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**ROLE OF TRANSIENT CREEP IN HIGH TEMPERATURE
TENSILE FAILURE OF ICE**

by N.K. Sinha

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ABSTRACT

The stress-strain relationship to fracture for polycrystalline ice in tension has been shown to be governed by elastic and delayed elastic deformation with negligible viscous flow. Delayed elasticity, associated with grain boundary sliding, dominates the deformation process as the grain size decreases leading to an apparent transition from brittle to ductile with the decrease in grain size.

RÉSUMÉ

La relation contrainte-déformation jusqu'à rupture de la glace polycristalline en tension s'est révélée de nature élastique instantanée et élastique différée avec écoulement visqueux négligeable. La déformation élastique différée associée au glissement des grains les uns sur les autres est prépondérante lorsque la taille des grains diminue, conduisant à une période transitoire apparente de l'état fragile à l'état ductile.

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ROLE OF TRANSIENT CREEP IN HIGH TEMPERATURE TENSILE FAILURE OF ICE

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Introduction

The effect of grain size on the strength of polycrystalline ice at a high homologous temperature of $0.96 T_m$ (-10°C), where T_m is the melting point in Kelvin, has been investigated experimentally by a number of investigators [1-6]. A review of these results showed that all these tests, however, have been affected by choice of improper specimen geometry, the presence of large number of inclusions in the materials and by undesirable interaction between the testing machine and test specimens [7]. Consequently it appears that the dependence of strength on grain size for pure ice is still not known with certainty. The investigations carried out by Currier et al. [1-3] are the best among all these reports because they documented the experimental conditions well, which others failed to do, and because they are the only people who measured the specimen deformation during the tests.

It will be shown in this paper that the mechanical response of the specimens used by Currier et al. is consistent with a previously formulated high temperature constitutive equation [8-10] primarily describing transient and steady-state creep. Since this model contains a number of material parameters that are related to micromechanical processes [9], the analysis also provides an insight into the mechanics involved in tensile failure. The paper introduces new concepts in the mechanics of deformation and failure that could provide food for thought and possible experimental direction to the investigators involved in understanding the high temperature failure mechanisms of polycrystalline materials in general.

Experimental Results and Preliminary Analysis

The tests reported by Currier et al. [1-3] were carried out under a closed-loop controlled constant cross-head displacement rate, $\dot{x}$, or under a nominally constant strain rate, $\dot{\epsilon}_n = \dot{x}/l = 1 \times 10^{-5} \text{ s}^{-1}$, where l is the effective specimen length. Under these test conditions, the tensile strength, σ_f , decreased with the increase in grain size, d (in the range of 1.0 to 7.3 mm), according to the Hall-Petch expression

$$\sigma_f = \sigma_i + k d^{-1/2} \quad (1)$$

where $\sigma_i = 0.6 \text{ MN}\cdot\text{m}^{-2}$ and $k = 0.02 \text{ MN}\cdot\text{m}^{-3/2}$.

If E is Young's modulus ($E = 9.5 \text{ GN}\cdot\text{m}^{-2}$ [8]), then equation (1) gives the elastic strain at fracture as

$$\epsilon_f (\text{elastic}) = \frac{\sigma_i}{E} + \frac{k}{E} d^{-1/2} = 6.3 \times 10^{-5} + 2.1 \times 10^{-6} d^{-1/2} \quad (2)$$

Figure 1 shows that equation (2) underestimates the strain actually measured, and that the deviation in elastic response depends greatly on grain size. The authors [2-3] also estimated the fracture strain as

$$\epsilon_f (\text{nominal}) = \dot{\epsilon}_n t_f \quad (3)$$

where t_f is the observed failure time, and noted a large discrepancy between this and the measured strains as shown in Fig. 1. Consequently the measured strain rates were not only about one order of magnitude lower but varied over a wide range (600%). The following analysis will show that experimental observations can be explained quantitatively using stress rate during loading as the basis of analysis.

