LA-UR- 01-3291

Approved for public release; distribution is unlimited.

c.1

Title: Influence of Temperature and Strain Rate on the Compressive Behavior of PMMA and Polycarbonate Polymers

Author(s): W.R. BLUMENTHAL, C.M. CADY, M.F. LOPEZ, G.T. GRAY III, and D.J. IDAR

MST-8

Submitted to: 12th APS Topical Conference on Shock Compression of Condensed Matter

June 24-29, 2001
Atlanta, GA

Los Alamos
NATIONAL LABORATORY

INFLUENCE OF TEMPERATURE AND STRAIN RATE ON THE COMPRESSIVE BEHAVIOR OF PMMA AND POLYCARBONATE POLYMERS

W.R. Blumenthal, C.M. Cady, M.F. Lopez, G.T. Gray III and D.J. Idar

Mail Stop G-755, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract. Compression stress-strain measurements have been made on commercial polymethylmethacrylate (PMMA) and polycarbonate (PC) polymers as a function of temperature (-197°C to 220°C) and strain rate. A split-Hopkinson-pressure bar (SHPB) was used to achieve strain rates of about 2500 s^{-1} and a servo-hydraulic tester was used for lower strain rate testing (0.001 to 5 s^{-1}). The mechanical response of these transparent polymers is quite different. The strength of PC is weakly dependent on strain rate, only moderately dependent on temperature, and remains ductile to -197°C. In contrast, the strength of PMMA is linearly dependent on temperature and strongly dependent on strain rate. Significantly, PMMA develops cracking and fails in compression with little ductility (7-8% total strain) at either low strain rates and very low temperatures (-197°C) or at high strain rates and temperatures very near ambient.

INTRODUCTION

Transparent, thermoplastic polymers such as polycarbonate (PC) and polymethylmethacrylate (PMMA) are very common in a range of commercial products and defense applications. In particular, these materials are used in components where their mechanical behavior is of critical interest to designers and engineers, such as impact-resistant eyewear and aircraft windows. Because components may be subject to extreme temperature and loading conditions, there is a need to test and accurately model the constitutive mechanical behavior as a function of *both* strain rate and temperature.

The split Hopkinson pressure bar (SHPB) is an established high strain rate test method for metals, but it has also been applied to evaluate polymers. However, due to many differences between the behavior of metals and polymers, the authors have modified the standard SHPB technique to improve the validity and fidelity of the results [1]. Specifically, because of their low sound speeds, the thickness of polymeric specimens must be reduced to achieve rapid stress uniformity within the specimen. Also, because polymer strength is much lower than metals, low elastic modulus pressure bars (e.g. titanium or magnesium alloys) must be used to obtain adequate strain gage signal output.

The compressive strength of PMMA and PC has been previously studied as a function of strain rate but almost exclusively at room temperature [2-4]. The authors have specifically developed the capability to dynamically test materials over a wide temperature range, allowing study of thermal effects on the strength of polymers. In general, the compressive strength and the loading modulus of polymeric materials have been observed to increase with decreasing temperature and with increasing strain rate. PC can be compressed to strains in excess of 50% at all strain rates at room temperature and the strain-rate dependence of the strength is weak, but appears to increase and then saturate or even soften at dynamic rates (>10^3 s^{-1}) [temperature [2, 4]. The strength of PMMA exhibits strong strain rate dependence compared to PC at room temperature. Significantly, at low strain rates PMMA is ductile to large strains (with strength levels similar to PC); however at dynamic strain rates (≥10^3 s^{-1}) the strength of PMMA increases dramatically and becomes brittle at room temperature [2]. The strength of PMMA also

appears to lose strength at very high rates between 10^3 to 10^4 s^{-1}, but this is likely a result of a non-uniform stress in the specimen [3].

In the present investigation, uniaxial compression tests were performed at a series of constant strain rates (0.001, 0.1, 5, ≈2000 s^{-1}) and at temperatures ranging from -197°C to 200°C commercially-available polycarbonate and polymethylmethacrylate to support the development of rate and temperature-dependent constitutive strength models. The results are discussed in comparison to selected literature data at ambient temperature.

