CRACK TIP TEMPERATURE FIELDS IN VISCO-PLASTIC MATERIALS

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ABSTRACT

An attempt is made to simulate the temperature field connected with a propagating crack in a visco-plastic material. The authors apply modern continuum thermodynamics of strain-rate sensitive work-hardening materials to describe heat dissipation, convection, and conduction phenomena connected with the temperature development in the crack region. The finite element technique has been used to solve the coupled thermomechanical system of field equations which are highly nonlinear.
The results are in a better agreement with recent experiments than those obtained by the classical uncoupled crack propagation models. Some aspects of micromechanics of defects near cracks following from this approach will be discussed.

KEYWORDS

Crack;crack temperature; crack propagation; finite element method; Viscoplasticity; continuum mechanics, fracture mechanics;

INTRODUCTION

Investigations of temperature fields within the near-crack tip region are important in two main areas of modern fracture mechanics and fracture physics:

I. Phenomenological fracture mechanics concerned with fast crack propagation and high temperature crack phenomena.

II. Micromechanics of fracture and crack formation, defect interaction and defect kinetics related to crack tip and crack flank mechanisms.

The crack tip zone structure has been shown to be important for both macroscopic and microscopic concepts of crack propagation, particularly in ductile materials. The fracture phenomenon indeed cannot be fully explained on a purely macroscopic level within the framework of isothermal mechanics as it was the aim of conventional approach to fracture mechanics. Modern fracture mechanics has to take into account to a certain extent both phenomenological and structural aspects. Thus, more realistic phenomenological concepts of crack and fracture are based on a more detailed description of the mechanical stress fields, deformation and deformation velocity fields and the related field quantities on the one hand and micromechanics of defects (including defect interaction mechanisms and defect kinetics) in the crack tip and crack flank regions on the other (Michel,1982,1983).The temperature field itself is an "interrelating field quantity" which appears both on the macroscopic and on the microscopic level, but in different ways. The abovementioned fundamental areas have to be dealt with in other branches of current solid mechanics also.

Fracture Mechanics and Temperature Fields

One of the main problems is the exact knowledge of temperature fields which enter nearly all microscopic concepts of crack and fracture. The micromechanical approach to fracture theory is above all directed towards the investigation of crack initiation mechanisms and the understanding of crack tip surroundings (process region etc.), where the known approximate continuum models have to be supported by additional concepts based on solid state physics (microphysics up to lattice theory based on quantum effects) and physical chemistry on a more microscopic scale. Because of the complexity of the elementary processes related to crack and fracture problems, fracture mechanics must also take into consideration field interactions. For example, in recent work, the stress field interaction with an electromagnetic field near a crack tip has been investigated (Farat, 1979). Most of the problems concerning such kinds of field interactions with cracks are, at present, unsolved. The most important field interaction which has to be taken into account in nearly all cases of practical importance in fast crack propagation and high temperature crack mechanics is that between the crack tip mechanical field quantities and the temperature field. The investigation of energy dissipation mechanisms near cracks is very important for understanding of macroscopic and microscopic fracture phenomena. The temperature-dependence of nearly all quantities of mechanical behaviour of solids (such as strength, yield stress, fracture toughness, Young's modulus etc.) is obvious and follows already from fundamental laws of statistical physics. In the phenomenological approach to fracture theory the generally accepted way to take the temperature into account is, as an effect on properties (temperature-dependent Young's modulus, work-hardening parameter etc.). However, temperature is also a field quantity which varies with position and is dependent on the mechanical field quantities. Thus, the fracture -mechanics models applying temperature-dependent material parameters(which are invariant with position), have to be characterized as more or less good approximations. Much more important is the fact that the quantity of energy dissipation strongly varies with position. For fast crack propagation a heat dissipation zone structure of the near-crack tip region superposes on the mechanically induced

structure of the "process zone". This can be taken into account only in a coupled-field mechanical-thermal interaction in both directions. We have to think of the significant fact that dissipation energy is immediately coupled to the mechanical field tensors (in visco-plastic materials this is achieved by the strain-rate tensor or in particular its second invariant). Little information is available for fracture physics studies of elementary processes occuring in the near region of the crack tip temperature field, but it must be realized that the overwhelming majority of defect interaction processes (and hence defect kinetics) are strongly dependent on temperature. This becomes obvious, if we examine the activation of a given active defect mechanism near the crack tip (point defect mechanism, dislocation mechanism, microvoid mechanism etc.). The activation factor exp (U/kT) plays a dominant role in every case, as would be expected from the statistical physics of defects (U_A - activation energy , k - Boltzmann's constant, T - equilibrium temperature within the defect region where the mechanism is observed).
In recent papers analytic formulae have been published for some kinds of elastic interaction energy between different defects near cracks, surfaces, interfaces etc. We write down two examples (Michel,1982,1980). The interaction energy beween two dilatation centres near an elastic boundary surface is

$$E^{(1)}_{int} = A\, R_1^3 R_2^3 \left(2(d_1+d_2)^2 - a^2\right)\left((d_1+d_2)^2 + a^2\right)^{-5/2} \qquad (1)$$

