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A large strain thermodynamically-based viscoelastic–viscoplastic model with application to finite element analysis of polytetrafluoroethylene (PTFE)

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ABSTRACT

We propose a phenomenological viscoelastic–viscoplastic model to simulate the large strain constitutive response of polymeric materials. The formulation is developed in a thermodynamic framework, based on the multiplicative decomposition of elastic, viscous and plastic deformation components. For the viscoplastic part, we use a Perzyna-like model including two components of kinematic hardening, one with pseudo-viscous evolution (Armstrong–Frederick model), and the other with real viscosity, so that the rate-dependency of the plastic stiffness is taken into account. The proposed model is implemented in a large-deformation finite element framework and applied to numerical simulations. The constitutive parameters are calibrated for the material polytetrafluoroethylene (PTFE) using uniaxial monotonic tests featuring different strain rates, and later validated with creep and relaxation experimental results. Finally, mesh and time convergence analyses are carried out in representative examples.

1. Introduction

With recent technological advances and refinement of industrial processes, such as additive manufacturing, the appropriate understanding of mechanical properties and the precise modelling of polymeric solids are in high demand. Polymers, in general, are known for presenting constitutive response with creep, relaxation, and rate-dependency in both elastic and plastic stages, as shown, for instance, in the experimental results of Khan and Zhang (2001), Rae and Brown (2005), Rae and Dattelbaum (2004) for polytetrafluoroethylene (PTFE), Lammens et al. (2017) for polyamide-12, and Lai and Bakker (1995a) for high-density polyethylene (HDPE).

In order to consider this behaviour in small strain analyses, authors like Lai and Bakker (1995b), Frank and Brockman (2001), Kim and Muliana (2009) and Miled et al. (2011), have proposed viscoelastic–viscoplastic models employing an additive decomposition of viscoelastic and viscoplastic strain components.

For finite strain models, however, a more suitable kinematic approach is the multiplicative decomposition, also known as Kröner–Lee decomposition, for being originally introduced by Kröner (1960) and Lee (1969). Such approach is based on the concept of an intermediate configuration, initially proposed, and well established, in the context of pure elasto-plastic models. For a general understanding of such models, refer, for instance, to Haupt (1985), Simo (1992), Khan and Huang (1995) and Simo and Hughes (2000). In Lagrangian thermodynamically-based approaches, the multiplicative decomposition commonly leads to the application of the so-called Mandel stress, as can be seen in the works of Mandel (1973), Svendsen (1998), Svendsen et al. (1998), Dettmer and Reese (2004) and Pascon and Coda (2013a).

Lion (2000) takes a further step on the multiplicative decomposition concept, applying it to split the plastic deformation into an 'elastic' part, which represents the plastic deformation induced by dislocations, and an 'inelastic' part, representing the irreversible displacements on crystallographic slip systems. This idea is used to develop a general finite strain kinematic hardening formulation, which can be particularized to an Armstrong–Frederick model, later applied in Dettmer and Reese (2004), Vladimirov et al. (2008) and Brepols et al. (2014), still within the elasto-plastic context.

In the context of elasto-viscoplastic models, the works of Ibrahimbegović and Chorfi (2000), Mähler et al. (2001) and Garino et al. (2013) feature large strain generalizations of the well-known Perzyna (Perzyna, 1966) and Duvaut–Lions (Duvaut and Lions, 1976) models. In finite strain viscoelasticity, the multiplicative decomposition is commonly associated with internal variable formulations, such as in Reese and Govindjee (1997), Huber and Tsakmakis (2000), Petiteau et al. (2013) and Pascon and Coda (2017), as opposed to the also widely employed convolution integral models (Petiteau et al., 2013).

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