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Smart Magnetic Composites

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1. Introduction

1.1 Smart Magnetic Composites

Smart Magnetic Composites (SMC) belong to the wider group named Smart Magnetic Materials (SMM). Various properties of the SMM, involving viscosity, shape, rigidity, temperature or resistance – could be stimulated with a magnetic field. SMMs in turn, belong to the still wider group of materials called Smart Materials, SMART in short, where stimulation of properties is possible with the use of electrical or magnetic field, or heat. Nowadays, we assume that the level of dissemination of the Smart Materials is one of the measures of economy innovativeness in countries and regions. Manufacturing of Smart Materials is also stimulating development of basic research in the various cross effects. The key significance, both civil and military, have the already existing and forecasted applications of the Smart Magnetic Materials. We could specify here examples of an „intelligent" vibration damping in such stationary objects as buildings, bridges, pipelines or power networks. Equally significant field of the SMM utilisation is transport (automotive vehicles, trains, airplanes). The number of applications in medicine is growing, which could be exemplified by intelligent prostheses, remote surgery, new methods of neoplasm therapy or the magnetic "markers" of medicines. Very promising are the SMM group materials providing safety for cable transmitted data. Among the examples one could also indicate the development in new methods of non-destructive testing such as magnetovision. Within the last several years, a great interest in the use of SMMs in energy harvesting might be noticed. The listed advantages of SMMs are the reason for intensive research in many scientific institutes and industrial centers.

Smart Magnetic Materials could be divided according to various criteria. One of the possible classifications distinguishes the following SMM types:

- Materials of variable internal structure:
  - MagnetoRheological Fluids - MRF,
  - FeRroFluids – FRF,
  - Porous materials saturated with magnetorheological fluids - MagnetoRheological Composite - MRC, gels/greases/... filled with ferromagnetic material powder,
  - fluids with powdered magnetocaloric materials.
- Materials of fixed internal structure:
  - solid magnetostrictive materials, including those with giant magnetostriction - Giant Magnetostrictive Materials – GMMs,

– elastomers filled with ferromagnetic material powders (e.g. carbonyl iron, GMM or their combination), polymers on the epoxy resin base containing powdered ferromagnetic materials,
– solid magnetocaloric materials.

Below, the following Smart Magnetic Composites have been discussed in detail:

- Composites of porous matrix filled with magnetorheological fluid (MagnetoRheological Composites - MRC),
- MagnetoRheological Elastomers – MRE, known also as Magneto-Active Elastomers - MAE),
- Composites containing powdered material of giant magnetostriction (Giant Magnetostrictive Materials composites - GMMc).

In each of the above cases the manufacturing technologies, ways of stimulating with magnetic field, methodology of research and properties identification as well as application examples, have been discussed. The material has been enriched with literature overview and results of the Authors' own research.

2. Magnetorheological composites – porous materials saturated with magnetorheological fluids

2.1 Introduction

The MagnetoRheological Fluid (MRF) in the gravity conditions requires external barriers, or a vessel, which keeps it in a defined place with maintaining geometry. This inconvenience could be overcome in several ways. The first one consists in substituting the carrier fluid with a material of definitely greater viscosity (e.g. a gel or grease Malcolm et al. (2002); Rankin et al. (1999)). That way the material is being created, similarly to MRF, of the variable internal structure, but more easily kept in the required place. Disadvantage of that solution is too high viscosity in the off-state – without the magnetic field, which could be an obstacle in some applications. The effect of shaping the external dimensions may also be obtained by saturating a porous material with MR fluid. That way the material with open cellular structure creates the matrix maintaining the magnetorheological fluid within the limits determined with its dimensions, thus enabling the relatively free interaction of the magnetic and mechanical field inside the structure. Under the cellular structure the material composed mainly of the internal spaces, or open pores connected amongst others, is understood. The curing matrix of a magnetorheological composite may be fabricated from a sponge, fabric, felt or any other elastic porous material Carlson & Jolly (2000). By saturating a matrix we achieve material characterised with dependence of its mechanical parameters on the magnetic field, similarly as in case of the MRFs. The new type of material shaped that way has no single, formalised name. In the subject literature one could find such definitions as: the field-responsive fluid-impregnated cellular solids Deshmukh & McKinley (2006), the magnetorheological foams Carlson (1999); Carlson & Jolly (2000), the magnetically responsive foams Purizhansky (2004). Because of the complex structure of the matrix and a filling, the Authors of this work considered as just to name it in the simpler form as Magneto–Rheological Composite, or shortly the MRC, used from here in the work. The MRC type composites belong to the materials, which despite of the completely different build are frequently treated as one of the science fields on magnetorheological fluids. The growing interest in these materials and the attempts of their wider application, especially in the areas of active suppressions, cause that they are more and more frequently the objects of research.

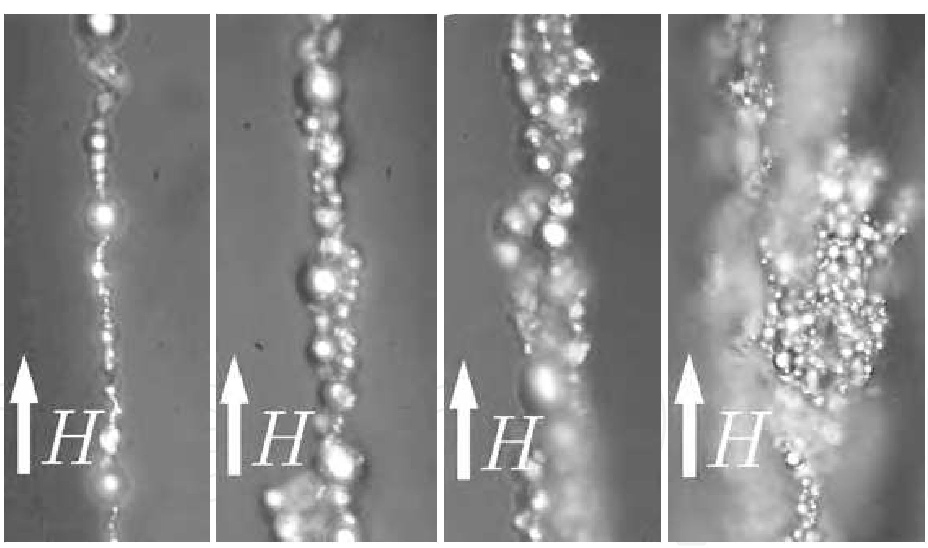
Among the still scarce literature concerning the magnetorheological composites, the first information on their properties and applications may be found in the works Carlson & Jolly (2000); Deshmukh & McKinley (2006); Purizhansky (2004).
As the key issues within the magnetorheological composite (MRC) field the following were recognised:

- composite manufacturing engineering,
- strain and stress measurement methodology in the conditions of variable mechanical and magnetic parameters,
- constitutive model and its parameters identification.

The above topics have been discussed further in the work.

2.2 Magnetorheological composites manufacturing procedure

The test specimens were manufactured independently Kaleta & Lewandowski (2007). The magnetorheological composite was obtained as combination of the two basic components, i.e. the magnetorheological fluid and the porous material. The magnetorheological fluid used in the tests was prepared according to the recipe similar to the first fluids used by Rabinow (1948). A base, i.e. the magnetically active component filling the fluid, was carbonyl iron powder type CC, from BASF. As a carrier fluid the silicon oil was used. Content of the iron powder in the fluid was 80% by weight. Interactions displayed by the ferromagnetic component in the fluid are shown in Figure 1. Various structures in the form of chains being created in the magnetic field are shown. Their breaking requires applying additional external force, which is understood as the magnetorheological effect.



(a) (b) (c) (d)

Fig. 1. The idea of magnetorheological fluid operation: ordering of the carbonyl iron powder and creation of structures in the magnetorheological fluid Lewandowski (2005).

Schematic diagram of the composite manufacturing has been shown in Figure 2. Composite matrices are made of polyurethane foam, characterised with open pores. This enabled free penetration of MRF to its interior. The phase terminating the composite manufacturing was saturation of the matrix with magnetorheological fluid using the injection method. The process of filling was conducted so, that part of the internal foam pores was filled with air and, at the same time, the fluid was uniformly covering the internal surfaces of matrix. Composites, for which the tests were performed, had the same filling with the magnetorheological fluid. The filling amounted to 70% of the matrix volume. That way, composites of the required features were achieved.

