



# Experimentally simulating adiabatic conditions: Approximating high rate polymer behavior using low rate experiments with temperature profiles



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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. This paper describes research that has been performed to better understand and predict the dependence on strain rate of mechanical properties such as yield and flow stress, by investigating the relationship between rate dependence and temperature dependence. In particular, the mechanical behavior of poly(vinyl chloride) with 20 wt% plasticizer has been studied at strain rates from  $0.001 \text{ s}^{-1}$  to  $4700 \text{ s}^{-1}$  and temperatures from  $-60$  to  $+80 \text{ }^\circ\text{C}$ . In addition to the use of time–temperature superposition, this paper presents a novel experimental method in which the yield stress and the effects of adiabatic heating at high strain rates are simulated in the low rate loading.

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## 1. Introduction

The mechanical properties of polymers are studied because of their widespread scientific and industrial importance, as seen in the automotive, aerospace, military, and medical industries. A considerable amount of research has been completed in both the impact behavior of polymers, and the sensitivity of polymers to variables such as temperature and strain rate. As high performance materials continue to be developed, there has been an increased demand for test methods capable of analyzing and comparing materials over a wide range of strain rates. The demand is particularly apparent in testing low-impedance materials at high rates, for which there can be difficulties in obtaining dynamic stress equilibrium.

A large amount of literature has been produced describing investigations of the rate dependence of polymers. Chou et al. [1] were some of the first to examine the structural performance of polymers over a wide range of strain rates ( $10^{-4} \text{ s}^{-1}$  to  $10^3 \text{ s}^{-1}$ ), looking at cellulose acetate butyrate, nylon 66, polymethyl methacrylate (PMMA), and polypropylene on a split Hopkinson bar (SHPB) apparatus and a medium rate testing machine. Examination of the mechanical strength, or yield stress, dependence upon the logarithm of strain rate, showed that the polymers were more

sensitive to increases in strain rate under high rate loading than they were under quasi-static. In such studies the yield stress is often recognized as the peak stress that the polymer reaches around yield: the intrinsic yield described by Bowden [2], and this approach will be used in the current research. Another extensive study of rate-dependence in polymers was conducted by Walley and Field [3–5], studying PVC and several other polymers at strain rates ranging from  $10^{-2} \text{ s}^{-1}$  to  $10^4 \text{ s}^{-1}$ , using four different apparatus, including a direct-impact Hopkinson bar for strain rates above  $10^3 \text{ s}^{-1}$ . More recently, Arruda and Boyce [6], Wang and Arruda [7], and Mulliken and Boyce [8–10] all made developments in understanding high rate behavior of polymers with constitutive model development and a large amount of experimental investigation, testing plasticized and un-plasticized polyvinyl chloride (PVC), polycarbonate (PC), PMMA, and various rubbers over a wide range of strain rates. In addition, Richeton et al. investigated several amorphous polymers in uniaxial compression including PC, PMMA, and polyamideimide (PAI). These authors made several developments in constitutive modeling, while helping improve the understanding of the secondary transition by linking yield behavior and the secondary mechanical loss peak seen in DMTA data [11–14]. Several of these developments highlighted, or utilized, the connection between strain rate and temperature in helping describe the constitutive behavior of polymers.

Polymers are very sensitive to both temperature and strain rate. In several polymers, the sensitivity is understood to increase at

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lower temperatures and/or higher rates of strain because of a lack of secondary mobility ( $\beta$  motions), which causes increased strength and stiffness. Alternatively, the increased strength in more rubbery or elastomeric polymers is accounted for by the change in molecular mobility during the glass transition (or  $\alpha$ -transition). In many cases, these transitions are observed in polymers at low temperatures, but can be shifted in temperature by changes in strain rate: the transition temperature increases with increasing rate. This phenomenon was observed in PVC by Bauwens in 1969 [15], where the effect was captured via the Ree–Eyring theory of non-Newtonian flow. Similarly, attempts to connect the effects of temperature and strain rate via time–temperature superposition have been investigated using the well-known WLF equation [16], or a linear time–temperature equivalence mapping [17–19]. In experimentally unifying these phenomena, Cady et al. [20] mentioned the possibility of simulating high rate response of polymers by low rate/low temperature tests, and more recently, Furmanski et al. [21,22] found a linear empirical formulation of time–temperature equivalence in HDPE, while using jump-rate compression tests to investigate isothermal high rate response with the absence of adiabatic heating.

