

## **Rheological Aspect of the Plastic Energy Dissipation**

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### **Abstract**

In this paper, the main emphasis and focus will be to study and illuminate the nature of Plastic Energy Dissipation (PED) in variety of polymers. This PED term represents the heat generated during the irreversible deformation of a polymer solid. A series of experiments for various polymers have been conducted in direct measurement method and indirect evaluation method - the incremental strain stress relaxation (ISSR) method. The experimental evidence to relate the stress relaxation and the sensible temperature rise were revealed by the series of direct method experiments.

### **Introduction**

The mechanical behavior of a polymer may deviate from that of ideal elastic solid obeying Hooke's law. These non-idealities are shown in Fig. 1 as a typical stress-strain diagram for a ductile polymer and a brittle polymer. In large deformations, polymer solid exhibits both recoverable as well as irreversible strains due to the viscoelastic nature of solid polymer. Recently, the term Distortional Plasticity has been used to describe such a post yielding region(1). Associated and accompanying such non-recoverable deformations is heat generation during and after deformation, called the Plastic Energy Dissipation (PED) (2,3,4,5), previously referred to as adiabatic heating (6,7,8) and adiabatic bulk temperature rise (9). Kim and Gogos were developed the method which could be evaluated and measured the amount of dissipated energy during the compressive deformation of polymeric materials (5). They also suggested this PED term as a one of major heating and melting mechanism, which play a main role in dissipative mix melting phenomena(3,4). In this paper the evaluation and the measurement method of PED among the total stress power will be discussed in detail. Also how these methods are related to the stress relaxation phenomena will be explained.

### **Theory**

#### **Relaxation Phenomena (Stress Relaxation)**

Relaxation phenomena can be observed in all non-equilibrium systems. Relaxation is the time-dependent return to equilibrium (or to a new equilibrium) after a disturbance. Because, in polymers, relaxation and experimental time, or times of application interests are similar, this time-dependent behavior is of particular importance.

Most polymers behave as viscoelastic solids under deformation. Our attention will be confined to the inelastic deformation in the plastic deformation region. Under

elastic behavior, the material deforms instantaneously under the action of a load and returns instantaneously to its original shape upon removal of the load. We associate the term inelastic with any deviation from elastic behavior. It is important to recognize, however, that the total polymer viscoelastic deformation is always associated with elastic deformation, and so when the term inelastic deformation is used, it is usually being applied to the inelastic part of the deformation.

For an elastic material, the level of the free energy remains constant indefinitely, as long as the external forces remain unchanged. In contrast, when external forces are applied to a liquid, the energy is immediately spent through the irreversible (viscous) deformation, and when the forces are removed, no strain energy is left to be returned, the fluid not returning to any other state. Usually, stress relaxation experiments are interested to study the linear viscoelastic region, but we extend this to the distortional plastic region as defined in Fig. 1. The general procedure for setting a desired strain level in the conventional experiment is to use extremely fast deformation rate up to that value, i.e., the speed is not an interesting variable. But in this work, the speed or rate of deformation is of main interest. Main difference is that a ramp deformation applied for the initial stage of deformation instead of a step deformation in typical response of stress relaxation experiments. In the step application of the strain, no stress relaxation occurring during the deformation; when the strain is applied at a constant rate, stress relaxation may occur during ramp deformation, depending on the relaxation time of particular motions.

Now considering the relaxation experiments at different strain levels (ISSR: Incremental Strain Stress Relaxation Experiment). As shown in Fig 2, the apparatus cross-head stops at different times, i.e., different strain levels, and sustains its position for a long period of time. Stress relaxation may occur to different amount as shown on Fig. 2b, which depicts stress relaxation starting at time  $t_0$ . Then the viscous part  $\sigma_v$  and the elastic part  $\sigma_e$  of stress time after  $t_1 = \lambda$  can be evaluated easily. Fig. 2c shows converting stress-time relationship to stress-strain chart. If we specify the evaluation time after relaxing the stress, the following relationship is hold at any evaluation points

$$\sigma_0(\epsilon) = \sigma_e(\epsilon) + \sigma_v(\epsilon) \quad (1)$$

## **Experimental**

Two different methods were used; the direct temperature measurement and the indirect PED evaluation. These methods and the experimental devices and the procedures can be found in the other references (3,5). The experiments were conducted with three amorphous polymers (PS, PC and SAN) and three semicrystalline polymers (PP, HDPE and LDPE).