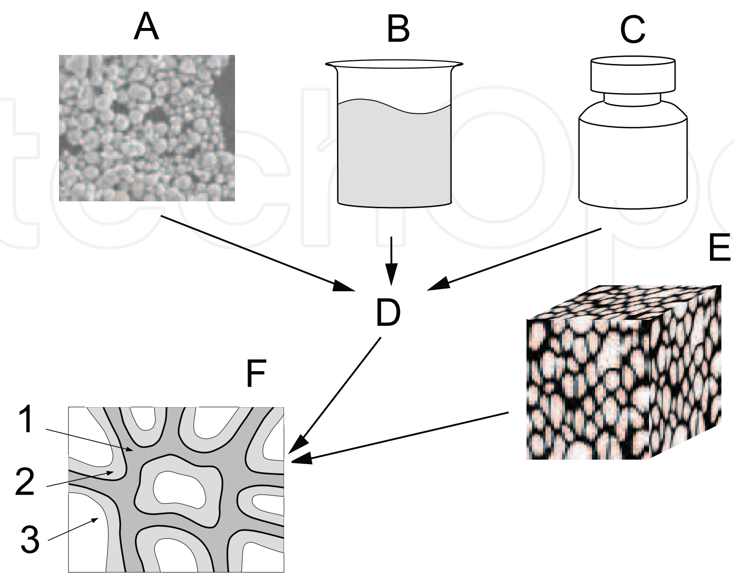


Fig. 2. Schematic diagram of the magnetorheological composite manufacturing process. Main components of the magnetorheological fluid : A – carbonyl iron powder, B – carrier fluid, C – additives. Carrier matrix of the composite – E. Schematic diagram of the matrix cell filled with fluid: 1 – matrix, 2 – the covering MR fluid 3 – remained volume filled with air Lewandowski (2005).

The spongy, elastic structure of matrix enabled maintaining of the MRF in one place defined with its external geometry and, at the same time, the free interaction of magnetic field with the fluid. Open pores enabled free flow of fluid between cells. Size of the pores was small enough to prevent the fluid getting out under the influence of gravity. Real structure of the matrix before saturation has been shown in Figure 3a and after saturation with fluid in Figure 3b.

(a) (b)

Fig. 3. (a) – internal structure of matrix before filling it with the MR fluid and (b) – after the filling.

2.3 The test stand

Schematic diagram of the test stand has been presented in Figure 4. The electromagnetic system was responsible for creating and directing the magnetic field interacting with the tested material specimen. A gap with two parallel surfaces was made in the steel core, inside which a tested material was placed. The magnetic field vector was perpendicular to the sample shear direction. The force straining the tested material was generated by an external exciter. Measurement of the magnetic field intensity was performed by the hall sensor placed beside the tested composite sample in the core gap. Samples for the tests were shaped so, as to obtain the homogeneous shear in the tested material. They were made from two identical pieces of cuboid composite attached symmetrically on both sides of the supporting plate. Fixing of a specimen in the magnetic core gap of the measurement stand has been shown in Figure 4a. That way of fixing enabled the state close to the pure shearing.

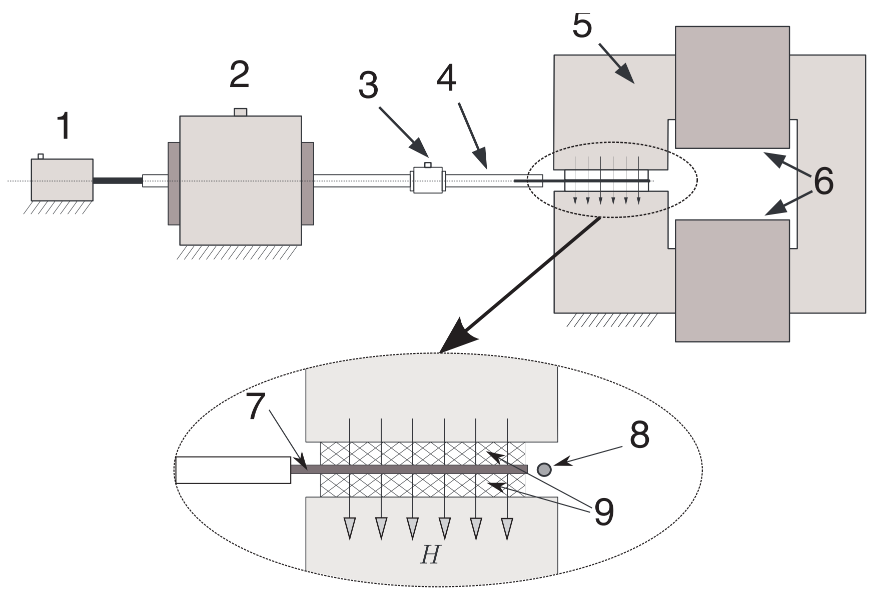


Fig. 4. The schematic diagram of the mechanical part of the test stand and mounted specimen: 1 – displacement sensor, 2 – shaker, 3 – piezoelectric force sensor, 4 – connector, 5 – magnetic core, 6 – coils, 7 – carrier plate, 8 – magnetic field sensor, 9 – magnetorheological composite material, H – direction of the magnetic field vector Kaleta & Lewandowski (2007).

2.4 Test results. Static and cyclic measurements.

Magnetorheological composite tests consist in seeking for relations between magnetic field interacting with the tested material, and mechanical properties of composite. Figure 5 presents two basic tests performed for the magnetorheological composites. The first of them is stroke load of the specimen with constant force for different values of magnetic field (Figure 5a). The changes of shearing stress τ in time were recorded. The influence of magnetic field is clearly visible. The higher values of the magnetic field intensity H, the smaller the shearing strain γ, which indicates for increase in the material stiffness. Figure 5b in turn, shows the cyclic test results. The specimen was strained with constant amplitude of the shearing strain γ_a. Increase in the magnetic field intensity H causes increase in the strain, and by that the increase in hysteresis loop area ΔW. Creation of the hysteresis loop suggests the existence of irreversible strains, which could depend on time scale, or on the strain trajectory length. Clear differences between loading and unloading suggest creation of plastic strains (independent of the time scale). Static shear tests confirm existence of both, viscous and plastic strains in the material. That is, the material is a viscoelastic body up to the yield point (dependent on the strain rate) and the viscoplastic above it Lewandowski & Ziętek (2010). Thus, above the yield point the irreversible strains appear dependent on the time scale and the plastic strain trajectory length. Therefore it is elastic/viscoplastic body.

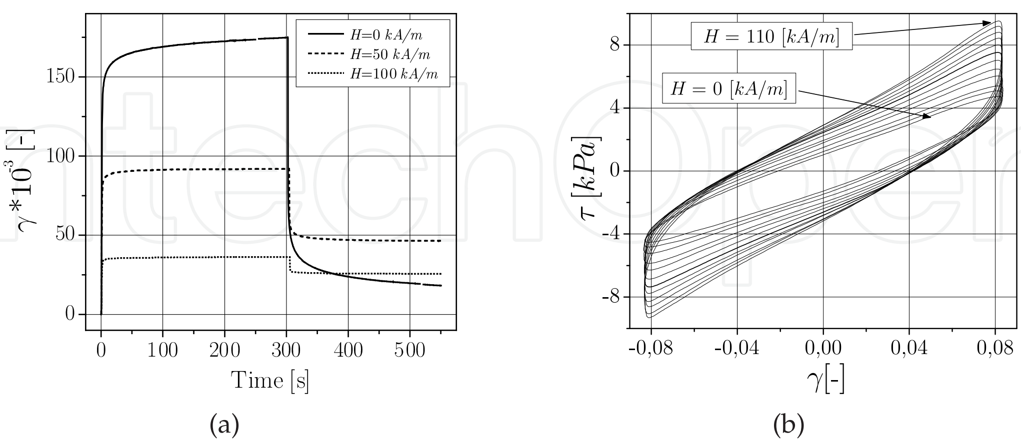


Fig. 5. (a) Change in the shearing strain of magnetorheological composite in time, under the influence of the constant loading and unloading, for three different values of the magnetic field intensity H, (b) change in the shear stress τ and the hysteresis loop area in the stress – strain coordinate system ($\tau - \gamma$), for the same amplitude value of shearing strain γ_a and the increasing values of magnetic field strength H, from 0 to 110 kA/m (with a step equal to 10 kA/m) Kaleta et al. (2007).

Next, the simultaneous influence of the shearing strain amplitude γ_a and of the magnetic field intensity H, on the character of the $\tau - \gamma$ relationship and the size of the hysteresis loop area ΔW, was tested. The tests were performed with controlled stress, yet in such a way, as to maintain the assumed value of shearing strain amplitude γ_a, independent of the applied magnetic field. The set of loops obtained for the subsequently raising values of magnetic field intensity and for three fixed values of strain amplitude has been presented in Figure 6a. It was found that the magnetic field intensity H, has significant influence on mechanical properties of the composite material. The change in magnetic field intensity H from 0 to 110 kA/m causes more than double increase in the stress amplitude τ_a, while maintaining the same amplitude of strain γ_a. Also, the increase in hysteresis loop area Δ_W and the change in its shape may be observed. The test results unequivocally confirm that value of the shearing strain, as well as the size of hysteresis loop area, depend both, on the magnetic field intensity H and on the strain amplitude value γ_a.
As a measure of the inelastic behavior of magnetorheological composite the energy dissipated by the material and expressed by the area of the hysteresis loop area ΔW (in the $\tau - \gamma$ coordinate system) was assumed. The ΔW value, acquired from the experiment, was calculated using the algorithm based at the signal analysis and synthesis by means of the Fourier transform. Figure 6b shows the ΔW values obtained for the selected frequency f = 5 Hz, at three different values of the strain amplitude γ_a. As can be seen, changes in ΔW as a function of the magnetic field intensity H, are not linear in their character.

