KINETICS OF INTERFACIAL ADHESION STRENGTH AND FRACTURE

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Summary A model for analysis of the interfacial adhesion kinetics, nucleation and growth of cracks is developed. It is assumed that a zone of weakened bonds exists at materials interface at an initial time moment. This weakened zone is considered as a crack-like defect and it is assumed that distributed spring-like bonds with time dependent properties link the crack surfaces. Bonds kinetics analysis is performed on the basis of the Zhurkov's fluctuation model of bonds destruction under external loads.

THEORY BACKGROUND

The bridging model of the interface crack [1-4] enables to assess the adhesion fracture toughness and the adhesion strength of different material junctions under quasi-static loading. The given development of this model is related to accounting for bonds properties variation in the bridging zone with time (bond kinetics) and evaluation of kinetics of interfacial adhesion strength, defects formation time and growth, durability of interface junction on the basis of the bridged cracks model. The weakened zone at the material interface is considered as a bridged interface crack. The fluctuation model of bonds destruction under external loads [5] is used and is assumed that: 1) a zone of a weakened bonds of length 2ℓ exists on the interface of two materials at the initial instant of time; 2) the bond density on the weakened zone depends upon the time and the bonds stresses due to Zhurkov's fluctuation model; 3) the part of size $2\ell_f$ near the center of the weakened zone is considered as nucleated defect without bonds if the bonds density in that part became below the critical value N_{cr} after the nucleation time t_f .

According to the fluctuation theory of fracture the lifetime of bonds at the crack bridged zone (τ_B) under the external loading is assumed to be the exponential function

$$\tau_B = \tau_o e^{\frac{U_o - A(x)}{kT}} \tag{1}$$

where τ_0 is the characteristic time (10^{-13}-10^{-12} s), k is the Boltzmann constant, T is absolute temperature, U_o is the energy of intermolecular bonds destruction, $A(x)$ is the work of the deformation per an intermolecular bond at the point x of the bridged zone of the crack. The work per an intermolecular bond can be defined as follows

$$dU(x,t) = \int_o^{u(x)} \sigma(u) du dx \qquad A(x) = \frac{dU(x,t)}{dN_n} \tag{2}$$

where $dU(x,t)$ is the work of the bond deformation (on the unit of the body thickness) over part of the crack bridged zone by size dx , $u(x)$ is the bridged crack opening at the current point x , $\sigma(u)$ is the bond deformation law, $dN_n = \varepsilon\, dn$, dn is number of the bonds over size dx , ε is the number of monomeric links between the crack surfaces.

Due to the relations (1) and (2) the lifetime of bonds in the crack bridged zone is the function of the bond position. It's assumed that the time decrease of the bonds surface density $n(x,t)$ is governed by the equation

$$n(x,t) = N_0 e^{-\frac{t}{\tau_B(x)}} \quad , \tag{3}$$

where $\tau_B(x)$ is the lifetime of the bond and N_o is the initial bond density. The decreasing of the bonds surface density over time can be modeled by the changing of the mechanical bonds properties in the weakened zone. Let's denote the bond stiffness by k_s. Then the effective compliance of bonds per unit area in the crack bridging zone $c(x,t)$, is determined as follows $c(x,t) = \left[k_s n(x,t)\right]^{-1} = c_0 e^{\frac{t}{\tau_B(x)}}$, where $c_0 = \left(k_s N_0\right)^{-1}$ is the initial effective compliance of bonds in the crack bridged zone.

The last relation enables us to model the kinetics of the bond rupture in the bridged zone of crack by means of the bonds compliance variation over time. The calculation method of the defect formation and growth time is based on the modeling of the weakened zone as a crack-like zone filled with bonds through the part or the whole length at the initial instant of time. The system of the singular integral-differential equations (SIDE) for the solving of crack bridging problems [1], [5] was extended for the time-steps scheme. On each time step the bond compliances are depended on the density of unbroken bonds (see (3)) and the SIDE is solved numerically.

