Analysis of singularities stress in a copper film on a polymer substrate system

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Abstract - ***The designers of microelectronic devices made from thin films of different materials (MEMS), are constantly confronted with problems of reliability and performance of these structures increasing miniaturized. In addition, the method of assembling the different elements generates thermal stresses that may be critical and can reduce the lifetime of these devices. Any deterioration in general is initiated at the discontinuities on the geometry or materials present when the stress state becomes singular. The analysis of these particular areas has become essential for an optimal design.***

In this study, we will look at a structure consisting of a copper deposited in the form of a disk on polymer substrate For this type of structure to work in a difficult environment (Airbus, Dassault), we will based on an asymptotic analysis to characterize the junction between the copper and the polymer. To this Copper / polymer intersection, the mode of damage will be highlighted from microtensile tests under microscope.

Key Words: *Copper film, polymer substrate, discontinuity, Stress singularity, Asymptotic analysis, micro-tensile, damage.*

1. INTRODUCTION

Advanced technology of various structures is characterized by an optimal design is offering a smooth operation with a long duration. This optimization includes not only the appearance of the geometry, but also the choice of materials constituting the structure. As a matter of fact, geometrical irregularity or a bad choice of material which create stress concentration that is usually the cause of damage process. From the particular areas that initiated the damage phenomena is called singular. In these areas, the material behavior can be described by a displacement or a stress asymptotic. For the singular field description, asymptotic three quantities are essential DB or Jones RG [1,2]: the stress intensity factor related to the materials' nature and the type of applied load, the normalized tensor which is a special function to illustrate the stress's distribution, and finally the order of the singularity that reflects the severity of the discontinuity in the presence. To determine these asymptotic parameters, we used an iterative finite element method whose principle was developed by RS Barsoum [3, 4].

Through this method, which has been adopted in the ANSYS code [Haloui al. 5-9], the boundary conditions change from one iteration to another until obtaining a stable exponent value ''λ''. By this method many analyses and studies of industrial structures have been made [Chouaf and al. 10, 11]

From this asymptotic analysis, we study with particularly interested in the identification and analysis of the order for singularity, stress intensity factor, and the constituent structure of two materials, Copper on a polymer substrate. Copper has been deposited vapor phase in the form of a disc on the polymer. This structure therefore has both a discontinuity at a different geometry and in material. Taking into account these two discontinuities, we analyzed the behavior of the local copper / polymer junction under the effect of traction applied to the polymer substrate.

2. THEORETICAL APPROACH

For a structure comprising a geometric discontinuity area as shown in "Fig -1", we recall that the components of the stress field at a point M of polar coordinates (ρ, θ), near the singular point, expressed by the following relationship [WC Carpenter, 12] and [J P. Slahle and al., 13]:

$$\sigma_{ij}(\rho,\theta) = K f_{ij}(\theta)\rho^{-\lambda} \quad (1)$$

with λ is taken between 0 < λ <1 which means that the stress increases with the decreasing radius ρ, the exponent depends on the geometry of the field around the singular point. This parameter characterizes the severity of the singularity.

K is the stress intensity factor, depending mainly on the type and intensity of loading, and elastic properties of the material near the singularity.
*f*ij (θ) is the normalized tensor reflecting variations stress with polar angle θ.
To determine these asymptotic quantities, so we will consider a numerical approach based on an iterative finite element method [RS Barsoum 3, 4], [G. Loppin, 14]. The principle of this method can be summarized by the following steps:
As a first step we created a D_0 domain around the singular point O "Fig.1b", with a limit and an interconnection inside Γ0 invariant in a homothetic of center O and ratio p (0 < p <1). Next, by successive applications of this homothetic transformation, the area D_0 is reduced to smaller areas D_i with bends Γ_i. At the first iteration, displacements, strains and stress are calculated in each element of the bend by applying the numerical values of displacements from internal procedure which is independent of calculation with finite elements on the overall structure in the knots of the bends Γ_0 .At iteration i, the displacements applied as conditions to limits on the bend Γ_0 are taken equal to the calculated values on the bend Γ_1 at iteration i-1 by the following equation:

$$u_i(M_0) = \frac{1}{\mathrm{p}} u_{i-1}(M_1) \quad (2)$$

with M_0 and M_1 are two points belonging respectively to the limits Γ_0 and Γ_1. To sum it up, to determine the stress state at a point $M_i \in \Gamma_i$ close enough to the supposed singular point O, just in approaching the stress state at a point $M_0 \in \Gamma_0$ by the finite elements method imposing the following displacement field on limit Γ_0 :