High Temperature Rheology of Polycrystals

Creep deformation in polycrystalline materials at high temperatures can be expressed phenomenologically [8] by

$$\epsilon = \epsilon_e + \epsilon_d + \epsilon_v \quad (4)$$

where ϵ_e is the pure elastic deformation, ϵ_d is the recoverable, delayed elastic strain, and ϵ_v is the viscous or permanent deformation. (The term "viscous" will be used in a general sense to describe flow leading to permanent deformation. The term "plastic" is avoided here because it is commonly used to describe both permanent and delayed elastic deformation.)

Under conditions where grain boundary diffusional processes do not play a dominant role and where the microstructure has not deteriorated by the formation of internal voids and cracks, uniaxial constant stress creep in previously undeformed, pure, randomly oriented, polycrystalline materials can be expressed in terms of stress, σ , and time, t , for a material with an average grain diameter of d at a given temperature T , by [9]

$$\epsilon = \frac{\sigma}{E} + c_1 \left(\frac{d_1}{d}\right) \left(\frac{\sigma}{E}\right)^s \{1 - \exp[-(a_T t)^b]\} + \dot{\epsilon}_{v1} \left(\frac{\sigma}{\sigma_1}\right)^n t \quad (5)$$

In this equation the three terms correspond to the three successive terms in equation (4). E is Young's modulus; a_T , b , c_1 , n and s are constants; d_1 is the unit of grain diameter; and $\dot{\epsilon}_{v1}$ is the viscous strain rate for unit stress σ_1 . The constant a_T is the inverse of relaxation time at temperature T in Kelvin; n is the stress exponent for viscous flow; and s is the stress exponent for delayed elasticity. Both a_T and $\dot{\epsilon}_{v1}$ vary with temperature according to an Arrhenius equation with the same activation energy, Q . Numerical values of these material constants for ice determined from previous creep experiments [8] and subsequent analysis [9] are given in Table 1. Note that $s=1$ for ice although it may be different in other materials [9].

A simple formulation for predicting strain corresponding to an arbitrary monotonically increasing stress history and hence the stress-strain relation has been developed [10] on the basis of equation (5) for polycrystalline materials like ice, i.e., for $s=1$. This theory has been tested successfully using information obtained from uniaxial unconfined compressive strength tests on ice in the temperature range of -5 to -30°C [10].

For loading conditions of constant stress-rate, $\dot{\sigma}$, it is shown [10] that equation (5) takes the following form for the strain at time t after the beginning of loading:

$$\epsilon = \frac{\sigma}{E} + \frac{c_1}{E} \left(\frac{d_1}{d}\right) \sum_{i=1}^{N+1} \Delta\sigma \{1 - \exp[-(a_T[N+1-i]\Delta t)^b]\} + \frac{\dot{\epsilon}_{v1} \sigma_1}{\dot{\sigma}(n+1)} \left(\frac{\sigma}{\sigma_1}\right)^{n+1} \quad (6)$$

where $\sigma = \dot{\sigma}t = N\Delta\sigma = N\dot{\sigma}\Delta t$. Note the use of a numerical integration method for formulating the second, delayed elastic term. This term, however, rapidly converges as Δt is decreased [10].

Experimental observations [11] showed that a constant cross-head displacement rate induces a monotonically increasing strain rate rather than the constant strain rate given by $\dot{\epsilon}_n$. This type of loading, however, gives a nearly linear stress rate during initial loading periods. Stress rate analysis should therefore be appropriate for the tests under consideration. Also, as was discussed in [7], it is less ambiguous because both load (and hence stress for the small strain involved in the present series of tests) and time can be measured accurately. Moreover, it provides an opportunity to examine the applicability of equation (6) to independent experimental observations under a tensile mode of loading.

