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On the conversion of plastic work to heat during high strain rate deformation of glassy polymers

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Abstract

It has long been known that the mechanical energy of plastic deformation tranforms partly into heat (ratio β_{int}) which can cause noticeable temperature rise under adiabatic conditions. Less is known about the *rate* of conversion of these quantities (ratio β_{diff}). High strain rate deformation of metals was recently investigated by Mason et al. (1994) and Kapoor and Nemat-Nasser (1998). The former investigated the rate ratio β_{diff} and observed a strain and strain rate dependence. The latter investigated β_{int} and concluded it is constant and equal to 1. Temperature measurement was made using infrared techniques. We investigate the thermomechanical behavior of glassy *polymers* (PC) deformed at strain rates ranging from 5000 to 8000 s^{-1}. The temperature is assessed using small embedded thermocouples whose applicability to transient measurements has been recently revisited (Rittel, 1998a). Our results show a definite dependence of both β factors on the strain and strain rate. We also observe that whereas the overall ratio (β_{int}) of the converted energy remains inferior to 1 as expected, the rate ratio (β_{diff}) may reach values superior to 1 at the higher strain rates. This original observation is rationalized in terms of a decrease of the stored energy of cold work which corresponds to the softening regime of the stress strain curve. This additional energy transforms into heat thus causing the observed values of β_{diff}. While the present observations apply to a glassy polymer, it can reasonably be assumed that they apply to the broader context of strain softening.

Keywords: Glassy polymer; Strain softening; Thermomechanical coupling; High strain rate; Temperature rise

1. Introduction

Since the early works of Farren and Taylor (1925) and Taylor and Quinney (1934) it is well established that plastic work invested in deforming a material transforms partly into heat. These authors measured this fraction and found that it is of the order of 0.9 for their copper specimens. Since the mechanical properties of engineering materials are temperature dependent, estimates of the temperature rise are quite important to determine the material's response. The nature of the thermal problem determines the temperature rise: if the generated heat flows away, little temperature rise will be noticed ("isothermal" conditions). On the other hand when adiabatic conditions prevail, the temperature can rise noticeably, as in the case of adiabatic shear bands (see, e.g., Marchand and Duffy, 1988). The transient heat equation expresses the relationship between the heat generation rates and the spatial-temporal variation of the temperature as follows:

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$$k\nabla^2 T - \alpha(3\lambda + 2\mu)T_0\dot{\varepsilon}^{\mathrm{e}}_{kk} + \beta\sigma_{ij}\dot{\varepsilon}^{\mathrm{p}}_{ij} = \rho c\dot{T}, \tag{1}$$

where k is the heat conductance and α the thermal expansion coefficient. ρ, c, λ and μ stand for the material's density, heat capacity and Lamé constants, respectively. The superposed dot indicates time derivative. T is the temperature and the strain rates $\dot{\epsilon}$ are divided into elastic and plastic. Finally the factor β expresses the fraction of the mechanical power converted into thermal power. If adiabatic conditions prevail ($k\nabla^2 T = 0$) as in the case of high strain rate loading, and if the elastic contribution is neglected too, Eq. (1) writes simply,

$$\beta_{\mathrm{diff}}(\epsilon)\,\mathrm{d}\dot{W}_{\mathrm{p}} = \rho c\dot{T}. \tag{2}$$

In Eq. (2) the subscript "diff" has been added to the β factor to emphasize the relationship between rate quantities, and $\dot{W}_{\mathrm{p}}$ stands for plastic work rate (power). Mason et al. (1994) investigated the strain rate dependence of β_{diff} for different metals tested at high loading rates.Very recently, Kapoor and Nemat-Nasser (1998) addressed the problem for additional metals tested at high strain rates too. They showed that the actual sample temperature is not accurately measured by infrared techniques. In their work, Kapoor and Nemat-Nasser (1998) investigated a factor η (subsequently noted β_{int} in Eq. (3)) equal to the total ratio of the mechanical energy converted into heat, as in Taylor and Quinney (1934). They concluded that one can reasonably assume that all of the plastic work is converted into heat.

At this point it is important to emphasize one additional distinction in order to avoid possible confusion between the two terms. When the thermal work is plotted as a function of the mechanical work, β_{int} is the secant slope and β_{diff} is the tangent slope according to

$$\beta_{\mathrm{diff}}(\epsilon) = \frac{\rho c\dot{T}}{\mathrm{d}\dot{W}_{\mathrm{p}}} \quad \text{and} \quad \beta_{\mathrm{int}}(\epsilon) = \frac{\rho c\,\Delta T}{\int \mathrm{d}W_{\mathrm{p}}}. \tag{3}$$

While β_{int} can be used to determine the global temperature rise of a given material, β_{diff} is required in a constitutive description of this material. Most of the available references on the subject address essentially metals where the underlying problem is that of the stored energy of cold work (Bever et al., 1973; Bodner and Lindenfeld, 1995).