$$u_i = \frac{1}{\mathrm{p}^{\mathrm{i}}} u_0 \quad (3)$$

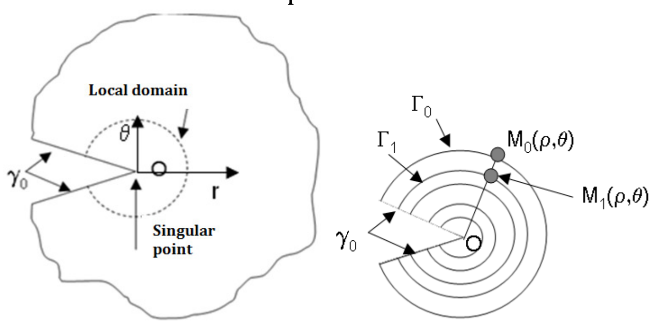

Fig -1: Diagram of a structure with a singular point
(a) Domain D of the structure with singular point O
(b) D_0 local domain included in the domain D, with Γ_0 and γ_0 as boundary.

We assume that the domain D_0 defined above is reduced to n sub-domain obtained by homothetic transformation of ratio p. The iterative calculation of finite elements will determine successively the displacements and stress for these reduced areas. Expressing the relationship (1) for two successive iterations n and n-1 we can calculate the exponent λ by the following expression:

$$\lambda = -\frac{1}{\ln(\mathrm{p})} \ln\left[\frac{\sigma_n(\rho_0,\theta)}{\sigma_{n-1}(\rho_0,\theta)}\right] \quad (4)$$

In each iteration, we can calculate the value of the exponent λ. This value is regarded as final, when it does not vary any more between two successive iterations.
In the case of an assembly of two different materials like our case, the value of λ, can also be determined from the graphs that include the exponent λ and parameters (α , β) of Dundurs [15]:

$$\alpha = \frac{(k_1+1)\frac{\mu_2}{\mu_1} - (k_2+1)}{(k_1+1)\frac{\mu_2}{\mu_1} + (k_2+1)} \qquad \beta = \frac{(k_1-1)\frac{\mu_2}{\mu_1} - (k_2-1)}{(k_1+1)\frac{\mu_2}{\mu_1} + (k_2+1)} \quad (5)$$

with μ_i shear modulus and $k_i = 3\text{-}4\nu_i$
From this value λ stable in iteration n, Gross and Mendelson [16, 17] have expressed the stress intensity factor by the following equation:

$$K_I = \sqrt{2\pi} \lim_{r\to 0} r^{\lambda}\, \sigma_{\theta\theta}(r, \theta{=}0) \quad (6)$$

To apply this relationship, we will consider the frame (O, r, θ) local, such as the axis Or through the bisector of the notch study.
To apply this theoretical approach, we used the ANSYS finite element code from which we made in the first place, a global analysis of the stress field. This is followed by an iterative local analysis around the singular point. Taking into account the repetition of this iterative method and the percentage of error we can commit manually, we therefore performed an appropriate computer program Visual C++.
This program is able to read files results displacements or stresses from the ANSYS software and extract the displacements of the Γ1 contour is imposed by renumbering nodes on the outline and the Γ_0 injected after in ANSYS until one obtains a constant value of the parameter λ.

3. GLOBAL ANALYSIS OF THE ASSEMBLY COPPER / POLYMER

In its simplest configuration, the structure that we studied is composed of a flexible polymer substrate (Young's modulus E = 2 GPa and Poisson's ratio ν = 0.3) on which pads copper (Module 'Young E = 120 GPa, Poisson's ratio ν = 0.4) of cylindrical shape were vapor deposited. This assembly generates a both discontinuities geometric and material between copper and polymer. It is in these specific areas we will analyze the mechanical behavior of the overall structure subjected to tensile traction (5N). To do so we will model by ANSYS code this structure, considering the geometry defined in "Fig -2".

