Modeling of Mechanical Behavior of SLA Parts

Zhanping Wu, Said Ahzi, Frank W. Paul, Elaine Hunt
Department of Mechanical Engineering
and Amod A. Ogale
Department of Chemical Engineering
Laboratory to Advance Industrial Prototyping (LAIP)
Clemson University, Clemson, SC 29634

ABSTRACT

In recent years, important efforts have been focused on producing functional parts using Stereolithography Apparatus (SLA). One of the applications is the development of rapid polymer tooling such as dies for injection molding. For these applications, optimal thermal as well as mechanical properties are of significance. In this paper, the mechanical behavior of the cured resin SL5170 is discussed by use of an elastic-viscoplastic material model. Uniaxial compression tests at different deformation rates are conducted. The stress-strain curves of these tests are predicted by the model, and comparisons of these results with experiments show good agreement.

1. Introduction

Recently, rapid prototypes made from polymers, ceramics and metals have lead to interest and research focus in the possibility of fabricating functional and semi-functional parts. Rapid prototyping and manufacturing (RP&M) techniques, having various building materials, can basically be classified into two fields: one is mainly aimed at directly making final parts and the second is concerned with building semi-functional parts or models. StereoLithography Apparatus (SLA) is used to produce parts by photopolymerization. This process is one of the main RP&M processes that were initially aimed at producing models. However, SLA has recently shown its great potential for rapid polymer tooling. One example in the development of rapid polymer tooling using SLA is the fabrication of dies for injection molding. It is commonly known that materials, building styles, environments and postcuring process all together account for parts' size limitation, accuracy and behavior. Compared to the earlier SL acrylate photopolymer systems, parts built in photopolymer SL5170 have significantly enhanced mechanical properties, that is, a high level of overall accuracy, negligible curl, improved flatness, minimal green creep distortions, better tensile modulus and flexural modulus [1]. The fabrication of polymer matrix composite dies for injection molding, using filed SL5170, is of current interest [2].

To characterize the mechanical behavior of the SLA die, it is necessary to understand the mechanical response of the cured resin. In this paper the mechanical response of the epoxy resin SL5170 is investigated. Our goal is to develop a model that will be used to simulate complex thermo-mechanical loading for the analysis of the die behavior during injection molding. In the current study, we considered homogeneous deformation such as uniaxial compression and implemented a three-dimensional model to simulate the elastic-viscoplastic response of SLA built samples using epoxy resin SL5170. Since the current effort of development of polymer

tooling is focused on composite dies, our current study is concerned only with the behavior of the matrix.

Postcured SL5170 parts have high degree of polymerization and cross-linking density. The cross-linking is formed by strong covalent bonds that connect the polymer chains to each other. Since the chemical forces must be overcome before molecular flow can be realized, solidified SL5170 part can not melt upon heating. Therefore, cured SL5170 is classified as a cross-linked thermoset polymer. However, the elastic-viscoplastic response of this resin under compression is similar to that of glassy thermoplastics such as polycarbonate. Note the glassy temperature of SL5170 is about 80°C.

In the past decades, various models have been developed to explain the mechanical response of different polymers including rubbers and glassy polymers. Treloar [3] reviewed physically-based models for rubber elasticity. For the plastic deformation of glassy polymers, Argon [4] proposed a model for local shear transformations in these materials. Boyce et al. [5] used Argon's model and developed a three-dimensional constitutive model for large elastic-viscoplastic deformation of glassy polymers. This model encompasses factors affecting the stress-strain curves, such as strain rate, temperature and pressure, and accounts for strain softening and hardening after yield. The strain hardening in these materials is due to molecular orientation and is modeled using a back stress as a measure of orientation hardening. In our work, we use the model of Boyce et al. (1988) [5] with the strain hardening model of Arruda and Boyce [6] to simulate uniaxial compression of postcured epoxy resin SL5170.

2. Experiments

Two kind of samples are used: the first one (designated as type I) is 50.8mm in height and 25.4mm in diameter, i.e., 2inch x 1inch (Fig.1.a); the second one (designated as type II) is 8mm in height and 8mm in diameter (Fig.1.b). All parts are built along the Z-direction at 28°C and under ACES part building style. The machine is a 3D Systems SLA 250/50. The samples were postcured.