EXPERIMENTAL TECHNIQUES

Materials and Preparation

The bisphenol A polycarbonate (PC) specimens were sampled from a one-inch thick compression-molded and stress-relieved sheet of unfilled, unmodified ZELUX M-machine grade polycarbonate and the polymethylmethacrylate (PMMA) specimens were sampled from a one-inch thick extruded sheet of ACRYLITE FF grade acrylic (both are manufactured by Westlake Plastics, Placentia, CA; www.westlakeplastics.com). Both materials were machined so that the specimen compression axis was parallel to the through-thickness direction of the sheets. SHPB specimens were machined with dimensions of 6.35mm diameter and 3.2mm length. Quasi-static compression specimens were machined to a diameter of 6.35mm and a length of 6.35mm. Specimen faces were machined to a fine surface finish to minimize friction during the test.

Off-ambient temperature specimens were ramped to the desired temperature in approximately 5 to 10 minutes and then equilibrated at temperature for approximately 10 minutes prior to testing. Samples were lubricated with a thin layer of molybdenum disulfide grease or, at -197°C, with a thin spray coating of boron nitride.

Low Strain Rate Compression Testing

Quasi-static compression tests were conducted on both PC and PMMA at temperature intervals of approximately 20°C from -55°C to +55°C and also at -197°C using a MTS (Eden Prairie, MN) model 880 load frame and ram extensometer at strain rates of 0.001, 0.1, and 5 s^{-1}. Specimens were loaded to strains of between 20% to 30% in air unless failure occurred. Specimens tested at -197°C were immersed in a liquid nitrogen bath during the test.

High Strain Rate Compression Testing

Dynamic tests were conducted on both materials at strain rates of 2000 to 4000 s^{-1} utilizing a split-Hopkinson pressure bar with 9.4mm diameter Ti-6Al-4V alloy pressure bars to improve the signal-to-noise output. Development of a uniform stress state within the specimen early in the loading is a necessary requirement for valid SHPB testing, especially when fracture occurs at low strain levels. This condition was satisfied for *each* test by comparing stress-strain curves calculated from the incident-reflected signals and the transmitted strain signal as described elsewhere [1]. Stress equilibrium for these materials was satisfied in all cases at total strain levels below about 3%. Minimizing the specimen thickness is critical for achieving rapid stress equilibrium, but we have also found that it is not possible to achieve acceptable stress equilibrium for these polymers above strain rates of about 6000 s^{-1} even using a specimen thickness of 3.2mm. Finally, an assumption of incompressibility was made for these materials so that the results are calculated and shown as true stress and true strain.

RESULTS AND DISCUSSION

Bisphenol A Polycarbonate (PC)

Room temperature stress-strain curves for PC are plotted in Fig. 1 over the range of strain rates. These results show that PC is very weakly dependent on strain rate up to 5 s^{-1}, but the rate sensitivity accelerates between 5 and 2000 s^{-1}. Specifically, the peak strength at 20°C increases by only 16% from 0.001 to 5 s^{-1}, but then increases by 38% from 5 to 2000 s^{-1}. Figure 1 also shows that the shape of the stress-strain curve for PC is consistent as a function of strain rate with an initial strength peak at between 6 to 8% strain, followed by a gradual strength-softening region out to at least 30% strain.

Tests were not taken to strain larger than 30%, so that a transition to a work-hardening mode observed in the literature was not confirmed. However, these stress-strain curves are otherwise in good agreement with prior studies [2, 4].

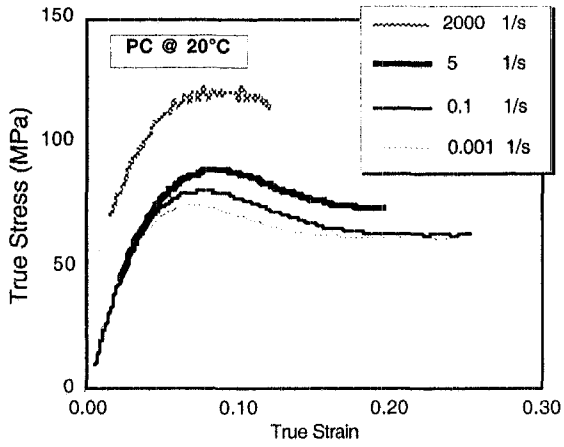

FIGURE 1. The strain rate sensitivity of polycarbonate (PC) is weak at 20°C.

