



# Experimentally simulating adiabatic behaviour: Capturing the high strain rate compressive response of polymers using low strain rate experiments with programmed temperature profiles

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## ABSTRACT

Polymers are widely used in applications where they may be subjected to impact loading leading to high strain rate deformation. Plastic work on deformation generates heat in the material. At high strain rates, there is insufficient time for this heat to diffuse out of the material, leading to adiabatic conditions. This leads to post-yield thermal softening in the mechanical response, which modifies the material response and must be considered in Engineering design. In this paper, a novel technique is presented in which this adiabatic self-heating can be simulated experimentally at low strain rates using programmed temperature profiles. We show that, in some cases, these simulations can very accurately capture the mechanical response at higher rates, but in others, the replication is less accurate. This may give further insights into the thermodynamics of high strain rate polymer mechanics. This technique therefore enables a number of avenues of research: the work to heat conversion can be investigated systematically; diagnostic tools that are limited to low strain rates can be applied; and we can better understand material behaviour and thereby improve predictive models.

## 1. Introduction

Polymers are ubiquitous in engineering applications, where they may be subjected to dynamic or impact loading, leading to high-rate deformation, at a variety of temperatures. The mechanical response of these materials is highly rate and temperature dependent, and as such, they must be well characterised and understood [1]. One observation that is common in the post-yield, large strain deformation of polymers under high-rate loading is adiabatic self-heating. This can lead to thermal softening in the sample as mechanical energy is converted to heat that cannot diffuse out of the sample on the time-scale of the high-rate event. This phenomenon makes it challenging to use the results of low temperature experiments to replicate the high strain rate behaviour and extend common concepts like time-temperature superposition [2,3] and the rate-temperature equivalence of yield [4,5] out to larger strains.

Various approaches including interrupted experiments [6] and manual alteration of the temperature during testing [7] have been proposed to better replicate high rate response using low rate, low temperature experiments, however they too have limitations. In the interrupted experiments, a series of strain rate jump tests were conducted to form a locus of isothermal flow stresses. These do not directly compare quasi-static tests with high rate and may suffer from the effects of relaxation

during the interruption. Manual input of the temperature rise requires the measurement of the temperature rise during high rate experiments, a significant challenge due to their short duration, and does not give sufficient repeatability or precision. Furthermore, the assumption that all applied mechanical work is converted to heat is not true for all polymers [8] - including polycarbonate, which is why it was selected to be the focus of this technique paper.

In previous research [9], it was shown that it was possible to predict the compressive high rate response of (plasticised) poly(vinyl chloride) using a model calibrated using simple, low rate experiments. This is consistent with experimental observations by Kendall and Siviour [7]. In both cases, details of this adiabatic self-heating were included by assuming a full conversion of the mechanical energy to heat.

In this paper, a novel experimental apparatus is presented, which allows the adiabatic self-heating to be simulated with a programmed temperature profile. By starting a quasi-static compression experiment at a low temperature, such that the yield stress corresponds to that at the high rate of interest, and subsequently increasing the temperature, it is possible to simulate the adiabatic self-heating observed during high-rate experiments under quasi-static loading. This process is applied to polycarbonate samples and the results are compared to medium

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and high strain rate experiments on the same material. Although this paper uses polycarbonate as a model material, the intention of this paper is to present the experimental technique and its potential application to investigating the mechanical-heat conversion in various polymer systems and gaining a better understanding with which to improve predictive models.

## 2. Experimental methods

### 2.1. Material

The material used in the study is a polycarbonate (PC) acquired from our project partners, Sabic. It is a LEXAN™103R with a glass transition temperature ( $T_g$ ) of 145 °C and a melt flow rate (MFR) of 6 at 300 °C/1.2 kg.s. The PC was obtained in the form of injection moulded sheets of 3 mm thickness. Prior to machining samples, the sheets were annealed for six hours at 155 °C to minimise the residual stresses from the manufacturing process. The heating rate was 25 °C/h and the cooling rate was 10 °C/h. Right circular cylinders of 5 mm diameter and plate thickness (3 mm) were machined from the annealed plates.

### 2.2. Compression experiments

#### 2.2.1. High strain rate

To perform high strain rate experiments, a split Hopkinson pressure bar (SHPB) was used. This apparatus sandwiches a specimen between the so-called input and output bars. A third striker bar is fired onto the input bar producing an elastic stress wave that propagates through the input bar, specimen, and output bar. By analysing the signals from the surface mounted strain gauges on the input and output bars, the strain and the force exerted on the specimen can be inferred. Information about this experimental technique can be found in more detail in [10,11].

