Viscoplasticity of magnetorheological materials - theoretical description and experimental investigations

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Abstract

The extension of viscoplasticity Perzyna's model for the field of magnetorheological materials is proposed. The model is adopted to identify the mechanisms of microscopic rearrangement of ferroelements producing visible increase of material stiffness, in particular increase of shear modulus. The project of laboratory test stand is presented. It is based on Split Hopkinson Pressure Bar set-up equipped with container for magnetorheological fluid and coil to control it.

Keywords: magnetorheological fluid, magnetorheological gel, Perzyna viscoplasticity model, Split Hopkinson Pressure Bar

1. Introduction

One of functional materials of increasing technical importance is magnetorheological fluid controlled by a magnetic field. This kind of material is a suspension of microsized ferroelements in a carrier viscous fluid. Ferroelements, are mostly made of Fe_3O_4 with diameter 12μm or carbonyl iron particles of 4.5-5.2μm diameter. Mineral oil is usually used as a carrier fluid. In order to avoid aggregation of magnetic sensitive elements, ferroelements are surrounded by silicon coat. According to the experimental data discussed in [1] the properties of magnetorheological fluid can be characterized by nonlinear behaviour of rheological material with magnetic active particles as regards the shear stress - shear strain rate relation. In the literature, the linear Bingham model is commonly used. In many cases the linear relations between shear stress and shear strain rate are not adequate in describing mechanism of magnetorheological fluid flow. On the other hand, the Bodner Partom and the Herschel Bulkely models describe nonlinear relation between shear stress and shear strain rate, cf. [1]. However, the disadvantage of these models is that they are of empirical character, with no firm physical basis are valid only for limited range of variables. Therefore the formulation of a new viscoplasticity model for magnetorheological materials that should be based on physical mechanisms responsible for rate dependency of yield stress remains an open question.

2. The Perzyna viscoplasticity model accounting for magnetic field effect

The linear Bingham model proposed originally in [2] is commonly adopted to describe magnetorheological materials

$$\tau = \tau_{0H}(H) + \mu\dot{\gamma}\,, \tag{1}$$

where the symbols denote: τ shear stress, τ_{0H} yield stress dependent of magnetic field strength H, μ viscosity factor, $\dot{\gamma}$ shear strain rate. It does not describe adequately the physical mechanisms in the range of high strain rates [3,4]. It can be observed that the results shown in Fig. 1 deviate from linear Bingham relations for higher shear strain rates Fig. 2. This observation confirm the necessity of the development of adequate viscoplasticity model of magnetorheological materials.

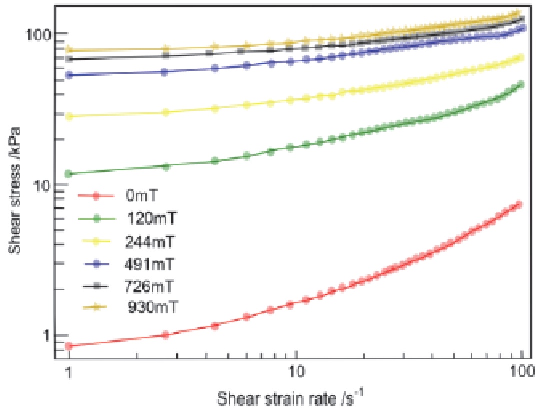

Figure 1: The own visualization of experimental data published in [3]

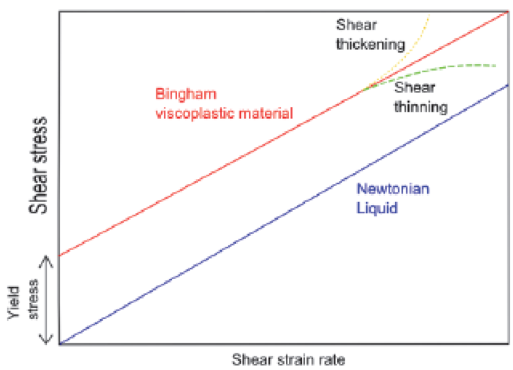

Figure 2: Schematic view of the inadequacy of Bingham model [4]

The mechanism of microscopic rearrangement of ferroelements producing visible increase of material stiffness and nonlinear dependence of yield stress - strain rate can be described by the nonlinear viscoplasticity model proposed by

Perzyna [5] extended for accounting of magnetic field strength H.

