unbalanced force vector.

$$|f_e - f_i^j|_2 \leq \varepsilon |f_e - f_i^1|_2 \tag{33}$$

where ϵ is typically equal to 10^{-3}. The main steps of this procedure is shown:

For each load or time step:

1. Iteration j= 0, $\Delta a^0 = 0$
2. Compute new external force vector: $f_e 0 = f_e^{t+\Delta t}$
3. Compute tangent stiffness matrix: $K^j = \int_V B^T D_i^j B dV$
4. Solve:$K^j da^{j+1} = f_e - f_i^j$
5. Add correction da^{j+1} to the incremental displacement vector: $\Delta a^{j+1} = \Delta a^j + da^{j+1}$
6. Compute strain increment $\Delta\epsilon^{j+1} = B\Delta a^{j+1}$ for each integration point
7. Stress update: $\Delta\sigma^{j+1} = D_i^{j+1}\Delta\epsilon^{j+1}$ for each integration point
8. Add stress increment to total stress $\sigma^{j+1} = \sigma^0 + \Delta\sigma^{j+1}$ for each integration point
9. Compute internal force vector: $f_i^{j+1} = \int_V B^T \sigma^{j+1} dV$
10. Check convergence. If YES, go to next step. if NO, $j = j + 1$ and go to 3.

6.2 Return mapping algorithm

An effective procedure for numerically integrate the elastoplastic problem is to employ the return mapping algorithms. From the converged solution at time t=t_n, the trial elastic stress σ^{trial} is computed. If the resulting state lies outside the elastic domain enclosed by the yield surface, one defines the final state as the closest-point projection of σ^{trial} onto the yield surface, Simo(1993) and Simo and Taylor(1985). The steps of the implicit Euler:

For each integration point

1. Iteration $k = 0$, $\Delta\lambda^0 = 0$, κ^0,σ^0
2. Compute trial stress state: $\sigma^{trial} = \sigma^0 + D_e \Delta\epsilon$
3. Plasticity if $f(\sigma^{trial}, \kappa^0) \geq 0$. Else $\sigma = \sigma^{trial}$ and go to 10.
4. Calculate m^k e n^k for current stress σ^k(σ^{trial} in first iteration)
5. Compute $\Delta\lambda^{k+1} = \Delta\lambda^k + f(\sigma^k, \kappa^k)/[h^k + (n^k)^T D_e m^k]$
6. Correction of stress: $\sigma^k = \sigma^{trial} - \Delta\lambda^{k+1} D_e m^k$
7. Calculate κ^{k+1} on basis of hardening hypotesis
8. Calculate h^{k+1} and $\bar{\sigma}^{k+1}$ for update κ^{k+1}
9. Check convergence: $f(\sigma^{k+1}, \kappa^{k+1}) <$ tolerance. If YES, go to 10. If NO, $k = k + 1$ and go to 4.
10. Next integration point

7. Numerical examples

In this section, the elastoplastic analysis of a tube containing FGM between two dissimilar materials is shown. Since analytical solutions for the FGM tube is hard or difficult to be calculated, a preliminary example with a two-layer tube with sharp interface is shown. In this case, the analytical solution is possible to calculate and it is compared to numerical solution. The tubes are subjected to internal pressure loading.

So as to solve this problem, some hypothesis are adopted:

- plane strain condition;
- the bonding between the layers are assumed to be mechanically ideal;
- perfect plasticity

The two base material properties used in this numerical experiment are listed in Table 1.

Table 1. Material properties of Al and SiC.

Material	Young's modulus(GPa)	Poisson's ration	Yield stress (MPa)
Al	70	0.30	150
SiC	427	0.17	

This assemble of the two-layer tube has the following dimensions and compositions:

- $1.0m < r < 1.15m$: Al
- $1.15m < r < 1.30m$: SiC

Under perfect plasticity hypothesis, the analytical solution for the two-layer tube is calculated and then, the numerical solution is compared to it, as seen in Fig.1. The Tresca criterion is used is this case.

Observing the graphic of Fig.1, one can see that the analytical and numerical solutions are very close. The numerical solution reproduce with accuracy the analytical solution. After that, the elastoplastic analysis of a tube containing a FGM layer is implemented. The von Mises yield criteria is used in this case.

The three-layer tube with FGM layer has the following dimensions and compositions:

- $1.0m < r < 1.10m$: Al
- $1.10m < r < 1.20m$: FGM layer
- $1.20m < r < 1.30m$: SiC

Figure 2 compares the hoop stress distribution of a two-layer tube with sharp interface and one with three-layer tube with FGM.

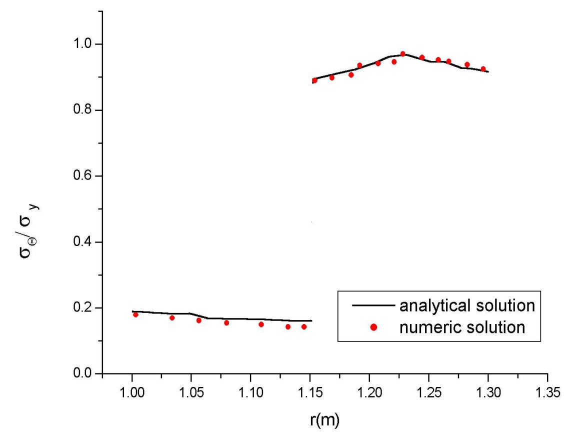

Figure 1. Hoop stress: comparison between analytical and numerical solution.