Fig. 2 shows that the compressive strength of PC is moderately temperature dependent, particularly at low temperatures and in combination with high-strain-rate loading. Interestingly, the low strain rate strength at -197°C is comparable to the high-strain-rate strength at -55°C. It will be shown later that a similar low temperature-high strain rate relationship exists with PMMA.

Polymethylmethacrylate (PMMA)

The room temperature compressive stress-strain response PMMA is shown in Fig. 3 for a range of strain rates. Again the shape of the stress-strain curves are similar with an initial strength peak between 6 to 8% strain, however both the magnitude of the strength and the strength-softening behavior is now strongly strain rate dependent. Specifically, the peak strength of PMMA increases by a factor of 3 between a strain rate of 0.001 and 2200 s^{-1} at room temperature.

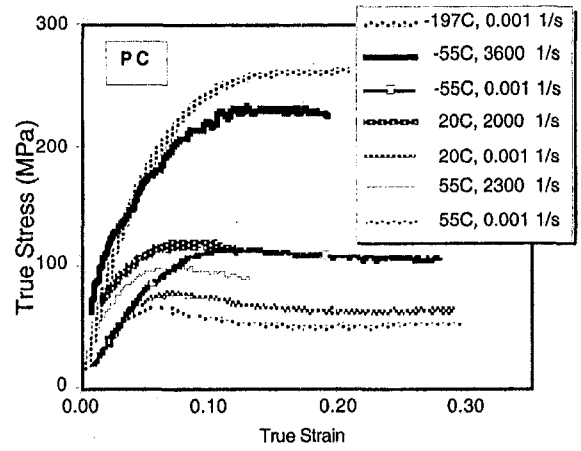

FIGURE 2. The compressive strength of PC is moderately temperature dependent.

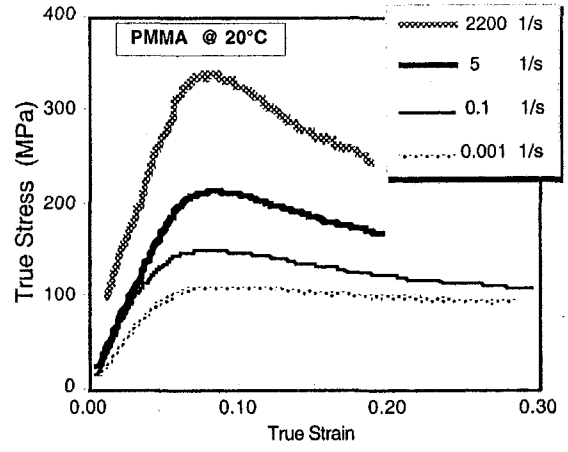

FIGURE 3. The room temperature compressive strength of PMMA is strongly strain rate dependent.

Figure 4 is a plot of strength versus temperature for PMMA at a constant strain rate of 0.001 s^{-1}. This result demonstrates a very linear temperature dependence of the peak strength of PMMA down to very low temperatures. However at -197°C the peak strength is truncated due to failure of the specimen. Also note that there is much less strain-softening of PMMA compare to PC at low strain rates. Figure 5 shows a similar linear temperature dependence of the peak strength at high strain rates. The strain-softening behavior of PMMA at high strain rates is also very temperature dependent and becomes stronger with decreasing temperature. In addition,

cracks develop under room temperature loading and complete specimen failure occurs below about 10°C. Again it is interesting to note that the quasi-static response at -197°C and the high strain rate behavior at -60°C are nearly identical.