By contrast, relatively little information is available on the thermomechanical behavior of polymeric materials at high rates of strain. Chou et al. (1973) used thermocouples embedded in polymeric disks to measure temperature rise in various polymers (PMMA, Nylon 6-6, cellulose acetate butyrate). Whereas a definite rise of the temperature with strain was observed, these authors did not rely on the thermocouple as the appropriate sensor at the higher strain rates superior to 45 s^{-1}. Adams and Farris (1988) carried out a detailed investigation of the thermomechanical coupling in polycarbonate using calorimetric techniques. In the range of (low) strain rates of 0.18–1.80 min^{-1} they observed that the fraction of mechanical work converted into heat increases with the strain rate. Trojanowski et al. (1997) used infrared detectors to monitor temperature rise in epoxy specimens tested in a split Hopkinson pressure bar. The strain rate was 2500 s^{-1} and the observed temperature rise reached 40°C. Rittel (1998a) showed that embedded thermocouples can yield reliable information about transient temperature changes which are characteristic of high rate compression tests. This technique was also applied to the investigation of transient crack-tip thermoelastic effects during dynamic crack initiation (Rittel, 1998b). The influence of thermomechanical coupling on the large strain behavior of polymers has been studied and modeled by Arruda et al. (1995).

It should be noted that whereas β_{int} can be determined by (relatively) simple procedures, the determination of β_{diff} requires the numerical differentiation of the temperature record. This is a delicate point, as emphasized by Mason et al. (1994) who used filtering techniques to smooth this derivative.

Consequently, this paper presents our *methodology and results* pertaining to the thermomechanical behavior of a glassy polymer (commercial polycarbonate) loaded in compression at high strain rates (5000–8000 s^{-1}). Specifically, we use embedded themocouples to record the evolution of the temperature and adequately devised filtering procedures to determine the evolution of β_{int} and β_{diff} with strain and strain rate. The point of view adopted here is purely phenomenological as no attempt is made to provide an underlying micromechanical model for the observed results.

The paper is organized as follows: in Section 2 we describe the experimental setup and the specimens. In Section 3 we describe and discuss the various stages and results of a typical experiment. We then present characteristic results for the strain and strain rate dependence of the β factors of additional specimens. Section 4 is dedicated to a brief discussion of the main results of this work to be followed by a concluding section.

2. Experimental

2.1. Specimens and data recording

Commercial polycarbonate (PC) disks with average diameter of 10 mm and thickness of 2–5 mm were turned out of a plate. A 4 mm long 0.3 mm diameter radial hole was drilled at mid-thickness of the disk to allow embedding of the sensing tip of a T-type (copper–constantan) thermocouple. The thermocouple wire was 127 μm in diameter. The thermocouple was carefully sealed with home made liquid polycarbonate to provide optimal thermal matching. A total of 30 disks were tested.

The experiment consisted of sandwiching the disk between two 12.5 mm diameter instrumented steel bars (Kolsky apparatus) to record the applied stress and temperature pulses, as shown in Fig. 1. The characteristic impact velocity was around 20 m/s. The strain gage and thermocouple signals were recorded simultaneously on a Nicollet 490 digital (12 bit) oscilloscope. Both signals were fed directly and differentially into the scope. Relevant data about the selected specimens presented in this work has been gathered in Table 1.

The stress–strain characteristics of each disk was determined using standard procedures (see e.g., Mason et al., 1994) and corrections for geometric dispersion (Lifshitz and Leber, 1994). As the specimens used were relatively thin, a comparison of the forces applied on both sides of the specimen showed in each case that the assumption of homogeneous deformations was reasonable.