A is a parameter which depends on the elastic moduli and on the kinds of the defects, R_1 and R_2 are the radii of the defects, a is the projection of the distance between the defects on the crack flank.
The near-crack flank interaction beween an edge dislocation and a point defect or an inclusion can be written in the following form (Michel, 1982):

$$E^{(2)}_{int} = E_C(1 - f(\alpha)) \quad , \qquad (2)$$

where E_C is the known expression for the energy of "COTTRELL"-interaction between the two defects in the unbounded medium and $f(\alpha)$ is a "shape function" expressing the position of the defects with respect to the crack. α is a geometric parameter which depends on the BURGERS vector of the dislocation and the mean distance beween defects and crack flank.
These two examples are mentioned here because it becomes obvious that there is no need to compute the energy terms U_A of mechanical interaction which are responsible for activation, if the temperature field within the defected region remains unknown. On the micromechanical level the combined factor (U_A/kT) occurs which is one of the dominant parameters for near-crack defect mechanisms. From the two examples above we can draw the conclusion that the two-directional exchange of mechanical and thermal energy is both related to phenomenological continuum mechanics and continuum-thermodynamics and to micromechanics of structural defects as well. In the following section of this paper we are going to deal with a continuum approach to the temperature problem in crack fracture mechanics

applying a visco-plastic strain-rate sensitive and strain-hardening material. The second step should include the discussion of consequences of the results on returning to the microscopic level again ,but will not be dealt with in this paper. The two-directional exchange between mechanical and thermal energies in the dissipation zone near the crack tip is the basic assumption of our model presented below (Michel, Gründemann, 1983). It may be one reason for the fact that the great variety of mechanical-thermal properties of materials during fracture processes is not understandable by present-day fracture mechanics which neglects the coupling effects. The authors express their opinion that energy dissipation mechanisms are important in this field and may not only contribute to an improved explanation of the temperature rise in the crack tip region of fast running cracks but should also be important for low-speed crack phenomena in several cases. Heat dissipation might be important also for describing some special phenomena in creep fracture mechanics as the thermo-visco-plastic approach can also be applied to some questions concerning defect kinetics (e.g. cavity growth, microvoid coalescence effects etc.). The latter are responsible for energy terms contributing to the process zone energy and therefore have also to be included in the exact evaluation of the energy balance equation valid for the fracture process and all the resulting generalized conservation integral concepts based on the energy-release rate. Though we do not go further into detail here it is useful to mention that the derivation of additional contributions to the well known integral fracture quantities (path-independent integrals) such as J , $\hat{J}$, C , C^*, L , M etc. taking in addition into consideration the temperature field and the coupling to the strain rate is possible.

Coupling between Strain-Rate and Temperature Fields in Visco-Plastic Materials

We start with the constitutive equations for isotropic work-hardening and strain-rate sensitive plastic material which have the form (see e.g. Gründemann, 1983):

$$S_{ij} = 2\mu(A)\,\dot{\varepsilon}_{ij} \,, \qquad (3)$$

with the second strain-rate invariant A

$$A = \left(\tfrac{1}{2}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}\right)^{1/2} \,, \qquad (4)$$

where the elastic part of the deformation tensor, for simplicity, is assumed to be small and therefore is neglected here. $\mu(A)$ is a generalized scalar-valued viscosity function. In the case of an incompressible non-Newton fluid (this model is widely used for high-speed deformation of visco-plastic solids in engineeering) the well-known formula

$$s_{ij} = \sigma_{ij} + \delta_{ij}\,p \qquad (5)$$

holds, where p is the mean (hydrostatic)pressure, σ_{ij} are the Cartesian components of the total stress tensor, and S_{ij} are the deviatoric stresses given by (3). This model of constitutive assumptions implies that crack tip moves through the medium or – in the rheological picture – the medium"flows" around the crack tip. We do not deal with the general kind of constitutive behaviour (3) but assume an exponential law of the following type which includes many cases of practical importance (steels etc.) and which has been widely used in metal cutting and metal forming theories:

$$\mu(A) = A^{-1}\left\{ \frac{\sigma_y}{\sqrt{3}} + \left(\frac{A}{\sqrt{3}\,\gamma}\right)^{1/n} \right\} \,. \qquad (6)$$

In (6) σ_y is the yield stress in the uniaxial tension test. γ and n are material parameters. They can be dependent on temperature. For pure plasticity we have $\gamma \to \infty$ and (6) then leads to the known formula

$$\mu(A) = \frac{\sigma_y}{A\sqrt{3}} \,. \qquad (7)$$

For simplicity, we neglect elastic effects within this paper. This is possible for the type of materials which is considered (special steels),if the strain rate is high enough.