Here, all three of the bars were Ti-6Al-4V alloy with a diameter of 12.7 mm. The striker bar reached speeds up to 10 m s<sup>-1</sup>, corresponding to an average strain rate of around  $3 \times 10^3$  s<sup>-1</sup> for a sample that is 3 mm thick. The striker bar was 400 mm long, the input bar 1000 mm long and the output bar 500 mm long. The input and output bars were instrumented with strain gauges, halfway along the bar and 50 mm along the bar respectively. The bar-specimen interfaces were lubricated using a thin layer of petroleum jelly, which has been shown to reduce friction [12] and the barrelling phenomenon. Furthermore, thin copper pulse shapers were used to remove high frequencies from the loading pulse.

#### 2.2.2. Medium strain rate

A bespoke hydraulic press was used to conduct intermediate strain rate experiments at c. 1–100 s<sup>-1</sup>. In this apparatus, the piston of the hydraulic system pushes the moving anvil upwards to compress the specimen at a pre-set displacement and speed. The specimen is sandwiched between this moving anvil and a static load cell. The force is measured using the load cell and the displacement by using calibrated linear variable differential transformers (LVDTs).

#### 2.2.3. Low strain rate

An Instron 5980 Series electromechanical static testing machine was used to perform low strain rate experiments at 10<sup>-3</sup>–10<sup>-1</sup> s<sup>-1</sup>. It was instrumented with a 2580 Series load cell and custom supports and loading anvils. An Instron 2620 Series dynamic strain gauge extensometer was attached to the anvils, close to the specimen to provide strain measurements and closed loop control.