Application of Theory

The test results reported in a tabulated form in [2,3] are presented here in Fig. 2 in terms of average stress rate to failure, $\dot{\sigma}_f = \sigma_f/t_f$. The strain at fracture time was calculated using material constants in Table 1 and equation (6) with $\dot{\sigma} = \dot{\sigma}_f$ for each test and grain size in Fig. 2. The results are compared with the measured values in Fig. 3. The agreement between theory (open circles) and experiment (solid circles) is considered excellent since no modification was made in either the method of calculation or the numerical values of the material constants determined several years ago [8] from creep tests on pure inclusion-free ice. One of the facts supporting the validity of the proposed model is that it can account for the discrepancy between the nominal strain and the measured failure strain shown in Fig. 1.

It should be noted that the predicted strains are, in general, somewhat lower than the measured values. This was anticipated [7] because the deformation of the specimens was measured by installing gauges between the top and the bottom end caps [1-3]. The measured strains therefore represented the sum of the deformations of the gauge section and the compliant grain-refined end zones of each specimen [2,3] in which the grains were smaller than those in the gauge section. For the same applied stress rate and loading time it was predicted in an independent study [12] that a finer grained material with more grain-boundary surface areas would deform more than a coarse grained one.

The consistency between the experimental observations and the theory is further illustrated in Fig. 4, which represents the maximum span in δ_f in which the experiments were conducted. Computed results are based on equation (6).

Discussion

Measurements of total strain alone do not necessarily lead to an understanding of the factors controlling the deformation behaviour of a material. Purely empirical constitutive relations, though extremely useful from a practical point of view, do not necessarily provide information on basic material properties either. Equation (5), however empirical it may appear to be, was developed [9] by giving consideration to deformation behaviour [8] and the micromechanics of deformation through separating the elastic, delayed elastic and viscous components. The elastic component is associated with the deformation of the lattice. It is assumed that the delayed elasticity component is associated with grain boundary sliding and that the viscous creep is linked primarily to intragranular creep due to dislocation motion. Subsequent development of equation (6) from (5) also involved further consideration of the micromechanisms of deformation [10]. These basic studies strongly indicated that experiments should be designed not only to study the stress-strain relations but also the stress and strain path and recovery history on unloading, as well as microstructural features.

Figure 4 clarifies this idea. Both the theory and the experiment consistently show a nonlinear stress-strain response for the entire duration of the test. The stress-strain diagrams indicate that considerable nonelastic deformation occurred before fracture. The theory, because of its three part form, brings a new insight into the relation between deformation and failure for the tests under consideration. This is illustrated in Fig. 5 in which the detailed calculations corresponding to the stress-strain diagram for test No. 54 in Fig. 4 are shown. The non-linear time dependence of the total strain and its large deviation from the nominal strain path are particularly noticeable. The theory suggests that the variation in the strain rate during the test was caused primarily by the time-wise nonlinear response of the delayed elastic strain. Note also the primarily elastic and delayed elastic (hence recoverable) nature of the total strain with very little contribution from the viscous term (i.e., permanent strain), even at the time of fracture.

The contribution of the three components of strain to the total strain at fracture (corresponding to all the results in Fig. 3) are presented in Fig. 6. The contribution of the viscous strain at fracture, ϵ_v^f , to the total strain, ϵ_f , defined as $\gamma_v^f = \epsilon_v^f / \epsilon_f$, is small in all the tests, in the range of 4 to 7%. Total strain, therefore, was dominated by the elastic and delayed elastic deformation. However, the relative importance of the elastic strain and the delayed elastic strain depends on grain size (Fig. 6). For large grains, elastic strain dominates whereas the delayed-elastic component dominates for finer grains. The contribution of the delayed elastic strain at fracture, ϵ_d^f , to the total strain, ϵ_f , denoted by $\gamma_d^f (= \epsilon_d^f / \epsilon_f)$, is 73% for the test with $d = 1.0$ mm, whereas it is only 26% for the test with $d = 7.3$ mm. In general, it is the large variation of γ_d^f with d that determines the grain size dependence of the fracture strain and hence the apparent increase in ductility with decrease in grain size. Finally, this explains the observed dependence between the decrease in grain size and the rapidly increasing deviation of the total strain from pure elastic strain (see Fig. 1). Since the delayed elastic strain is associated with the grain boundary sliding strain [9], γ_d^f gives a measure of the contribution of the sliding to the total strain at failure. This brings in interesting possibilities of introducing the subject of intergranular fracture and discussing the above results accordingly. However, this is outside the scope of this paper.