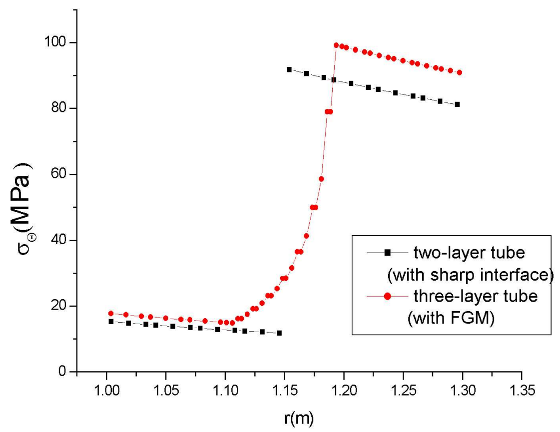

Figure 2. Hoop stress: comparison between a two-layer tube and a three-layer tube.

Observing Fig. 2 one can conclude that Functionally Graded Materials can effectively suppress severe stress concentrations and singularities. The hoop stress, discontinuous in a two-layer assembly, is made continuous introducing a FGM layer between the two dissimilar materials.

Figure 3 and Fig.4 show the radial and hoop stresses for a tube containing FGM when the internal pressure reaches p= $0.174\sigma_y$, where σ_y is the metal yielding stress.

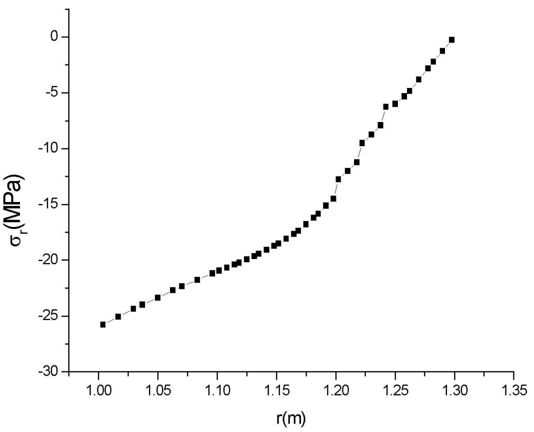

Figure 3. Radial stress when p= $0.174\sigma_y$.

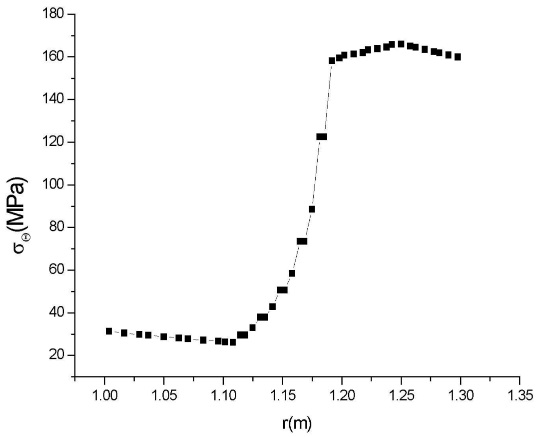

Figure 4. Hoop stress when p= $0.174\sigma_y$.

Figure 5 shows the evolution of plastic region, with hoop stress in three different instants. The von Mises equivalent stress graphic in Fig. 6 shows plastic region when equivalent stress is equal to zero.

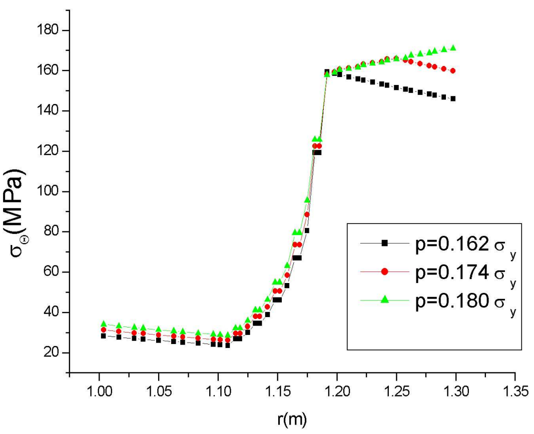

Figure 5. Evolution of plastic hoop stress .

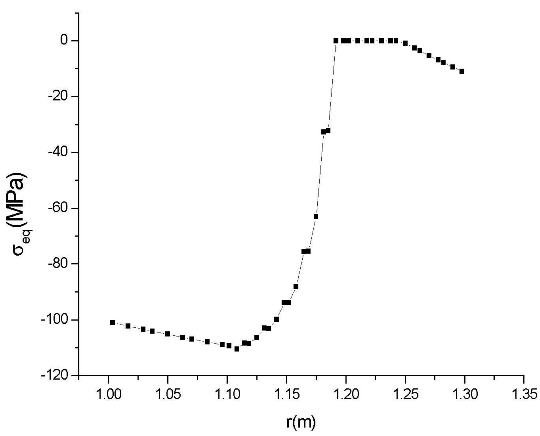

Figure 6. Mises equivalent stress when p= $0.174\sigma_y$.

8. Concluding remarks

This paper showed that the use of FGM between two dissimilar materials works very well. Severe stress concentrations and singularities are suppressed.

The elastoplastic analysis of a structural component using a FGM layer is very incipient. Further progress in this area would inevitable call for an analysis a several factors, because of the complexity of microstructure. This paper is an attempt to make an elastoplastic analysis using an incremental-iterative algorithm, associated with Euler implicit method to integrate the flow rules.

Because of the lack of analytical or experimental results, several tests with homogeneous and a two-layer tube with dissimilar materials had been done. The analytical solutions of these cases are possible and easy to be obtained. Both numerical and analytical solutions were compared and the results were very close and similar. After the efficiency of the method in a two-layer tube, it was applied in a tube containing FGM. von Mises yield and perfect plasticity criterion have been employed. The Newton-Raphson algorithm showed a fast convergence and it converged in two or three iterations, depending on the time step. In a future work, hardening hypothesis will be applied.

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