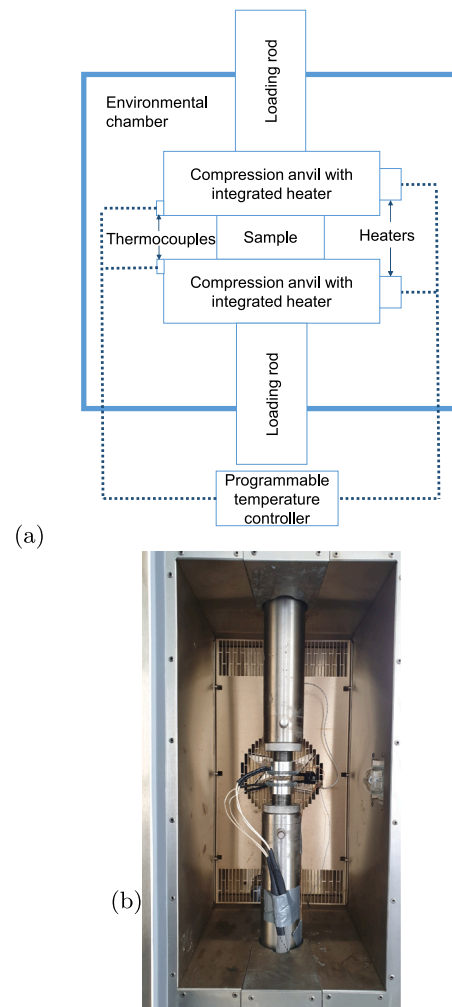


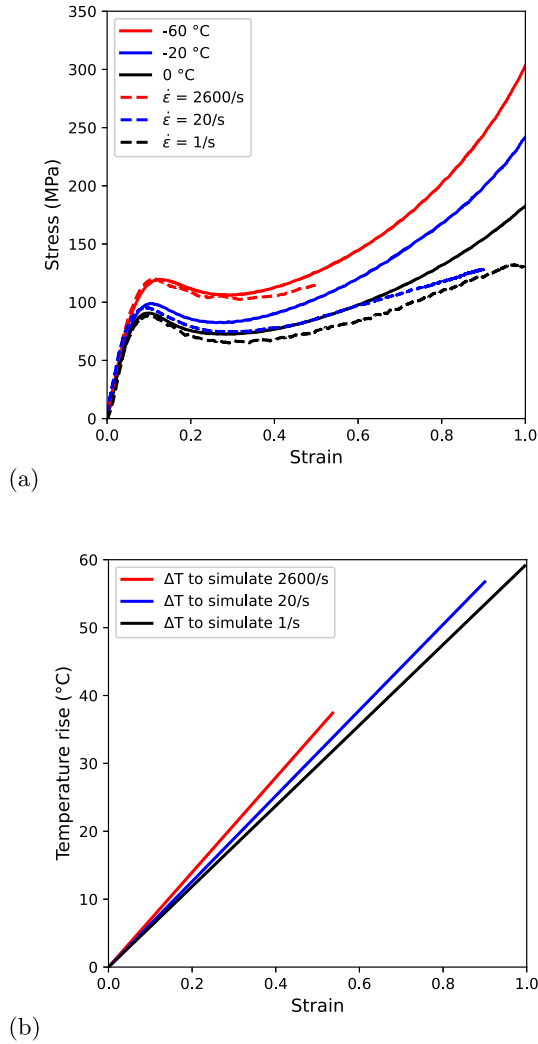
Fig. 1. (a) Schematic of the adiabatic simulation experimental design and (b) photograph illustrating the actual experimental setup.

### 2.3. Adiabatic simulations

Fig. 1a shows the design of the experimental simulation set-up. It consists of a sample sandwiched in between two heated anvils: 6061 T6 aluminium alloy platens integrated with Omega® high power density electric cartridge heaters. These heaters are controlled using a Eurotherm® AC relay based PID temperature controller. The anvils are 38 mm in diameter and 20 mm in length, with a threaded end to attach to rods, which can all be contained within an environmental chamber compatible with our Instron electromechanical testing machine. The actual set-up as used for the experiments in this study can be seen in Fig. 1b.

## 3. Results and discussion

To perform adiabatic simulation experiments, there are two prerequisites: an understanding of the rate-temperature equivalence of the pre-yield behaviour; and an estimate for the temperature rise experienced during high-rate compression. Fig. 2a shows a comparison between varying temperature experiments performed at a fixed true strain rate of 0.01 s<sup>-1</sup> (solid lines) and varying rate experiments performed at a fixed temperature of 20 °C (dashed lines). It is evident from these that there is a clear pre-yield equivalence between the two sets of experiments. The post-yield behaviour shows a lower strength for the



**Fig. 2.** (a) Rate-temperature equivalence for PC at three different conditions and (b) linear approximations of the temperature rises, implemented into the temperature controller to simulate the varying rate experiments.

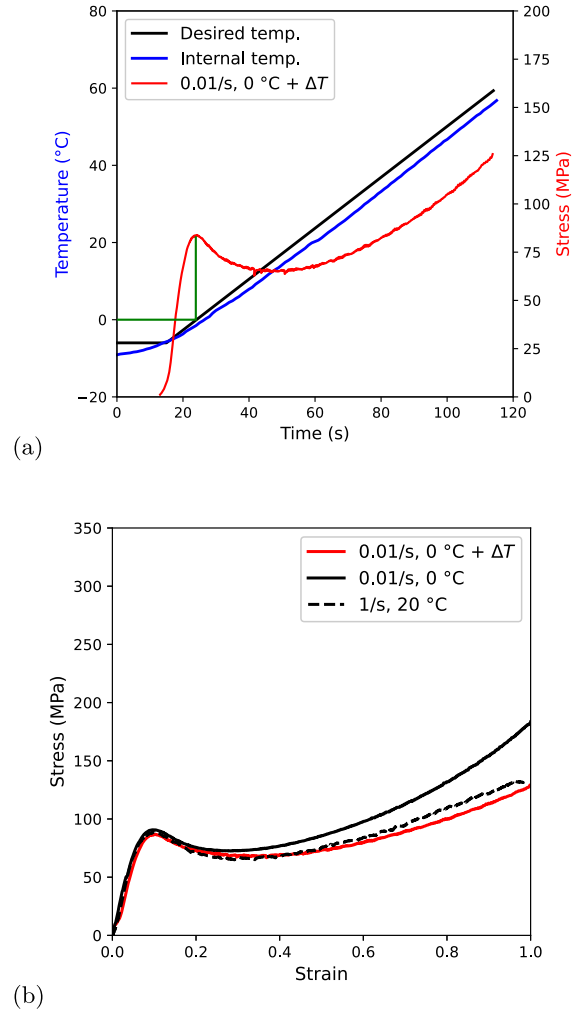
varying rate experiments as there is thermal softening present, which is most significant for the medium rate experiments (1 and 20 s<sup>-1</sup>).