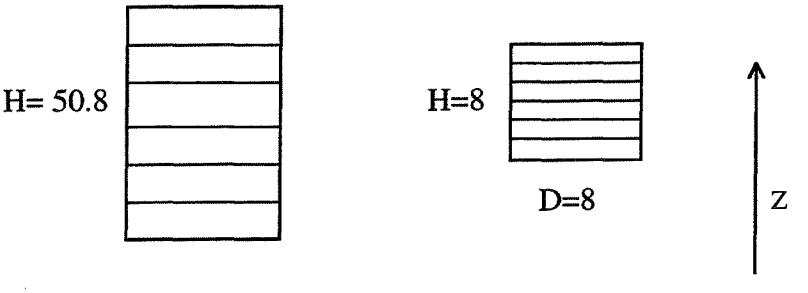
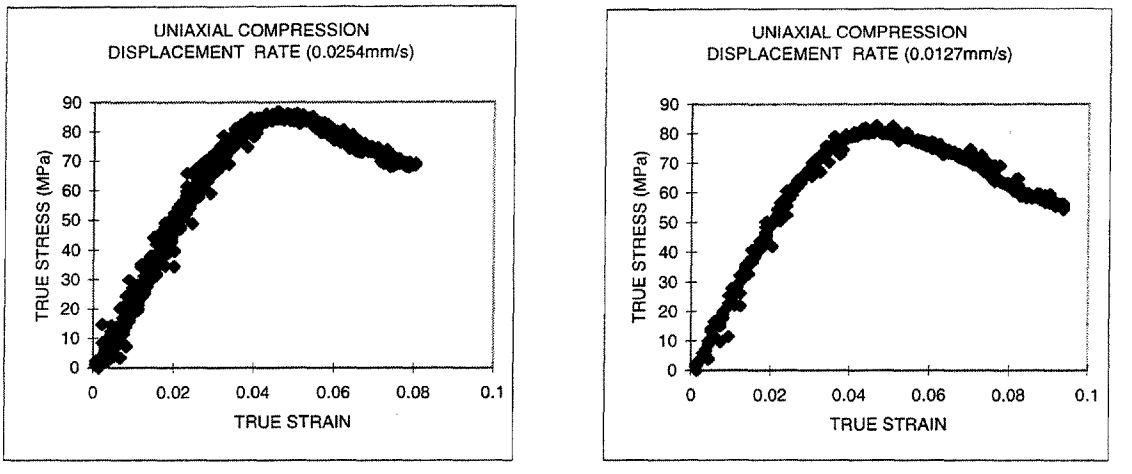


Fig.1

Uniaxial compression tests at constant displacement rates of deformation are imposed on Instron machine. Thin teflon films are used as lubricant to reduce friction between the platens and the sample. Compression direction is parallel to the Z-direction. Series of tests are carried out to get stress-strain response and material parameters necessary to the mathematical model. Results are listed as follows:

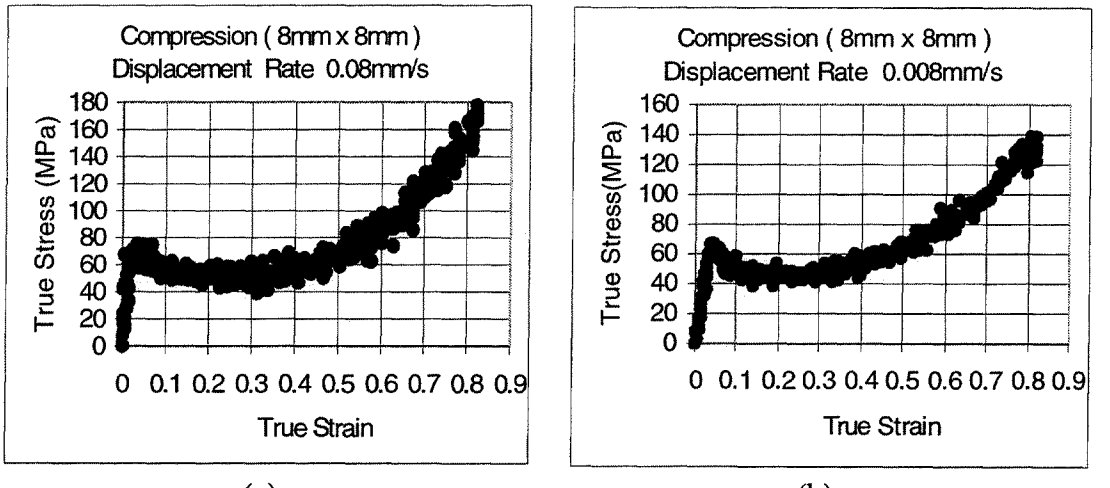
(1) Rate dependent yield: As shown in Fig.2, at different displacement rates, stresses at yield point are significantly different. A yield stress of 85MPa is observed for displacement rate of 0.0254mm/s, and 80MPa for displacement rate of 0.0127mm/s. Samples of type I are uniaxially compressed in this case. The strain rate at small deformation is approximately the same as the ratio of the displacement rate to the initial sample height, thus, strain rate dependent yield is concluded.