2.5 Modeling mechanical properties of magnetorheological composites.

The basic model known from the subject literature, concerning mainly the magnetorheological fluid properties, is the so called Bingham body Seval (2002). It belongs to the "segment-linear" model group created by combining the elastic, viscous and rigid-plastic elements (Fig. 7).

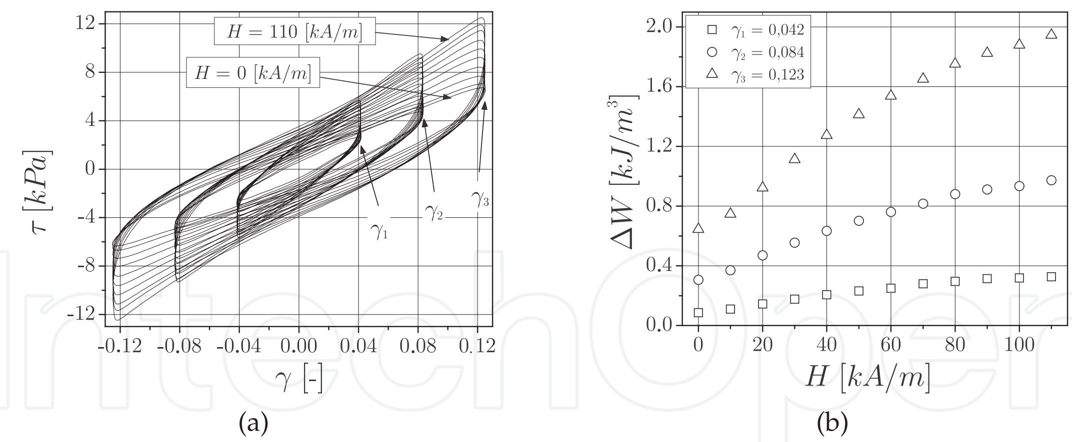


Fig. 6. (a) - hysteresis loops obtained for growing values of magnetic field strength, from 0 to 110 kA/m (with a step equal to 10 kA/m), and three constant strain amplitudes at excitation frequency f = 10 Hz, (b) - changes of hysteresis loops area ΔW in function of magnetic field intensity H, at frequency excitations $f = 5\ Hz$ and three strain amplitudes γ_a Kaleta & Lewandowski (2007).

Viscous effects appearing in the material – the same as for the typical Newton liquid – are described by means of the viscosity parameter. As shown by the experimental tests Weihua (2000), the linear dependence of shear stress on the shearing rate appears only in the limited range. The additional complication results from the influence of magnetic field, which is capable of causing changes in the model parameters, also in the non-linear way. Magnetorheological fluids show, for example, the non-linear dependence of apparent viscosity on the magnetic field intensity and the strain rate Yamamoto & Nakano (1999). Also, the other models used for description of magnetorheological fluids Butz & von Stryk (1999), e.g. the models of: Cross, Casson, or Herschel–Bulkley, the so called structural and numerical simulations, have limited application.

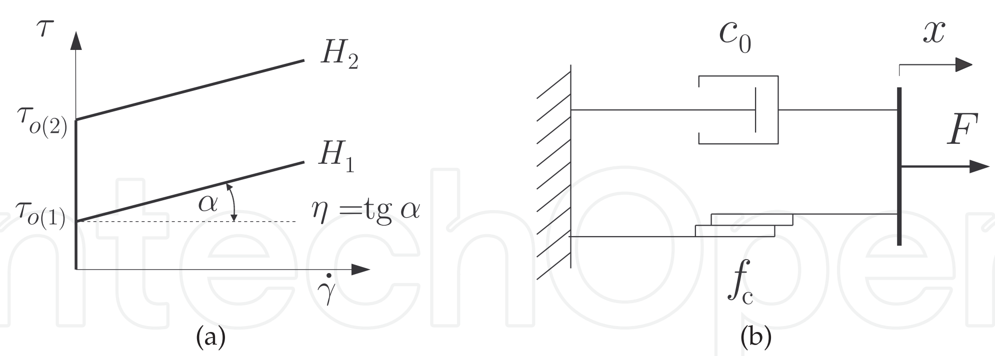


Fig. 7. Bingham model. (a) – dependence of the strain rate on plasticising stress as a function of the magnetic field H, (b) – mechanical form of the Bingham model - a parallel combination of two elements - the viscous and the plastic one.

While observing the magnetorheological composite behavior it could be noted (Fig. 5a), that above the yield point the irreversible strains appear dependable on the time scale and the plastic strain trajectory length. Thus, it is the elastic/viscoplastic body Kaleta et al. (2007). One of the description methods for such a material is the parallel and series combination of the elastic, viscous and plastic elements Hart (1976). They were used in the soil rheology Kisiel (1967), for describing polymeric materials, in the small and large strain range (finite deformation) Bardenhagen et al. (1997). The viscous element could be the non-Newtonian type liquid. In that case it is assumed that the viscosity coefficient is a non-linear function of strain rate. Further, the plastic member takes into account various types of amplification both, kinematic and isotropic, as well as the mixed one. Non-linear equations and differences in the way of describing the loading and unloading process are a reason for difficulties in determining the material parameters appearing in the model. This is particularly significant when the application area involves both, the static and cyclic loads. The essential challenge here is also building a model useful also in the complex load conditions. Considering the results achieved in the previous experimental trials Kaleta & Lewandowski (2007), the possibility was analysed of describing properties of the discussed magnetorheological composite with the four-parameter rheological model Drescher (1967) of the following form:

$$\tau + t_\gamma \dot{\tau} = 2G_2(\gamma + t_\tau \dot{\gamma}), \tag{1}$$

for the first cycle, and

$$\tau + t_\gamma \dot{\tau} = 2G_2(\gamma + t_\tau \dot{\gamma}) - 2G_2\gamma_k + \tau_{o2}\mathrm{sgn}\dot{\tau}, \tag{2}$$

if the yield point in the second element has not been exceeded. Otherwise,

$$\tau + t_\gamma \dot{\tau} = 2\eta\dot{\gamma} + \tau_{o2}\mathrm{sgn}\dot{\tau} \qquad \text{for} \qquad \tau_2 = \tau_{o2}, \tag{3}$$

where

$$t_\gamma(H) = \frac{\eta(H)}{G_1(H)}, \qquad t_\tau(H) = \eta(H)\frac{G_1(H) + G_2(H)}{G_1(H)G_2(H)} = t_\gamma(H)\left(1 + \frac{G_1(H)}{G_2(H)}\right). \tag{4}$$

The model diagram and comparison of the loops acquired from the experiment and from the model have been presented in Figure 8.

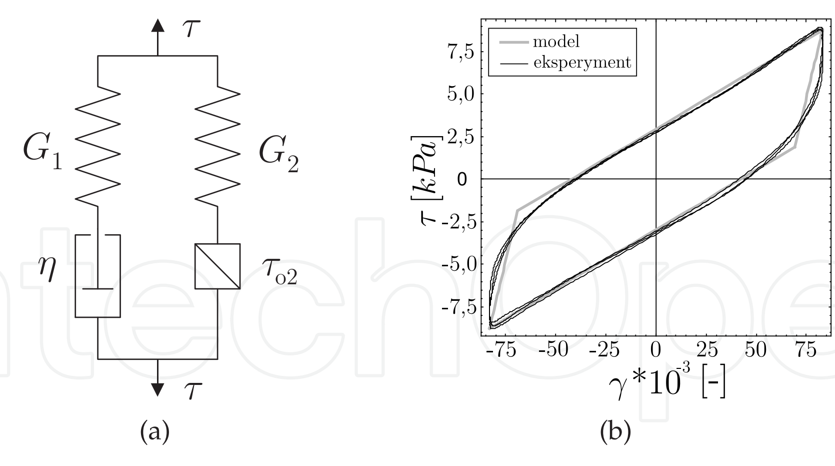


Fig. 8. a) – the elastic-viscoplastic material model of the magnetorheological composite, b) comparison of hysteresis loops obtained from the elastic-plastic model with linear amplification and the experimental ones for the selected values of magnetic field intensities H=90 kA/m Kaleta et al. (2007).

The model is well reflecting the real course during the material loading. However, for unloading phase the straight line crosses the convex part of the loop. Comparison of the experimental and the model data for the selected value of γ_a has been shown in Figure 8b .

2.6 MRC applications

Possibility of controlling the magnetorheological composite properties enables building of active devices, applicable in various structures of the SMART. As an example, a structure of semi-active damper has been presented and its damping capacities checked. Within the task the following stages have been accomplished:

- building the damper prototype with magnetorheological composite use,
- application of the damper in the selected mechanical system and analysis of its influence on vibrations.

Structure of the damper has been presented in Figure 9 Kaleta et al. (2009). Its capacities of the mechanical vibration damping were verified at the steel beam with two supports. In the subject literature, which discusses applications of similar dampers with magnetorheological fluids, usually the attempts of applying them in the discrete vibrating systems with one or two degrees of freedom could be found Carlson (1999); Müller (2000). However, the selected beam could be included to the continuous systems group, characterised with multiple forms of vibrations. For that reason the damping problem requires radically different approach, ready to take into account the nature of vibration and the frequency range appearing in a given object. Schematic diagram of the utilised measurement stand has been presented in Figure 10.