To estimate the total temperature rise ( $\Delta T$ ) over the experimental duration causing this thermal softening, the following analytical expression was used:

$$\Delta T = \frac{\beta}{\rho C_p} \int_0^{\epsilon_f} \sigma(\epsilon) d\epsilon \quad (1)$$

where  $\beta$  is the Taylor–Quinney coefficient giving the mechanical work to heat conversion factor (assumed to be 1 here),  $\rho$  is the density of the PC (1.2 kg m<sup>-3</sup> here),  $C_p$  is the heat capacity (1.2 kJ/kg/°C here) and  $\epsilon_f$  is the final strain for the high-rate experiment. A linear temperature ramp profile is then created using the total temperature rise such that it can be implemented onto the programmable temperature controller. Fig. 2b shows these linear temperature rise profiles required in order to simulate the three varying rate conditions shown in Fig. 2a.

A more physically accurate expression would integrate only the plastic strain from the elastic limit onwards, but the elastic approximation used here is acceptable for the purpose of programming a simple temperature ramp for the adiabatic simulations. Further, because of compliance effects it is challenging to calculate plastic strain in compression tests because the initial stiffness calculated is lower than the modulus of the material. Hence, some level of approximation

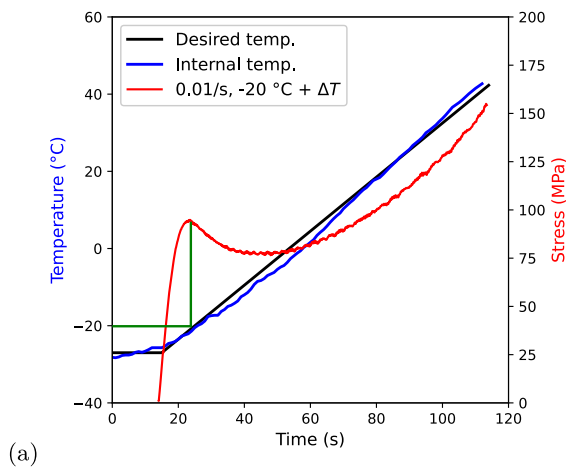


**Fig. 3.** (a) Temperature- and stress-time curves for simulating the adiabatic self-heating at 1 s<sup>-1</sup> and (b) comparing the stress-strain profiles for the compression at 1 s<sup>-1</sup> and the two quasi-static experiments with and without temperature profiling.

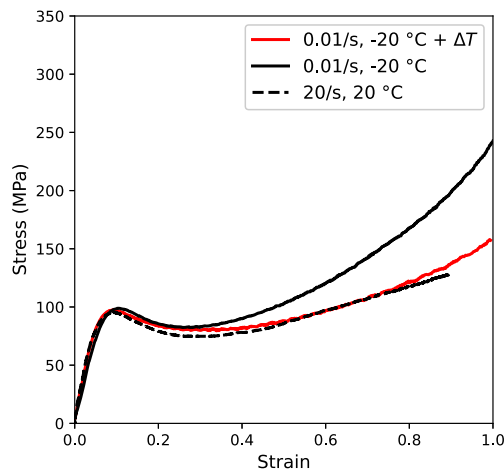
is required to calculate the plastic strain. Because no practical difference was observed to the overall temperature ramp when integrating with respect to (approximate) plastic strain, the calculation above was deemed sufficient for demonstrating the technique.

For each simulation experiment, the temperature rises are programmed into the AC PID controller as a gradient. These are obtained by taking the slope of the curves in Fig. 2b and multiplying by the true strain rate. Since these experiments were performed under constant true strain rate control, this calculation allows the temperature rise per unit time to be obtained. By programming gradients for each simulation experiment, it allows the practical benefit of avoiding finite duration ramping up from and down to the start and end temperatures. By implementing gradients on the programmable controller, linear ramps in the temperature range of interest resembling the curves in Fig. 2b can be assured.

