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Novel temperature measurement method & thermodynamic investigations of amorphous polymers during high rate deformation

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ABSTRACT

Polymers are frequently used in applications in which they may be exposed to high rate or impact loading, and there is growing industrial importance in understanding their mechanical behavior at different strain rates. An important aspect of this is the temperature rise due to adiabatic conditions in high rate loading. This paper describes research that has been performed to measure the temperature rise that occurs in specimens undergoing rapid deformation. A novel thermocouple design is presented and applied to PMMA and 20 wt% DINP-plasticized PVC, deformed at moderate and high strain rates. The measurements are accompanied by investigations of strain energy.

1. Introduction

In order to design materials to exhibit desired state-of-the-art behaviors, research in impact properties has become more and more important, as seen in the medical, aerospace, military, and automotive industries. The thermal transitions experienced by polymers undergoing high rate loading can have a strong effect on the observed mechanical response (e.g. Refs. [1–3]). Moving from an isothermal to adiabatic response can consequentially cause large post-yield softening depending on the thermal sensitivity of the polymer. These transitions and the extent of their effects have been studied in a large amount of literature, covering a wide range of polymers, rates of deformation, and thermal measurement techniques (e.g. infrared, embedded thermocouples described below). More recently these heating effects have been exploited in order to recreate high rate behavior at quasi-static rates. In conducting this experimental methodology, 100% of the post-yield plastic work is assumed to be converted into heat, and no heat is assumed escape the specimen when recreating the temperature rise (for further discussion see Refs. [4,16]). In order to further investigate this assumption, accurate measurements of temperature rise in deforming specimens are required, this is the subject of the current paper.

Walley et al. [5] have conducted tests comparing the use of thermocouples and an infrared (IR) temperature measurement system during high rate deformation of iron and copper. In this study, the authors also presented an insightful review of the different techniques available for measuring rapid temperature changes, including their strengths and weaknesses. In the review, some of the advantages of thermocouples included being well calibrated over a wide temperature range, and monitoring temperature inside a body. Alternatively, some of the disadvantages included their invasive nature, which may alter the observed specimen response, and the fact that heat takes a certain amount of time to diffuse into the thermocouple even if the two media are in good thermal contact with one another. Walley et al. found that the thermocouple measurements were within a range of 3 °C of the IR method when studying copper, with a slightly higher difference of 8 °C in iron. In comparing these data to theoretical data (calculated assuming that all plastic work is converted to heat), the authors found that the IR data were higher than theoretical temperature rise values for iron, but lower for copper. Alternatively, thermocouples measured temperature rise values to within 1 °C of their theoretical value. These results demonstrated the theoretical efficacy of the thermocouple temperature measurement method, and also showed that all of the plastic mechanical work performed on these materials was converted to heat.

Chou and co-workers [6] were among the first to measure the temperature rise of polymers during deformation from low to high strain rates. Using embedded thermocouples they measured the temperature rise in polymers such as PMMA, cellulose acetate

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butyrate (CAB), polypropylene (PP), and nylon 6-6. As part of their discussion of the efficacy of their temperature method, the authors presented the equation:

$$\tau = \frac{V\rho C}{\kappa A} \quad (1)$$

where τ is the response time of the thermocouple, V is the volume of the thermocouple, ρ is its density, C its specific heat capacity and A its surface area; κ is the thermal conductivity of the specimen material. However the authors did not use equation (1) in determining the validity of their thermocouple method, but instead did this by observing the time-lag or lack thereof observed in their data. Rittel [3,7] implemented this same embedded-thermocouple technique to investigate the temperature rises of PC and PMMA during moderate rates[1] (0.14 s^{-1}), and PC at high rates (5000, 6500, and 8000 s^{-1}) of deformation. Prior to these investigations, Rabin and Rittel [8] developed a sophisticated analysis of the time response of solid-embedded thermocouples and concluded that the thermal diffusivity of the thermocouple is required to be at least one order of magnitude higher than that of the measured body in order to obtain useful results, and that the transient response time is governed by the radius of the thermocouple and the thermal diffusivity of the material being measured. Subsequently, Rittel and colleagues have produced a large amount of research using thermocouples in high strain rate studies investigating the temperature rise which occurs in amorphous polymers.

Arruda et al. [9] successfully studied the temperature rise which occurs in PMMA deformed at low to moderate rates using an IR method. Focusing optics are arranged around the specimen to direct surface radiation onto a photovoltaic detector (approximately 100 μm × 100 μm). The detector is then calibrated to measure the voltage change associated with a given temperature rise of the specimen. This technique has also been used by several other authors to study the adiabatic heating which occurs in polymeric materials at high strain rates (e.g. Refs. [1,2,10–13]). Results, from Arruda and other authors, of the two different temperature measurement methods (IR versus thermocouple) are presented in Figs. 1 and 2.