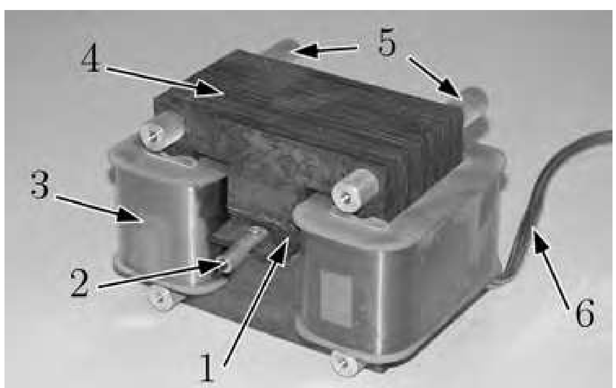


Fig. 9. General view of the damper with magnetorheological composite: 1 – MR composite, 2 – fastener, place of attachment to the vibrating structure, 3 – coils, 4 – core, 5 – damper fixing to the base, 6 – wires conducting current signal to the damper Kaleta et al. (2009).

The damper test results have been presented in Figure 11. A change in the control current intensity has essential influence on the beam vibration (Figure 11a). A drop in amplitude is the most noticeable effect here, and that is why as the estimation of damping influence just the time was assumed (marked as t_w), needed for damping the amplitude to the 20% level of its maximum value. For a beam, as the object simplified to the single-dimension scale, a full series of measurements was performed in sixteen points uniformly distributed over the beam length L. Current intensity value I was changed within the 0 to 4 Amps range for each measurement point. The collected results in the form of three-dimensional graph have been presented in Figure 11b.

2.7 Conclusions and further research directions

The research described above enabled formulation of the following conclusions:

- A composite was manufactured using the magnetorheological fluid and porous elastic matrices. Strong susceptibility of mechanical damping to the magnetic field intensity value was shown.

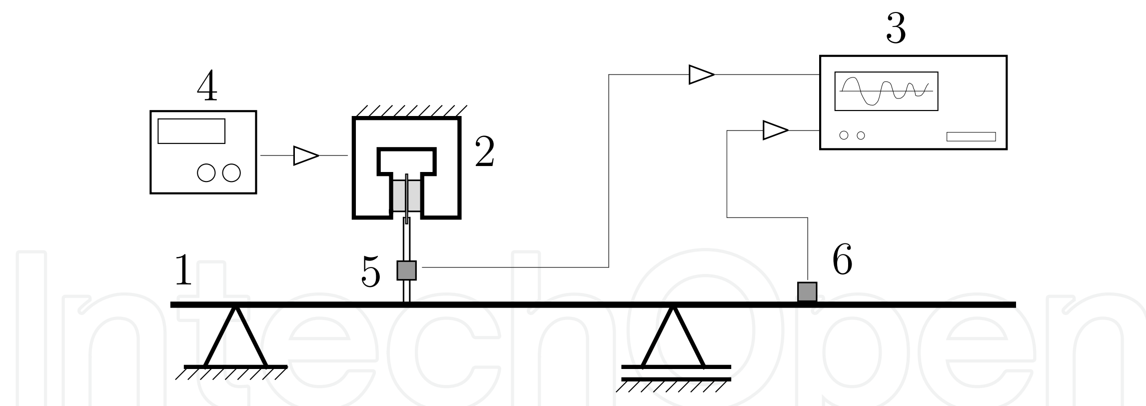
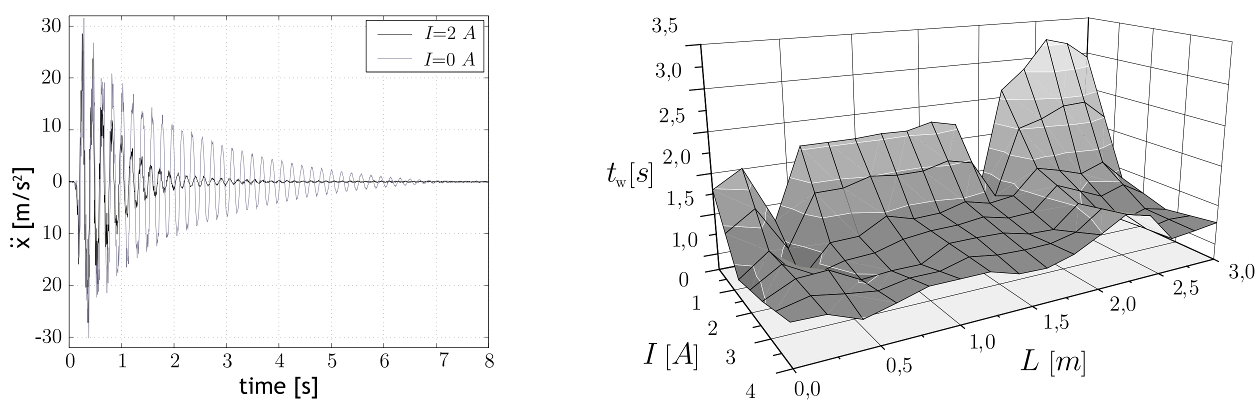


Fig. 10. Test stand: 1 – test object, a beam at two supports, 2 – the tested damper with MR composite, 3 – data collection and processing system, the HP35639A spectrum analyser, 4 – regulated power supply, 5 – force sensor, 6 – acceleration sensor Kaleta et al. (2009).



(a) (b)

Fig. 11. a) – free vibration observed at the beam end (L = 3 m) for two intensity values of the current controlling the damper equal to I = 0 and I = 2 A, correspondingly. b) – time of the free vibration amplitude damping t_w in the individual beam locations depending on the control current intensity I Kaleta et al. (2009).

- Experimental conditions were created for determining the damping in composites influenced by the variable parameters of mechanical and magnetic field.
- A description of the tested composite properties was proposed, in the form of four-parameter model of elastic-viscoplastic body. Individual coefficients of the model were assumed as functionally depending on the magnetic field intensity H. The model identification procedure was performed.
- The own prototype structure of the so called semi-active damper with composite containing magnetorheological fluid was presented. As the test vibrating object a beam on two supports was selected. Efficiency of the vibration damping was verified with recording of the free vibration damping time.

It could be forecasted that the main research directions in the nearest future will concern:

- Improvement in the manufacturing engineering of the „wet”, porous magnetorheological composites saturated with MRF. The new grades of ferromagnetic micro and nano–powders for magnetorheological fluids and ferrorheological fluids will be manufactured, in which the sol-gel technology will be used.

- The research will be undertaken on the fatigue life of MRC, as well as on the ageing processes of matrices and fluids.
- Key significance will be assigned to simplification and efficiency increase of the magnetic stimulation. As particularly promising in this area the discrete systems for magnetic field control are considered.
- A development in the constitutive MRC models and the ways of their identification will follow.
- In the MRC application domain, first of all they are going to be used for building of cheap, the so called semi-active dampers with wide application potential and the scope of loads born. The main application areas are going to be: transport, buildings and structures for the seismic or quasi-seismic conditions, large industrial structures and home appliances.

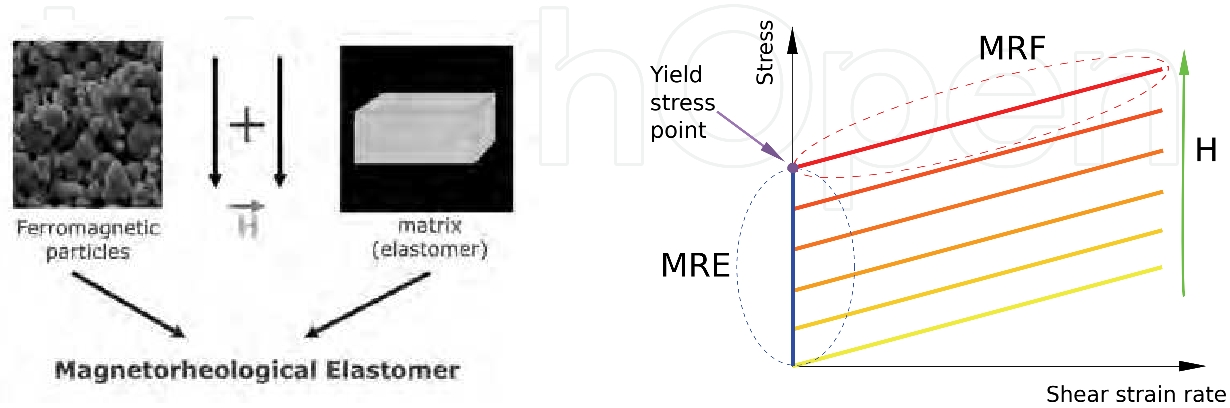
3. Magnetorheological Elastomers

3.1 Introduction

Magnetorheological Elastomers, MREs or MAEs in short (Magneto-Active Elastomers), are the controllable materials built of the magnetically polarised particles placed in the non-polarised elastomer matrix. They exhibit variation in mechanical properties under the influence of external magnetic field, which has been named as the magnetorheological effect. As opposed to the magnetorheological fluids (MRF) already known for several tens of years, the MRE are the new materials. Optimal selection of the MRE components, the technology of their manufacture, or the mathematical models of their mechanical properties, are very valid scientific issues. MREs are the investigation objects in the top research centers, among others in the USA, China, Finland, France, Canada, Switzerland, or Sweden.

