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A NOTE ON THE TRANSITION FROM COUPLED PLASTICITY AND DAMAGE TO DECOHESION IN THE EVOLUTION OF SOLDER FAILURE[1]

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Introduction

A key issue of solder joint reliability is joint failure due to thermomechanical fatigue (TMF). TMF is caused by different coefficients of thermal expansion (CTEs) of the materials in an electronic package, combined with changes in the ambient temperature. Different CTEs result in cyclical strain in the assembly, and this strain is concentrated almost entirely in the solder because it is the most deformable portion of the package. Since solder alloy is at a significant fraction of its melting point even at room temperature, the cyclical strain enhances mass diffusion and causes dramatic changes in the alloy

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microstructure over time. As the microstructure changes and becomes coarser, the solder alloy weakens and eventually microcracks nucleate and grow in the joint, leading to component failure. The failure of solder joints is difficult to detect due to the inert nature of the electrical system. If the system is not on for extended periods then failures can not be observed. Therefore it is important to develop an advanced predicitive capability which allows scientists and engineers to predict solder degradation and identify reliability problems in aging electronics early.

In order to accurately predict the lifetime and reliability of solder joints, and hence the lifetime and reliability of electronic components, critical aspects of solder joint behavior, such as viscoplasticity, damage development, microstructural coarsening, and crack initiation and propagation, etc., must be considered. At Sandia National Laboratories, a multi-level simulation methodology is being developed to achieve the goal of lifetime prediction of solder joint. This methodology links continuum mechanics models, microstructural evolution models, and micromechanics models to treat the different length scales that exist between the macroscopic response of solder joint and the microstructural changes occurring in the solder alloy. At the macroscopic level, a coupled plasticity and damage model is now used to predict distributions of stress, temperature and damage in the joint due to environmental variable fluctuations, with all the field variables being continuous (Chow and Wei, 1999). At the microscopic level, the microstructural evolution models predict the changes of solder microstructure such as heterogeneous coarsening and recrystalization during TMF, while the corresponding micromechanics models identify microcracks initiation, development and coalescence in detail, based on the spatial information provided by the continuum mechanics models. In the micromechanics simulations, a decohesion model is employed to model the microcracking in solder. In addition to passing boundary conditions between macro and micro levels correctly, exchanging information back and forth between the continuous damage model and the discontinuous decohesion model accurately is a key to the trustworthy predictions of failure and lifetime of solder joint in the current multi-level approach.

Since the material failure is an evolving process that involves jumps in certain field variables, the transition from continuous to discontinuous failure modes can be identified based on the jump forms of conservation laws for the following kinds of jumps in the kinematic field variables (Chen, 1996):

Continuous Failure : $v_1 = v_2$ and $\varepsilon_1^Y = \varepsilon_2^Y$

Localized Failure : $v_1 = v_2$ and $\varepsilon_1^Y \neq \varepsilon_2^Y$

Discontinuous Failure : $v_1 \neq v_2$ and $\varepsilon_1^Y \neq \varepsilon_2^Y$

with v_1 and v_2, and ε_1^Y and ε_2^Y being the velocity and total strain rate on the side 1 and 2 of a moving surface of discontinuity, respectively. As can be seen, the transition from continuous to discontinuous failure states is characterized by the condition of localized failure that must be determined via the bifurcation analysis of an acoustic tensor. The acoustic tensor can be obtained from the continuum tangent stiffness tensor. Based on the bifurcation analysis, the decohesion model can then be inserted along the orientation of the critical mode without making an assumption a priori.