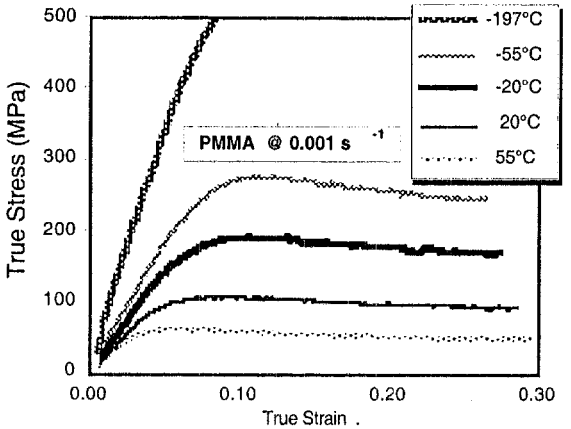

FIGURE 4. The peak strength of PMMA is linearly dependent on temperature at low strain rates. Failure at low strain occurs at liquid nitrogen temperatures.

Figure 4 is a plot of flow stress (at 10% strain) versus temperature for Kel-F 800™ that demonstrates linear temperature dependencies at both high and low strain rates. High strain rate loading increases the temperature dependence (slope) of the flow stress and shifts the line to higher stress (or, equivalently, to higher temperatures).

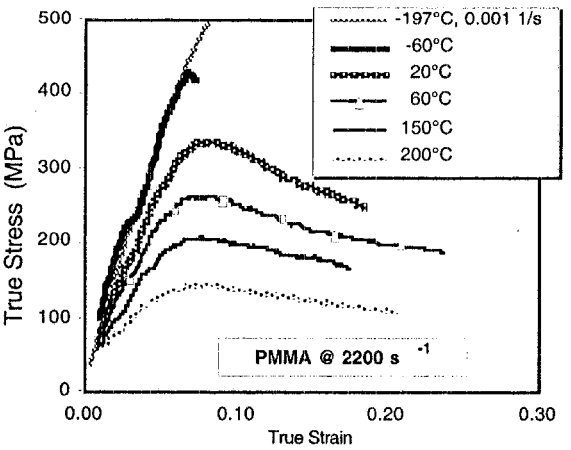

FIGURE 5. The peak strength of PMMA is also nearly linearly dependent on temperature at high strain rates. However, cracking and failure occurs at temperatures very near room temperature.

Note that the quasi-static x-axis intercept of 299°K corresponds closely to the measured glass-transition temperature of Kel-F 800™ of 301°K and that the x-axis intercept at high strain rates (350°K) is approaching the melting temperature of Kel-F 800™ (378°K) (5).

SUMMARY AND CONCLUSIONS

The following conclusions can be drawn. First, the compressive stress-strain response of PMMA and PC are very different as a function of both temperature and strain rate. Second, the strength of PC is weakly dependent on strain rate, only moderately dependent on temperature, and remains ductile to at least -197°C under low strain rate loading. Third, in contrast to PC, the strength of PMMA is linearly dependent on temperature and strongly dependent on strain rate. Finally, PMMA develops cracking and fails in compression with little ductility (7-8% total strain) at either low strain rates and very low temperatures (-197°C) or at high strain rates near ambient temperatures.

ACKNOWLEDGMENTS

This work was performed at the Los Alamos National Laboratory under the auspices of the U.S. Department of Energy (contract W-7405-ENG-36).

REFERENCES

1. Gray III, G.T. and W.R. Blumenthal, *Split-Hopkinson pressure bar testing of soft materials*, in *ASM Handbook. Vol. 8: Mechanical Testing and Evaluation*, H. Kuhn and D. Medlin, Editors. 2000, ASM International: Materials Park, Ohio. p. 488-496.
2. Li, Z. and J. Lambros, *Strain rate effects on the thermomechanical behavior of polymers.* Int. J. Solids and Structures, 2001. **38**: p. 3549-3562.
3. Walley, S.M., et al., *A Study of the Rapid Deformation-Behavior of a Range of Polymers.* Philosophical Transactions of the Royal Society of London Series a-Physical Sciences and Engineering, 1989. **328**(1597): p. 1-33.
4. Walley, S.M. and J.E. Field, *Strain rate sensitivity of polymers in compression from low to high rates.* DYMAT Journal, 1994. **1**(3): p. 211-227.