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Material behaviour

Large-strain behaviour of Magneto-Rheological Elastomers tested under uniaxial compression and tension, and pure shear deformations

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ABSTRACT

The large-strain behaviour of Magneto-Rheological Elastomers (MREs) is characterised experimentally under uniaxial compression, uniaxial tension and pure shear deformation, in the absence and in the presence of magnetic fields. MREs are ‘smart’ materials that can alter their properties instantaneously by the application of external stimuli. They hold great potential for use in adaptive stiffness devices. So far, the large-strain behaviour of MREs has not been well explored, and their behaviour under pure shear deformation has not been characterised. Tests on silicone rubber based isotropic and anisotropic MREs, with and without the application of an external magnetic field have been performed in this investigation. The MR effect, defined as the increase in tangent moduli, is studied versus large engineering strain. Strains were measured optically using a Digital Image Correlation (DIC) system. Relative MR effects up to 284% were found under uniaxial tension, when a magnetic field strength of 290 mT was applied with the loading direction parallel to the direction of particle alignment.

1. Introduction

Magneto-Rheological Elastomers (MREs) are smart materials whose properties can be altered reversibly and almost instantaneously by the application of external magnetic fields. This behaviour is caused by the interaction of micron-sized magnetisable particles dispersed in an elastomeric material. The magneto-rheological effect was first explored by Rabinow [1], working on Magneto-Rheological Fluids (MRFs). In MREs, the magnetic particles are locked in position by the solid rubber matrix. Anisotropic materials can be prepared by exposing the fluid MRE mixture to a magnetic field while curing, this forces the magnetised particles to align in chains, resulting in strong mechanical and magnetic anisotropy [2]. The first preliminary tests on MREs were performed by Rigbi and Jilken [3] and the dynamic small strain behaviour of MREs has since become a well-explored property [4–6, i.e.], using different types of matrix materials and magnetisable particles. Also, the influence of several factors on the final properties of MREs, such as the strength of the magnetic field used during manufacture of anisotropic MREs, was investigated by Chen et al. [7]. The magnetostriction [8] and the magnetic properties of MREs [9] have also been studied.

In order to develop constitutive models characterising the complex behaviour of MREs, extensive experimental data derived from uniaxial and multi-axial deformation modes on the same type of material are required [10–12]. The large strain behaviour of MREs has been studied mainly under compression and simple shear [13–17] while, to the best of the author's knowledge, the behaviour of MREs under pure shear or multi-axial deformations has yet to be investigated. So far, the variety of materials used in

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previous large-strain experiments makes it difficult to compare results from different investigations.

In this research work, uniaxial compression tests up to 50% strain, uniaxial tension tests up to a maximum of 100% strain and pure shear experiments up to a maximum of 70% strain were conducted to characterise both the mechanical behaviour and the MR effect of the manufactured MREs. Magnetic field strengths up to 450 mT were applied parallel to the loading direction. For anisotropic MREs, the particle alignment direction was oriented both parallel and perpendicular to the loading direction. The MR effect, defined here as the increase in tangent moduli due to the application of a magnetic field, is studied versus large strain. Together with earlier work in which MREs were studied under equi-biaxial tension up to 10% strain [18], the combined experimental data represent a comprehensive dataset essential for the development of accurate constitutive models for MREs.

2. Materials

Silicone rubber MM 240TV mixed with 30w% silicone oil ACC 34, both purchased from ACC Silicones, were used to create the elastomeric matrix material. Carbonyl iron particles (CIP), provided by BASF, were used as the magnetisable particles. The average particle size ranged from 3.7 to 4.7 μm (CIP type SQ). Samples of neat rubber material together with both isotropic and anisotropic MREs, each with volume particle concentrations of 10%, 20% and 30%, were prepared. All the components were mixed thoroughly for three minutes with a hand mixer before degassing in a vacuum chamber for 10 min both before and after the mixture was poured into the moulds. The MREs were fast-cured for 1.5 h at 100 °C. To prepare anisotropic MREs, the mixture inside the moulds was exposed to 400 mT magnetic field strength during the curing process. Optical microscopy revealed uniform particle distribution in isotropic MREs and strong particle alignment in anisotropic MREs.

Cylindrical samples with a diameter of 29 mm and a height of 12.5 mm were prepared for the compression tests. Dumbbell shaped samples were manufactured with a gauge section measuring 16 × 4 mm, with a thickness of 2 mm, and with an overall length of 50 mm for tensile tests. Sample sheets with dimensions 50 × 30 × 1 mm were manufactured in moulds for the pure shear experiments. The dimensions of the MRE samples tested are in accordance with the British Standards [19,20,11]. All moulds used to prepare samples were made of aluminium and brass to avoid any unwanted magnetisation of the moulds during the manufacturing process.

3. Test setup and procedure

Large-strain experiments on both isotropic and anisotropic MREs with 0, 10, 20, and 30 vol% iron content have been conducted. The experiments were carried out using a Zwick Z250 uniaxial test machine equipped with a 250 kN load-cell for compression tests, whereas a 1 kN load-cell was used for the other tests. Bespoke test rigs were designed for each of the experiments, enabling the use of strong permanent magnets (Neodymium N52, measuring 50 × 50 × 25 mm), to induce magnetic fields during the tests. The top and bottom magnets remained stationary, while the crosshead of the test machine was moved; consequently the distance between magnets remained fixed throughout the tests, ensuring a relatively constant magnetic flux density (although small changes were inevitable due to the changing shape of the test specimens) and reducing the influence of a changing attractive force between the magnets during the tests. All test-rigs were built using non-magnetic materials (aluminium and brass). The magnetic flux was measured with a Gaussmeter (Model 5180 from F.W. Bell), and the distribution and level of the magnetic flux density was simulated using the multi-physics commercial finite element software Comsol. All tests were displacement controlled. Where possible, strains were measured optically using Digital Image Correlation (DIC). The Limess DIC system consisting of two high-resolution cameras (4M pixels) able to record up to 15 frames per second, two lights, and the software VIC-3D were used. To facilitate DIC measurements, samples were sprayed with a white paint random speckle pattern, and a series of images was taken during the tests.

The MRE materials are sensitive to stress softening, a well-known effect in rubber-like materials known as the *Mullins* effect [21]. A comprehensive review of the *Mullins* effect is provided by Diani et al. [22]. The highest stresses occur in the first loading cycle, but are much lower in subsequent cycles. After the first cycle, the samples retain a remnant deformation, which can be either permanent or temporary or a combination of both. The strain level that samples experience in the first cycle is called the 'preconditioning strain'. Note that the preconditioning strain has been found to be of great importance for the material's subsequent mechanical behaviour. Preconditioning a sample up to a larger strain results in a softer material, and as soon as the material is tested up to new larger strain levels its properties significantly change once again [10]. Note that the Mullins effect is also time-dependant, so when repeatedly testing the same MRE specimen, given enough time between tests, the stress softening again becomes apparent. In order to mitigate the influence of the Mullins effect, a four-cycle test procedure was performed. The third loading cycle was consistently used to characterise the material while the fourth cycle was performed merely to check that no further significant changes occurred after the third cycle.

To characterise the response of the MRE material both in the absence and in the presence of magnetic fields, a minimum of three distinct testing steps were conducted, each step consisting of four loading-unloading cycle tests. The MRE samples were re-used in each subsequent step in the test series. In general, the test series consisted of three test steps:

(i) Tests in the absence of a magnetic field (NoField01)
(ii) Tests with different levels of magnetic field strength
(iii) Repetition of the no-field tests (NoField02)

However, in the tension experiments, additional test steps were introduced to examine issues such as stress