3.2 Magnetorheological Elastomers build

The two basic components constituting the MRE structure are the elastomer creating the matrix, and the magnetically active particles distributed in it (Fig. 12a). As opposed to the magnetorheological fluids (MRF), the working area of which is located below the flow limit, the magnetorheological elastomers work above that limit. Thus, it could be stated, that the materials do not pose the competition for the magnetorheological fluids, but are rather their supplementation. The schematic Bingham diagram represents this at the Fig. 12b).



(a) (b)

Fig. 12. (a) - the MRE build diagram and (b) - comparison of the MRE and MRF operation areas in the Bingham model Zając (2011).

Among the materials for the MRE matrix, the rubbers predominate: the natural ones Davis (1999), the silicon ones Blom & Kari (2005), as well as the butadieneacrylonitrile ones with various content of the acrylic acid Lokander & Stenberg (2003b). Natural rubbers were also modified by adding polybutadiene (Buna CB55) Ginder et al. (2002), or the zinc oxide, stearic acid and the sulphur Shen et al. (2004). The silicone rubbers, in turn, were mixed with the silicon oil Gong et al. (2005a), vinyl and toluene Wang et al. (2006), as well as polyurethanes and the silicone oil Hu et al. (2005). Also the magnetorheological elastomers with a whole range of other matrices, among others containing synthetic rubber Davis (1999) , polyurethane Shen et al. (2004) , silicone Bose & Roder (2009a) and others Kamińska et al. (2006), were created.
The ferromagnetic particles must be the soft magnetic materials with the low value of residual magnetisation. Moreover, the material of which they are made should be featured with the high permeability and high magnetic saturation value. This provides for the maximum intermolecular attraction producing the large magnetorheological effect. The most frequently selected material for production of MRE is iron, with the saturation induction equal to B_s=2,15 T, whereas the maximum value of the relative magnetic permeability μ_r=9000 – for the iron containing 0,2 % of impurities, and reaches even μ_r=200000 for the pure iron Rawa (2001). While selecting the particles, one has to consider that they should be big enough to contains several magnetic domains, as in the other case the magnetorheological effect could be unnoticeable Lokander & Stenberg (2003b).
However, most frequently the carbonyl iron is used, the particles of which have spherical shape. Usually the particles have rather small diameter, beginning with some 2 μm Bellan & Bossis (2002), through the range of 3 to 5 μm Deng & Gong (2008), and up to 10 μm Kallio (2005). The tests were also performed at materials filled with decidedly larger particles of the pure iron of diameter 400 μm and 800 μm Zhang et al. (2008). In case of the isotropic magnetorheological elastomers the particles of iron with porous surface and much larger in size, from some 60 μm Kari et al. (2002), or even up to 200 μm Lokander (2004), are usually used. The materials filled with a mixture of small particles (with diameters of 3 – 5 μm) and large (with diameters of 70 – 80 μm), in the identical proportions by volume, where all iron particles had 36% share by volume in the material were also tested Stepanov et al. (2009). The composites filled with the needle-shaped iron particles Lokander (2004), as well as the nano-wires of some 300 nm in diameter and 15 μm length Song et al. (2009) were also manufactured.
Two fundamental types of MRE could be distinguished: anisotropic and isotropic ones. In the subject literature the term of isotropic magnetorheological elastomers, the Elastomer Ferromagnet Composite (EFC) Zhou & Jiang (2004) could also be found. As the first ones, the anisotropic composites became the subject of research. In those materials the particles create the chain structures in the matrix. During hardening, the composite is being placed in the magnetic field, which induces the dipole momentum in each of the particles. The particles tend to the energy minimum, which, in this case corresponds to the chain packing with the dipole momentums in parallel to the magnetic field vector line. When later the composite is being strained in the presence of magnetic field, the particles are being led out of the energy minimum state, which requires additional work. Value of that work grows with the increase of the applied magnetic field intensity. Anisotropic MREs are the extremely curious materials from the scientific point of view, yet the technology of their manufacture may prove to be too complicated in case of the large-series production. This results from the necessity of placing the composite in magnetic field during the matrix hardening. That obstacle may be eliminated by applying the isotropic magnetorheological elastomers, in which the particles

are distributed homogeneously in the whole material volume. Besides the particle size, the second important parameter is their quantity. In case of the isotropic MREs it has been found that the maximum magnetorheological effect may be obtained if the percent share of particles by volume will be close to the Critical Particle Volume Concentration (CPVC) value Lokander (2004). This corresponds to such particle packing, as appears in the container after their pouring in. The particles contact the others and gaps between them are filled with air. In the composite, air is being substituted with elastomer. If the number of particles is lower than the CPVC value, then the distances between them are larger and the result is a drop in the mutual magnetic interaction. However, if the particles will have too big percent share in relation to the matrix, then the quantity of elastomer will be insufficient for filling in all spaces between the particles. The air voids left decrease the material strength. For iron particles of about 60 μm diameter the CPVC value reaches 36,5%. Part of the isotropic MREs presented in the subject literature contains the number of particles close to the CPVC value: 37% Lokander et al. (2004), 36,5% Kari et al. (2002). MREs of lower particle content were also investigated, among others: 28% Lokander & Stenberg (2003b), 27% Farshad & Benine (2004), while they contained the carbonyl iron of much lower diameter than 60 μm, for which the CPVC value was calculated. In case of the anisotropic MREs the subject literature does not present the relationship enabling determination of the optimum number of ferromagnetic particles. The anisotropic composites of the very high range of particle share by volume from 20,1% Shen et al. (2004), through the intermittent values, among others: 25% Shen et al. (2004), 27 % Farshad & Benine (2004), or about 30% Kallio (2005), up to 50 % of the volume share were investigated Zhou & Jiang (2004). In order to improve the MRE properties, similarly as in the case of magnetorheological fluids, various additives are being applied:

- In order to increase the adhesion between the particles and the matrix, silanes are being used, which improve wettability of particle surfaces. It has been observed that in composites with silane the particles are distributed uniformly in the whole volume, and the elastomer surrounds precisely each of them. Its lack causes that particles glue up and create agglomerates, leaving free spaces between particles and the matrix. Not all types of silanes increase the magnetorheological effect – some of them even decrease it in relation to the base material, despite the improvement of adhesion between particles and the matrix Wang et al. (2006).
- Addition of carbon black to composite matrix improves binding of the matrix with iron particles, thanks to what the magnetorheological effect and tensile strength increases, though the composite suppression drops Chen et al. (2008).
- Iron particles are covered with thin layer of ferric oxides, so the large number of oxides penetrates the material. In addition, the iron ions accelerate the elastomer oxidation, and therefore the antioxidants are also being added Lokander et al. (2004).
- Plasticisers are lowering the modulus of stiffness in the absence of the external magnetic field. This, in turn, leads to among others, the greater relative magnetorheological effect Lokander & Stenberg (2003a). It has been observed that magnetic particles in the composite with silicon oil additive have greater freedom of displacement, thanks to what more regular structures are being created in the magnetic field, increasing that way the magnetorheological effect. Tests have confirmed that increase in the oil content in the composite improves the relative magnetorheological effect, but only to a certain value. On its exceeding the value of stiffness modulus drops in the absence of the external magnetic field, but the magnetorheological effect also drops.

3.3 Manufacturing of Magnetorheological Elastomers. Own research

For manufacturing the MRE the thermoplastic polymer - elastomer type TPE-S (mixture of polypropylene and the G SEBS craton) was used. While selecting the elastomer type for matrix the strength properties, large elongation at rapture and the low hardness were considered, as it has been found that the larger relative magnetorheological effect is obtained for MREs with softer matrix Wang et al. (2006). From the offered products of various hardnesses the material of 30 Shore hardness was selected, and as the ferromagnetic filling the ACS 300 iron powder (from Höganäs AB) was used. As opposed to the carbonyl iron particles, the use attempts of which in the specimens manufacturing were also made, they have rather irregular shape and porous surface as seen at the Figure 13. Most of the ASC 300 powder is constituted by particles of up to 60 μm size.

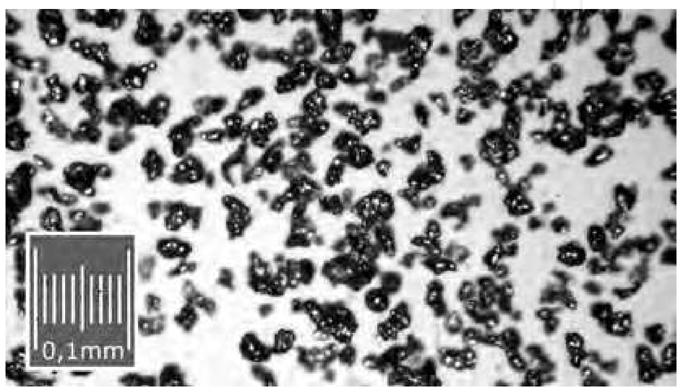


Fig. 13. Ferromagnetic material – filling of the magnetorheological elastomer Zając (2011).