Adiabatic simulation experiments were performed by first bringing samples to an equilibrium temperature slightly lower than that required to match the higher rate yield stress. The controller was then started to allow sufficient time to ramp up to the required gradient, with the compression experiment commencing as soon as the temperature passes a threshold value. This value is calculated – given the programmed gradient, yield strain and strain rate – such that the temperature at yield is the value shown in Fig. 2a required for equivalence with the strain



(a)



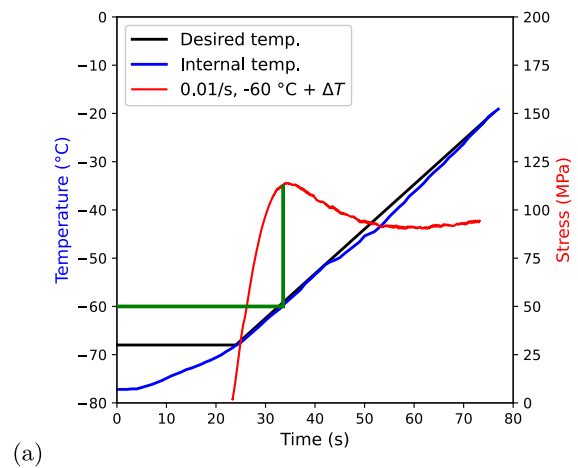
(b)

**Fig. 4.** (a) Temperature- and stress-time curves for simulating the adiabatic self-heating at  $20 \text{ s}^{-1}$  and (b) comparing the stress-strain profiles for the compression at  $20 \text{ s}^{-1}$  and the two quasi-static experiments with and without temperature profiling.

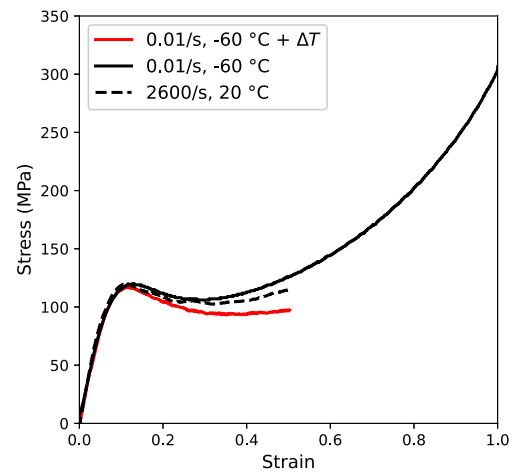
rate of interest. The simulation experiment is continued until the true strain is at least  $\epsilon_f$ .

Results showing the temperature-time and stress-time for a simulation of the  $1 \text{ s}^{-1}$  experiment are presented in Fig. 3a. The threshold temperature is  $-6 \text{ }^{\circ}\text{C}$ , which is where the compression is started, and the temperature at yield is the desired  $0 \text{ }^{\circ}\text{C}$ . To check that the temperature of the specimen is tracking the desired temperature, experiments were performed with thermocouples embedded in the specimen. Previous research has shown that embedding a thermocouple in this manner does not significantly affect the mechanical response [13]. Additional experiments were performed on the polycarbonate in this study to confirm this and are shown in Appendix A. The stress profile in Fig. 3a is plotted against strain and compared against the stress-strain profiles for both isothermal, quasi-static and adiabatic, high-rate experiments in Fig. 3b. This shows that the mechanical behaviour at  $1 \text{ s}^{-1}$ , including post-yield thermal softening, can be captured using an adiabatic simulation experiment where the temperature at yield is  $0 \text{ }^{\circ}\text{C}$ .

Results showing the temperature-time and stress-time for a simulation of the  $20 \text{ s}^{-1}$  experiment are shown in Fig. 4a. Here, the threshold temperature is  $-26 \text{ }^{\circ}\text{C}$ , and the temperature at yield is  $-20 \text{ }^{\circ}\text{C}$ . The stress profile is plotted against strain and compared in Fig. 4b. The mechanical behaviour at  $20 \text{ s}^{-1}$  is captured excellently using an adiabatic simulation experiment where the temperature at yield is  $-20 \text{ }^{\circ}\text{C}$ .



(a)



(b)

**Fig. 5.** (a) Temperature- and stress-time curves for simulating the adiabatic self-heating at  $2600 \text{ s}^{-1}$  and (b) comparing the stress-strain profiles for the compression at  $2600 \text{ s}^{-1}$  and the two quasi-static experiments with and without temperature profiling.

The same procedure is implemented for the high-rate experiment at  $2600 \text{ s}^{-1}$ , with the temperature- and stress-time curves shown in Fig. 5a and the comparison of the simulation with the high-rate experiment in Fig. 5b. In this case, the simulation leads to a greater than expected stress drop from thermal softening. This implies that at high rates the energy is not simply going into heating the sample, but another process. It is also worth noting that the yield stress is a strong function of the temperature and strain rate and is subject to specimen to specimen variability, Appendix B, therefore it is challenging to precisely match the high rate yield in a given simulation experiment.