The data sets in Figs. 1 and 2 have very subtle differences, but are consistent when acknowledging the differences in mechanical response between examples such as PMMA deformation at 0.1 s^{-1} in Arruda et al. [9] versus Mulliken [12]. Observing Fig. 1 it is noted that at 40% true strain, the PMMA temperature rise is 4 K less in Arruda et al.'s data when compared to Mulliken's data. Looking at the true stress–true strain behavior associated with these temperature rises, Arruda et al.'s PMMA specimens demonstrated a true stress of 100 MPa at 40% true strain, versus a ~130 MPa true stress seen by Mulliken at the same strain. These differences explain the observed differences in temperature rise between different studies. There are further subtle differences in behavior between the data sets presented in Figs. 1 and 2, particularly the slightly exponential nature of Rittel et al.'s temperature measurements versus the more linear response reported in other literature. In order to confirm their temperature measurements, Regev and Rittel [13] conducted an additional temperature measurement study on PC implementing both IR and embedded thermocouple techniques at high strain rates (3000, 6000, and 8000 s^{-1}). The authors found no difference in results between the two techniques until a rate of 8000 s^{-1}. At this rate, after a true strain of 50% was reached, it was noted that the field of view of the IR detector was obscured by the loading device used in testing.

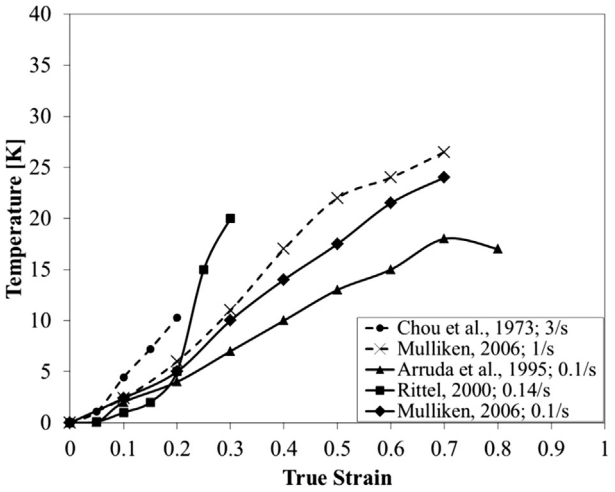

Fig. 1. Literature data on the temperature rise in PMMA during uniaxial compression. The dashed lines present data at ~1 s^{-1} and the solid lines present data at ~0.1 s^{-1}. PMMA is an example of a brittle material at high rates of deformation.

Lastly, it is noted that the results of the two different temperature measurement methods seen in literature are consistent in showing that 75–100% of the plastic work is converted to heat during moderate to high rates of deformation of polymers.

In the following sections, high and moderate rate temperature measurements are conducted on two amorphous polymers: PVC with 20 wt% DINP plasticiser (PPVC) and PMMA. The temperature rise experienced during deformation is analyzed in tandem with the resultant changes in strain energy. With a goal to improve the validity of temperature measurements in these experiments two novel thermocouple layouts are presented and evaluated.

2. Calculations, equipment, and materials

2.1. Materials and theoretical calculations

The change from isothermal to adiabatic conditions as the strain rate increases is an important feature of high rate deformation,

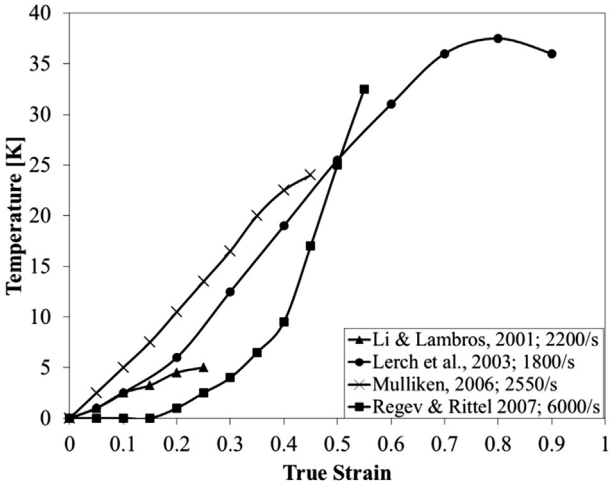

Fig. 2. Literature data on the temperature rise in PC during uniaxial compression at high rates of deformation. All tests were conducted on SHPB apparatuses. PC is an example of a ductile material at high rates of deformation.

[1] Thermomechanical effects in PMMA are most commonly studied at low to moderate rates of deformation because of its brittle failure observed at higher strain rates (~10^3 s^{-1}).