Two groups of MREs were manufactured. The first one involved elastomers filled with the ASC300 iron particles only. Volume share of the iron particles in the composite was established at the base of CPVC value, which amounts to about 36,5 %for the ASC300 iron. The maximum magnetorheological effect should be obtained for specimens containing iron in quantity close to the calculated CPVC value. However, the scientific research has shown, that maximum changes in the mechanical properties induced by the magnetic field activity, were obtained for the material containing 30% by volume of iron particles Lokander (2004). Finally, the specimens containing 35% by volume of the ASC300 particles were manufactured for the tests. The production process of magnetorheological elastomer specimens consisted of the two stages: hot mixing of iron particles with elastomer and shaping the specimens in press. For mixing the two ingredients the Brabender type mixer with chamber heated to the temperature of $190^o C$ was used. Simultaneously with granulate, the iron particles were poured, and in case of some of the manufactured composites, also additives such as oil or silane. The whole was mixed for achieving the homogeneous constitution. In the subsequent production stage the plastic mix was placed in the mould and then pressed hot as well as cold. On removing from the mould, two cubicoids were cut out of each of the composite plates. The material sample has been shown in Figure 14 a), and Figure 14b [1] presents the internal structure of the MRE. The cut samples were glued in between the three supporting plates, as has been schematically shown in Figure 15 . This enabled the assumed state of load and strain of the sample. During cyclic tests the external plates remained fixed and the central plate was moving, enabling that way symmetric shear of both material parts. Magnetic field was applied perpendicularly to the strain direction. Figure 16 presents general view of the measurement stand – its magnetic part and the elastomer sample placed in the core center are visible.

[1] http://www.sgml.pwr.wroc.pl/

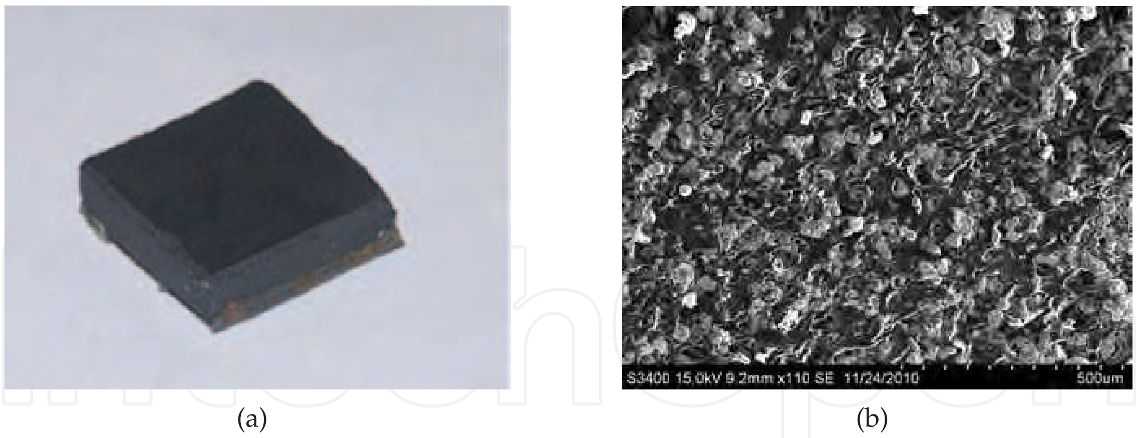


Fig. 14. a) – macro view of the sample , b) – SEM image of the magnetorheological elastomer Zając (2011).

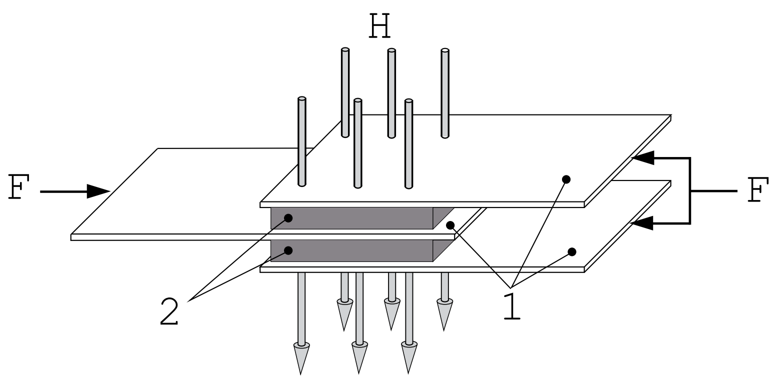


Fig. 15. Schematic diagram of the sample prepared for tests: 1 – laminate plates, 2 – magnetorheological composite Zając (2011); Zając et al. (2010).

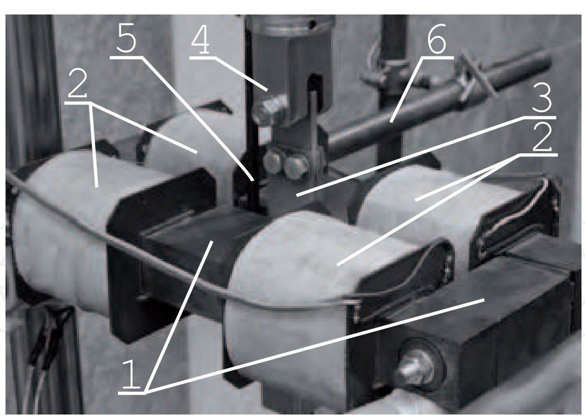


Fig. 16. View of the measurement stand: 1 – magnetic core, 2 – coils, 3 – laminate plates with the glued up magnetorheological composite samples, 4 – stainless steel holder, 5 –Hall probe sensor, 6 – support element Zając (2011); Zając et al. (2010).

3.4 Magnetomechanical properties of MRE

The magnetorheological elastomer investigations described in the subject literature involve, first of all, the sample shearing Lokander (2004); Zając et al. (2010) also their compression Farshad & LeRoux (2004); Popp et al. (2009), as well as tension Bellan & Bossis

(2002); Gong et al. (2005b) in the magnetic field of various intensity, in order to determine their magnetomechanical properties. In addition, the research has been conducted, aimed at finding the other features, such as the electrical parameters of MRE Bica (2010) and their magnetic permeability Bellan & Bossis (2002).

In order to show the changes happening in the matrix material as a result of its doping with powder of the ferromagnetic material, at the first stage the tests for samples of pure thermoplastic elastomer were performed. Next, the tests of MRE filled with the ASC 300 particles, constituting 30% of the volume were performed. The samples were tested in the pure cyclic shear conditions with various amplitude and frequency of the displacement signal values. The hysteresis loops were analysed in the stress – shearing strain ($\tau - \gamma$) co-ordinates, for all the tested materials in the absence of the magnetic field (Figure 17). The differences in the composite and pure elastomer matrix properties are clearly visible.

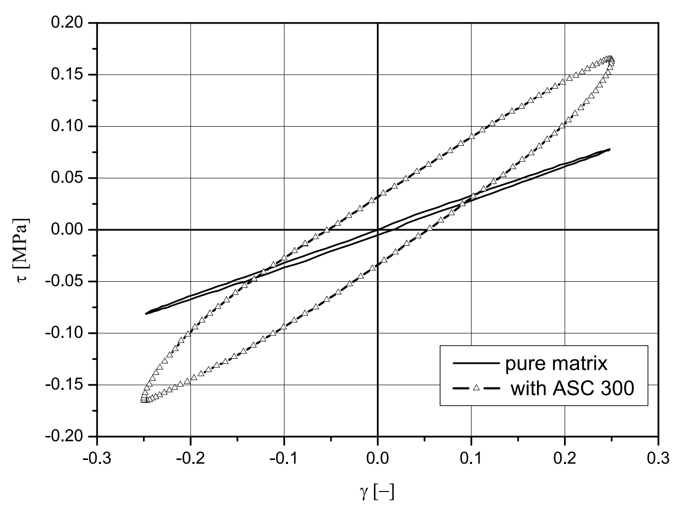
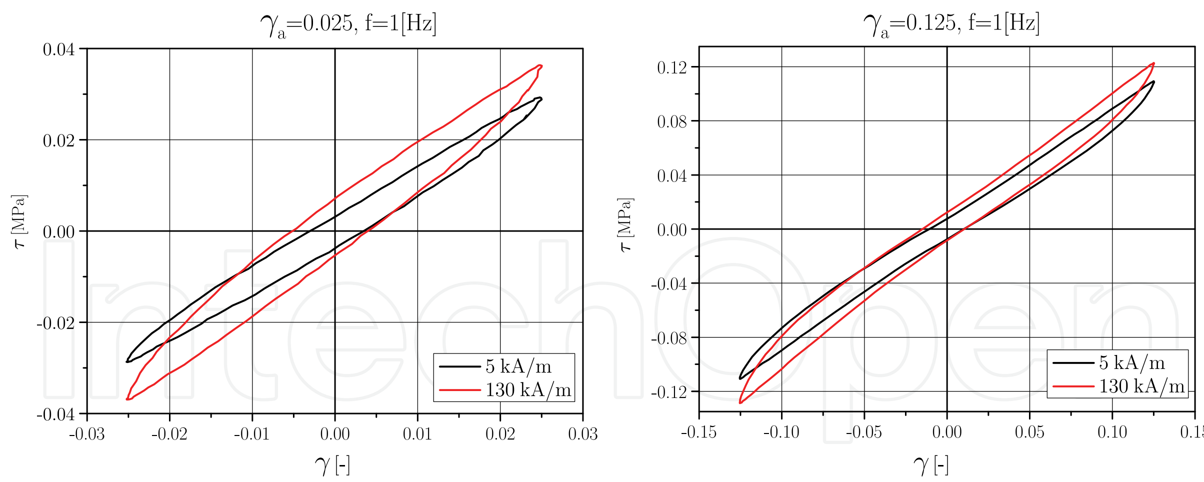


Fig. 17. Influence of the matrix filling with the magnetic particles. Hysteresis loop obtained for cyclic shearing tests Zając (2011).

