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

D. Rittel ¹

Faculty of Mechanical Engineering, Technion Israel Institute of Technology, 32000 Haifa, Israel

Received 20 February 1998; received in revised form 12 August 1998

Abstract

It has long been known that the mechanical energy of plastic deformation transforms partly into heat (ratio \( \beta_{\text{int}} \)) which can cause noticeable temperature rise under adiabatic conditions. Less is known about the rate of conversion of these quantities (ratio \( \beta_{\text{diff}} \)). 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 \( \beta_{\text{diff}} \) and observed a strain and strain rate dependence. The latter investigated \( \beta_{\text{int}} \) 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 \( \beta \) factors on the strain and strain rate. We also observe that whereas the overall ratio (\( \beta_{\text{int}} \)) of the converted energy remains inferior to 1 as expected, the rate ratio (\( \beta_{\text{diff}} \)) 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 \( \beta_{\text{diff}} \). While the present observations apply to a glassy polymer, it can reasonably be assumed that they apply to the broader context of strain softening. © 1999 Elsevier Science Ltd. All rights reserved.

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:

¹ E-mail: rittel@dany.technion.ac.il

0167-6636/99 – see front matter © 1999 Elsevier Science Ltd. All rights reserved.

PII: S 0 1 6 7 - 6 6 3 6 ( 9 8 ) 0 0 0 6 3 - 5
where \( k \) is the heat conductance and \( z \) the thermal expansion coefficient. \( \rho, c, \lambda \) and \( \mu \) 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 \( \dot{\varepsilon} \) are divided into elastic and plastic. Finally the factor \( \beta \) 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,

\[
\beta_{\text{diff}}(\dot{\varepsilon}) \frac{d\dot{W}_p}{dt} = \rho c \dot{T},
\]

In Eq. (2) the subscript "diff" has been added to \( \beta \) to emphasize the relationship between rate quantities, and \( \dot{W}_p \) stands for plastic work rate (power). Mason et al. (1994) investigated the strain rate dependence of \( \beta_{\text{diff}} \) 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 \( \eta \) \((\text{subsequently noted } \beta_{\text{int}} \text{ in Eq. (3)})\) 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, \( \beta_{\text{int}} \) is the secant slope and \( \beta_{\text{diff}} \) is the tangent slope according to

\[
\beta_{\text{diff}}(\varepsilon) = \frac{\rho c \dot{T}}{\dot{W}_p} \quad \text{and} \quad \beta_{\text{int}}(\varepsilon) = \frac{\rho c \Delta T}{\int dW_p}.
\]

While \( \beta_{\text{int}} \) can be used to determine the global temperature rise of a given material, \( \beta_{\text{diff}} \) 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 \((\text{Bever et al., 1973; Bodner and Lindenfeld, 1995})\). 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 \((\text{low})\) strain rates of 0.18–1.80 \( \text{min}^{-1} \) 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 \((\text{Rittel, 1998b})\). 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 \( \beta_{\text{int}} \) can be determined by \((\text{relatively})\) simple procedures, the determination of \( \beta_{\text{diff}} \) 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 \((5000–8000 \text{ s}^{-1})\). Specifically, we use embedded thermocouples to record the evolution of the temperature and adequately devised filtering procedures to determine the evolution of \( \beta_{\text{int}} \) and \( \beta_{\text{diff}} \) with strain and strain rate. The point of view adopted here is purely phenomenological as no
an attempt is made to provide an underlying micro-
 mechanical model for the observed results.

The paper is organized as follows: in Section 2 we
describe the experimental setup and the speci-
cmens. 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 $\beta$ 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) ther-
mcouple. The thermocouple wire was $127$ $\mu$m 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
generic 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 as-
sumption of homogeneous deformations was
reasonable.

3. Results

3.1. Data reduction and methodology

In this section, we will show and discuss results
from one characteristic experiment (disk41) to il-
lustrate our methodology. This specimen can be
considered as representative and it was not se-
lected for aesthetic considerations only. Through-
out this work a typical constant value of $\rho c$ 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 $71 \mu$s. The signal is
partly reflected and partly transmitted through the
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 $\varepsilon = 0.1$. Such domain is commonly observed for polymers (Kolsky, 1949) and was also

