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Material Properties

Temperature-dependent mechanical behaviour of PMMA: Experimental analysis and modelling

Adel A. Abdel-Wahab [a, c, *], Sabbah Ataya [b, c], Vadim V. Silberschmidt [d]

[a] Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, 21544, Egypt
[b] Department of Metallurgy and Materials Engineering, Faculty of Petroleum and Mining Engineering, Suez University, Suez, 43721, Egypt
[c] Mechanical Engineering Department, College of Engineering, Al Imam Mohammad Ibn Saud Islamic University, Riyadh 11432, Saudi Arabia
[d] Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Loughborough Leicestershire LE11 3TU, UK

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ABSTRACT

An experimental study of temperature-dependent mechanical behaviour of Poly-methyl methacrylate (PMMA) was performed at a range of temperatures (20 °C, 40 °C, 60 °C and 80 °C) below its glass transition point (108 °C) under uniaxial tension and three-point bending loading conditions. This study was accompanied by simulations aimed at identification of material parameters for two different constitutive material models. Experimental flow curves obtained for PMMA were used in elasto-plastic analysis, while a sim-flow optimization tool was employed for a two-layer viscoplasticity model. The temperature increase significantly affected mechanical behaviour of PMMA, with quasi-brittle fracture at room temperature and super-plastic behaviour (ε>110%) at 80 °C. The two-layer viscoplasticity material model was found to agree better with the experimental data obtained for uniaxial tension than the elasto-plastic description.

1. Introduction

Poly-methyl methacrylate (PMMA) is an amorphous thermoplastic with moderate mechanical properties at room temperature and strain rate of 10^{-3} s^{-1}: tensile strength (σ_{UTS}) of 70 MPa, elastic modulus (E) of 3300 MPa and low density as compared to metallic materials: $\rho = 1.19$ g cm^{-3}. Importantly, PMMA is biocompatible, making it highly desirable for use in electronics, micro-electro-mechanical systems (MEMS), biomedical, micro-optics and micro-fluidic devices [1].

In many of its applications, PMMA is exposed to a wide range of environmental and loading conditions [2]. Hence, several experimental studies were carried out to characterize its mechanical behaviour in terms of temperature and strain-rate sensitivity [3–5]. In particular, various studies investigated response of PMMA to quasi-static and dynamic conditions. For instance, Arruda et al. [6] analyzed the effect of temperature on compression of PMMA in quasi-static and intermediate strain-rate regions. They found that softening of the material occurring after its yield was a combined effect of strain hardening/softening and thermal softening. Also, Richeton et al. [7] studied the effect of a wide range of strain rates (from 0.0001 s^{-1} up to 5000 s^{-1}) and temperatures (from −40 °C up to 180 °C) on mechanical response using compression tests. They found that yield stress increased with decreasing temperature and increasing strain rate for the studied materials including PMMA. Similar analysis for yield stress was performed by Chou et al. [8] and Briscoe and Nosker [9]. More recently, Jancar et al. [10] studied the effect of temperature and strain rate on yield stresses and post-yield softening of PMMA. Additionally, Raha and Bowsen [11] conducted plane-strain compression tests on PMMA to study the structural changes employing birefringence measurements. They reported that the model of dissociable cohesion points gave a reasonable explanation to all the observations on the polymer for its optical and mechanical properties. Arruda and Boyce [12] also performed uniaxial and plane-strain compression tests at temperatures below the glass transition to study the effect of anisotropy on deformation; stress-strain behaviour was found to depend strongly on the state of deformation.

Dissimilar to metallic materials, PMMA demonstrates initial yielding that depends on pressure, strain rate and temperature, but true strain softening after yielding, i.e., a drop in level of true stress

* Corresponding author. Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, 21544, Egypt.
E-mail address: a.a.abdel-wahab@alexu.edu.eg (A.A. Abdel-Wahab).