## **Results and Discussions**

### **Direct Measurement of PED**

From the experiment of the direct method, the following comment pertain on the behavior observed:

1. Noticeable temperature rise is observed after the yield strain. Temperature rises are different in different polymers, but the amount of temperature rise increases as strain increases after the yield strain of each material.
2. The amount of temperature rise and the amount of work energy input bear no direct relationship. Comparing the work energy input for the PS and the PC up to a strain of 1.0, the work energy input of the PC is larger than that of PS. However the temperature rise of PS is larger than that of PC.
3. A very brittle polymer like PS under tension shows ductile deformation and yield behavior under compression.

#### Effects of the thermal diffusivity on the PED Measurement

Two heat related phenomena occurred during the experiment: generation mainly during deformation but also during relaxation, and diffusion of the generated heat into the environment. The two effects are competing, one raising, the other reducing the sample temperature. To evaluate the two effects, it is useful to use the Fourier number ( $F_0$ ), defined as the ratio of the heat conduction rate to the rate of thermal energy storage in a solid.

$$F_0 = \alpha t_{\text{exp}} / l^2 \quad (4)$$

where  $\alpha$  is thermal diffusivity,  $l$  is a characteristic length, half of the specimen thickness. Fig. 3 plots the Fourier number versus the amount of compression at various cross-head speeds and an assumed thermal diffusivity of all polymers  $10.0 \times 10^{-4} \text{ cm}^2/\text{sec}$ . If the cross-head speed is fast, then  $t_{\text{exp}}$  is small and for  $F_0 \ll 1$  and the effects of conduction can be neglected (curve C; 25.4 cm/min). As a consequence, the temperatures obtained from the 25.4 cm/min cross-head speed experiments are unaffected by thermal conduction. But when the cross-head speed is very slow, the Fourier number is large (curve A; 0.254 cm/min), and the effect of heat diffusion away from the specimen can not be neglected. The temperature rise obtained from such speed is smaller than the actual temperature rise. Such medium cross-head speeds (curve B; 2.54 cm/min) in the beginning of compression, the effects of heat diffusion are negligible. They can not be neglected later on. It also shows that the above discussion is valid when the deformation speed are fast enough..

Fig. 4 shows the stress-time data for polystyrene specimens subjected to compressive deformation at cross-head speed 25.4 cm/min (curve A) and 2.54 cm/min (curve B). Each sample is compressed to a Cauchy strain of 0.28 (Hencky strain 0.34) attained at times  $t_{dA}$  and  $t_{dB}$ , respectively. This strain level is then maintained constant where upon stress relaxation occurs. During the deformation process, up to time  $t_d$ , PS deforms, cold flows and undergoes internal stress relaxing flows.

Both the yield stress and the stress at  $t_d$  are similar for the cross-head speeds 2.54 and 25.4 cm/min. What are drastically different for the two speeds are:

1. The rates of the stress decay or stress relaxation is very rapid for 25.4 cm/min.
2. The amount of stress decay 60 seconds later, being 70 % (50/72) for 25.4 cm/min and 50 % (38/72) for 2.54 cm/min.

As seen on Figs. 5 and 6, the temperature rise at  $t = t_d$  as measured by the imbedded thermocouples, on the other hand, is only 4 °C for the rapid compression and 12 °C for the 25.4 cm/min. Part of the reason for the low temperature rise at

td for 25.4 cm/min is the sluggishness of the thermocouple, with a  $t_{tc} \sim 0.15$  sec. But an important reason is also the amount of stress relaxation during deformation, which contributes to the temperature rise, as is discussed below.