RESULTS

Numerical calculations were performed for the physical and mechanical parameters of the joint materials and bonds which are used in microelectronics applications [7]: $U_0 = 150\,kJoule/mole$; the elasticity modulii of joined materials are $E_1 = 130\,GPa$ (Cu-based alloy) and $E_2 = 2\,GPa$ (epoxy based polymer); Poisson's factors are $\nu_1 = 0.3$ and $\nu_2 = 0.35$; the elasticity modulus of bonds is $E_b = E_2$. The initial size of the weakened zone – fully bridged crack is $2\ell = 10^{-5}m$ and the initial density of bonds in this zone is $n_0 = 10^{18}\,m^{-2}$. The bonds deformation law at the initial time instant is assumed as linear-elastic with constant the initial effective compliance of bonds along the bridged zone. Let's call as an initial flaw formation time the formation time of a part of a crack without bonds on the edge of the weakened zone. Dependences the formation time of the initial flaw $Ln(t/t_0)$ versus the relative size of bridged zone for various values of the initial effective compliance of bonds c_0 are shown on fig.1. Increase of an initial effective compliance of bonds leads to extension of durability of junction more than one order. The growth rate dependences of the crack part without bonds $Ln(u/u_0)$ versus its relative length ℓ_f/ℓ for different values of ambient temperature $T = 350K, 375K, 400K$ are shown on fig. 2 (u_0 is the rate of defect growth for an uniform bonds stresses distribution). On the last steps of increasing of the crack length the growth rate of the crack is decreased. This effect can be explained that bonds on the part of the weakened zone adjoining to its tip are exposed to decay from the beginning of kinetics process. When the size of the crack without bonds is about $\ell_f \sim (0.8-0.9)\ell$, the density of bonds on remained part of the weakened zone is small, the compliance of bonds essentially increases in comparison with the initial one and, accordingly, bonds stresses essentially decrease. It leads to decreasing of work of bonds deforming and, as a result, dropping of the growth rate of the crack. The detailed analysis of kinetics of interfacial adhesion strength, defects formation time and growth, durability of interface junction is presented in unabridged paper.

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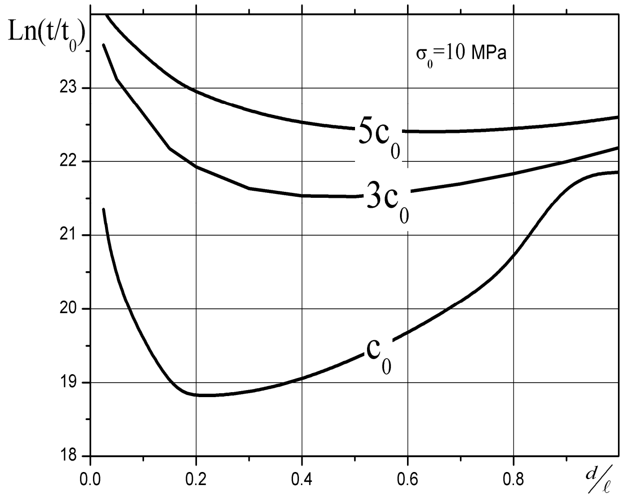

Fig. 1 Dependences of formation time of the initial flaw versus the relative size of bridged zone d/ℓ, $t_0 = 1s$

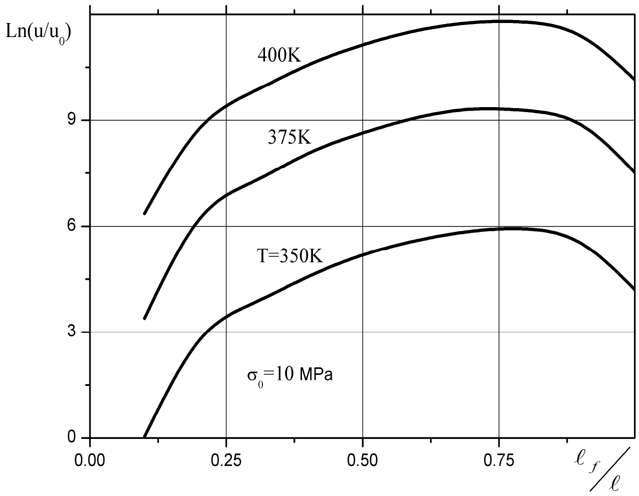

Fig. 2 Dependences of the growth rate of the part of the crack without bonds versus its relative length ℓ_f/ℓ

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