The change from isothermal to adiabatic conditions as the strain rate increases is an important feature of high rate deformation, which must be considered alongside the temperature dependence of  $\beta$  stress when considering changes in material behavior as a function of strain rate. Important studies involving the measurement of temperature rise in specimens during high rate deformation have been conducted by a number of authors. A notable achievement was by Chou et al. [1], who showed that the temperature rise in specimens increases significantly after yield. Furthermore, Arruda et al. [23] presented visible increases in strain softening with increases in strain rate, coupled with corresponding temperature measurements using infrared detectors. Rittel [24,25] used thermocouples to measure the temperature rise in specimens undergoing high rate deformation and later confirmed the accuracy of this method via infrared techniques. Li and Lambros used a high speed infrared detector array to investigate mechanical work being converted to heat at rates surrounding  $10^3 \text{ s}^{-1}$ . These authors found that the amount of plastic work converted to heat for PC ranged from 100% to 50% depending upon the applied strain [26]. Additionally, Garg et al. [10] used infrared techniques to measure the temperature rise of PC undergoing high rate deformation. Good agreement was observed between the experimentally measured temperature rise and the ‘theoretical’ rise obtained by assuming that 100% of the mechanical work is converted to heat, and adiabatic conditions prevail. Hillmansen et al. [27,28] studied plastic work being converted to heat by studying high density polyethylene (HDPE) and found, similarly, that conversion was approximately 100%.

By combining an understanding of temperature dependence with an appreciation of adiabatic conditions, there is an opportunity to better understand and capitalize on the analogous effects of temperature and strain rate in polymers. This is particularly timely considering the several obstacles of high rate testing, especially when the materials of interest are soft (e.g. rubbers and biomaterials), or have large representative volume elements, requiring large specimens (composites). An important consideration when measuring high rate properties of materials, especially those with a low sound speed, is the well-described requirement for a specimen to reach mechanical equilibrium before the results of an experiment may be regarded as valid [29]. The specimen is loaded from one end with a stress wave, which imposes a deformation rate on that end of the specimen. The wave oscillates a number of times within the specimen, each time increasing the specimen stress in a stepwise manner. Eventually, enough oscillations occur so that the stress does not vary significantly with position in the specimen; the

specimen is now in quasi-static equilibrium, although deformed at a high strain rate. Equilibrium is required because in the classical Hopkinson bar technique, only forces and velocities at the bar specimen interface are calculated, and thus average specimen properties are derived, and because, until equilibrium is achieved, the forces measured in the bars are not necessarily the same as those experienced by the specimen.

Although the difficulties of achieving specimen equilibrium are therefore obvious for materials with low sound speeds, composites create similar difficulties in testing, and would similarly profit from an experimental simulation method in order to better understand high rate behavior. Composites often have a polymer, or soft material, as a filler, such as 3D fiber reinforced polymers [30] and polymer bonded explosives [31]. Modern 3D reinforced fiber composites can have complex deformation behaviors [32]. Experimental determination of these behaviors is complicated by the fact that the characteristic length of the polymer filler may be on the order of a  $100 \mu\text{m}$  length scale, while the damage formation is on a  $1\text{--}10 \mu\text{m}$  length scale and the repeat units in the weave are on  $10\text{--}100 \text{ mm}$  length scales. This means that large specimens are desirable to have a suitable representative volume element, but in-situ microscopic examination is required to fully understand damage formation. Both of these requirements are difficult to meet in a high strain rate experiment. As an example of a particulate composite, polymer bonded explosives (PBXs) typically use soft rubbers or polymers as a binder; the binder might only constitute 10% of the material, but has a large effect on the mechanical response, and in particular the rate and temperature dependence. Biomaterials provide another example of composite materials with a wide range of length scales which provide similar challenges in high strain rate characterization. These materials share the challenge of in-situ microscopic examination during deformation, and also the problem of achieving equilibrium, this time because of the relatively low sound speed in the material.

This paper presents data obtained using a novel experimental method that aims to predict and experimentally simulate the stress–strain response expected in a polymer, by performing a low rate experiment at reduced temperatures. A key development is to simulate not only the increase in modulus and yield stress, by reducing the temperature at the start of the experiment, but also the effects of adiabatic heating by increasing appropriately the temperature as the experiment progresses. The opportunity to predict or simulate high rate loading not only avoids several obstacles of high rate testing, such as dynamic equilibrium, but also allows for microscopic investigation on much smaller length scales through the use of electron and optical microscopy, especially in composite materials in which one component exhibits rate and temperature dependence whilst the other does not. In addition, future development of the technique to increase its fidelity beyond that presented in this paper may provide an opportunity to better understand the mechanisms of high rate deformation, especially the conversion of work to either heat or to structural changes in the material.

## 2. Experimental method

### 2.1. Materials

Low, medium, and high rate compression tests were conducted with cylindrical diisononyl phthalate (DINP) plasticized PVC (hereafter referred to as PPVC) specimens of 2.5 mm length and 5 mm diameter. The PPVC chosen was manufactured by Solvin using the resin Solvin 264-01PC, with a low plasticizer level of 20 wt%. The PPVC came as pressed plates with dimensions of  $11.5 \times 20 \text{ cm}$  and a thickness of 2.5 mm. These plates were machined to the specified specimen geometry, such that the axis of the specimen in the loading

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