A Bifurcation Analysis of Coupled Plasticity and Damage

Based on the theory of continuum damage mechanics, a constitutive model capable of characterizing fatigue damage and plastic damage has been developed for predicting the rate-independent solder failure evolution under multiaxial loading conditions (Chow and

Wei, 1999). The elastoplastic constitutive equations coupled with damage are expressed in the effective stress-effective strain space, and the effective stress tensor, $\overline{\boldsymbol{\sigma}}$, is related to the Cauchy stress tensor, $\boldsymbol{\sigma}$, through

$$\overline{\boldsymbol{\sigma}} = \boldsymbol{M} : \boldsymbol{\sigma} = (\frac{1+2\mu}{1-D}\boldsymbol{P}^s + \frac{1-\mu}{1-D}\boldsymbol{P}^d) : \boldsymbol{\sigma} \tag{1}$$

where $\boldsymbol{P}^s$ and $\boldsymbol{P}^d$ are the spherical and deviatoric orthogonal projection tensors, respectively. The scalar variables μ and D are associated with the damage evolution. Since the mapping between the effective stress and Cauchy stress is isotropic and the stress-strain relations in both effective and true spaces are also isotropic, the orientation of material failure in the effective space should be the same in the true space. As will be shown next, a closed-form solution can be obtained to determine the failure orientation by using a geometrical procedure if the bifurcation analysis is performed in the effective space, which can not be done in the true space because of the coupling between fatigue damage and plastic damage.

In the effective space, the elasticity relation is given by

$$\overline{\boldsymbol{\sigma}} = \boldsymbol{C}_0 : \overline{\boldsymbol{\varepsilon}}^e \qquad \text{with} \qquad \boldsymbol{C}_0 = 3K_0\boldsymbol{P}^s + 2G_0\boldsymbol{P}^d \tag{2}$$

where K_0 and G_0 denote the bulk and shear modulus of undamaged material, respectively. The yield surface is postulated to be

$$F_p = \sqrt{\sigma_p} - [R_0 + R(p)] = 0 \qquad \text{with} \qquad \sigma_p = \frac{3}{2}\overline{\boldsymbol{\sigma}}^d : \overline{\boldsymbol{\sigma}}^d \tag{3}$$

in which R_0 is the yield stress, and R is the strain hardening function of the effective equivalent plastic strain, p. With the use of

$$d\overline{\boldsymbol{\varepsilon}}^p = \lambda_p \frac{\partial F_p}{\partial \overline{\boldsymbol{\sigma}}} = \frac{3\lambda_p}{2\sqrt{\overline{\sigma}}}\overline{\boldsymbol{\sigma}}^d \qquad \text{and} \qquad dp = \lambda_p \frac{\partial F}{\partial(-R)} = \lambda_p \tag{4}$$

the continuum tangent stiffness tensor of the associated elastoplasticity model can be found, via the plastic consistency condition, as

$$C_0^{ep} = 3K_0 P^s + 2G_0 P^d - H\bar{\sigma}^d \otimes \bar{\sigma}^d \qquad \text{with} \qquad H = \frac{9G_0^2}{\sigma_p(\frac{dR}{dp} + 3G_0)} \tag{5}$$

With $\boldsymbol{n}$ denoting the normal vector to the moving surface of discontinuity, the corresponding acoustic tensor takes the form of

$$A^{ep} = A^{el} - H\boldsymbol{a} \otimes \boldsymbol{a} \qquad \text{with} \qquad \boldsymbol{a} = \boldsymbol{n} \cdot \bar{\sigma}^d = \bar{\sigma}^d \cdot \boldsymbol{n} \tag{6}$$

where A^{el} is the acoustic tensor of elasticity. The localization condition can be written as

$$\frac{\det A^{ep}}{\det A^{el}} = 1 - H\boldsymbol{a} \cdot \left(A^{el}\right)^{-1} \cdot \boldsymbol{a} = 0 \tag{7}$$

as discussed by Ottosen and Runesson (1991).

With the use of a geometrical procedure (Iordache and Willam, 1998) in the effective principal space, the critical hardening parameter and failure angle are obtained when the localization ellipse osculates the major principal circle of effective stresses, namely,

$$\frac{dR}{dp} = \frac{9G_0\left[3G_0(\sigma_0 - \sigma_c)^2 + (G_0 + 3K_0)r^2\right]}{\sigma_p(G_0 + 3K_0)} - 3G_0 \tag{8}$$