(a) (b)

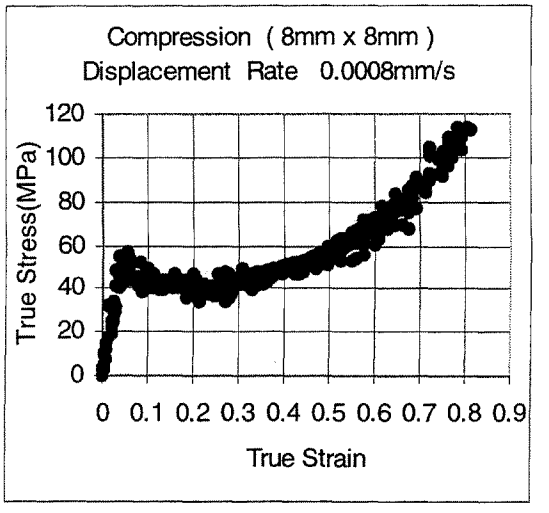
Fig.2

(2) Large deformation behavior: In addition to linear elastic and nonlinear part before the yield point (Fig.2), the stress-strain curves in Fig.3 are the response at large strain. These figures display strain softening after yield followed with a steady state and strain hardening. The compression tests in Fig.3 are conducted using type II samples. Here again, strain rate effects on the yield are observed.



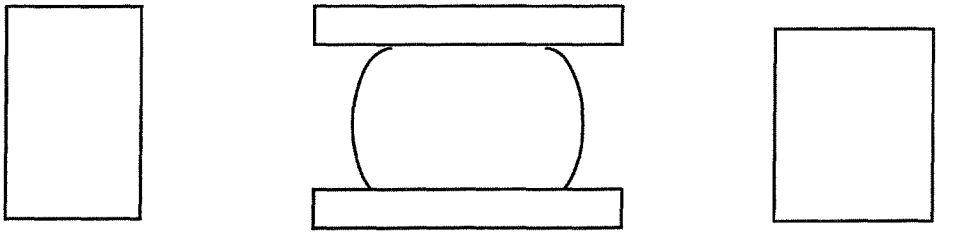
(a) (b)

Fig.3



(c)
Fig.3

(3) Recovery test (Fig.4) : After uniaxial compression in the Z-direction, a type I sample is compressed to 1.44 inch in height and 1.23 inch in diameter, which exhibits a true strain of about 32%. The compressed sample was then put in an oven at 90°C for four hours. Note that postcured SL5170 sample has a glass transition temperature at about 80°C. When the sample was taken out of the oven, its original size was almost totally recovered. This is a well known phenomenon in glassy polymers that are plastically deformed then heated above their glass transition temperature.



(a) (b) (c)

Fig. 4

3. Model Description

Several models have been developed for rubbers and glassy polymers. The proposed constitutive model for the simulation of the stress-strain behavior is briefly summarized below. Details are given in the work of Boyce et al. [5].