When a viscoelastic material undergoes the phenomenon of stress relaxation, it does so because internal irreversible chain segmental motions take place. Some of these motions are rapid (and thus have a small relaxation time), some take longer and the rest, which involve entire chain motions and flows may have very long relaxation times. We are interested in short relaxation (solid like) phenomena. Turning to Fig. 6, and in the particular instant,  $t_R=8.5$  seconds denotes the short relaxation time when a very slow linear drop in stress commences for the slow cross-head speed 2.54 cm/min. But for the fast speed, the time of  $t_R$  corresponds only 1.4 seconds.

Let us examine the temperature rise during the time interval from  $t_d$  (or  $t_d+t_{tc}$ ) to  $t_R$  for both cross-head speeds:

1. For 2.54 cm/min most of the temperature rise has taken place at  $t_d=4$  seconds; namely 13 °C out of the maximum of 14 °C.
2. On the other hand, for the fast cross-head speed of 25.4 cm/min, the temperature rise at  $t_d=0.6$  seconds is only 8 °C out of the maximum temperature rise of 15 °C, that is only 50 % of the maximum.

The reason for this difference is that for the rapid deformation, very little stress relaxation (irreversible internal chain motion) have time to take place and most of the temperature rise is due to the deformation itself. Upon cessation of the deformation a great deal of stress relaxation occurs almost 70% of the stress and it occurs is less than 3 seconds.. This massive stress relaxation inducing internal motions give rise to twice the temperature rise observed during deformation, from 8 °C to 15 °C. On the other hand, there is almost no increase of the temperature rise after  $t_d$ , indicating that the irreversible stress relaxing motion of chains/chain segments and the irreversible deformation-induced chain segment motions occur during the deformation time which is 4 seconds and 0.6 seconds as in the 25.4 cm/min compression. At any rate in around 4~5 seconds whether concurrently or sequentially, the deformation induced and the stress relaxation inducing irreversible motions add up to a total of 14 to 15 oC temperature rise for both rates of compression. As follows the main material property which governs the PED is  $\sigma_v$  rather than  $\sigma$ . The value of  $\sigma_v$  are obtained from the incremental strain stress relaxation method (ISSR) and the value of  $\sigma$  can be obtained from normal stress-strain experiment, respectively. As already noted these  $\sigma_v$  are a function of time after motion cessation, but in the fast motion the vast amount of stress relaxation occurs after 4~5 seconds. Later that the net effect of temperature rise can be diminished by the concurrent heat conduction effect.

## **Conclusion**

The nature of PED by examining the stress-strain, stress relaxation and heat generation behavior of viscoelastic solid polymer was studied. The resulting temperature increases were measured directly by the imbedded thermocouple(s) and

evaluated indirectly by integrating the viscous portion of the stress  $\sigma_v$  up to the deformation of interest using the incremental strain stress relaxation (ISSR) method. It was concluded that the sensible temperature rise are associated with internal frictional motion which involve translation migration flow of chain segments during the deformation and the stress relaxation stage which deduced from the stress-strain behavior and the temperature rise behavior in direct method. The movements of chain segments generate heat, which increase the temperature. Only recoverable chain movements are stored in chain configurations as a higher internal energy. Very slow relaxation chain segmental motions, although they may result in a very small-dissipated power. During the time heat diffusion occurs concurrently and, thus, no measurable temperature rise can be detected.

**References**

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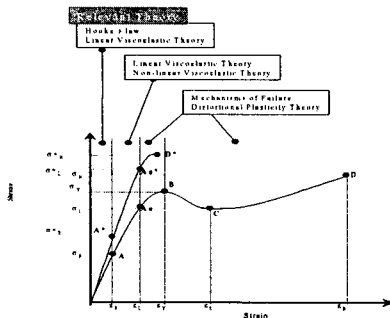


Fig. 1 Schematic representation of the tensile stress as a function of strain and the relationship with the theory to explain the phenomena involving various stage of deformation.