$$\dot{e}_{ij} = \frac{1}{2G(H)}\dot{s}_{ij} + \gamma(H)\left\langle \Phi\left(\frac{\sqrt{J_2}}{\varkappa(H)} - 1\right)\right\rangle \frac{s_{ij}}{\sqrt{J_2}} \quad (2)$$

The symbol Φ describes the nonlinear excess stress function

$$\langle\Phi\rangle = \begin{cases} \Phi, & on\ \sigma > f(\varepsilon) \\ 0, & on\ \sigma \leq f(\varepsilon) \end{cases}, \quad (3)$$

$\sigma = f(\varepsilon)$ is material characteristic for statical tension test, ε is nominal small strain, $2G(H)$ is elastic shear modulus, depending on magnetic field strength H, $\gamma(H)$ is the viscosity parameter of material depending on magnetic field strength H, $\varkappa(H)$ is quasi - static yield stress depending on magnetic field strength H, s_{ij} is deviator of stress tensor, $\dot{s}_{ij}$ is deviator of stress rate, J_2 is second invariant of stress deviator, $\dot{e}_{ij}$is small strain rate deviator.

In order to identify the proposed magneto - viscoplasticity model two kinds of experimental tests are required: quasi - static compression test and dynamic axial compression with use of the modified Split Hopkinson Pressure Bar.

3. Laboratory test stand

The physical mechanism responsible for behaviour of magnetorheological materials subjected to magnetic field is illustrated in Fig. 3. The application of magnetic field produces solidification of material volume.

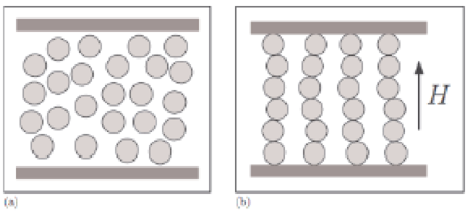

Figure 3: a) Magnetorheological fluid at neutral state (without dynamic loads and magnetic field H), b) under the influence of magnetic field, H: magnetic field strength $[\frac{kA}{m}]$

The testing stand is made on basis of Split Hopkinson Pressure Bar [6]. The main idea is to use the present laboratory device and prepare it to test magnetorheological fluid in magnetic field at high strain rates. Laboratory device to investigate dynamic properties of magnetorheological materials is adopted from present device and adequately modified to work with controlable viscoplasticity material. The idea of proposed modification, which is based on earlier studies with use of Hopkinson Pressure Bar [1,7] is presented in Fig 4.

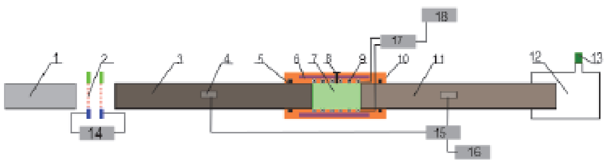

Figure 4: modified Spilt Hopkinson Pressure Bar where is: 1) striker, 2) sensors to measure velocity of striker, 3) incident bar, 4) strain gauges, 5) seal, 6) water cooling for coils, 7) MR fluid, 8) infusion, 9) coils, 10) sleeve, 11) transmiter bar, 12) gas accumulator, 13)valve, 14) photo diode gates, 15) signal amplifier, 16) data acquisition system, 17) power supply for coils, 18) signal generator for coils controls.

The new set-up is based on Split Hopkinson Pressure Bar with novel grip (container) for MR fluid. The idea of experiment is to create incident wave inside the MR fluid under the influence of magnetic field. The container is equipped with the seals (to prevent leakage of fluid and keep constant pressure in the specimen), coils (to produce magnetic field) and water cooling system (to keep coils in constant temperature). At the end of transmiter bar the gas accumulator is fixed to prevent too large displacement of the bar. The novelty of the proposed laboratory test stand is the application of coils for the sleeves shown in Fig. 4 to induce the constant magnetic field. Due to this the dynamic axial compression tests of solidified magnetorheological material will be possible.

4. Conclusions

The paper shows that a new methodology of experimental investigation is required to indentify the proposed model accounting for magnetic field effect. Therefore, a new set up of Split Hopkinson Pressure Bar equipped with electromagnetic coils to investigate specimens of magnetorheological material is proposed. The extension of Perzyna viscoplasticity model, which includes influence of magnetic field strength brings a new perspective in advanced mechanics of magnethorheological material. The Perzyna magnethoviscoplasticity model accounting for mechanisms of microscopic rearrangements of ferroelements should better describe the material stiffness and nonlinear dependence of yield stress - strain rate than traditional Bingham model or empirical descriptions discussed in [1].

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