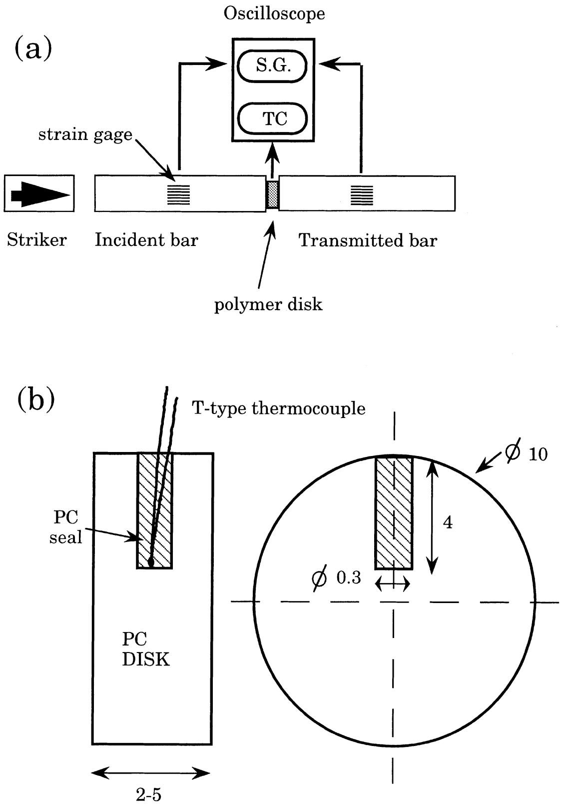

Fig. 1. Experimental setup and specimen geometry. The disk specimen is inserted between instrumented bars. A thermocouple is embedded in the specimen to record transient temperature changes. The boundary conditions on the specimen's faces are determined from the incident (reflected) and transmitted bar gage signals. All dimensions are in mm.

3. Results

3.1. Data reduction and methodology

In this section, we will show and discuss results from one characteristic experiment (disk41) to illustrate our methodology. This specimen can be considered as representative and it was not selected for aesthetic considerations only. Throughout this work a typical constant value of ρc was taken as $\rho c = 10^6$ J/m^3/K (Ashby, 1992).

Characteristic "raw" signals are shown in Fig. 2. The incident pulse reaches the specimen after a typical travel time of 71 μs. The signal is partly reflected and partly transmitted through the

Table 1
Experimental data about the three specimens presented in this work

Disk	d_0 [mm]	t_0 [mm]	$(\bar{\dot{\epsilon}})_{\text{nom}}$ [s^{-1}]	V_{imp} [m/s]	max ϵ_t	max ΔT [°C]	max β_{int}	max β_{diff}
Epoxy	9.00	5.50	2500	–	0.60	40	0.15	0.25
43	10.30	2.42	5000	18	0.43	14	0.4	1.05
41	10.09	2.06	6500	19	0.48	29	1.0	2.25
34	10.18	2.04	8000	21	0.61	37	1.0	2.25

d_0 and t_0 are the initial diameter and thickness, respectively. Also indicated is the impact velocity (V_{imp}), the maximum strain achieved and the corresponding recorded maximum temperature rise. The average nominal strain rate is indicated along with the peak values recorded for the two β factors. The results of Trojanowski et al. (1997) who used infrared techniques are included for epoxy resin.

disk to the transmitted bar. The thermal signal from the embedded thermocouple is quiet until a short time after the stress wave loads the specimen. Then, a noticeable temperature rise is evidenced. The maximum temperature rise in these experiments did not exceed 40°C. The assumption of the adiabatic regime during such tests has been justified in a previous report by Rittel (1998b) who observed that the temperature rose in a steplike manner and remained constant over several hundreds of microseconds. In these experiments, the disks were thicker whereas in the present experiments the thinner disks shattered in numerous cases. As a result the temperature dropped upon completion of the loading as the sensing tip is exposed to air. In some experiments where the disk did not shatter immediately, the temperature pattern reproduced the previous observations of a steplike temperature variation.

In Fig. 3 a characteristic true stress–true strain curve is shown along with the recorded temperature rise. The stress–strain curve has been smoothed by filtering the high frequency oscillations which are characteristic of high strain rate testing experiments with the Kolsky bar. The stress–strain curve exhibits two interesting characteristics: firstly a rather large “macroscopically” linear domain exists which extends to strains of the order of $\epsilon = 0.1$. Such domain is commonly observed for polymers (Kolsky, 1949) and was also

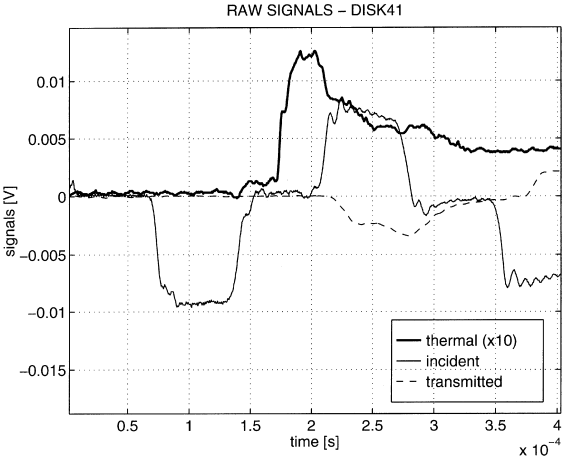

Fig. 2. Raw signals for a typical experiment (disk 41). The incident pulse reflects partly upon reaching the specimen after 71 μs and gets partly transmitted through the disk. Shortly after the disk is loaded, a noticeable temperature rise is detected. The temperature usually settles after the rise unless the specimen fractures thus exposing the sensing junction to air (as in the present case).

