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Modelling the mechanical aspects of the curing process of magneto-sensitive elastomeric materials

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ABSTRACT

In this paper, a phenomenologically motivated magneto-mechanically coupled finite strain elastic framework for simulating the curing process of polymers in the presence of a magnetic load is proposed. This approach is in line with previous works by Hossain and co-workers on finite strain curing modelling framework for the purely mechanical polymer curing (Hossain et al., 2009b). The proposed thermodynamically consistent approach is independent of any particular free energy function that may be used for the fully-cured magneto-sensitive polymer modelling, i.e. any phenomenological or micromechanical-inspired free energy can be inserted into the main modelling framework. For the fabrication of magneto-sensitive polymers, micron-size ferromagnetic particles are mixed with the liquid matrix material in the uncured stage. The particles align in a preferred direction with the application of a magnetic field during the curing process. The polymer curing process is a complex (visco) elastic process that transforms a fluid to a solid with time. Such transformation process is modelled by an appropriate constitutive relation which takes into account the temporal evolution of the material parameters appearing in a particular energy function. For demonstration in this work, a frequently used energy function is chosen, i.e. the classical Mooney–Rivlin free energy enhanced by coupling terms. Several representative numerical examples are demonstrated that prove the capability of our approach to correctly capture common features in polymers undergoing curing processes in the presence of a magneto-mechanical coupled load.

1. Introduction and outline

In recent years, the so-called magnetorheological elastomers (MREs) or magneto-active elastomers have obtained considerable attention as smart materials whose mechanical properties such as the shear modulus can be tuned by the application of an external magnetic induction. They consist of magnetically permeable particles embedded in a non-magnetic polymeric matrix. Mutual interactions between the particles and between the particles and the matrix are responsible for the macroscopic changes in the magnetomechanical properties of the elastomer. MREs are a relatively new group of smart materials. Due to their magnetically controllable stiffness and damping behaviour, they are attractive candidates for various technical applications. These applications range from automotive industry, e.g. suspension bushing, brakes, clutches, smart springs in dynamic vibration absorber to civil engineering devices such as building vibration isolators (Böse et al., 2012; Chen et al., 2007).

Magneto-sensitive polymers are prepared by dispersing micro-sized magnetically permeable particles in a non-magnetic matrix during the curing process. The most common ferromagnetic particle used is carbonyl iron (Böse et al., 2012; Boczkowska and Awietjan, 2009; Böse and Röder, 2009). Pure iron particle has the highest saturation magnetization of the known elements along with a high permeability and a low remnant magnetization, which provides high, short-term interparticle attraction (Boczkowska and Awietjan, 2009). The particle concentration varies between 0–30 percent, mainly expressed in terms of % by volume (Jolly et al., 1996). A high iron concentration may influence the long-term stability of the MRE materials. There are many materials that might be used as the matrix material of an MR composite. Most commonly used matrix elastomers are silicones or natural rubbers (Ginder et al., 2002; Lokander, 2004; Zhou, 2003). The shape and the size of the magnetically active filler particles have a major influence on the properties of an overall MR composite. Most often, spherical carbonyl iron particles with a diameter of several micrometres are used (Kaleta et al., 2011). As a result, the mechanical

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properties of these materials can be varied by the application of a magnetic field.

According to the way in which the magnetic particles are dispersed in the matrix as well as the magnetic induction is applied during the curing process, two kinds of MREs can be manufactured (Kaleta et al., 2011). Firstly, if the magnetic field is applied during the curing process anisotropic elastomers are produced where the magnetic particles are aligned strictly in a particular orientation, cf. Fig. (1, right). Polarized magnetorheological elastomers tend to show anisotropy in mechanical, magnetic and thermal properties (Jolly et al., 1996). Secondly, an isotropic elastomer composite will be formed when there will be no presence of the magnetic induction during the entire curing process, especially at the initial stage of the curing process, cf. Fig. (1, left). Such process of composite material formation will be characterized by a uniform particle distribution (Kaleta et al., 2011). It can be assumed that in the case of the isotropic magnetorheological composites, the magnetically active particles are dispersed homogeneously within the matrix. When a magnetic induction is applied after the fully-cured phase, the filler particles are not able to move freely due to the resistance offered by the cross-linked polymer structure. In such a situation, these particles tend to arrange themselves along the field vector direction. As result, a deformation of the matrix is observed, which can be interpreted as the magnetostriction. Scanning electron microscopy (SEM) can be used to observe MRE microstructure after the curing process. Here, we present both isotropic and transversally isotropic MREs that are produced using our laboratory facilities, cf. Fig. (1).