and

$$\tan^2\theta = \frac{2(\bar{\sigma}_2 - \bar{\sigma}_3) + \alpha(\bar{\sigma}_1 - \bar{\sigma}_3)}{2(\bar{\sigma}_1 - \bar{\sigma}_2) + \alpha(\bar{\sigma}_1 - \bar{\sigma}_3)} \qquad \text{with} \qquad \alpha = \frac{3K_0}{G_0} \tag{9}$$

in which $\sigma_0 = \frac{1}{3}(\bar{\sigma}_1 + \bar{\sigma}_2 + \bar{\sigma}_3)$, $\sigma_c = \frac{\bar{\sigma}_1 + \bar{\sigma}_3}{2}$ and $r = \frac{\bar{\sigma}_1 - \bar{\sigma}_3}{3}$, with $\bar{\sigma}_1 \geq \bar{\sigma}_2 \geq \bar{\sigma}_3$ being the effective principal stresses.

As can be seen from Eq. (9), the failure angle is only a function of the principal stresses and the ratio of elasticity moduli without depending on the critical hardening parameter. Hence, the critical failure angle is determined as long as the yield surface is reached under given loading conditions. Since the failure angle identified in the effective space is the same as that in the true space for this isotropic coupled plasticity and damage model, the decohesion model can be inserted along the orientation of the critical mode to trace the evolution of discontinuous failure if the degree of discontinuity reaches a critical value in the true space. Thus, a very effective numerical procedure might be designed for large-scale computer simulation of the transition from continuous to discontinuous failure modes.

To demonstrate the relationship between the critical failure angle and the stress state and elasticity moduli, $G_0 = 28GPa$ and $R_0 = 330MPa$ are used here, which are representative of solder materials. The changes of localization ellipse and mohr's circle with different elastic moduli are shown in Figs. 1 and 2 for pure shear and uniaxial tension loading paths, respectively. The bifurcation analysis of the acoustic tensor corresponding to Figs. 1 and 2 is demonstrated in Fig. 3. As can be seen, the failure angle (45°) is independent of the elastic moduli under pure shear, while it is not the case under uniaxial tension. In general, the failure angle depends on the stress state and elastic moduli in the effective space.

Conclusions and Future Work

To predict the transition from continuous to discontinuous modes as observed in the evolution of solder material failure, a bifurcation analysis is performed based on the continuum tangent stiffness tensor in the effective space of a coupled plasticity and damage model. As a result, continuum damage and decohesion approaches can be combined, based on a rigorous theoretical framework, for multi-scale modeling of solder failure problems. Future work is required to verify the proposed procedure with experimental data available.