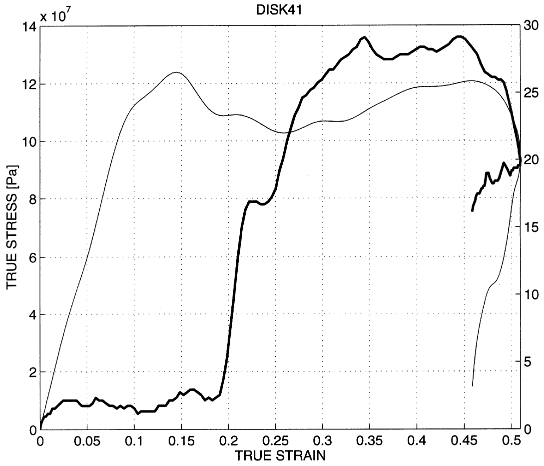

Fig. 3. True stress–true strain and temperature record for disk 41. The temperature rises significantly in the softening region of the stress–strain curve.

reported for PC (Steer et al., 1985). This domain is one order of magnitude greater than the typical linear elastic domain of metals. However, no further comparison is established as it is well known that the Kolsky apparatus is not ideally suited for the determination of dynamic elastic properties. Secondly, following macroscopic yielding, a pronounced softening domain is noticed up to a strain of about 0.3 beyond which the material strain hardens. This behavior has been noted in many other works and it has been related to the combined operation of material softening and thermal softening (Arruda et al., 1995). The respective extent of the strain softening and hardening regions is strain rate dependent. The temperature record does not rise significantly below 0.2 strain beyond which it rises steeply and levels off before dropping (eventually). The noticeable temperature rise corresponds to the strain softening region of the stress–strain curve (strains between 0.2 and 0.35 for this specimen).

In Fig. 4 we have plotted the thermal work ($\rho c\ \Delta T$) as a function of the plastic work ($\int \sigma\ \mathrm{d}\epsilon_p$). The plastic work is defined as the total work minus the work corresponding to the end of the linear domain and the temperature rise has been corrected to subtract the corresponding "elastic" temperature rise. As previously stated, the tangent and the secant slopes of such plot define β_{diff} and β_{int}, respectively.

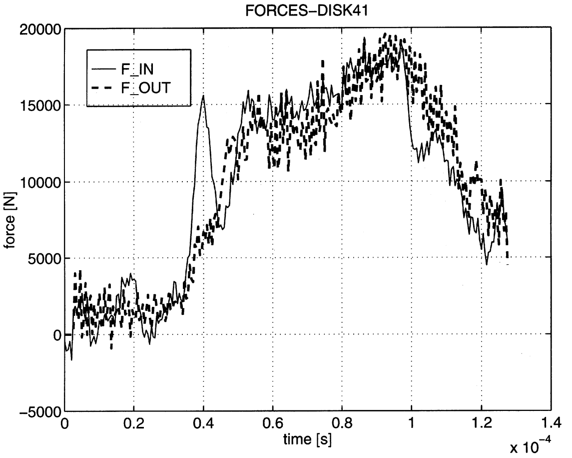

Fig. 5. Input and output forces for disk 41. The forces are quite similar, thus justifying assumptions of homogeneous deformation.

In Fig. 5 are shown the forces on both sides of the impacted disk, and it can be noted that the assumptions of equilibrium are reasonable as both forces are rather similar. Fig. 6 is a plot of the true stress–true strain characteristics of the disk. The large linear domain shows that the elastic work term is not negligible and it must be subtracted

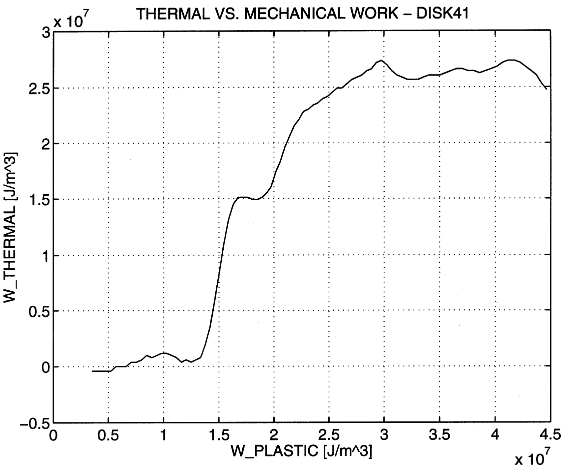

Fig. 4. Thermal work ($\rho c\ \Delta T$) vs. plastic work ($\int \sigma\ \mathrm{d}\epsilon_p$) for disk 41. The tangent and the secant slopes of such plot define β_{diff} and β_{int}, respectively.

