AD-A190 952 HEATING AT A PROPAGATING CRACK TIP IN A VISCOPLASTIC MATERIAL(U) NORTHWESTERN UNIV EVANSTON IL STRUCTURAL MECHANICS LAB J C SUNG ET AL. SEP 87 NU-SML-TR-87-3 1/1

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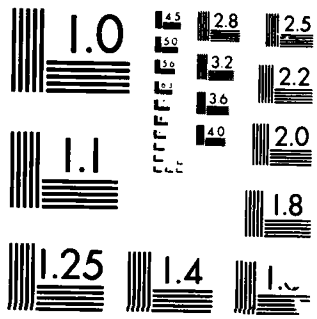

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HEATING AT A PROPAGATING CRACK TIP IN A VISCOPLASTIC MATERIAL

J.C. Sung* and J. D. Achenbach

Center for Quality Engineering and Failure Prevention
Northwestern University
Evanston, IL. 60208

Office of Naval Research

N00014-85-K-0401

September 1987

NU-SML-TR-87-3

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NU-SML-87-3	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Heating at a Propagating Crack Tip in a Viscoplastic Material	5. TYPE OF REPORT & PERIOD COVERED: Interim
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): J. C. Sung and J. D. Achenbach	8. CONTRACT OR GRANT NUMBER(s): N00014-85-0401
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Northwestern University, Evanston, IL 60208	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Structural Mechanics Department, Department of the Navy, Arlington, VA 22217	12. REPORT DATE: September 1987
	13. NUMBER OF PAGES: 18
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

crack tip
viscoplastic material
temperature

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The crack tip temperature due to near-tip dissipation of mechanical energy has been calculated for a crack propagating in a viscoplastic material. The mechanical behavior of the material was represented by a model proposed by Bodner and Partom. On the basis of the adiabatic approximation the maximum temperature has been investigated as a function of the crack-tip speed and the material parameters. For a specific crack-tip speed, T_{max} is displayed as a function of the material constant, D_o, which defines the asymptotic limit of the inelastic strain rate as the stress level increases. The maximum temperature increases with increasing value of D_o.

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Abstract

The crack tip temperature due to near-tip dissipation of mechanical energy has been calculated for a crack propagating in a viscoplastic material. The mechanical behavior of the material was represented by a model proposed by Bodner and Partom. On the basis of the adiabatic approximation the maximum temperature has been investigated as a function of the crack-tip speed and the material parameters. For a specific crack-tip speed, T_{max} is displayed as a function of the material constant, D_0, which defines the asymptotic limit of the inelastic strain rate as the stress level increases. The maximum temperature increases with increasing values of D_0.

Introduction

The rupture processes at a propagating crack tip and the dissipation of mechanical energy due to inelastic material behavior in the highly deformed near-tip zone, provide sources of heat which can give rise to substantial increases in the temperature near a crack tip. These temperature increases are of obvious interest since they may affect the mechanical behavior of the near-tip material, particularly its fracture properties. An early study of near-tip temperatures, motivated by interest in temperature effects on the fracture toughness for fast fracture, was included in a paper by Krafft and Irwin [1].

For essentially brittle materials, a propagating crack tip acts as a sink of mechanical energy. Part of this energy will be converted into surface energy of the new crack faces. It is, however, generally assumed that the remainder and perhaps larger part, is converted into heat. In the mathematical formulation a propagating crack edge is, therefore, a line source of heat, and hence the temperature at a propagating crack edge will display a logarithmic singularity, see e.g. Bui et al. [2]. To circumvent this temperature singularity, some investigators have distributed the energy release rate at the crack tip over a small area. Studies of the steady-state temperature induced by regions of near-tip heat production which move with a constant velocity, have been carried out by Weichert and Schönert [3]-[5]. Other studies are those of Döll [6] and Fuller et al [7]. Recently Kuang and Atluri [8] have employed a finite element procedure to calculate transient crack-tip temperatues, considering certain nonlinear effects due to temperature dependent material properties and convective and radiative heat losses.

When the crack propagates in an inelastic material, the dissipation of mechanical energy in the vicinity of the crack tip provides another source of heat. The corresponding transient crack-tip temperatures have been calculated by Rice and Levy [9], for the case that the plastic work rate is computed by the use of the Dugdale model.

For time-dependent (transient) temperature fields, the present authors have shown [10] that near the center of a source region, and under certain restrictions on the time of observation, the effect of heat conduction on the maximum temperature is negligible if a dimensionless constant is sufficiently larger than unity. The constant involves the velocity and a characteristic length parameter of the source region, and the thermal diffusivity. When this condition holds, the adiabatic approximation which completely ignores heat conduction gives a very acceptable approximation to the temperature field.