The deformation gradient tensor $\mathbf{F}$ is multiplicatively decomposed as elastic part $\mathbf{F}^e$ and plastic part $\mathbf{F}^p$:

$$\mathbf{F} = \mathbf{F}^e\mathbf{F}^p \tag{1}$$

The plastic part $\mathbf{F}^p$ designates the deformation gradient from the undeformed configuration to the relaxed one. The relaxed configuration is obtained by elastic unloading. The elastic deformation gradient is assumed symmetric and represents elastic stretching of the material. The plastic velocity gradient $\mathbf{L}^p$ is defined in terms of $\mathbf{F}^p$ as:

$$L^p = \dot{F}^p F^{p-1} = D^p \tag{2}$$

Note that $\mathbf{L}^p = \mathbf{D}^p + \mathbf{W}^p$ where the plastic spin is assumed null and the plastic strain rate $\mathbf{D}^p$ is given by the flow rule:

$$D^p = \dot{Y}^p N \tag{3}$$

with,

$$N = \frac{1}{\sqrt{2}\tau} T^{*'} \tag{4}$$

Here, $\dot{Y}^p$ is the plastic shear rate, τ is the equivalent shear stress, $\mathbf{T}^{*'}$ is the deviatoric part of driving stress $\mathbf{T}^*$ given by:

$$T^* = T - \frac{1}{J} F^e B F^{eT} \tag{5}$$

In relation (5), $\mathbf{T}$ is Cauchy stress tensor and $\mathbf{B}$ is the back stress tensor representing a measure of the orientational hardening. The elasticity relation gives:

$$T = \frac{1}{J} C^e [\ln F^e] \tag{6}$$

where $\mathbf{C}^e$ is the elastic stiffness tensor of the material, J is the volume change, and $\ln\mathbf{F}^e$ represents the logarithmic strain. In the applications, isotropic elasticity is assumed.

Now, we consider the Argon's model for the shear rate $\dot{Y}^p$. This model was modified by Boyce et al. [5] and Hasan et al. [7] to include pressure and rate sensitivity and it is expressed as:

$$\dot{Y}^p = \dot{Y}_0 \exp[-\frac{AS}{\theta}(1-\frac{\tau}{S})] \tag{7}$$

with,

$$\dot{S} = h \cdot (1 - \frac{S}{S_{ss}}) \cdot \dot{Y}^p \tag{8}$$

Here, $\dot{Y}_0$, pre-exponential factor; A, a constant dependent on rate and temperature; θ, absolute temperature. Eqn.(8) is the evolution of athermal deformation resistance S, h is the slope of yield drop with respect to plastic strain and Sss is the steady state resistance.

For an initially undeformed glassy polymer, the principal components of the of the back stress $\mathbf{B}$ evolve with straining and can be expressed as [5] [6] [7]:

$$B_i = \frac{C^R}{3}\sqrt{N} L^{-1}(\frac{\lambda_{chain}}{\sqrt{N}}) \frac{\lambda_i^2 - \frac{1}{3} I_1}{\lambda_{chain}} \tag{9}$$

In Eqn.(9), L^{-1} is the inverse Langevin function; $\sqrt{N}$ is equal to the locking stretch; C^R is rubbery modulus; λ_{chain}, stretch experienced by each network chain; I_1, first invariant of plastic stretch.

The material parameters used in the model are obtained from the experimental results in Fig.2 and Fig.3. Material constants such as Young' modulus, locking stretch, coefficients for rate dependent yield are measured directly from the experimental stress-strain curves. The other parameters, such as rubbery modulus, are selected to fit the compression stress-strain curves to the experimental ones. The Poisson ration is estimated based on results in literature to be 0.45. The following is a list of factors put in the mathematical model.

Shear modulus:	$\mu = 900$ MPa
Poison's ratio:	$\nu = 0.45$
Pre-exponential constant:	$\dot{Y}_0 = 3.65 \times 10^{12}$
Constant A:	A = 118.85 K/MPa
Temperature of test:	Tem = 298 K
Initial athermal shear resistance:	$S_0 \cong 0.077*\mu/(1-\nu) \cong 126$ MPa
Steady stress:	$S_{ss} = 0.71*S_0 = 90$ MPa
Slope of yield drop:	h = 400 MPa
Rubbery Modulus:	$C^R = 20$ MPa
Locking Stretch:	$\sqrt{N} = \lambda_L = 3$