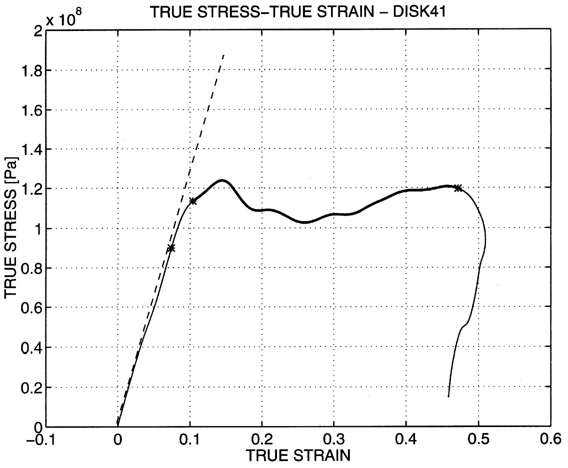

Fig. 6. True stress–true strain curve for disk 41. The linear domain and its extent are indicated by the dotted line and the first asterisk. The bold part bounded by the two other asterisks indicates the studied domain of the stress–strain curve.

from the overall work. The bold part of the stress–strain curve is selected to assess the β factors. The determination of β_{diff} requires the derivative of the temperature with respect to time (or strain). As this derivative is inherently noisy, Mason et al. (1994) used a specific smoothing algorithm to perform this derivative. In this work we adopt the same approach based on a slightly a different procedure. The idea is to examine the spectral content of the temperature signal and determine a cutoff frequency below which the essential information is found. A numerical low-pass filter is then designed accordingly (Butterworth filter, MATLAB, 1994). Fig. 7 shows the power spectrum of the temperature signal shown in Fig. 3. This plot shows distinctly that little information is available beyond a normalized frequency superior to 0.07. The original and filtered signals are shown in Fig. 8 and it can be noted that the filtered signal retains the salient features of the original temperature record without the noisy component.

In Fig. 9 are plotted the nominal strain rates of three selected disks. Disk 34 was deformed at the higher nominal strain rate of about 8000 s^{-1} while disks 41 and 43 were deformed at nominal strain rates of about 6500 and 5000 s^{-1}, respectively. The evolutions of the β factors can now be determined according to Eq. (3), as shown next.

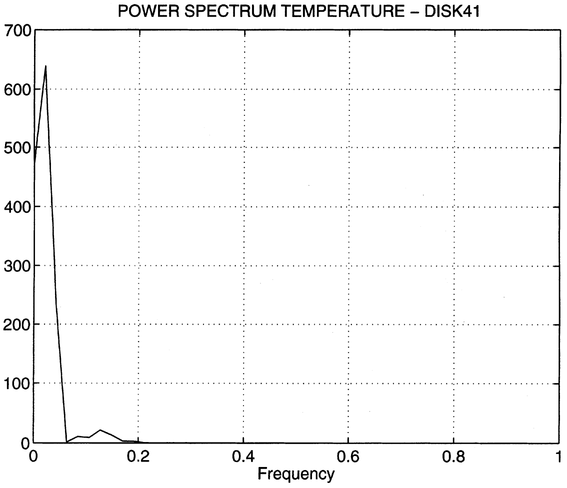

Fig. 7. Power spectrum of the temperature record shown in Fig. 3 for disk 41. The highest frequency is Nyquist frequency and it is noted that most of the information lies in the frequency domain below 0.07.

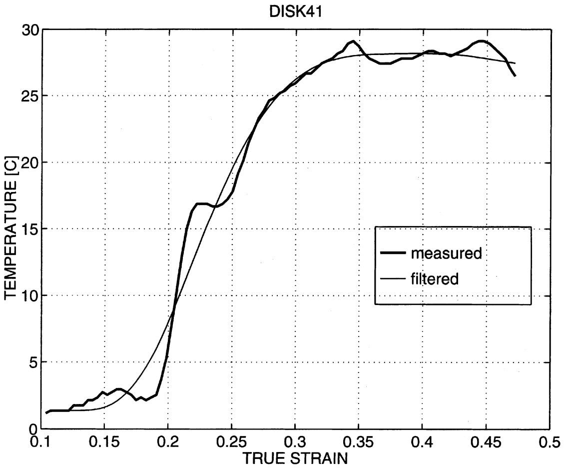

Fig. 8. Original and (low-pass) filtered reconstruction of the thermal signal for disk 41.