In the present paper, the adiabatic approximation has been used to calculate the crack tip temperature for a crack which propagates in a viscoplastic material. The mechanical behavior of the material is represented by a model proposed by Bodner and Partom [11]. The general form of the near-tip fields of stress and deformation for this model have been studied by Achenbach et al [12] and Sung and Achenbach [13]. The Bodner-Partom model accounts for flux of energy into the crack tip, as well as for considerable dissipation of mechanical energy in the near-tip region. In this paper, the temperatures due to the dissipation of energy have been analyzed in some detail. For a specified crack-tip speed (300 m/s), particular attention has been devoted to the dependence of the maximum temperature on a characteristic parameter, D_o, of the Bodner-Partom model. This parameter defines the asymptotic limit of the inelastic strain rate as the stress increases. The maximum temperature increases with increasing values of D_o.

2. Constitutive Model

In this paper we use the constitutive relations for a viscoplastic material proposed by Bodner and Partom [11]. The basic equation that distinguishes the Bodner-Partom model from other constitutive models, is the one which defines the rate of inelastic (plastic) strain as:

$$\dot{\epsilon}^p_{ij} = D_o \frac{s_{ij}}{(J_2)^{1/2}} \exp[-\frac{1}{2} (Z^2/3J_2)^n] \quad , \tag{2.1}$$

where s_{ij} are the components of the stress deviator,

$$s_{ij} = \sigma_{ij} - \frac{1}{3} \delta_{ij}\sigma_{kk} \quad , \tag{2.2}$$

and

$$J_2 = \frac{1}{2} s_{ij}s_{ij} \tag{2.3}$$

Also

$$Z = Z_1 + (Z_o - Z_1)e^{-mW_p} \tag{2.4}$$

In Eqs. (2.1) and (2.4), Z_o, Z_1, m, n and D_o are material constants, and W_p is the work over the inelastic strains

$$W_p = \int s_{ij}\dot{\epsilon}^p_{ij} dt \tag{2.5}$$

The Bodner-Partom constitutive equations have the convenient property that no separate specification of a yield criterion is required, and loading and unloading are governed by the same set of equations. Both elastic and inelastic deformations are present at all stages of loading and unloading. For loading in uniaxial tension it is simple to plot the inelastic strain rate, $\dot{\epsilon}^p_{11}$, versus σ_{11}/Z. Figure 1 shows that $\dot{\epsilon}^p_{11}$ remains very small at small stresses, with a rapid change over a small range of σ_{11}/Z (the "yield" region), whereupon an asymptotic limit (proportional to D_o) is approached as σ_{11} becomes large.

It has been shown by Sung and Achenbach [13] that a bounded inelastic strain rate implies a square-root singular near-tip stress field. In the moving coordinates we have:

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{12} \\ \sigma_{22} \end{Bmatrix} = \frac{K_I(t)}{R^{1/2}} \begin{Bmatrix} \frac{3}{4}\cos\frac{1}{2}\theta + \frac{1}{4}\cos\frac{5}{2}\theta \\ -\frac{1}{4}\sin\frac{1}{2}\theta + \frac{1}{4}\sin\frac{5}{2}\theta \\ \frac{5}{4}\cos\frac{1}{2}\theta - \frac{1}{4}\cos\frac{5}{2}\theta \end{Bmatrix} . \tag{2.6}$$

It should be noted that the usual factor $(2\pi)^{1/2}$ in the denominator has been omitted, and that the variations with angle are the usual ones for elastic near-tip stress fields.

Sung and Achenbach [13] have used the finite element method to calculate the quasi-static stress intensity factor, $K_I(t)$. They considered a case of plane strain and small-scale yielding, for a body containing a stationary crack which is loaded at time $t = 0$. It was assumed that the load immediately generates the initial elastic field everywhere in the cracked body. In particular the initial fields near the crack tip were assumed to consist of the usual static elastic singular fields. At time

$t = 0^+$ the crack starts, however, to propagate with a constant velocity. Curves for $K_I(t^*)/K_I^E$, where K_I^E is the initial elastic stress intensity factor, are shown in Fig. 2, for various values of the crack tip speed. The dimensionless time is defined by

$$t^* = t(\mu D_o)/(Z/\sqrt{3}) \tag{2.7}$$

For the purpose of the present paper the curves of Fig. 2 are fitted by

$$K_I(t^*) = K_I^E e^{-\alpha^* t^*} = K_I^E e^{-\alpha t} \tag{2.8}$$

where α^* and α depend on the crack-tip speed.