#### 4. Conclusions

In this paper, a novel experimental approach is presented, which provides a complementary tool to better understand the conversion of mechanical work to heat for varying rate experiments. It was shown that this apparatus could accurately simulate the adiabatic self-heating and subsequent thermal softening for experiments at  $1$  and  $20 \text{ s}^{-1}$ . However, the same process led to an overly softened response for a simulation of the high-rate  $2600 \text{ s}^{-1}$  experiment. This experiment has the potential to provide valuable insight into the energy balance during the deformation of polymers, which would be the focus for future research activities.

## CRediT authorship contribution statement

**Akash R. Trivedi:** Conceptualization, Methodology, Software, Resources, Investigation, Formal analysis, Visualisation, Writing – original draft, Project administration. **Peihao Song:** Investigation, Writing – review & editing. **Clive R. Siviour:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Embedded thermocouple experiments

In this appendix, data are presented showing the comparison between the compressive response of both pristine samples and those embedded with thermocouples (Fig. 6). Note that the addition of embedded thermocouples does slightly decrease the yield stress, but the large strain response is unaffected. It is the large strain response that drives the thermal softening and forms the basis for the simulation comparisons. For this reason, it is acceptable that the yield stress is slightly lower in the samples with embedded thermocouples.

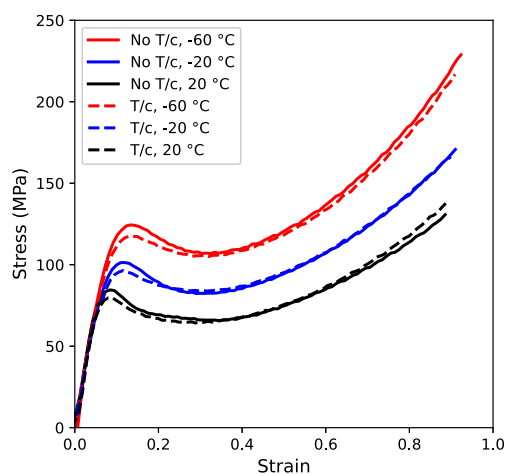


Fig. 6. Comparison of pristine samples with no drilled hole for thermocouples (T/c) and drilled samples with embedded thermocouples.