4. Simulations and Comparisons

After all required material constants have been identified as listed above, computer simulations

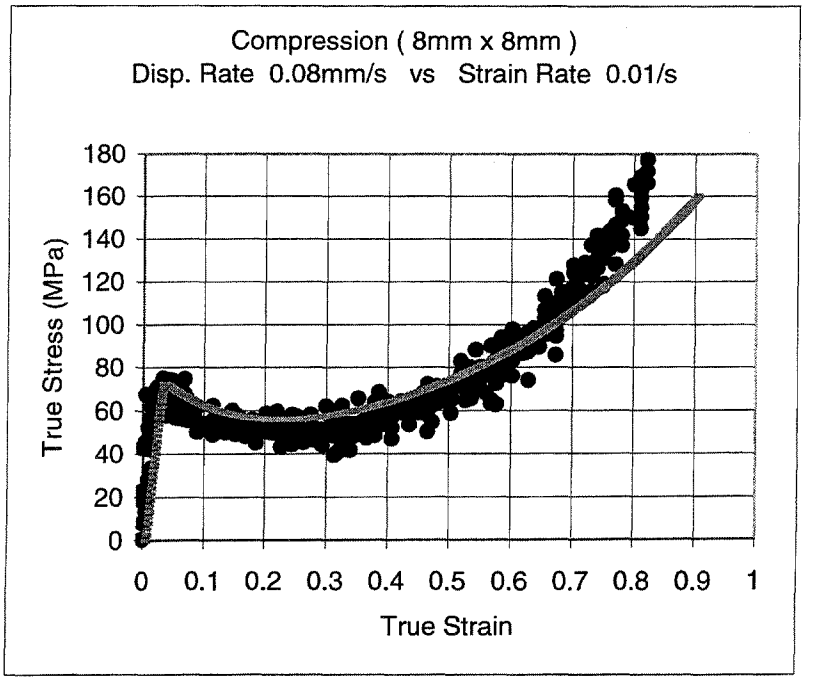


Fig.5

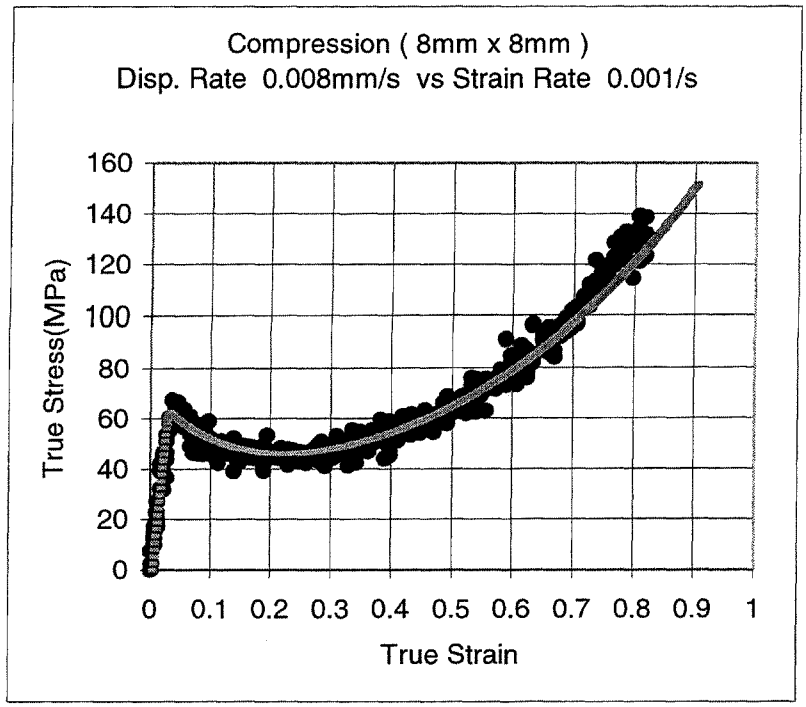


Fig.6

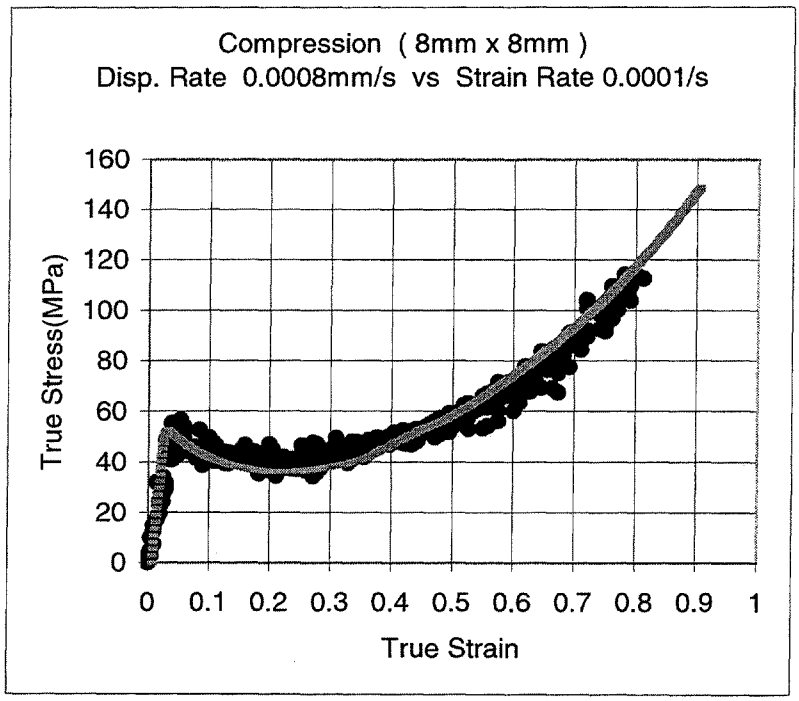


Fig.7

of uniaxial compression tests are accomplished for different strain rates: 0.01/s, 0.001/s and 0.0001/s. The comparison with the computed stress-strain curves with experimental ones in Figures 5-7 show a good agreement for different strain rates. Note that the rate dependent yield is well predicted as well as the softening after yield and orientational hardening. Since the

simulations are conducted based on constant strain rate rather that displacement rate, this leads to some discrepancies especially at large strains. At small strains, the ratio of displacement rate to initial sample height and the strain rate are almost identical.

5. Conclusions

The mechanical behavior of postcured SL5170 layered parts, deformed in uniaxial compression perpendicular to the layers, exhibits elastic and inelastic response. These show a rate dependent yield and high ductility when deformed in compression at room temperature. The rate dependent yield and large deformation properties of the photopolymerized and postcured SL5170 are thus characterized using uniaxial compression tests. The mechanical response of these SLA parts is simulated by use of an elastic-viscoplastic material model. We