We now regard the crack propagation phenomenon as a material transport problem around the crack. This idea enables us to apply the thermo-rheological model of crack propagation (adiabatic conditions). For our thermomechanical model the temperature development depends decisively on the dissipation energy Q occuring in the plastic process. This quantity is given by the expression (Michel, Gründemann, Sommer, 1984):

$$Q = S_{ij}\,\dot{\varepsilon}_{ij} \,. \qquad (8)$$

(Note that in (8) Einstein's summation convention is used). From the first law of thermodynamics the heat equation follows which in our case of steady state is written in the form

$$-\operatorname{div}(k \operatorname{grad} T) + \rho c \vec{v} \operatorname{grad} T = Q \,. \qquad (9)$$

k – thermal conductivity for isotropic material

c – specific heat at constant external pressure (which is different from p in equation (5))

ρ – mass density.

All the quantities above may be dependent on temperature within this model. The velocity distribution $\vec{v}$ is determined by the momentum balance equation. In the stationary case we have

$$\operatorname{div}\sigma + \vec{K} = 0 \,, \qquad (10)$$

where σ is the stress tensor in dyadic form (the components are given in (5)) and $\vec{K}$ are the volume forces.

Taking into account for the strain-rates

$$\dot{\varepsilon} = (\nabla\vec{v} + \nabla\vec{v}^{T}) \,, \qquad (11)$$

we finally arrive at the following form of the momentum equation

$$\mathrm{div}\ (\ \mu(A)\ (\mathrm{grad}\ \vec{v} + \mathrm{grad}\ \vec{v}^{T})\ ) - \mathrm{grad}\ p + \vec{K} = o\ . \qquad (\ 12\ )$$

In addition we also have to fulfil the continuity equation which in our model reduces to the well-known incompressibility condition

$$\mathrm{div}\ \vec{v} = o\ . \qquad (\ 13\ )$$

The equations (9), (12) and (13) are said to be "fully coupled" and a simultanious solution is asked for which in addition must satisfy the boundary conditions for the moving crack. We do not deal with the analysis in detail here (see also Gründemann 1983; Sommer,1983). Applying numerical discretization by means of Finite Element Method (9) and (12) can be written as a matrix equation :

$$\begin{bmatrix} A\ (v,T) & o \\ o & B\ (v,T) \end{bmatrix} \begin{bmatrix} \underset{\sim}{v} \\ \underset{\sim}{T} \end{bmatrix} = \begin{bmatrix} \underset{\sim}{f} \\ \underset{\sim}{q} \end{bmatrix} , \qquad (\ 14\ )$$

where $\underset{\sim}{v}$ and $\underset{\sim}{T}$ represent a set of parameters defining velocity and temperature, respectively, on a suitable finite element grid. The matrix B in contrary to the usual FEM discretization is non-symmetric. A is symmetric. The generalized heat equation (9) is highly convective. It is convenient to make use of the so-called "upwinding" technique to avoid instabilities (Sommer, 1983). The system of partial differential equations and whence the discretized equations (14) are highly non-linear. This means that as a rule the solution could be obtained by iterative procedures only. The mean pressure p could be eliminated as a dependent variable. This approach is called "penalty function" method which we have applied here as we are interested above all in the temperature field as the decisive field quantity.
The model has been applied to two different cases of practical importance:

1) The crack tip geometry is prescribed by means of characteristic parameters
2) The crack tip geometry also is computed by means of a"free boundary value problem".

The authors dealt with both cases. The second problem is much more difficult (Sommer, 1983).

Fig.1 and Fig. 2 show some typical results obtained for crack propagation (crack tip velocity v = o.1 m/s, steel Ck 45). The examples show the case where the crack tip geometry is prescribed (non-vanishing crack-tip radius).For sharp crack tips the temperature rise effect is greater than for rounded crack tips.

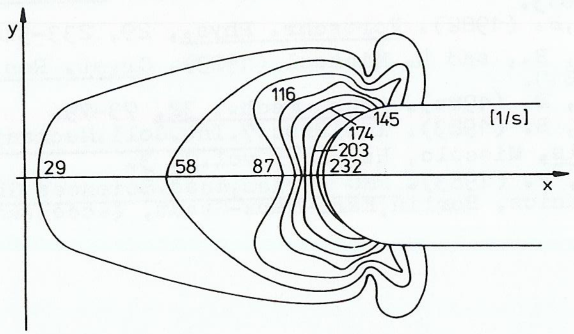

Fig. 1. Isoline -representation of effective strain rate around a crack tip, crack tip velocity <u>v = o.1m/s</u>

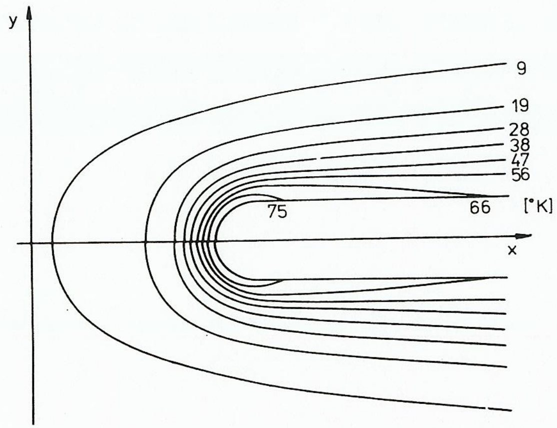

Fig. 2. Temperature-isoline-representation around a moving crack <u>v = o.1 m/s</u>

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