It should be noted that the components of $\dot{\epsilon}^p_{ij}$, as defined by Eq.(2.1), are bounded at a crack tip. Even though s_{ij} blows up as a crack tip is approached, in the term $s_{ij}/(J_2)^{1/2}$ that singularity is cancelled by the one of $(J_2)^{1/2}$. The term $\exp[-(Z^2/3J_2)^n/2]$ is bounded whether J_2 is singular or not. At a crack tip we therefore have

$$\dot{\epsilon}^p_{ij} = \frac{D_o s_{ij}}{(\frac{1}{2}s_{k\ell}s_{k\ell})^{1/2}} \tag{2.9}$$

This expression displays the strong dependence of the near-tip inelastic strain rate on the parameter D_o.

Equations (2.5), (2.6) and (2.8) are now used to compute the rate of dissipation of mechanical energy in the immediate vicinity of the crack tip. The result is

$$\dot{W}_p(X,Y,t) = D_o K_I^E e^{-\alpha t} \frac{\Sigma(\theta)}{R^{1/2}} \tag{2.10}$$

where

$$\Sigma(\theta) = 2\{\frac{1}{3}[1 + 4\nu(\nu-1)]\cos^2\frac{1}{2}\theta + \frac{1}{4}\sin^2\theta\}^{1/2} \tag{2.11}$$

3. Adiabatic Approximation

The calculation of the temperature at a propagating crack tip is a moving heat-source problem. The rupture processes right at the propagating tip and the dissipation of mechanical energy in the vicinity of the crack tip, provide the moving heat sources.

When the source is distributed and of the general form $Q_o f(X,Y,t)$, where X and Y are the moving coordinates shown in Fig. 1, and if the system of sources moves at a constant velocity, V, the temperature in the moving coordinate system may be written as, see [10],

$$\bar{T}(\bar{X},\bar{Y},\bar{t}) = \frac{2}{\pi}\int_o^{\bar{t}} \frac{d\bar{s}}{\bar{t}-\bar{s}} \int_A f(\bar{\xi},\bar{\eta},\bar{s}) \exp\left(-\frac{[(\bar{X}-\bar{\xi})+\bar{V}(\bar{t}-\bar{s})]^2 + (\bar{Y}-\bar{\eta})^2}{2(\bar{t}-\bar{s})}\right) d\bar{\xi}d\bar{\eta}. \tag{3.1}$$

where the dimensionless variables are defined as

$$(\bar{X},\bar{Y}) = (X,Y)/\ell \quad , \quad (\bar{\xi},\bar{\eta}) = (\xi,\eta)/\ell \quad , \quad (\bar{t},\bar{s}) = (2\kappa/\ell^2)(t,s), \tag{3.2a,b,c}$$

$$\bar{T} = T/(Q_o\ell^2/8k) \quad , \quad \bar{V} = (\ell/2\kappa)V. \tag{3.3a,b}$$

In these expressions ℓ is a characteristic length of the area A, k is the thermal conductivity, and κ is the thermal diffusivity

$$\kappa = k/\rho c \quad , \tag{3.4}$$

where ρ is the mass density and c is the specific heat.

Equation (3.1) reveals the potentially dominant influence of $\bar{V}$. Suppose that $\bar{X},\bar{Y} < 1$, and that $\bar{V} >> 1$. The exponential term will then be very small, unless $t\text{-}s << 1$. When $t\text{-}s << 1$ the terms $[(\bar{X}-\bar{\xi})+\bar{V}(\bar{t}-\bar{s})]^2/2(\bar{t}-\bar{s})$ and $(\bar{Y}-\bar{\eta})^2/2(t-s)$ will, however, be very large, and the exponential term will decay rapidly as $\bar{\xi}$ and $\bar{\eta}$ vary from $\bar{X}$ and $\bar{Y}$. These observations suggest that for large values of $\bar{V}$, the major contribution from $f(\bar{\xi},\bar{\eta},\bar{s})$ comes from the neighborhood of $\xi=\bar{X}+\bar{V}(\bar{t}-\bar{s}),\eta=\bar{Y}$. Hence we bring $f(\bar{X},\bar{Y},\bar{s})$ outside the integration over A. Since the exponential term is either very small ($t\text{-}s = 0(1)$) or decays rapidly ($\bar{t}-\bar{s} << 1$), the limits of integration may be extended to $\pm\infty$. Use of the integral

$$\int_{-\infty}^{\infty} e^{-\alpha x^2}\, dx = \frac{\sqrt{\pi}}{\alpha} \tag{3.5}$$

then finally reduces Eq.(3.1) to

$$T(\bar{X},\bar{Y},\bar{t}) = 4 \int_0^{\bar{t}} f(\bar{X}+\bar{V}(\bar{t}-\bar{s}),\bar{Y},\bar{s})d\bar{s} \tag{3.6}$$