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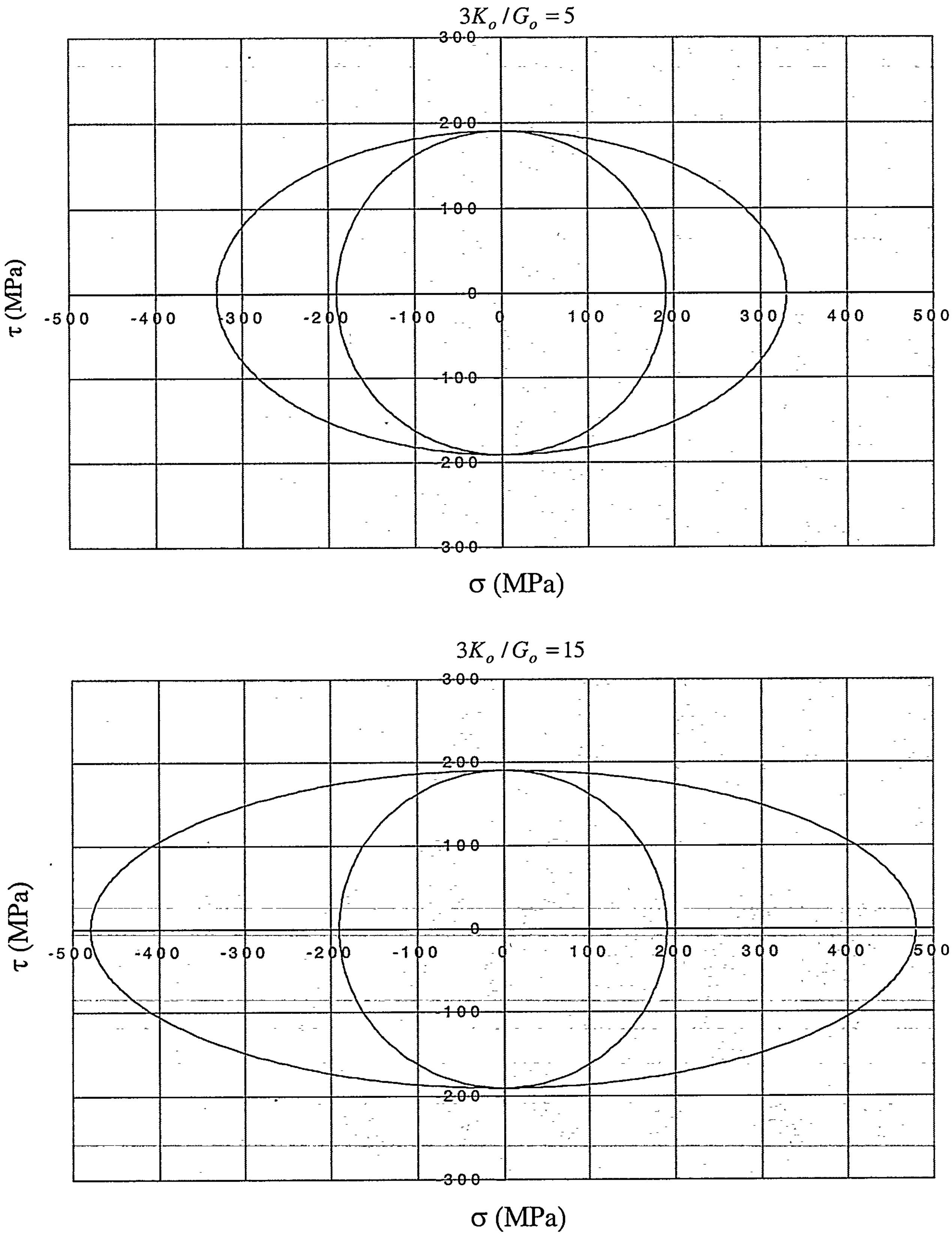


Figure 1. The change of localization ellipse and mohr's circle with the ratio of $3K_o/G_o$ under pure shear.