The deformations of elastomers are typically quite large. Hence the development of the constitutive model of such materials should be in a finite strain framework. The constitutive modelling of pure elastomers as well as magneto-sensitive polymers has a large amount of literature, see Boyce and Arruda (2000), Steinmann et al. (2012) and Hossain and Steinmann (2013) for reviews on the purely polymeric material modelling. The coupling between magnetism and nonlinear elasticity has generated much interest over last several decades which is reflected by variety of research publications in this area. The research of Eringen and Maugin (1990), Jackson (1975) and Pao (1978) are few important earliest works in this field. The works of Dorfmann and Ogden (2003, 2004), Brigadnov and Dorfmann (2003), Bustamante et al. (2007), Bustamante (2009, 2010), Saxena et al. (2013, 2014) and Kankanala and Triantafyllidis (2004) discussed mainly the constitutive relation of the nonlinear magneto-mechanical coupled problem while Vogel et al. (2013, 2012) and Miehe et al. (2011,) present the numerical implementation of coupled boundary value problems in the context of the finite element analysis. Several experimental results on magneto-mechanical coupled loadings are presented by Jolly et al. (1996), Kaleta et al. (2011) and Varga et al. (2006). Very recently, Danas et al. (2012) presented several experimental results and proposed a transversely isotropic energy density function that is able to reproduce the experimentally measured magnetization, magnetostriction and simple shear curves under different prestresses, initial particle chain orientations and magnetic fields.

In the curing process of polymers, a viscoelastic fluid transforms into a viscoelastic solid due to a series of chemical reactions. Such reactions result in polymer chains cross-linking to each other resulting in the formation of chemical bonds that allow the chains to come closer. Packing of chains due to cross-linking will yield a decrease in specific volume which is noted as the volume or curing shrinkage. During curing reactions with time, the viscosity and the stiffness of the liquid resin increase. The chemical reaction of the cross-linking polymers can be an exothermal reaction especially in the case of thermoset curing process, i.e. the formation of the polymer network is accompanied by a heat generation which is added to the external source of heating applied for the curing.

For an illustrative review on the constitutive modelling of the curing process of polymers, our previous works, cf. Hossain et al. (2009a, 2011, 2010) can be consulted. Only limited references for models for the evolution of viscoelastic properties during curing are available in the literature (Ruiz and Trochu, 2005; Suzuki and Miyano, 1977). In developing a cure-dependent small strain constitutive model for a thermosetting polymer, Kiasat (2000) assumed that the formation of new cross-links during curing does not affect the current stress state caused by previously applied strains, i.e. new cross-links form unstrained and stress-free. Several researches do agree with this assumption (Hojjati et al., 2004; Gillen, 1988). Lion and co-workers (Liebl et al., 2012a,b; Lion and Höfer, 2007; Lion and Johlitz, 2012; Lion et al., 2008; Lion and Yagimli, 2008) proposed a phenomenologically-inspired thermo-viscoelastic curing model for finite strains. This modular constitutive model includes thermally and chemically induced volume changes via a ternary multiplicative decomposition of the deformation gradient into mechanical, thermal and chemical parts. In order to realize the evolution of material parameters during curing, the so-called intrinsic time concept is introduced which is then related to the degree of cure. Yagimli and Lion (2011) reformulated their large strain model into a small strain version and validated it with sufficient experimental results.

Mergheim et al. (2012) developed a constitutive model to simulate the curing process-induced damage which evolves during the volume-shrinkage of curing in the case of a thermosetting material. They incorporated an isotropic gradient-enhanced damage model in small strain to describe the damage evolution. Very recently, Klinge et al. (2012a,b) proposed a multi-scale framework for the curing process modelling which deals with the viscoelastic curing together with the volume shrinkage. It is interesting to mention here that the works of Mergheim et al. (2012) and Klinge et al. (2012a,b) are mainly based on the hypoelastic framework for the curing modelling proposed by Hossain et al. (2009a,b, 2010), Hossain (2010) and Hossain and Steinmann (2011). Recently,

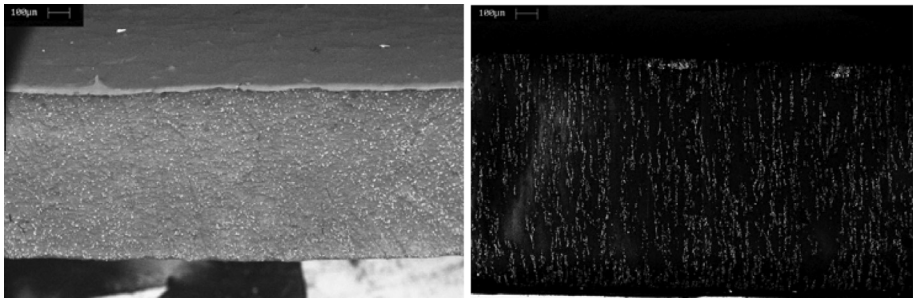

Fig. 1. SEM images (Courtesy of Bastian Walter) for 10% (by volume) iron-particle filled silicone elastomers; (Left) Isotropic MRE due to the absence of a magnetic induction during the curing process. (Right) transversally isotropic MRE produced under a magnetic induction applied in the vertical direction during the curing process.