It follows from (3.3b) that $\bar{V}$ is large for $V\ell$ large and/or κ small. However, even for moderate values of $V\ell$, one may find quite large values of $\bar{V}$. For example, for steel we have

$$\rho c = 3.64 \times 10^6 \text{ J/m}^3 \,{}^0\text{C}, \qquad k = 5.36 \times 10 \text{ J/ms } {}^0\text{C} \tag{3.7a,b}$$

and hence

$$\kappa = \frac{k}{\rho c} = 1.47 \times 10^{-5} \text{ m}^2/\text{s} \tag{3.8}$$

It then follows from Eqs.(3.3b) and (3.8) that

$$\bar{V} = V\ell \times 10^5/2.94 \tag{3.9}$$

Clearly $\bar{V}$ can be quite large even for small values of V or ℓ.

For certain simple moving source regions the temperatures according to Eqs. (3.1) and (3.6) have been compared in Ref.[10]. For $\bar{V} = 50$ the agreement is very good at small times, but it degenerates as time increases.

Equation (3.6) may be called an adiabatic approximation. It assumes that the source region moves sufficiently fast that the effect of heat conduction is negligible in the source region, at least at relatively small times. The purely adiabatic approximation can also be obtained directly by simply setting $k \equiv 0$ in the heat conduction equation. The equation for the temperature then reduces to

$$\rho c\dot{T} = Q \tag{3.10}$$

Suppose $Q = Q_o f(x - a(t), y, t)$ is given in the stationary coordinate system. The temperature at a <u>fixed</u> point x,y relative to the stationary coordinate system is

$$T(x,y,t) = \frac{Q_o}{\rho c} \int_o^t f(x-a(s),y,s)ds \tag{3.11}$$

where we assume $T(x,y,t) \equiv 0$ for $t \leq 0$. Equation (3.11) is generally quite easy to evaluate, even numerically when $f(x - a(t),y,t)$ is known only in the form of numerical data. In the moving coordinates Eq. (3.11) becomes

$$T(X,Y,t) = \frac{Q_o}{\rho c} \int_o^t f(X+a(t)-a(s),Y,s)ds \tag{3.12}$$

The corresponding dimensionless results in the moving coordinate system are obtained by using the dimensionless quantities defined by Eq.(3.2) and Eq.(3.3). Note that the actual value of k appears in these quantities, even though Eq.(3.12) is for $k \equiv 0$. We have

$$T(\bar{X},\bar{Y},\bar{t}) = 4 \int_o^{\bar{t}} f(\bar{X}+a(\bar{t})-a(\bar{s}),\bar{Y},\bar{s})d\bar{s} \tag{3.13}$$

In the absence of heat conduction, and since the source region moves parallel to the x axis, the coordinate y simply appears as a parameter. It is noted that for a source moving with constant velocity V, Eq.(3.13) is identical to Eq.(3.6).

Under the assumption that the dissipated mechanical energy is converted into heat, the temperature generated by the singular part of $\dot{W}_p(X,Y,t)$ can now be obtained by substitution of (2.10) into Eq.(3.12). The result is

$$T(X,Y,t) = \frac{D_o K_I^E \Sigma(\theta)}{\rho c} \int_o^t \frac{e^{-\alpha s} ds}{([X+a(t)-a(s)]^2 + Y^2)^{1/4}} \tag{3.14}$$

where α is defined by Eq.(2.8). For constant crack tip speed, V, and after some manipulation, we find on the crack line ($Y = 0$):

$$T(X,0,t) = \frac{D_o K_I^E \Sigma(0)}{\rho c} \frac{e^{-\alpha(t+X/V)}}{(\alpha V)^{1/2}} g(\alpha X/V, \alpha t) \quad , \tag{3.15}$$

where

$$g(\alpha X/V, \alpha t) = \int_{\alpha X/V}^{\alpha(X/V+t)} \frac{e^s}{s^{1/2}} ds \quad . \tag{3.16}$$

At the crack tip the temperature further simplifies to

$$T(0,0,t) = \frac{D_o K_I^E \Sigma(0)}{\rho c} \frac{1}{(\alpha V)^{1/2}} e^{-\alpha t} g(0,\alpha t) \tag{3.17}$$