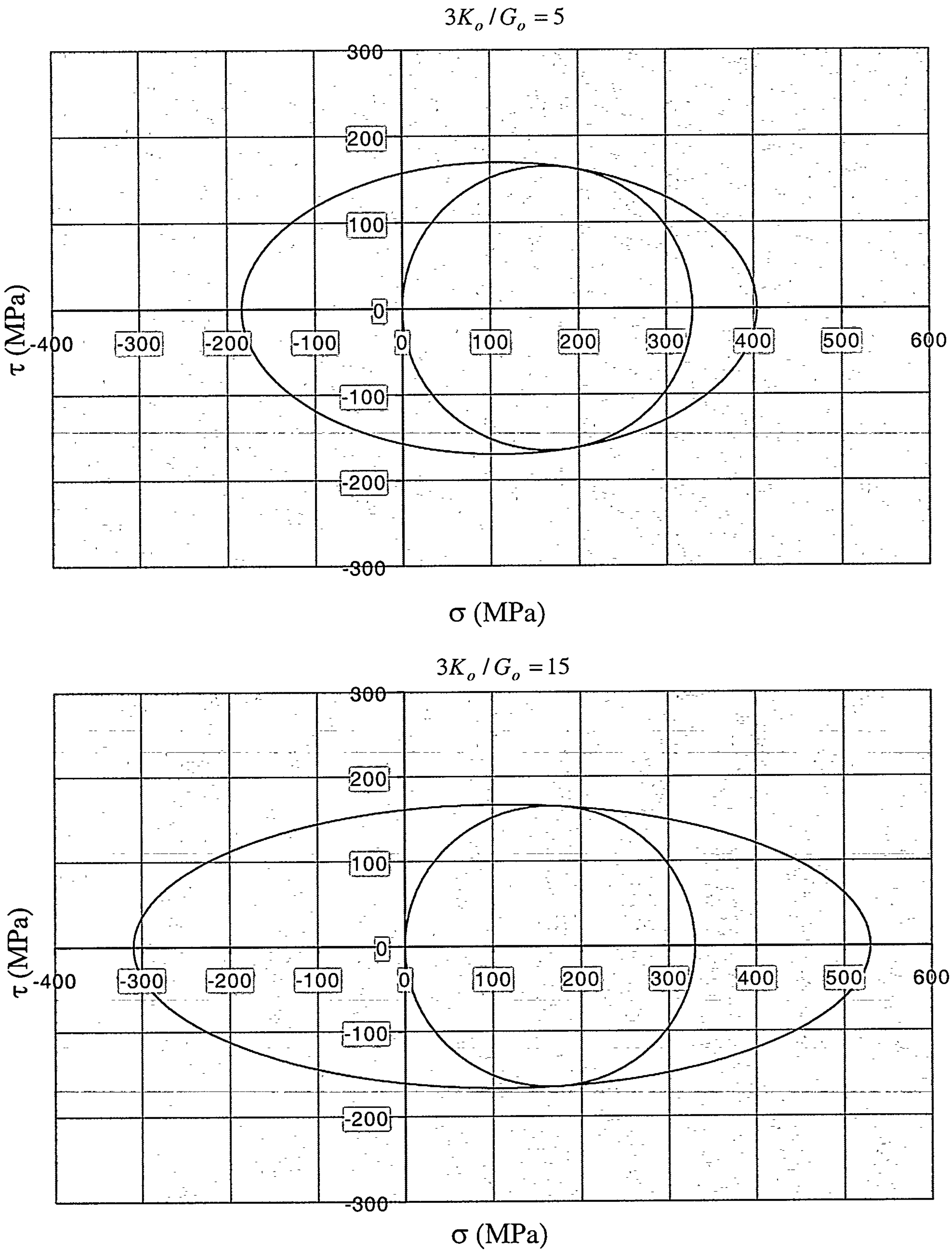
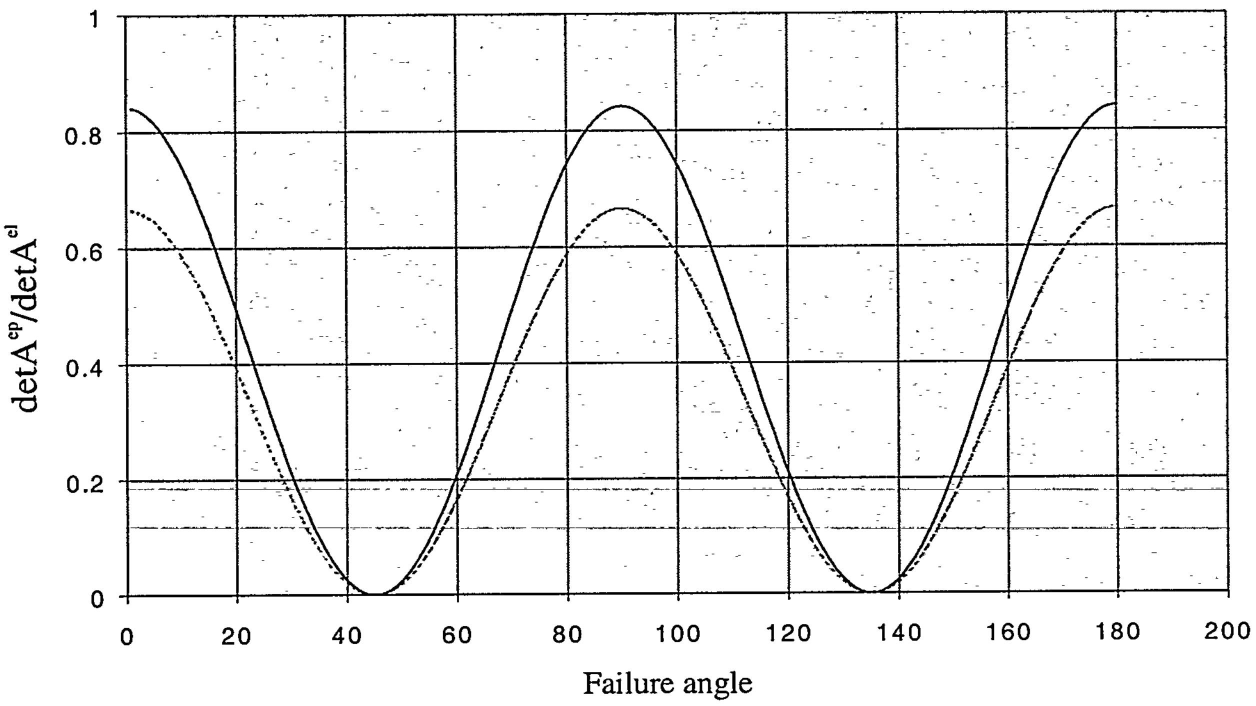