The subsequent graphs (Figure 18) present the hysteresis loops within the $\tau - \gamma$ co-ordinates for the magnetorheological composite filled with the ASC 300 particles. The loops for the two extreme values of the magnetic field intensity equal to 5 kA/m and 130 kA/m correspondingly. The change in shape and area of the loop with the increase in the magnetic field intensity is visible.

Influence of the magnetic field on mechanical properties of a material is designated as the magnetorheological effect. Hysteresis loops increase their area and change the size. The stress amplitude value τ_a increases for the higher values of the magnetic field intensity, while keeping up to the constant amplitude of the shearing strain γ_a. Creation of the mechanical hysteresis loop at the harmonic loads testifies for the irreversible energy dissipation. The constitutive equations, i.e. the relations between the strain and stress tensors, should consider this phenomenon. The most frequently used models of the body in the subject literature are the linear equations for the viscoelastic body Kallio (2005). In that case, for the sinusoidal loads, the hysteresis loop is an ellipse. At Figures 18a , and 18 b, it could be observed that for describing the loops the more complex body models should be used: the non-linear viscoelastic relationships or the viscoelastic/viscoplastic body models. Selection of the model depends on the type of the irreversible strains being created in the loading process. For that



(a) (b)

Fig. 18. Hysteresis loops for the extreme enforcement values: (a) γ_a =0,025 and f=1 Hz, (b) γ_a=0,125 and f=1 Hz. Zając (2011); Zając et al. (2010).

aim it is necessary to perform subsequent experiments giving answer to the question whether the existing irreversible strains depend on the straining trajectory (the plastic strain), or these are the strains depending on the time scale (the viscous strains), as well as determining the area (the yield point), in which they appear. At present the problems are the subject of intensive research Zając (2011).

3.5 Applicability of the MRE

The magnetorheological elastomers have much shorter history than, for example, the magnetorheological fluids, and therefore they yield in the number of industrial applications. Patent applications in that domain began to appear in the 90. of the 20th century, yet their number began to grow only after the year 2000. Both, the material itself Bose & Roder (2009b), and its applications using the unique properties of the MRE have been patented. It could be noted that mainly the solutions with anisotropic magnetorheological elastomers were patented so far. On the fact that magnetorheological composites have high potential of wider existence on the market testifies the establishment in 1999 the Nevada (USA) located the Advanced Materials and Devices (AMAD) enterprise specialising just in the magnetorheological elastomers. An example of the research conducted for the US Navy was development of the suppressing inserts of variable stiffness for the missile launched system on the submarines. The inserts are located between the external missile surface and the internal surface of barrel. From the automotive branch comes large number of the patent applications for the use of magnetorheological composites. One of the first patents for the magnetorheological elastomers use developed just in the Ford Motor Company Watson (n.d.), concerns regulation of the vehicle suspension element stiffness through the use of a sleeve with the controlled stiffness. In that solution the magnetorheological elastomer is located between two sleeves, where the internal one is attached to the movable suspension element and the external one is attached to the body. Ford Global Technologies developed also a device for measuring the displacement and force in the automotive suspension on the run Elie et al. (1998). In the German ThyssenKrupp AG company a steering gear column with the adaptive energy absorption system during a car accident Klukowski & Meier (2006) was developed. Other examples of the MRE application have been described in Brei et al. (2006); Browne & Johnson (2006); Lerner & Cunefar (2006).

3.6 Further research justification and directions

Composites of the MRE type give evidence to their numerous advantages, including the operating range above the yield point (in comparison for example to the magnetorheological fluids), their recyclability in case of matrices of the plastic elastomer, as well as the relatively simple manufacturing process engineering. This allows for predicting the further numerous applications of MREs and, at the same time, justifies the need for further research.

It could be assumed that in the nearest period the activity of scientific and engineering teams will focus mainly on:

- Improvement of the magnetorheological composites manufacturing engineering. The works in that area are to be related with searching for the optimum matrices, active ferromagnetic fillings (types and sizes of powders), as well as the manufacturing parameters such as the magnetic field intensity and temperature.
- Development of the constitutive models enabling description of the MREs' magnetomechanical properties. The models identification will enable foreseeing the MREs' behaviour and will lower the costs of experimental works.
- Optimising the systems for applying magnetic field with the stress on the role of the strong permanent magnets. That would diminish the size and costs of magnetic field generation.
- Presentation of the wide spectrum of applications, mainly in the suppression of mechanical vibration, leading to increase in production of MREs and lowering their production costs.

4. Composites with giant magnetostrictive particles

4.1 Introduction

Below, the composites containing selected powder of magnetostrictive materials have been described. In relation to that, it has been considered as just to clarify the notion of magnetostriction, and then characterize the magnetostrictive materials, including the materials with the so called giant magnetostriction. The main representative of the last group is Terfenol-D. Next, the study methodology for those materials, their properties and the justification for creating composites containing the materials with giant magnetostriction, has been described. Attention was also paid to the current applications of these composites and possible directions of their further development.

4.2 Magnetostriction

Magnetostriction (from Greek 'magnet' - magnet and Latin 'strictus' - compressed, tight, tense) is a domain of magnetism dealing with "phenomena related to interaction between magnetic quantities and the stresses and mechanical deformations" Bomba (2009); Kaleta (2004). Magnetostriction as the phenomenon could also be defined as a change in material dimensions caused by a change in its magnetic state Buschow & de Boer (2004). Most often, the magnetostrictive materials change their dimensions as a result of a change in magnetic field applied to them, as well as change their magnetic properties under the force applied to them. The most commonly used is more general definition, which says that: "magnetostriction consists in changing shape and dimensions, as well as mechanical properties, as a result of magnetic field influence, or - the opposite - in changing magnetic properties, e.g. induction (or magnetisation) and permeability (or susceptibility), under the influence of stresses and strains" Bomba (2009); Kaleta (2004). The most commonly known phenomenon related to magnetostriction is the Joule effect, otherwise called as plain magnetostriction phenomenon, or the linear magnetostriction Buschow & de Boer (2004). It consists in change in length of the material in one of the directions, under the influence of the applied magnetic field with simultaneous change in the proper transverse section, while the material volume is being kept constant all the time. This is caused by the fact, that in the remaining directions the magnetic domains are being set so, as to mutually neutralise their interaction (the compensation of transverse and longitudinal magnetostriction takes place), due to which the internal energy of the system is lowered. We talk of longitudinal magnetostriction Bomba (2009); Kaleta (2004) when the strain in material, to which the magnetic field H was applied, is consistent with the field lines. The longitudinal magnetostriction coefficient is then defined as:

$$\lambda_{\parallel} = \lambda_1 = \frac{\lambda_1 - \lambda_0}{\lambda_0} = \frac{\Delta\lambda}{\lambda}, \tag{5}$$

where:

- $\Delta\lambda$ - change in length as a function of magnetic field intensity,
- λ_0 - initial specimen length,
- λ - specimen length in the magnetic field.

The transverse magnetostriction Bomba (2009); Kaleta (2004) in turn, appears when strain in material takes place in the direction perpendicular to the applied magnetic field. The coefficient of transverse magnetostriction $\lambda_{\perp}$ (or λ_t) is defined the same way as the longitudinal one. For the saturation field H_s the magnetostriction coefficients are marked as λ_s , λ_{ls} and λ_{ts} correspondingly.

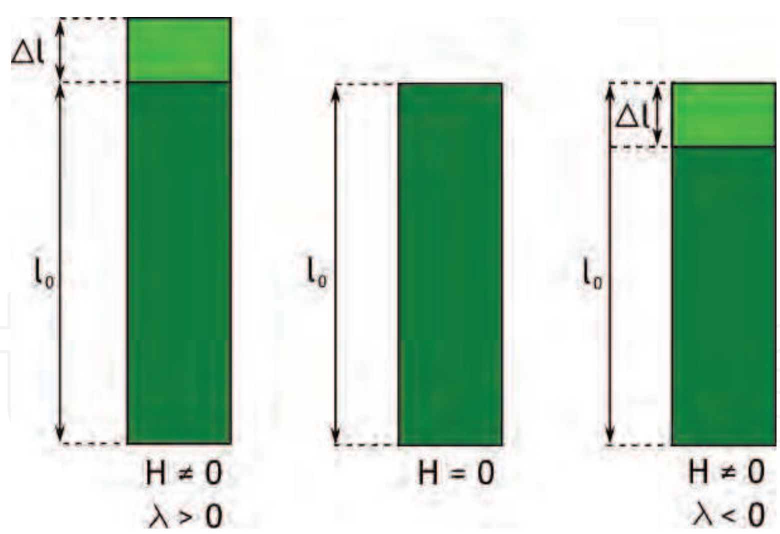


Fig. 19. The essence of positive and negative magnetostriction.