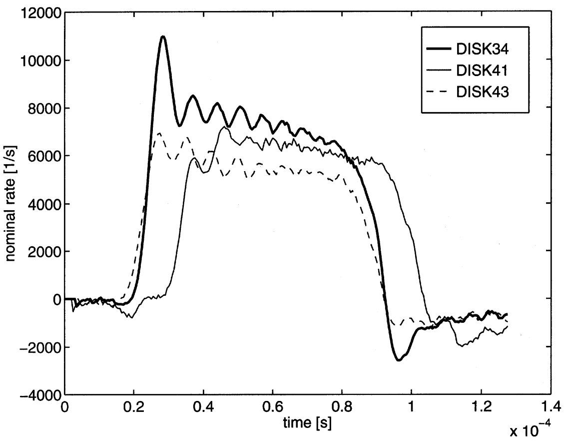

Fig. 9. Nominal strain rates for disk 34, disk 41 and disk 43.

3.2. The β factors

The corresponding evolutions of β_{diff} and β_{int} are plotted in Fig. 10 for the three above mentioned specimens.

The integral factor – β_{int} – varies with strain, as expected. Starting at very low values up to a strain of about 0.2, it reaches rapidly a maximal value in the vicinity of $\epsilon = 0.3$ and then decreases slowly with increasing strain. The same general behavior was noted by Trojanowski et al. (1997) and also by Chou et al. (1973) who reported low temperature rise at low strains followed by a noticeable rise with increasing plastic strain. The peak value reached by β_{int} increases with the strain rate. This observation is consistent with the maximal observed temperature rises, as shown in Table 1. However, β_{int} remains always inferior to 1 *as expected.* The differential factor – β_{diff} – behaves quite differently. Its functional dependence upon strain comprises consecutive gaussian curves. A comparison of the stress–strain characteristics of the various specimens and the corresponding β_{diff} curves showed that the gaussian curves always develop in the softening domain. The peak value reached by β_{diff} increases with the strain rate (Table 1). By contrast to β_{int}, β_{diff} does not remain inferior to 1 and it reaches maximal values superior to 2. Finally, we have applied our approach to the data of Trojanowski et al. (1997) to establish a comparison. As shown in Fig. 11, both values of β_{int} and β_{diff} for their epoxy resin remain smaller than those observed for the present polycarbonate. Two factors are most likely responsible for this difference: the first is the compositional difference and the second is related to the smaller strain rates applied in these experiments (2500 s^{-1}). With this proviso, it may nevertheless be concluded that both β_{int} and β_{diff} are strain and strain rate dependent.

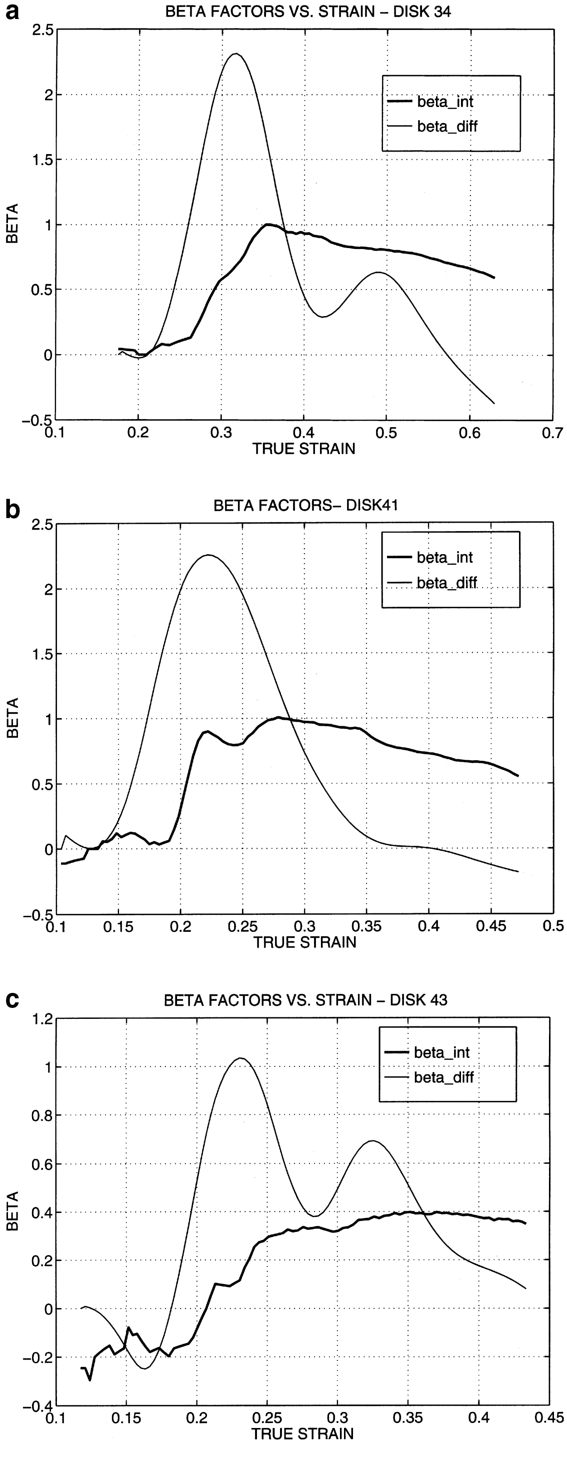

Fig. 10. Evolution of β_{diff} and β_{int} with the true strain for (1) disk 34 at $(\bar{\dot{\epsilon}})_{\text{nom}} = 8500$ s^{-1}, (2) disk 41 at $(\bar{\dot{\epsilon}})_{\text{nom}} = 6500$ s^{-1} and (3) (1) disk 43 at $(\bar{\dot{\epsilon}})_{\text{nom}} = 5000$ s^{-1}.