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Nomenclature

B	Width of specimen
c_Y, c_{UTS}	Material constants
d	Specimen's deflection at mid-span
E	Elastic modulus
e	Engineering strain
F	Applied force
f	Ratio of elastic modulus of elastic network (K_v) to total (instantaneous) modulus ($K_p + K_v$)
H'	Hardening parameter
h	Thickness of specimen
K	Elastic modulus of material at highest loading rate
K_p	Modulus of elastic-plastic network
K_v	Modulus of elastic-viscous network
l	Beam span
S	Slope of force-deflection curve
T	Test temperature
T_0	Reference temperature (room temperature)
T_g	Glass transition temperature
U1	Translation in x-axis
U2	Translation in y-axis
UR1	Rotation about x-axis
UR2	Rotation about y-axis
A, m, n	Norton-Hoff rate parameters
$b, h_0, h_1, m_1, m_2, w, \sigma_1, \sigma_2$	Material parameters
σ_{UTS}	Tensile strength
ε	True strain
$\dot{\varepsilon}$	Strain rate
$\dot{\varepsilon_0}$	Reference strain rate
ε_b	Flexure strain
ε_{fr}	Strain at fracture
ε_t	Total strain
$\dot{\varepsilon}_v^v$	Steady-state creep rate
ν	Poisson's ratio
ρ	Density
σ	Engineering stress
σ'	True stress
$\sigma_{0.2\%}$	Proof stress
σ_b	Flexure stress
σ_f	Flow stress
σ_p	Stress in elastic-plastic network
σ_t	Total stress
σ_v	Stress in elastic-viscous network
σ_Y, σ_{UTS}	Yield stress and ultimate tensile stress
σ_{0_Y}, $\sigma_{0_{UTS}}$	Yield stress and ultimate tensile stress at reference temperature T_0

with plastic straining can be observed. At large strains, the material hardens [13] (more information about the true stress - true strain response of PMMA can be found in Refs. [6,13]). This feature of stress - strain curves of PMMA makes it cumbersome to model.

Various material models have been suggested in the literature to describe amorphous polymers; their main application is to simulate different processing techniques [14]. There are many efforts to provide a constitutive model to capture mechanical behaviour of PMMA. Some of the early works on modelling of glassy polymers developed by many researchers can be found in Refs. [15–20].

This work focuses on analysis of the temperature-dependent behaviour of PMMA and applicability of two constitutive models - elastic-plastic and two-layer viscoplastic - available in Abaqus 6.13 finite-element software. Tensile and bending tests of PMMA were performed over an application-relevant temperature range (20 °C, 40 °C, 60 °C and 80 °C) below its glass transition point (108 °C). The obtained experimental data were used to quantify parameters of the two constitutive models.

To the best of the authors' knowledge, this is the first study aimed at identification of parameters for two different material formulations of PMMA using an optimization simulation process flow 'sim-flow'.

2. Experimental procedure

2.1. Materials and manufacturing process

The material used in this study was standard-grade MD001 commercial poly (methyl methacrylate) (PMMA) with mass density of 1.19 g/cm^3 at room temperature. PMMA samples for tension and bending were produced using a multipurpose injection moulding machine Arburg Allrounder 420 C, Golden Edition (Lossburg, Germany) in a sample set mould containing different specimens with their standard dimensions. This process was implemented according to standard ISO 8257 [21].

Dimensions of tensile test samples were according to BS 2782-3 [22,23] or ISO 527 [23]. Dumbbell tensile-test specimens had a total length of 170 mm, width of 10 mm for the middle section and a thickness of 4 mm. Three-point bending specimens were prepared and produced according to ISO 178 [24] with a total length of 80 mm, a width of 10 mm and a thickness of 4 mm.

2.2. Uniaxial tension test

Tensile tests of the PMMA were performed using an Instron 3367 system with a maximum load capacity of 30 kN equipped with an environmental chamber with a temperature range from −70 to 350 °C and feedback temperature control. Before a test, the chamber was preheated to the designated temperature and left until the temperature became stable. Then, each specimen was mounted and left for 5 min in the chamber to reach the desired temperature, see Fig. 1.

The tensile tests on PMMA were carried out at temperatures of 20 °C, 40 °C, 60 °C and 80 °C. In order to perform the test with a strain rate of 0.001 s^{-1}, the speed of the crosshead was adjusted to 0.08 mm/s. Two specimens were tested for each temperature.

2.3. Three-point bending test

Three-point bending tests were performed using a universal testing machine Zwick/Roell Z100 with a 100 kN load cell. A pair of supports was manufactured using tool steel (Fig. 2); the span between the lower supports $\boldsymbol{l}$ was adjusted at 64 mm and the loading speed was 3 mm/min.

Three-point bending tests were performed at the same temperatures as tensile tests. A dedicated heating chamber was built, with temperature measured with a thermocouple near the middle section of the specimen; a supply of hot air and temperature level were manually controlled. The test was performed either until fracture of the specimen or reaching a deflection of 0.7 of a half span length. Here, also, two specimens were tested for each temperature.