Mechanical Properties of Polymers under Electron Irradiation

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Synopsis

The Zhurkov approach to the strength of solids has been applied to polystyrene under electron irradiation. The results indicate that Zhurkov modeling may be applied to predictions of mechanical property behavior under various electron fluxes.

INTRODUCTION

The behavior of materials under ionizing radiation is of continuing concern because of its practical importance. With the increased use of advanced materials such as graphite/epoxy composites, especially in spacecraft, predicting lifetime of any mechanical property is of prime importance.

In approaching this problem in the laboratory, generally an irradiated polymer is removed from the radiation source and tested in some other place. As a consequence, there is a considerable lapse in time as well as the potential for contamination, for example, with oxygen. Also, it is well known that irradiation of a polymer results in the formation of free radicals. In order to model such a procedure, the kinetics of radical reaction as well as the chemistry is required. In the solid state the complexities of such reactions are compounded making the predictive task almost hopeless. The purpose of this communication is to show that under the appropriate conditions, i.e., testing while under irradiation, which in a practical case is similar to a spacecraft maneuver under space irradiating conditions, it may be possible to predict mechanical properties.

Recently a detailed discussion[1] of the Zhurkov approach to the strength of solids was presented, and thermodynamic considerations[2] developed the method from a more rigorous basis. Zhurkov's method determines the time to failure under constant stress (here defined as creep rupture). It has been shown[3] that the Zhurkov method can also be applied to a variety of mechanical properties.

The purpose of the present communication is to give another example of the versatility of the Zhurkov approach. A literature search uncovered only one study in which irradiation and property testing were carried out concurrently.[4] Data from this study will be discussed here in the Zhurkov framework.

BACKGROUND

Zhurkov developed his creep rupture method by successfully applying his relationships to a variety of materials. The relationships of Zhurkov are

$$\tau = A\, e^{-\alpha\sigma} \quad \text{(at constant temp)} \tag{1}$$

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$$\tau = \tau_0 \, e^{U^*/kT} \quad \text{(at constant stress)} \tag{2}$$

which may be combined into the well-known form

$$\tau = \tau_0 \, e^{(U_0 - \gamma\sigma)/kT} \tag{3}$$

where τ = time to rupture, α = const, A = const, σ = applied uniaxial stress, τ_0 = const, $U^* = U_0 - \gamma\sigma$ (energy), U_0 = an activation energy, γ = const, k = Boltzmann's constant, and T = absolute temperature. According to Zhurkov, when a material behaves according to eqs. (1) and (2), τ_0 is considered to be the period of natural oscillation in the solid (10^{-12} s) and γ is a constant that depends on the structure of the material. Equations (1) and (2) are related through $A = \tau_0 \exp(U_0/kT)$ and $\alpha = \gamma/kT$.

Equation (1) can be used to predict failure times at low loads where the failure times are long. With high load tests at two, or at most three, temperatures the constants of eq. (2) can be evaluated. Prediction of failure times then can be made at other temperatures and loads.

RESULTS

In Ref. 4 the creep rate of polystyrene was studied during irradiation with high energy electrons. Since it was shown earlier[5] that the time to a given strain could be given by the Zhurkov model, creep rate data was extracted from Figures 5 and 9 of Ref. 4 and reciprocals presented below as τ (=time) in order to be consistent with earlier discussions and to clearly show the Zhurkov framework.

Figure 1 shows the relationship of τ with the electron beam current. From this figure, stress data at constant beam current may be extracted. Figure 2 shows the dependence of τ on stress, which is of the form of eq. (1), and clearly under irradiation polystyrene behaves in accordance with the first Zhurkov relationship.

Figure 3 shows the dependence of τ on temperature. The nonirradiated results behave as expected and follow Zhurkov's second relationship. The irradiated specimens behave similarly with no apparent change in activation energy.

Thus both of Zhurkov's equations can be applied to results under irradiation.

DISCUSSION

Even though creep is enhanced under electron irradiation, the response to stress may be formulated within the Zhurkov approach to the strength of solids *not* under ionizing radiation. The results indicate that under these conditions it may be possible to model and therefore predict mechanical property behavior.

The beam current I appears to be related to a temperature. Note that the results of Figure 2 are of the form of Zhurkov's first equation except that beam current rather than temperature is held constant. From Figure

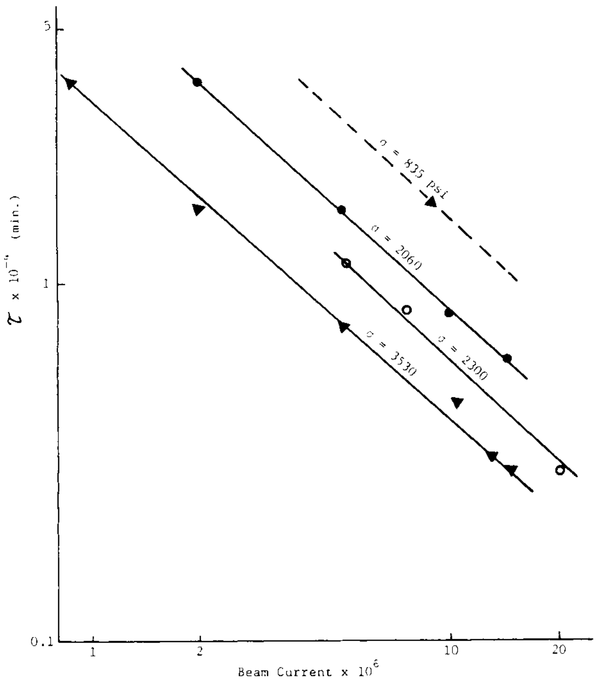

Fig. 1. Dependence of τ on beam current at constant stress: $T = 23.5°C$; (○) 3 MeV; (▲, ●, ▼) 8 MeV.