Fig. 11. Evolution of β_{diff} and β_{int} with the true strain for epoxy disk (Trojanowski et al., 1997) tested at $(\bar{\dot{\epsilon}})_{\text{nom}} = 2500$ s^{-1}.

4. Discussion

The present work reports new results about the nature of the thermomechanical coupling in glassy polymers deformed at high strain rates. Throughout this work, we use relatively simple experimental and numerical techniques based on information provided by small embedded thermocouples. This technique complements noncontact techniques such as infrared temperature monitoring (with its own limitations). However, a more accurate determination of the local strains should account for the possible local strain concentration in the vicinity of the sensing tip. Visual observation of the disks shows that they deform homogeneously on the macroscopic scale. Microscopic examination of the failed disks (Fig. 12) shows a profusion of homogeneously distributed microshear bands. Such bands are characteristic of the deformation of polycarbonate. We did not notice a tendency for clustering of shear bands around the thermocouple tip nor did we observe macroscopic shear bands such as those observed during dynamic fracture of this material (Ravi-Chandar, 1995). Consequently, it can be concluded that while the embedded thermocouple may cause a certain strain concentration, the latter is certainly not severe such as to induce strain localization.

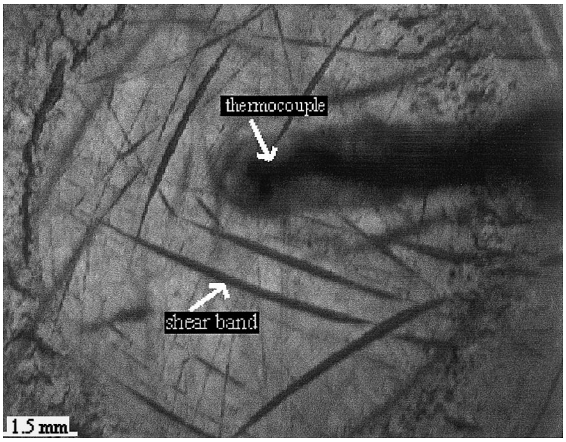

Fig. 12. Through the thickness view of disk 41. This micrograph covers almost the entire disk. A large number of microshear bands is homogeneously distributed in the disk. Lack of shear localization in the vicinity of the thermocouple's tip indicates that there is no marked strain concentration related to the embedded thermocouple.

The results show that both the mechanical to thermal work conversion (characterized by β_{int}) and its rate (characterized by β_{diff}) are dependent upon the strain and strain rate for this polymer. Consequently, the assumption of β_{int} being constant and equal to 1 will only provide an upper bound on the temperature reached. All our observations show that β_{int} remains bounded and inferior to 1 and this is result is quite expectable.

By contrast, our observations show that β_{diff} reaches values which are *superior to* 1. Such result may seem confusing and contradictory as a similar behavior was not reported for metals subjected to impact loading (Mason et al., 1994). In the context of cyclic loading, it should be mentioned that Dillon (1966) performed cyclic torsion experiments on copper tubes. He observed that the "rate of doing plastic work sometimes exceeds the rate of heat generation and vice versa". This observation is identical to our present result.

As noted by Bodner and Lindenfeld (1995), the rate of plastic work ($\dot{W}_{\mathrm{p}}$) equals the dissipation rate ($\dot{D}$) added to the rate of the stored energy of cold work ($\dot{W}_{\mathrm{s}}$). As they looked into cyclic loading, these authors noted (and showed) that the *rate* of the stored energy of cold work can be negative under reversed straining conditions so that $\dot{D}$ will be greater than $\dot{W}_{\mathrm{p}}$. Keeping in mind that β_{diff} is defined as the ratio of $\dot{D}$ to $\dot{W}_{\mathrm{p}}$ (alternatively stated as $\beta_{\mathrm{diff}} = 1 - \dot{W}_{\mathrm{s}}$), the softening regime can be interpreted as corresponding to a decrease in the stored energy of cold work. Such reduction creates additional heat. A similar softening regime was neither reported by Mason et al. (1994) nor by Kapoor and Nemat-Nasser (1998) for their homogeneously deformed metallic specimens subjected to monotonic loading. By contrast, careful examination of Adams and Farris' (Adams and Farris, 1988) data (their Fig. 2) clearly shows a limited strain softening region following yielding. For this monotonically loaded polycarbonate specimen, the corresponding change of internal energy is *globally positive with a negative slope* in the softening region. The measured heating rate increases correspondingly. Consequently, while the present observations relate to the specific mechanical behavior of glassy polymers, similar results are likely to be observed for a metal exhibiting similar softening effects, which are usually associated with thermomechanical instabilites.

