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Towards mechanical characterization of soft digital materials for multimaterial 3D-printing

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ABSTRACT

We study mechanical behavior of soft rubber-like digital materials used in Polyjet multi-material 3D-printing to create deformable composite materials and flexible structures. These soft digital materials are frequently treated as linear elastic materials in the literature. However, our experiments clearly show that these materials exhibit significant non-linearities under large strain regime. Moreover, the materials demonstrate pronounced rate-dependent behavior. In particular, their instantaneous moduli as well as ultimate strain and stress significantly depend on the strain rate. To take into account both hyper- and viscoelasticity phenomena, we employ the Quasi-Linear Viscoelastic (QLV) model with instantaneous Yeoh strain-energy density function. We show that the QLV-Yeoh model accurately describes the mechanical behavior of the majority of the soft digital materials under uniaxial tension.

1. Introduction

Recently, additive manufacturing or 3D printing of architected materials has attracted significant attention (Haghpanah, Salari-Sharif, Pourrajab, Hopkins, & Valdevit, 2016; Schaedler & Carter, 2016; Shan et al., 2015; Zheng et al., 2014). Additive manufacturing, combined with rational design, allows one to create ultrastiff and ultralight materials (Zheng et al., 2014), or materials, consisting of stiff components, but capable of recovering after large compressive deformation up to 50% (Meza, Das, & Greer, 2014). Motivated by design and fabrication of reconfigurable and tunable materials and structures, soft microstructured materials capable of large deformations have become an active field of research. Architected materials with soft constituents demonstrate unique mechanical properties, such as negative Poisson's ratio (Babaee, Shim, Weaver, & Chen, 2013), or act as machine-augmented composites, converting the applied force direction or absorbing elastic energy (Bafekrpour, Molotnikov, Weaver, Brechet, & Estrin, 2014; Rudykh & Boyce, 2014a). By varying the amount of soft constituents, together with their geometrical arrangements, it is possible to tailor the mechanical performance of the composites (Cho et al., 2016; Dalaq, Abueidda, & Abu Al-Rub, 2016). Moreover, such composites may be used to actively and reversibly control wave propagation via deformations and elastic instabilities (Rudykh & Boyce, 2014b; Shan et al., 2014). Though an addition of soft components in architected materials may be beneficial for achieving new functionalities, it requires more complicated material fabrication techniques that allow producing soft-stiff deformable composites. Recently, new UV-curing materials have been introduced into multimaterial 3D printing; the developed by Stratasys rubber-like materials show the ability of sustaining extremely large elastic deformations before failure at around 200–300% strain level. These soft UV curing resins are used in the Polyjet printing process. During Polyjet 3D-printing, small droplets of photopolymers are deposited

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Table 1
Elastic modulus of TangoPlus/TangoBlackPlus materials, reported in different studies. LE – linear elastic model, NH – neo-Hookean model, AB – Arruda-Boyce model.

Reference	Constitutive Model	Reported modulus (Y – Young's S – shear), [MPa]	Poisson's Ratio	Shear modulus[a] [MPa]
Dalaq et al. (2016)	LE	0.47 (Y)	-	0.158
Cho et al. (2016)	NH	0.56 (Y)	0.49	0.188
Slesarenko and Rudykh (2016)	NH	0.2 (S)	–	0.200
Slesarenko et al. (2017)	NH	0.21 (S)	–	0.210
Lin et al. (2014)	LE	0.63 (Y)	–	0.211
Wang, Lau, Thomas and Boyce (2011)	AB	0.213 (S)	–	0.213
Rudykh et al. (2015)	–	0.78 (Y)	–	0.261
Li, Kaynia, Rudykh and Boyce (2013)	LE	0.9 (Y)	–	0.302
Shen et al. (2014)	LE	0.99 (Y)	0.48	0.330

[a] For comparison reasons, the initial shear modulus is calculated for LE model as $\mu = 0.5\ E/(1+\nu)$. If Poisson's ratio is not reported, we consider the material to be nearly incompressible with $\nu = 0.49$ in the calculation of the initial shear modulus. If the anisotropy of the elastic modulus is reported, we calculate the average elastic modulus.

onto the horizontal platform through the series of inkjet printing heads. After deposition of each layer, the ultraviolet lamps cure the photopolymer. This Polyjet 3D-printing technique allows fabrication of multimaterial structures with the resolution as fine as 16 μm with up to three different materials in printed models. Furthermore, by using different nozzles for different materials, it is possible to locally mix several materials and, therefore, to obtain homogeneous soft resins with various mechanical properties. In particular, by mixing soft TangoPlus (TP) polymer with stiff VeroWhite (VW) polymer, it is possible to obtain the so-called digital materials (DMs) with different mechanical properties.