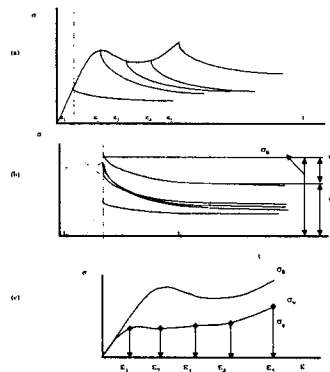


Fig. 2. Schematic representations of obtaining elastic part and viscous part of stress from stress relaxation experiment.

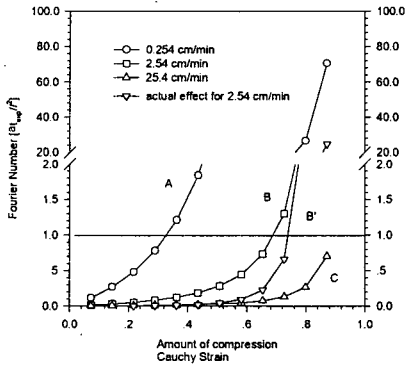


Fig. 3. Fourier number for uniaxial compression experiments carried out at different strain rates and to different strains. The thermal diffusivity is assumed to be  $10.0 \times 10^{-4} \text{ cm}^2/\text{sec}$ .

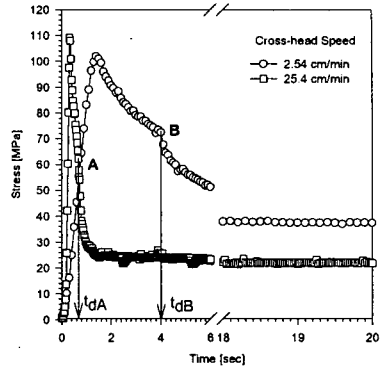


Fig. 4. Stress [MPa] versus time [sec] for a PS under uniaxial compression at the room temperature for a slow and a fast compression.

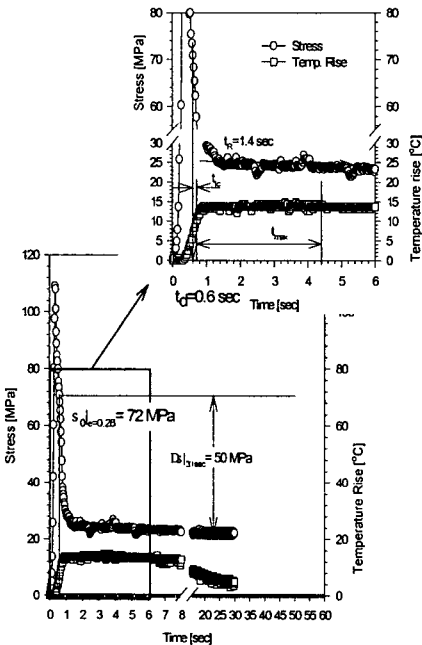


Fig. 5. Stress [MPa] versus time [sec] and temperature rise versus time plot for a polystyrene under uni-axial compression to 0.28 Cauchy strain, followed by stress relaxation; cross-head speed 25.4 cm/min

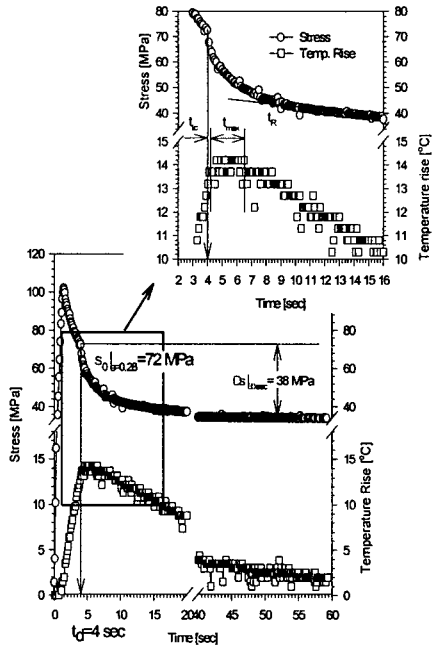


Fig. 6. Stress [MPa] versus time [sec] and temperature rise versus time plot for a polystyrene under uni-axial compression to 0.28 Cauchy strain, followed by stress relaxation; cross-head speed 2.54 cm/min.