The function $e^{-\alpha t} g(0,\alpha t)$, which is known as Dawson's integral, has been plotted in Fig. 3. It is noted that the maximum value of the integral is approximately 1.1. Hence, at the crack tip we have

$$T_{max} = \frac{1.1}{(\alpha V)^{1/2}} \frac{D_o K_I^E \Sigma(0)}{\rho c} \tag{3.18}$$

It is of interest to plot the dependence of T_{max} on D_o. To do that, we use the nondimensional time introduced by Eq.(2.7). The crack-tip speed, V, is then related to the normalized crack-tip speed, V^*, by the following expression:

$$V = \frac{(K_I^E)^2 \mu D_o}{Z^3} 3\sqrt{3}\, V^* \quad . \tag{3.19}$$

Let us consider the following numerical values

$$K_I^E = 70 \text{ MPa } m^{1/2} = 0.7 \times 10^8 N/m^{3/2}$$

$$\mu = .44 \times 10^5 \text{ N/mm}^2 \quad , \quad \nu = 0.2$$

$$Z = 1550 \text{ N/mm}^2 \quad , \quad V = 300 \text{ m/s}$$

Equation (3.19) then becomes

$$D_o V^* \approx 10^{-3} \text{ 1/s} \quad . \tag{3.20}$$

Therefore, for various values of D_o, we can compute the corresponding values for V^* by the above formula. The results are shown in Table 1. As pointed out earlier, the quasi-static stress intensity factor $K_I(t^*)$ computed numerically in Ref.[13] for various normalized crack-tip speeds V^* (see Fig. 2), can be fitted for short time by Eq.(2.8), by adjusting the parameter α (or α^* if the normalized time scale $t^* = \mu D_o/Z/\sqrt{3}$ is used), where

$$\alpha = \alpha^* \frac{\mu D_o}{Z/\sqrt{3}} \tag{3.21}$$

For various normalized crack-tip speeds, V^*, the fitted values for the parameter α^* are shown in Table 1.

For a specific value of V (in our case V = 300 m/s) the calculation of T_{max} as a function of D_o now proceeds as follows. For various selected values of D_o, the corresponding V^* are obtained from (3.20). Next, the corresponding values of α^* are obtained by interpolation from Table 1. For each D_o the value of α then follows from Eq.(3.21). Finally for each D_o the corresponding α is substituted in Eq.(3.17), to yield T_{max}. The curve of T_{max} versus D_o is shown in Fig. 4. It is noted that T_{max} increases monotonically with D_o. The increase is more dramatic at higher values of D_o. For example, for $D_o = 10^6$ 1/s we have $T_{max} \simeq 360^oC$, while for $D_o = 10^4$ 1/s, we have $T_{max} \simeq 20^oC$.

Crack tip temperatures due to flux of energy into the crack tip have been computed in Ref.[10].

Acknowledgment

This paper was written in the course of research sponsored by the Office of Naval Research under Contract No. N00014-85-K-0401 with Northwestern University.

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Table 1. The fitted values of the parameter α^* for various normalized crack-tip speeds, and the corresponding values of T_{max} (°C) calculated from Eq.(3.18), for V = 300 m/s and various values of D_o.

D_o(1/s)	V^*	α^*	$\frac{\alpha}{\mu/(2/\sqrt{3})} = D_o\alpha^*$	T_{max} (°C)
10^3	1	1/2	$\frac{1}{2}\cdot 10^3$	5
10^4	10^{-1}	1/3	$\frac{1}{3}\cdot 10^4$	20
10^5	10^{-2}	1/6	$\frac{1}{6}\cdot 10^5$	90
10^6	10^{-3}	1/9	$\frac{1}{9}\cdot 10^6$	360
10^7	10^{-4}	1/20	$\frac{1}{20}\cdot 10^7$	1690