Figure 2. The change of localization ellipse and mohr's circle with the ratio of $3K_o/G_o$ under uniaxial tension


Pure shear

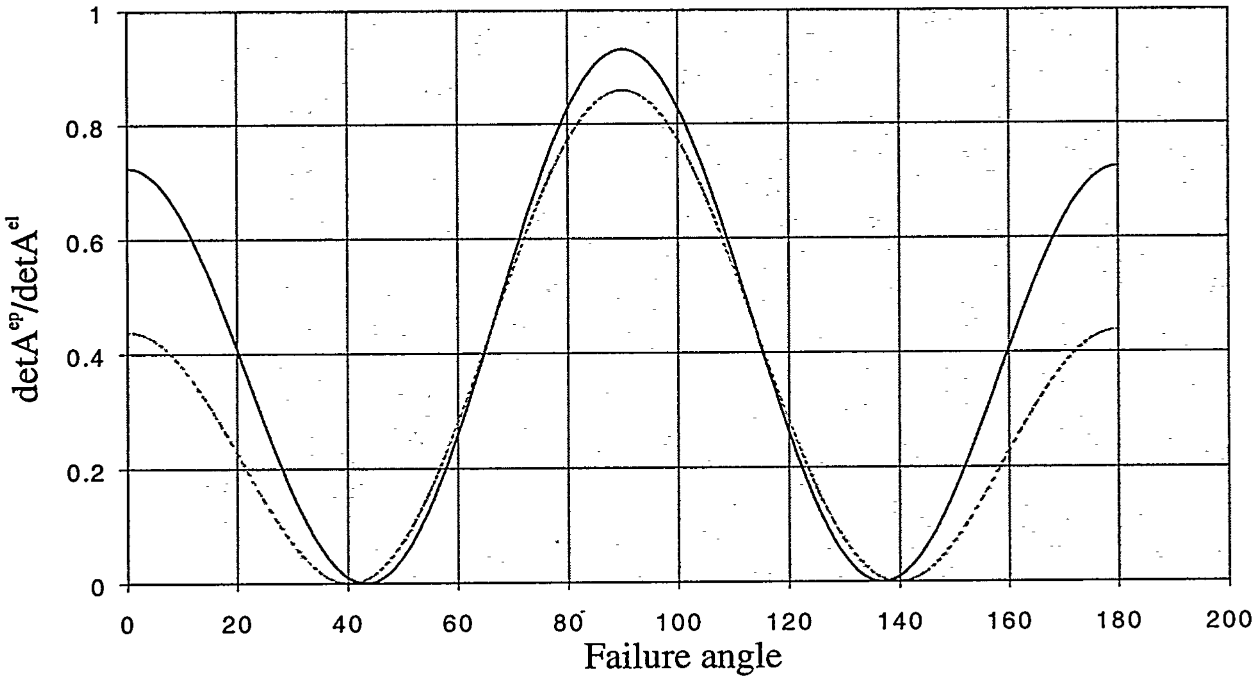

Uniaxial tension

Figure 3. Bifurcation analysis corresponding to Fig.1 and Fig. 2, respectively.