If a specimen is unloaded fully and instantly just before it fractures, most of the deformation will be recovered. This prediction can be investigated readily and directly by measuring the deformation during loading of a specimen, under a specific stress rate, to a required stress level followed by rapid unloading to zero stress. A series of constant stress rate tests, over a wide range of loading rates, has been conducted to examine the validity of the

above hypothesis using a 1 MN capacity servo-hydraulic closed-loop test system. Test procedures described in [13] were followed. Results of these tests will be presented elsewhere in detail. An example is shown here in Fig. 7 that is relevant to the loading conditions shown in Fig. 2. It illustrates the results obtained on transparent, inclusion free, transversely isotropic columnar-grained S-2 ice with compressive load applied perpendicular to the columns. The specimen was loaded to a stress level of 1.2 MPa at a constant rate of $5 \times 10^{-3} \text{ MN}\cdot\text{m}^{-2} \text{ s}^{-1}$ at -10°C and then unloaded rapidly. The axial strain was measured by means of a displacement gauge mounted directly on the specimen. Note the monotonically increasing strain rate during loading and the small amount of permanent deformation on unloading.

Conclusions

Experimental observations by Currier et al. made on tensile strength and deformation of polycrystalline ice at $0.96 T_m$ have been examined on the basis of a proposed high temperature rheological model developed specifically for describing transient creep and its dependence on grain size. The model shows that the stress-strain relationship is governed by elastic and delayed elastic deformation with very little permanent deformation due to viscous flow. The apparent brittle to ductile transition with the decrease in grain size, as indicated by the strain at fracture, is shown to be the result of the complementary relationship between the elastic strain and the delayed elastic strain. Delayed elasticity, associated with grain boundary sliding, dominates the deformation process as the grain size decreases.

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TABLE 1

Creep Parameters for Ice Obtained from Earlier
Creep Experiments [8,9].

E	$= 9.5 \text{ GN}\cdot\text{m}^{-2}$;	$G = 3.8 \text{ GN}\cdot\text{m}^{-2}$;
Q	$= 67 \text{ kJ/mol}$	$c_1 = 9$;
d_1	$= 1 \text{ mm}$;	$s = 1$; $n = 3$; $b = 0.34$;
a_T	$(T = 263 \text{ K}) = 2.5 \times 10^{-4} \text{ s}^{-1}$;	
$\dot{\epsilon}_{v_1}$	$= 1.76 \times 10^{-7} \text{ s}^{-1}$;	$\sigma_1 = 1 \text{ MN}\cdot\text{m}^{-2}$, $T = 263 \text{ K}$.

FIGURE 1

FIGURE 3

FIG. 3 Dependence of failure strain on grain size

FIGURE 2

FIG. 1 Grain size dependence of fracture strain measured between the top and bottom platens from [2,3]; (N) indicates necked-down samples.

FIG. 2 Dependence of tensile strength of granular ice on stress rate and grain size

FIGURE 4

FIG. 4 Stress-strain diagram for tension tests on granular ice at 263 K

FIGURE 5

FIGURE 6

FIG. 5 Computed strain components and the total strain for test No. 54

FIG. 6 Grain size dependence of the contribution of elastic strain, delayed elastic strain and viscous strain to the total strain at fracture

FIGURE 7

FIG. 7 Stress and strain history for S-2 ice during loading and unloading

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