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

<table>
<thead>
<tr>
<th>Disk</th>
<th>$d_0$ [mm]</th>
<th>$t_0$ [mm]</th>
<th>$\dot{\varepsilon}_{\text{nom}}$ [s$^{-1}$]</th>
<th>$V_{\text{imp}}$ [m/s]</th>
<th>max $\varepsilon$</th>
<th>max $\Delta T$ [°C]</th>
<th>max $\beta_{\text{int}}$</th>
<th>max $\beta_{\text{diff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>9.00</td>
<td>5.50</td>
<td>2500</td>
<td>-</td>
<td>0.60</td>
<td>40</td>
<td>0.15</td>
<td>0.25</td>
</tr>
<tr>
<td>43</td>
<td>10.30</td>
<td>2.42</td>
<td>5000</td>
<td>18</td>
<td>0.43</td>
<td>14</td>
<td>0.4</td>
<td>1.05</td>
</tr>
<tr>
<td>41</td>
<td>10.09</td>
<td>2.06</td>
<td>6500</td>
<td>19</td>
<td>0.48</td>
<td>29</td>
<td>1.0</td>
<td>2.25</td>
</tr>
<tr>
<td>34</td>
<td>10.18</td>
<td>2.04</td>
<td>8000</td>
<td>21</td>
<td>0.61</td>
<td>37</td>
<td>1.0</td>
<td>2.25</td>
</tr>
</tbody>
</table>

$d_0$ and $t_0$ are the initial diameter and thickness, respectively. Also indicated is the impact velocity ($V_{\text{imp}}$), 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 $\beta$ factors. The results of Trojanowski et al. (1997) who used infrared techniques are included for epoxy resin.

---

Fig. 2. Raw signals for a typical experiment (disk 41). The incident pulse reflects partly upon reaching the specimen after 71 $\mu$s 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 \((\int \sigma \, d\varepsilon_p)\). 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 \(\beta_{\text{diff}}\) and \(\beta_{\text{int}}\), respectively.

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
from the overall work. The bold part of the stress–
strain curve is selected to assess the $\beta$ factors. The
determination of $\beta_{\text{diff}}$ 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 different
procedure. The idea is to examine the spectral
content of the temperature signal and determine a
cutoff frequency below which the essential infor-
mation is found. A numerical low-pass filter is
then designed accordingly (Butterworth filter,
MATLAB, 1994). Fig. 7 shows the power spec-
trum 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 temper-
ature 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 $\beta$ factors can now be determined
according to Eq. (3), as shown next.

3.2. The $\beta$ factors

The corresponding evolutions of $\beta_{\text{diff}}$ and $\beta_{\text{int}}$
are plotted in Fig. 10 for the three above men-
tioned specimens.

The integral factor – $\beta_{\text{int}}$ – 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 $\beta_{\text{int}}$ increases with the strain rate. This observation is consistent with the maximal observed temperature rises, as shown in Table 1. However, $\beta_{\text{int}}$ remains always inferior to 1 as expected. The differential factor $-\beta_{\text{diff}}$ 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 $\beta_{\text{diff}}$ curves showed that the gaussian curves always develop in the softening domain. The peak value reached by $\beta_{\text{diff}}$ increases with the strain rate (Table 1). By contrast to $\beta_{\text{int}}$, $\beta_{\text{diff}}$ 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 $\beta_{\text{int}}$ and $\beta_{\text{diff}}$ 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 $\beta_{\text{int}}$ and $\beta_{\text{diff}}$ are strain and strain rate dependent.

---

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

**Fig. 11.** Evolution of $\beta_{\text{diff}}$ and $\beta_{\text{int}}$ with the true strain for epoxy disk (Trojanowski et al., 1997) tested at $\dot{\varepsilon}_{\text{nom}} = 2500$ 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 non-contact 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.

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

By contrast, our observations show that $\beta_{diff}$ 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 ($\dot{W}_p$) equals the dissipation rate ($\dot{D}$) added to the rate of the stored energy of cold work ($\dot{W}_s$). 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 $\dot{W}_p$. Keeping in mind that $\beta_{diff}$ is defined as the ratio of $\dot{D}$ to $\dot{W}_p$ (alternatively stated as $\beta_{diff} = 1 - \dot{W}_s$), 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

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.
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 ther-
momechanical instabilities.

5. Conclusions

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

Acknowledgements

This research is supported by the Israel Science
Foundation under grant #030-039 and by Techn-
on V.P. Fund for Promotion of Research. Dr. R.
Levin’s assistance is gratefully acknowledged. So
are useful discussions with Profs. S.R. Bodner,

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.

Ashby, M.F., 1992. Materials Selection in Mechanical Design,

the stored energy of cold work under cyclic loading. Eur. J.

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.L., 1925. The heat developed during

Hopkinson pressure bar tests. Int. J. Impact Eng. 15 (6),
723–733.

Kapoor, R., Nemat-Nasser, S., 1998. Determination of tem-
perature rise during high strain rate deformation. Mechan-
ics 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.,

formation process of adiabatic shear bands in a structural

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.

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

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

Steer, P., Rietsch, F., Latailade, J.L., Marchand, A., El
Bounia, N.E., 1985. Viscoelasticité dynamique de polycar-
bonates aux grandes vitesses de déformation. Relations
structure propriétés. J. Physique Coll. C5 Suppl no. 8 tome
46, 415–423.

Taylor, G.I., Quinney, H., 1934. The latent energy remaining in
326.

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