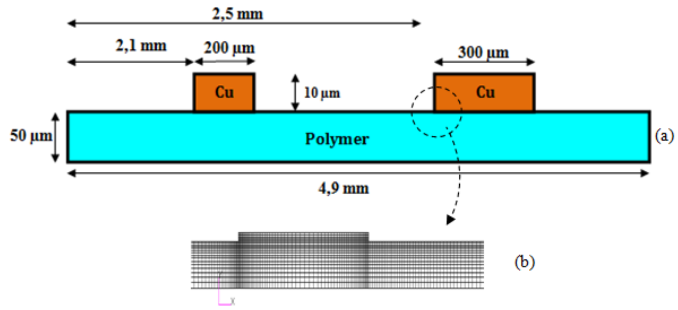

Fig -2: (a) Geometric description of the structure studied.
(b) Part mesh representation of the global structure

Some of the results we have shown in "Fig -3" a global description of the stress field equivalent Von Mises:

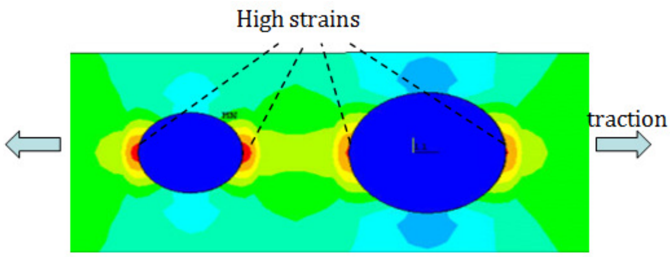

Fig -3 : Field equivalent Von Mises Stress

With this first result, we can see that the direction of the tensile, are developing strong localized deformations at the joints between copper and polymer. This localized behavior has been well observed during the tensile test of the studied structure "Fig -4" [18]:

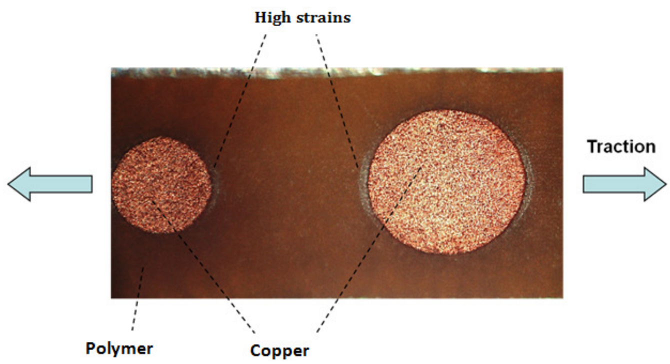

Fig -4 : Micrographics showing strong highly localized deformations.

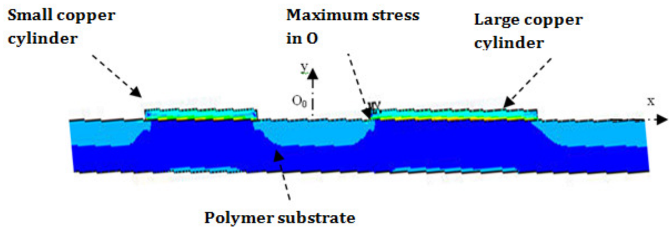

Fig -5: Distribution of equivalent Von Mises stresses in the overall structure

This state of deformation results in a particularly high stress field at the Copper / Polymer interface; material discontinuity zone "Chart 1". At this discontinuity, when added that due to the geometry of the critical stress values can be observed, as is the case around the singular point "O" "Fig -5". To highlight the contribution of each component of the stress tensor in this unique area, we have represented their evolution as a function of the distance x (mm) from the point O_0. Stress values were therefore taken from points on the axis O_0x and corresponding curves are plotted in "Chart 1".

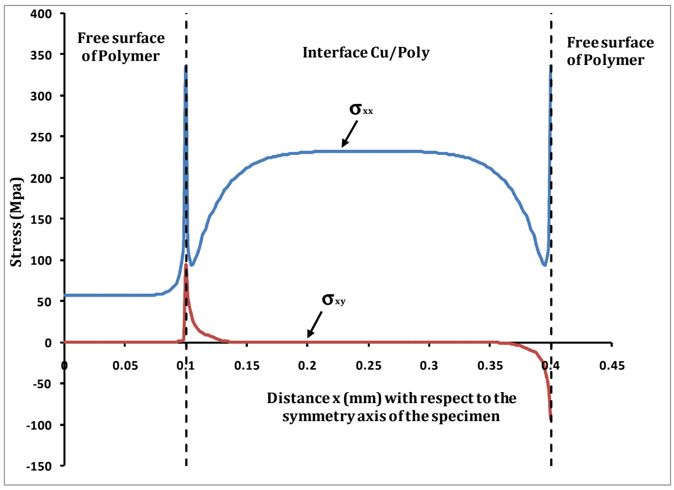

Chart -1 : Evolution of the stress components along the axis O_0x.