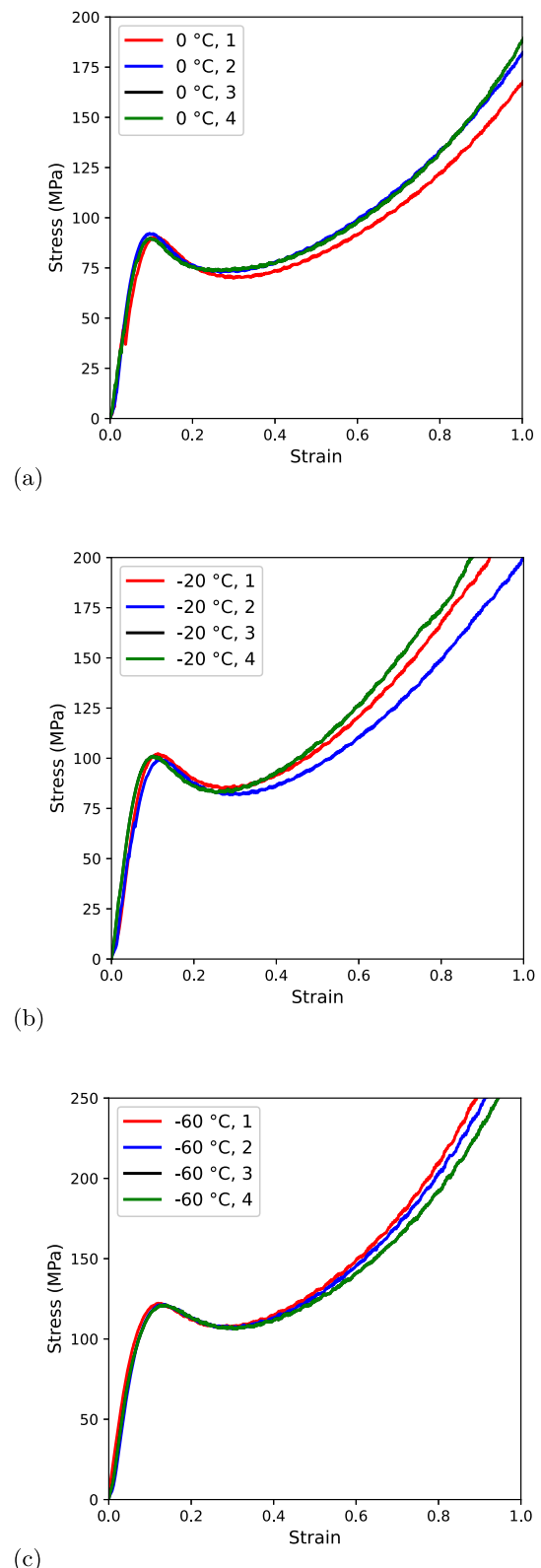


Fig. 7. Repeat compression experiments at (a) 0 °C, (b) -20 °C, and (c) -60 °C.

## Appendix B. Further experimental data

In the body of this paper, only one set of experimental data were used to highlight the use of this experimental technique to simulate

adiabatic self-heating and subsequent thermal softening of polymers. Here, we present additional stress-strain data at varying rates and

temperatures to demonstrate the experimental variation expected in these types of tests.

### B.1. Varying temperature experiments

See Fig. 7.

### B.2. Varying rate experiments

See Fig. 8.

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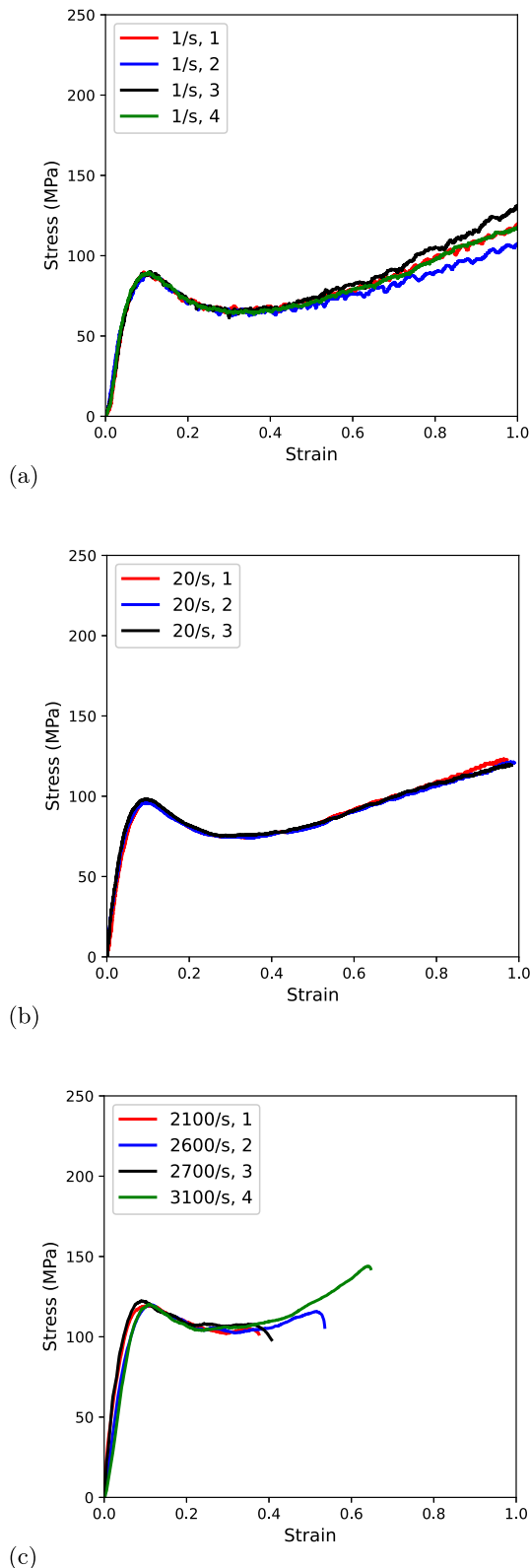


Fig. 8. Repeat compression experiments at (a) c. 1 s<sup>-1</sup>, (b) c. 20 s<sup>-1</sup>, and (c) high strain rate (c. 2500 s<sup>-1</sup>).