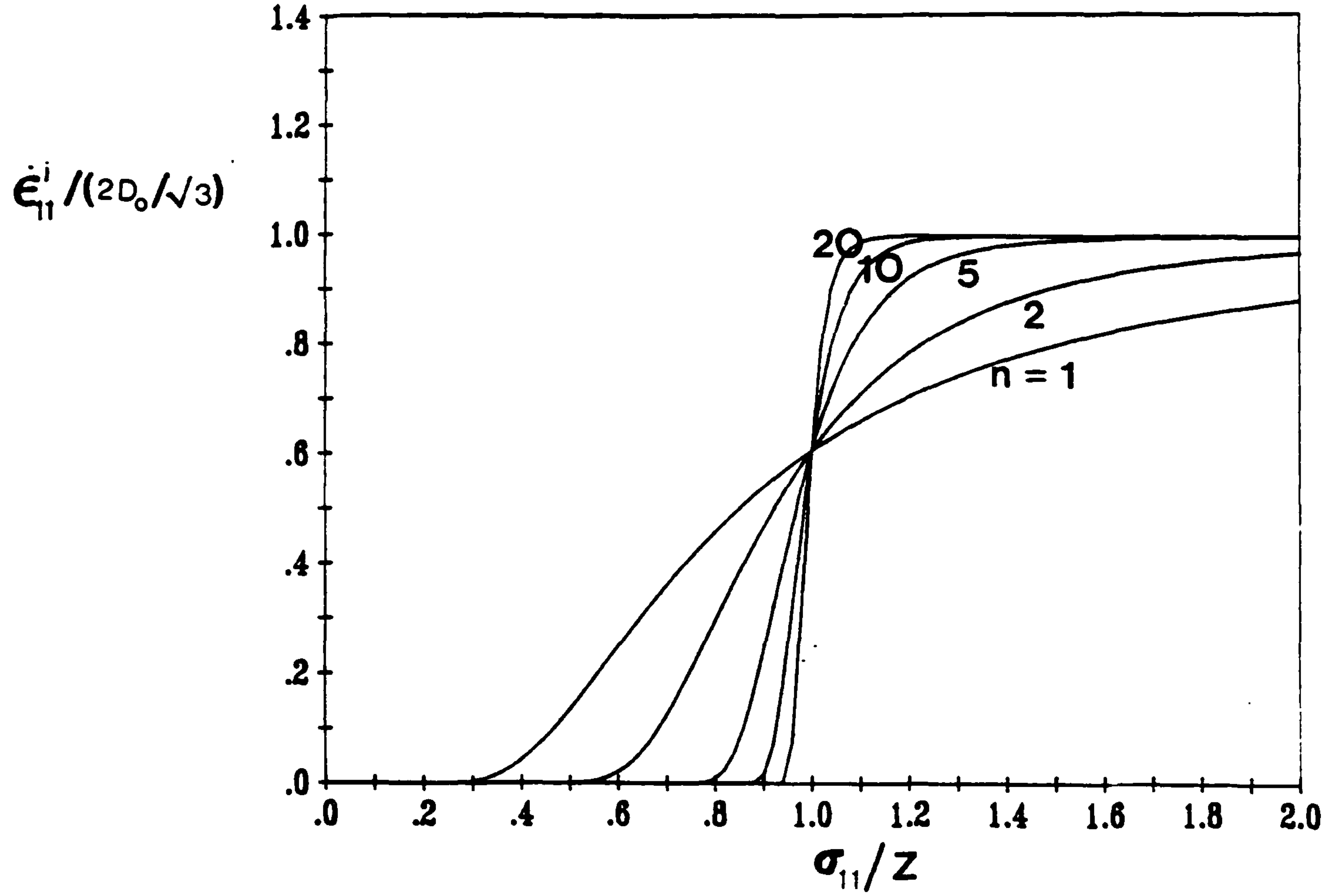

Fig. 1 Plastic strain rate versus σ_{11}/Z, for uniaxial stress, and for various values of n.