are currently implementing the model in a finite element code to simulate non-homogeneous deformations. The proposed work finds its application in the simulation of complex loading conditions of SLA parts made from the photopolymer SL5170. We are also conducting other tests to identify temperature effects and to investigate the response under compression at directions other than the Z-direction.

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References

1. Jacobs, P.F., *"Stereolithography and Other RP&M Technologies"*, SME, New York, New York, 1996.
2. Douglas Taft, A. Ogale, Elaine Hunt, Said Ahzi, Frank Paul, *"Particulate Filled Resins for Rapid SLA Injection Tools"*, SFFS, Austin, Texas, 1997.
3. Treloar, L.R.G., *"The elasticity and related properties of rubbers"*, Rep. Prog.Phys., 1973, Vol. 36, pp.755-826.
4. Argon, A.S., *"A theory for the low-temperature plastic deformation of glassy polymers"*, Phil. Mag. 28, Vol. 39, 1973.
5. Boyce, M.C., Parks, D.M. and Argon, A.S., *"Large inelastic deformation of glassy polymers"*, Mechanics of Materials, 7.(1988).15-33.
6. Arruda, E.M. and Boyce, M.C., *"A 3-dimensional constitutive model for the large stretch behavior of rubber elastic materials"*, J. Mech. Phys. of Solids, Vol. 41, 1993, pp. 389-412.
7. Hasan, O.A. and Boyce, M.C., *"A constitutive model for the nonlinear viscoelastic viscoplastic behavior of glassy polymers"*, Polymer Engineering and Science, 1995, Vol. 35, N0. 4, pp.331-344.