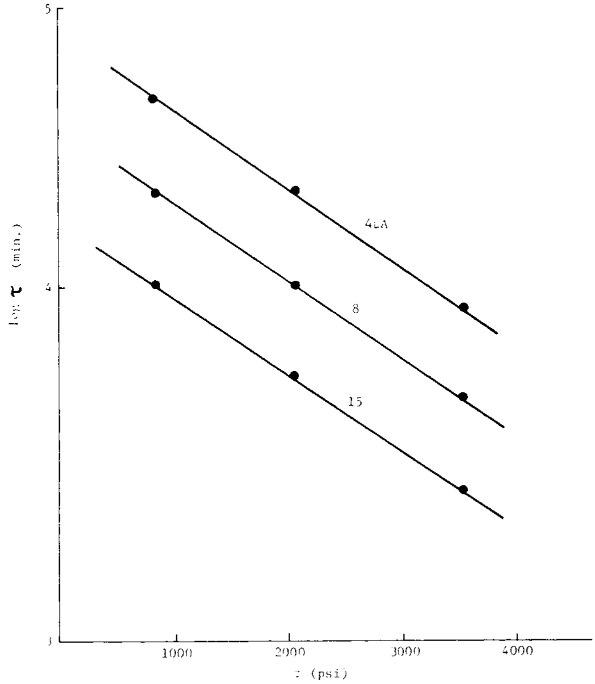

Fig. 2. Dependence of τ on stress at constant beam current: $T = 23.5°C$; 8 MeV.

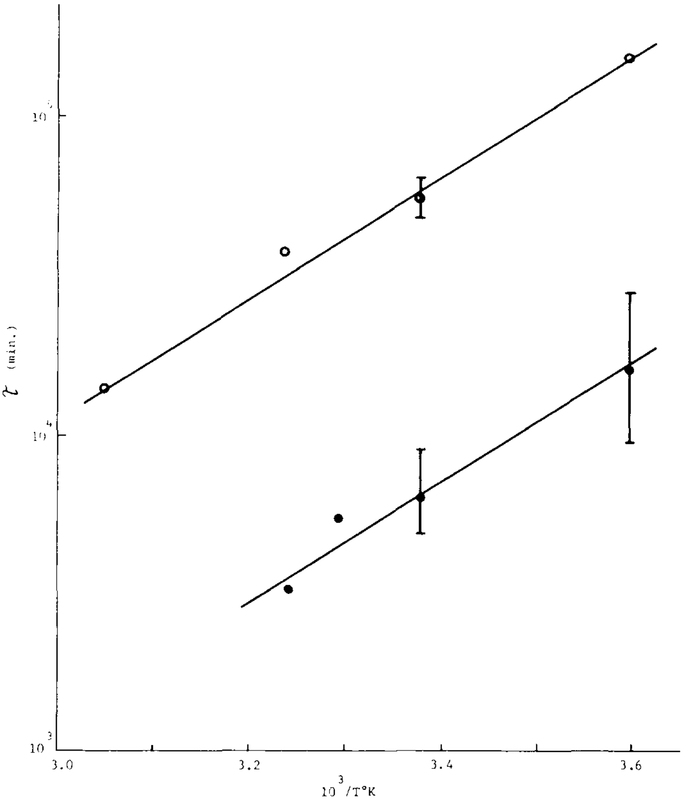

Fig. 3. Temperature dependence of τ: $\sigma = 2060$ psi; (●) 10 μA, 3 MeV; (○) no irradiation.

1, $\tau \propto 1/I$, and, from Figure 3, $\tau \propto U^*/kT$, from which it may be implied that $I \propto e^{U^*/kT}$. However, since current is an electron *rate* which in turn leads to a rate of damage, which is temperature-dependent through an Arrhenius-type rate constant, the implied relationship of current with temperature is superficial and merely reflects a damage/temperature relationship. This relationship, which leads to the enhanced creep observed for specimens under irradiation can be considered as an enhanced temperature at the damage site even though the macroscopic temperature is, presumably, held constant. These comments indicate why, under irradiation, polymers may be expected to behave according to the Zhurkov model for unirradiated specimens.

As suggested in the Introduction, when time lapses between irradiation and test, generally a nonrealistic situation, modeling may be an impossible task since unknown rates of damage healing can take place. More work similar to that carried out in Ref. 4 is required to firmly establish the Zhurkov approach under ionizing conditions. An important part of this would be to study the effect of temperature for more than one stress level (see Fig. 3). The present results do, however, show that under appropriate, more realistic, conditions (i.e., behavior during irradiation) property predictions within the Zhurkov framework are possible.

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