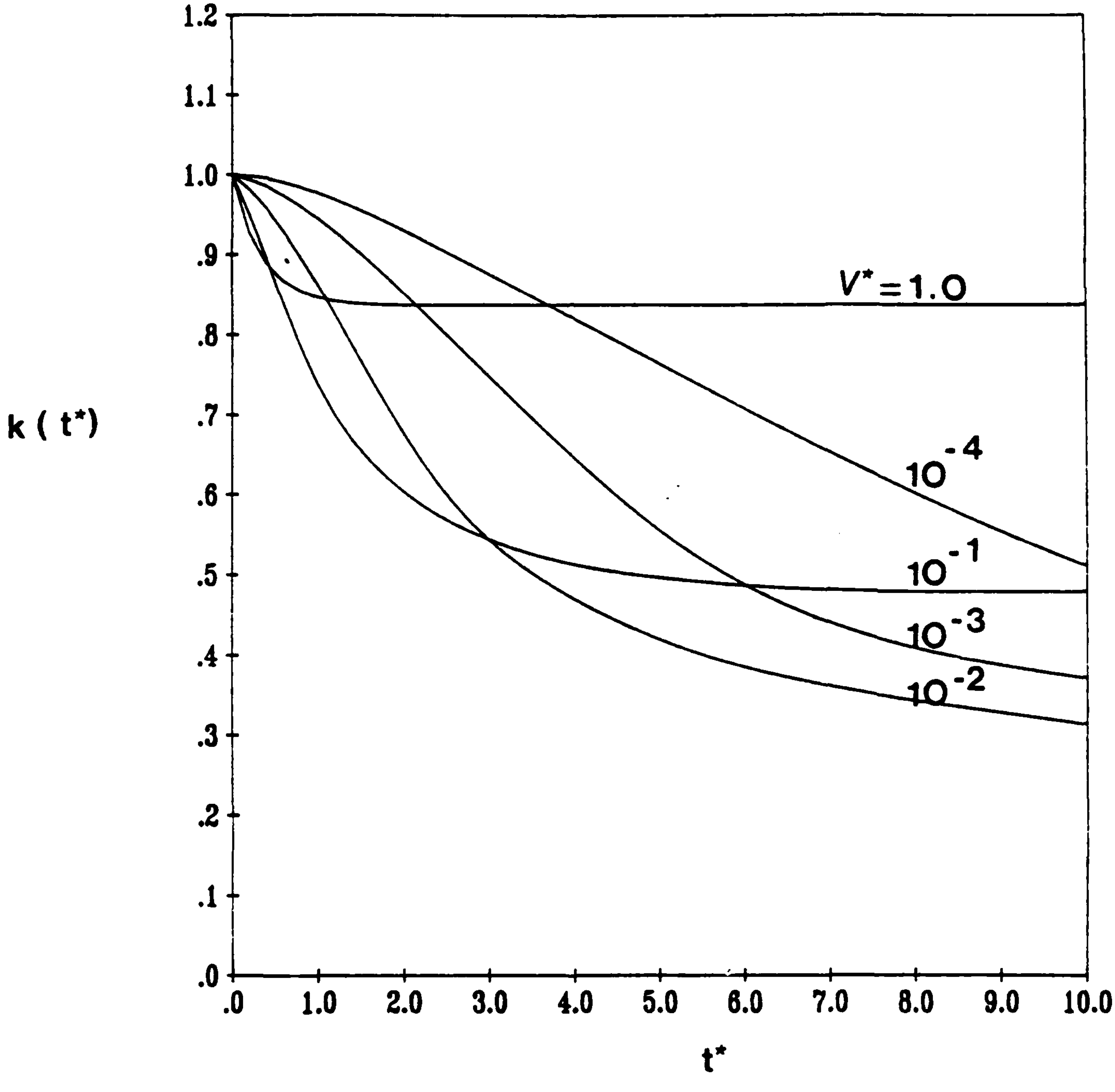

Fig. 2 Time varying stress-intensity factor, $k(t^*) = K_I(t^*)/K_I^E$, versus the dimensionless time, for various crack-tip speeds, where V^* is defined by Eq.(3.19).

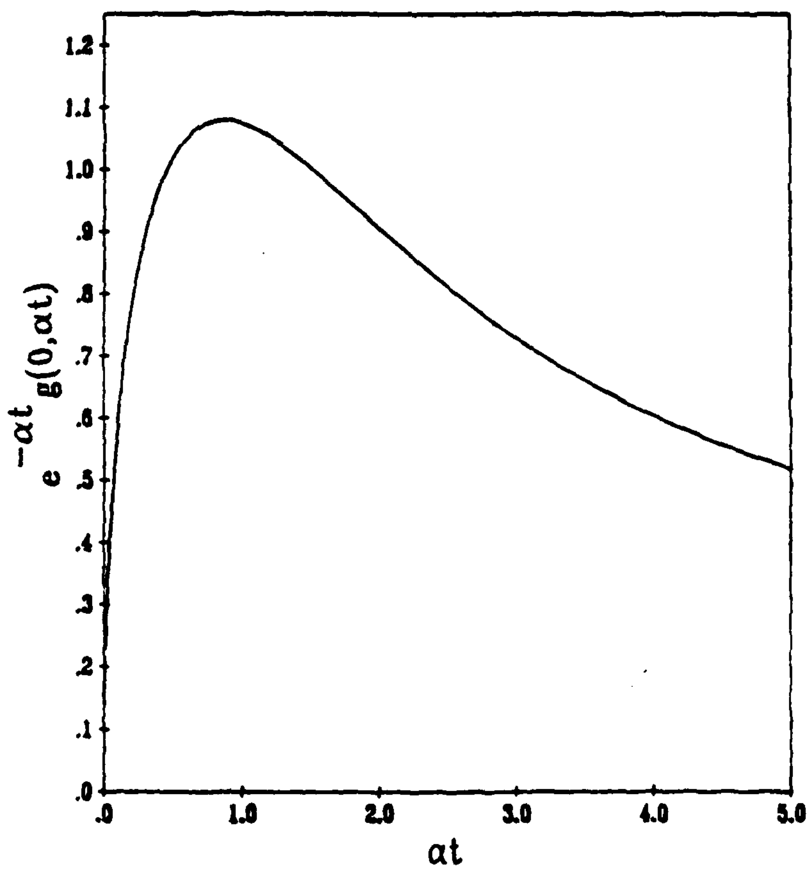

Fig. 3 Function $e^{-\alpha t}g(0,\alpha t)$ versus αt, where $g(0,\alpha t)$ is defined by Eq.(3.16).