5. Conclusions

- The high strain rate thermomechanical behavior of PC has been studied using small embedded thermocouples.
- The total (β_{int}) and rate (β_{diff}) conversion of the mechanical into thermal energy has been assessed for this material in the range of strain rates of 5000–8000 s^{-1}.
- Both β_{int} and β_{diff} are strain and strain rate dependent.
- β_{int} evolves with strain but remains always inferior to 1 as expected.
- β_{diff} exhibits a gaussian dependence in the strain softening domain and its peak value increases with the strain rate.
- The peak values of β_{diff} is greater than 1 at the higher strain rates. This observation corresponds to a decrease of the stored energy of cold work which thus transforms into heat.

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References

Adams, G.W., Farris, R.J., 1988. Latent energy of deformation of bisphenol A polycarbonate. J. Polymer Sci. (part B) 26, 433–445.

Arruda, E.M., Boyce, M.C., Jayachandran, A., 1995. Effects of strain rate, temperature and thermomechanical coupling on the finite strain deformation of glassy polymers. Mechanics of Materials 19, 193–212.

Ashby, M.F., 1992. Materials Selection in Mechanical Design, Pergamon Press, Oxford.

Bodner, S.R., Lindenfeld, A., 1995. Constitutive modelling of the stored energy of cold work under cyclic loading. Eur. J. Mech., A/Solids 14 (3), 333–348.

Bever, M.B., Holt, D.L., Titchener, A.L., 1973. The stored energy of cold work. In: Chalmers, B., Christian, J.W., Massalski, T.B. (Eds.), Progress in Materials Science, vol. 17.

Chou, S.C., Robertson, K.D., Rainey, J.H., 1973. The effect of strain rate and heat developed during deformation on the stress–strain curve of plastics. Experimental Mechanics October, 422–432.

Dillon, O.W., 1966. The heat generated during the torsional oscillations of copper tubes. Int. J. Solids and Structures 2, 181–204.

Farren, W.S., Taylor, G.I., 1925. The heat developed during plastic extension of metals. Proc. R. Soc. CVII, 422–451.

Lifshitz, J.M., Leber, H., 1994. Data processing in the split Hopkinson pressure bar tests. Int. J. Impact Eng. 15 (6), 723–733.

Kapoor, R., Nemat-Nasser, S., 1998. Determination of temperature rise during high strain rate deformation. Mechanics of Materials 27, 1–12.

Kolsky, H., 1949. An investigation of the mechanical properties of materials at very high rates of loading. Proc. R. Soc., Ser. B 62, 676–700.

Marchand, A., Duffy, J., 1988. An experimental study of the formation process of adiabatic shear bands in a structural steel. J. Mech. Phys. Solids 36 (3), 251–283.

Mason, J.J., Rosakis, A.J., Ravichandran, G., 1994. On the strain and strain rate dependence of the fraction of plastic work converted into heat: an experimental study using high speed infrared detectors and the Kolsky bar. Mech. Mat. 17, 135–145.

MATLAB, 1994. Signal Processing Toolbox User's Guide. The MathWorks, Natick, MA.

Ravi-Chandar, K., 1995. On the failure mode transitions in polycarbonate under dynamic mixed mode loading. Int.J. Solids and Structures 32 (6/7), 925–938.

Rittel, D., 1998a. Transient temperature measurement using embedded thermocouples. Exp. Mech. 38 (2), 73–79.

Rittel, D., 1998b. Experimental investigation of transient thermoelastic effects in dynamic fracture. Int. J. Solids Structures 35 (22), 2959–2973.

Steer, P., Rietsch, F., Lataillade, J.L., Marchand, A., El Bounia, N.E., 1985. Viscoplasticité dynamique de polycarbonates aux grandes vitesses de déformation. Relations structure-propriété. J. Physique Coll. C5 Suppt no. 8 tome 46, 415–423.

Taylor, G.I., Quinney, H., 1934. The latent energy remaining in a metal after cold working. Proc. R. Soc., Ser. A 143, 307–326.

Trojanowski, A., Ruiz, C., Harding, J., 1997. Thermomechanical properties of polymers at high rates of strain. J. Phys. IV France 7, C3-447–C3-452.