The evolution of the stress components along the axis O_0x perfectly shows the location of areas of stress concentration. Indeed, in the area of polymer alone, the σ_{xx} component stays constant with a value slightly greater than 50 MPa and σ_{xy} component remains zero. This value of 50 MPa for σ_{xx}, going to 225 MPa in the interface Cu / polymer. However at the singular point O, we can observe the two components mentioned, very localized peaks (σ_{xx} = 350 MPa and σ_{xy} = 100 MPa)
Therefore, the potential risk of damage can not be initiated that in those areas where we will focus our local asymptotic analysis.

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4. LOCAL ASYMPTOTIC ANALYSIS

To realize this local analysis near the singular point highlighted by the global analysis, we applied a local domain"Fig.6", the theoretical approach presented in Section 2.

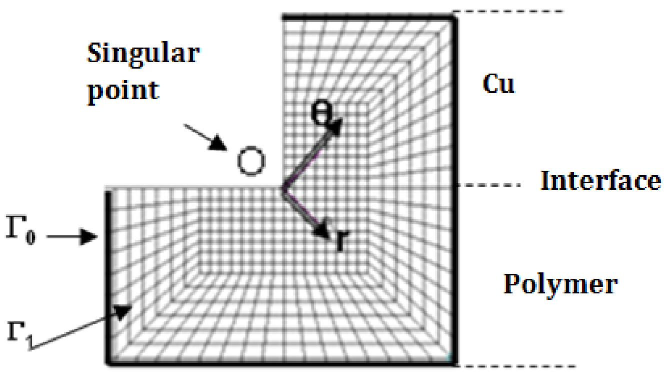

Fig -6: Local area surrounding the singular point O, the mesh is invariant by homothety the center O.

From this approach, we therefore determined the asymptotic variables of singularity. The first factor is the order of the singularity λ for which we obtained as a stable value $\lambda \approx 0.3$. This value was verified by using abacuses Bogy settings Dunders (α, β). We recall that this value corresponds to an opening angle 90° of O, and when the opening tends to zero this setting takes the value of 0.5 as usual cases treated in fracture mechanics. With this parameter, so we can qualify the severity of this singularity as an average over the most critical one of the crack.
Having determined the value of the exponent λ, we deduced by the relation of Gross and Mendelson an average value of asymptotic second parameter, the stress intensity (FIC) for a tensile load of 5N factor KI ≈ 2,62 MPa $m^{1-\lambda}$. It is close to the average critical value of polymers is of the order of KIC ≈ 3MPa $m^{0,5}$ [book] from any damage by cracking mode I can be initiated. Indeed, when considering the local description of the stress field, we can see that the stress normal cylindrical $\sigma_{\theta\theta}$ is predominant near of the singular point "Chart -2". This is the stress of the order of 184 MPa could foster any openings mode I.

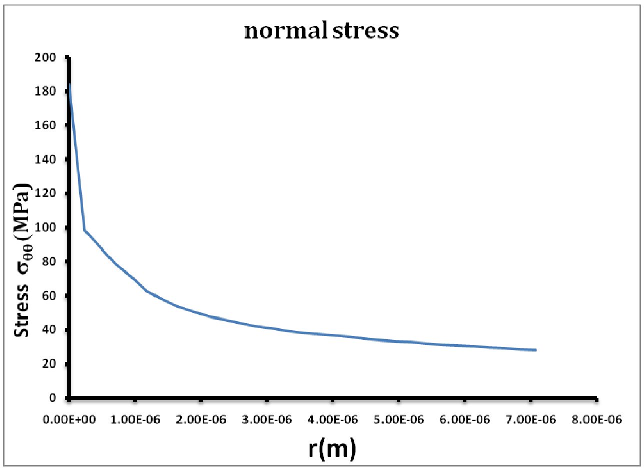

Chart -2 : Evolution of the normal stress cylindrical $\sigma_{\theta\theta}$ depending on the position relative r to the singular point.

4. CONCLUSIONS

Through this study, we have developed an asymptotic analysis of singularities of stresses generated in a copper system / polymer subjected to tensile load. First, by a global finite element analysis we highlighted the areas of concentration of stress in the system studied; copper film / polymer substrate. These results were confirmed by observations from traction tests. From this comprehensive analysis, we developed our asymptotic study. This study has allowed us to calculate the order of the singularity, λ = 0.3. From this value, we deduced that the stress intensity factor K_I=2,62 MPa $m^{1-\lambda}$. This value is close to that of polymer equal KIC ≈ 3MPa $m^{0,5}$ against the Copper is 9 MPa $m^{0,5}$.
According to this result, a crack initiation is possible in the polymer rather than in copper. However, at the interface, it is likely that the damage caused by cracking is initiated.

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