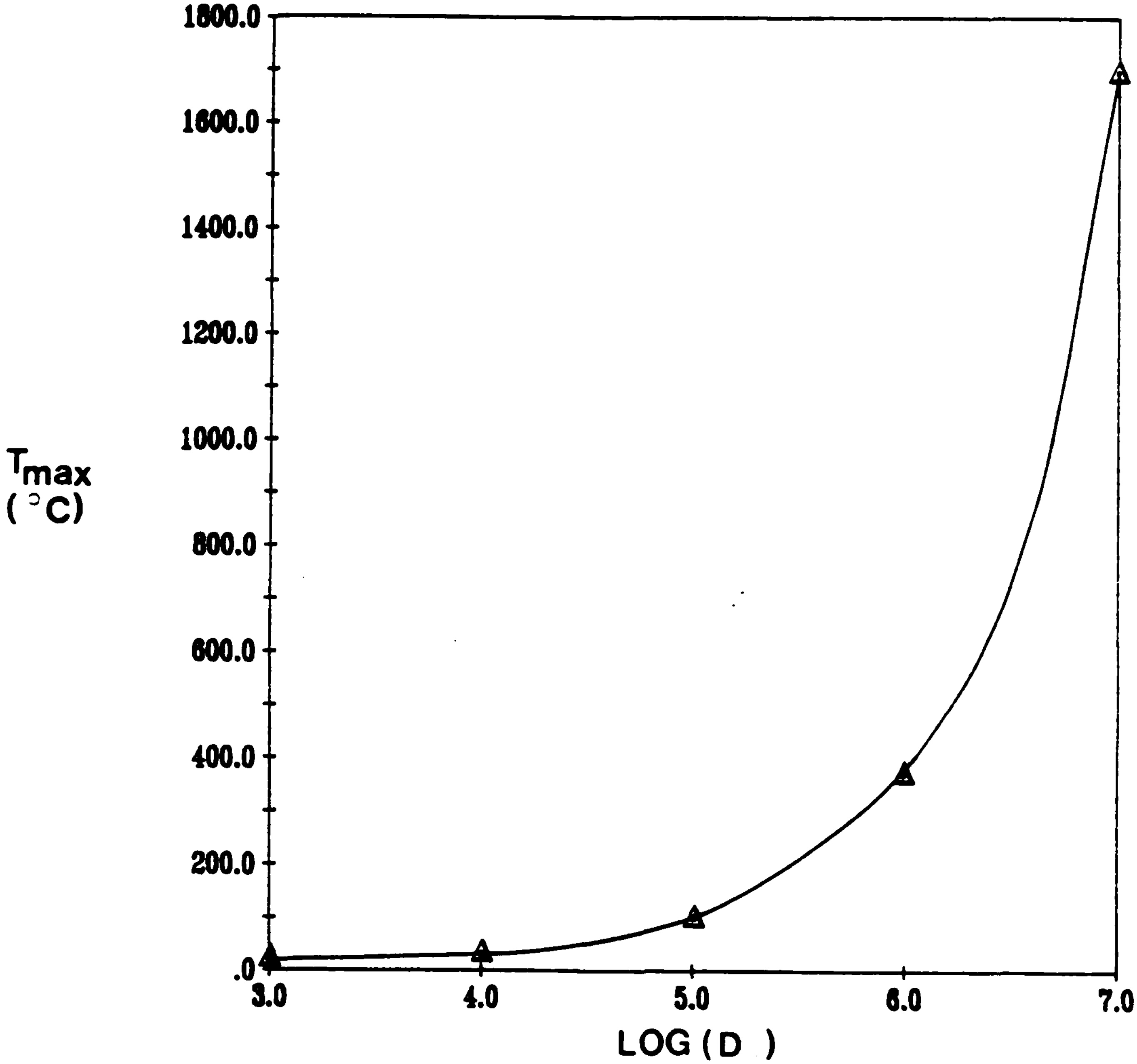

Fig. 4 Maximum value of the crack tip temperature versus D_o.

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