The DMs have been employed to develop the concept of flexible armor (Rudykh, Ortiz, & Boyce, 2015), or to mimic the natural structures of nacre (Slesarenko, Kazarinov, & Rudykh, 2017), suture interfaces (Lin & Li, 2014; Lin, Li, Weaver, Ortiz, & Boyce, 2014) and other biological materials (Dimas, Bratzel, Eylon, & Buehler, 2013). DMs have also been used to prototype membranes (Philamore, Rossiter, Walters, Winfield, & Ieropoulos, 2015), arteries (Biglino, Verschueren, Zegels, Taylor, & Schievano, 2013). Surprisingly, the reported mechanical properties of the materials under study vary significantly in the literature. Table 1 summarizes the mechanical properties of TangoPlus material as reported in different studies. Note the significant variations of the initial shear modulus of the digital material. Recent works have revealed that certain variation of the shear modulus can be caused by the printing process anisotropy (Bass, Meisel, & Williams, 2016; Blanco, Fernandez, & Noriega, 2014). However, the reported anisotropy of the mechanical properties does not exceed 20% (Dalaq et al., 2016; Shen, Zhou, Huang, & Xie, 2014). Additional factors that may affect mechanical performance include temperature, humidity or illumination during printing as well as during testing (Bass et al., 2016). The DMs under study have glass transition temperatures in the -10 to + 58 °C range (Ge, Dunn, Qi, & Dunn, 2014), therefore, small temperature deviations during UV-curing or testing may affect measured mechanical properties. The properties of DMs can also change with time, due to aging occurring in photopolymers. Therefore, time interval from manufacturing to testing can cause some alteration in the properties of the materials (Bass et al., 2016). Summarizing, we would like to emphasize that full characterization of the DMs is a challenging task, and most studies of composite materials require preliminary testing of the constituents under specific conditions of 3D printing and testing. Thus, UV-curing soft resins and DMs require specific attention and careful consideration of their complicated mechanical behavior.

We would like to note that soft DMs exhibit significant nonlinear mechanical behavior, which is frequently neglected in the available literature – we summarize reported mechanical models in Table 1. For example, these DMs are frequently considered as linear elastic materials. Linear elastic model can provide adequate approximations for material behavior for the small strains, typically not exceeding 5%; application of linear elastic model under the large strain regime may, however, lead to inaccurate results and conclusions. Another simplification of the mechanical behavior occurs when their mechanical response is considered to be independent of the strain rate. The effects of viscoelasticity on composite behavior have been analyzed in Blanco et al. (2014), Slesarenko and Rudykh (2016) and Zhang, Heyne, and To (2015), showing significant influence of rate-dependent behavior on the overall response of the composites. Rate-dependent behavior of the DMs drastically increases the complexity of the constitutive models, but however, it is of importance for accurate modeling of the materials and predictions of their behavior. For example, the studies by Alur, Bowling, and Meaud (2015) and Slesarenko and Rudykh (2016) showed that viscoelasticity leads to an increased tunability of wrinkling patterns, occurring in the soft laminates.

Rate dependency and non-linearities due to large deformations are the essential aspects of rich mechanical behavior of the soft DMs used in multimaterial 3D-printing. Here we address these important factors in our attempt to describe mechanical behavior of the DMs using the Quasi-Linear Viscoelastic (QLV) model, which combines hyper- and viscoelasticity phenomena, and to discuss its features and limitations. We note that the paper objective is not the attempt to provide full characterization of the DMs in the complexity of their behavior but exploration of possible ways of accounting for some significant aspects of their mechanical behavior, such as material non-linearity and rate sensitivity.