Magnetostriction could be positive or negative. The positive magnetostriction ($\lambda > 0$) occurs in magnetite, permendur, permalloys – usually with content of 45 - 65 % of Ni – alfers, or weakly magnetised iron. The negative magnetostriction ($\lambda < 0$) is characteristic for such materials as nickel and nickel ferrites. Figure 19, presents both types of magnetostriction. As seen in case of the positive magnetostriction the material increases its length, and in case of the negative one, the length is decreasing.
Features, which characterise magnetostriction are:

- even phenomenon, which signifies that a change in magnetic polarization sign (of the field or induction intensity) is not accompanied by a change in the magnetostriction sign,
- magnetic and thermal hysteresis,
- anisotropy, i.e. dependence on the shape and temperature.

Other phenomena related to magnetostriction are:

- Barnett effect,
- Villari effect or magnetoelasticity,
- Guillemin and Wiedemann effects (derivatives of the Joule effect),
- Barnett and Einstein-de Haas effects,
- Barkhausen effect.

The phenomena are widely discussed in the subject literature and are not to be analysed here.

4.3 Giant Magnetostrictive Materials

Materials, which possess the strong magnetic properties involve materials of the so called giant magnetostriction (GMM - Giant Magnetostrictive Materials). These are the alloys composed mainly of terbium (Tb), dysprosium (Dy) and pure iron Kaleta (2004). Elements such as Tb, Dy, as well as gadolinium (Gd), holmium (Ho), erbium (Er) possess the unfilled subshell 4f, due to which, similarly as it was in case of Fe, Ni, or Co, they have uncompensated spins, which characterizes their ferromagnetic properties Mech (2008). Materials with giant magnetostriction may change the magnetic energy into mechanical one and vice versa. Due to such properties the materials could be used as sensors or actuators. The GMMs obtain much larger strains (even up to 70 times) than the traditional magnetostrictive materials, and for obtaining that effect, the relatively low magnetic field intensity H is required. Very important feature of those materials is their wide working temperature range, as well as their low inertia (small area of hysteresis loop), which allows for their application in various conditions. The Curie temperature for these materials amounts to 653-693 K, and the working temperature for these materials may reach 473 K. Stresses created by the GMMs may amount up to 30 MPa Claeyssen & Lhermet (2002). Possibility of predicting the mechanical and magnetic properties of such materials as the Terfenol-D caused that they find all the wider application in various engineering domains Monaco et al. (2008). Typical examples of their application are magnetostrictive relays, which could be controlled by conventional amplifiers, much below the resonance frequencies, which in effect enables for much lower control voltage. This advantage has special meaning in case of the medical applications and enables simplification of the control systems.

4.4 Composites - new approach to GMMs

The solid magnetostrictive materials, despite their numerous advantages, have several disadvantages making their wider industrial application difficult. First of all, their significant drawback is high brittleness, resulting in the low tensile strength. The other limitations are the eddy currents of significant value, which restrict the effective working frequency of devices to several kilohertz. Important parameter is also the price of Terfenol-D, which is kept at the level of 2 $/1 g. The above limitations are generating the need for finding new solutions. One of them is magnetostrictive composites. The main object of the research are composites based on epoxy resins, where the magnetically active filling usually have the form of powder Lo et al. (2006); McKnight (2002), but also the filaments Lo et al. (2006); Or & Carman (2005), or flakes of the magnetostrictive material Liu et al. (2006). Aim of the research is determining properties of the created composites and their potential applications. Usually, properties of the composites and the monolithic magnetostrictive material, which, because of its good properties in the room temperature is Terfenol-D, are also being compared. Having in mind the above, it has been assumed that this is particularly important topic as scientific and engineering issue, and at the same time the aim of the chapter, is presentation of:

- production engineering for the new composite types with the GMM powders ,
- composite tests methodology in the conditions of simultaneous stimulation with the mechanical and magnetic field,
- magnetomechanical properties (magnetostriction) for the created composite and comparison with the solid GMM material.

4.5 Magnetomechanical properties of the GMMc. Manufacturing, research methodology, properties

Magnetostrictive composite (from now on called the GMM composite, or shortly the GMMc), has been manufactured by combining the epoxy resin and the powder of GMM type material (Terfenol-D) of grain size ranging from 5-300 μm - the shape and grain sizes are shown in Figure 20. It is clearly visible that powder particles have diversified shape and size, and their edges are sharp.

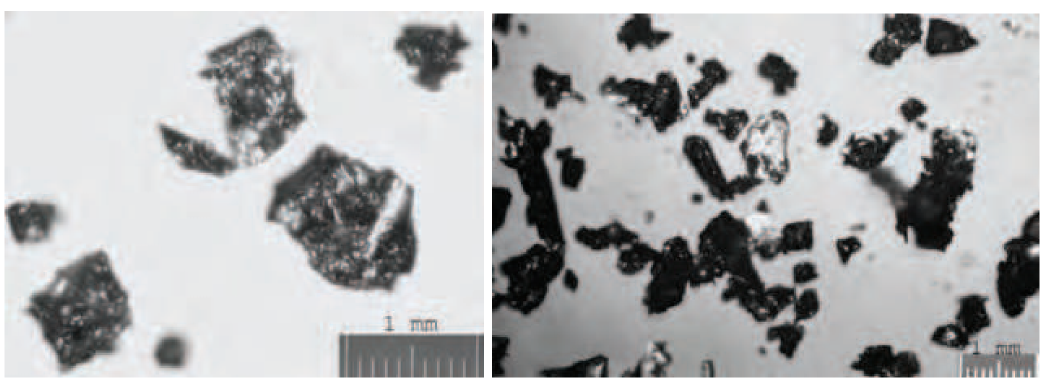


Fig. 20. Microscopic images of the Terfenol-D powder grains.

Specimens of diversified parameters have been manufactured. The manufacturing procedure is presented in Figure 21. At the first stage (A), a hardening agent was introduced into the Epolam 2015 epoxy resin (from Axons Technologies), and next (D), the measured quantity of the Terfenol-D powder (from Gansu Tianxing Rare Earth Functional Materials Co.,Ltd.). Then, (F) the whole was mixed until homogenization of all ingredients was reached. The mixture was subjected to deaeration process (G) and poured over to containers of cylindrical shape (H). The containers were subjected to initial polarization (I) and again deaerated. The specimens were subjected to subsequent polarization (J), which prevented sedimentation of the powder particles during the resin binding process.

Subsequently, the specimens were subjected to tests in order to determine their magnetomechanical properties. Magnetostriction measurement required specialist test stand. Its main part was electromagnetic circuitry composed of coil and steel casing. Current flowing through the coil created magnetic field inside it and the external casing had the task of limiting propagation of the magnetic flux outside and increasing the field inside the coil. Diameter of a hole passing through the coil axis was small enough to cause the maximum impact of the

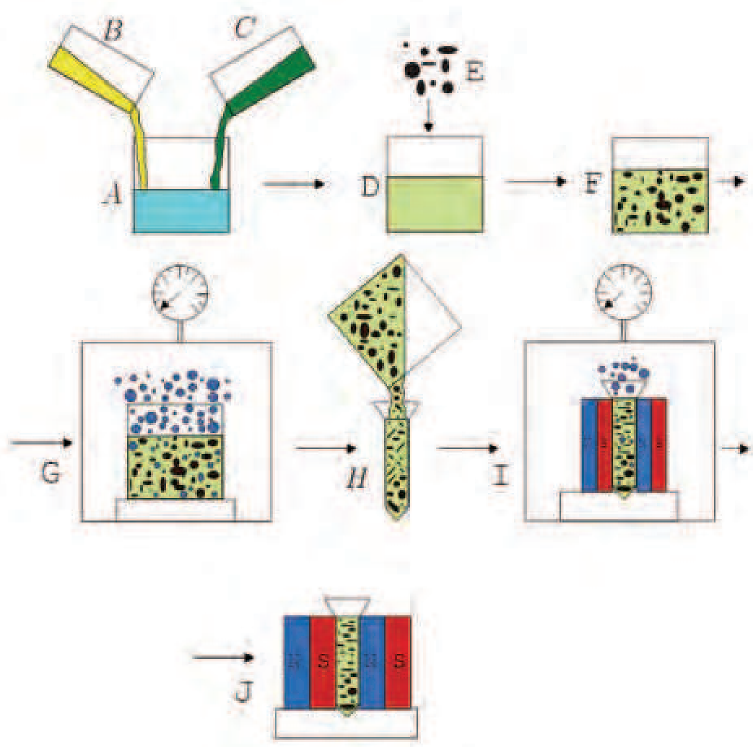


Fig. 21. Manufacturing procedure of composite specimen.

created magnetic field on a specimen located in it. Moreover, the fibre-optic displacement sensor was placed in the hole (the Fiber Bragg Gratings - FBG), as well as the temperature and magnetic field sensors. Localization of strain sensors at the specimen has been presented in Figure 22a and b.

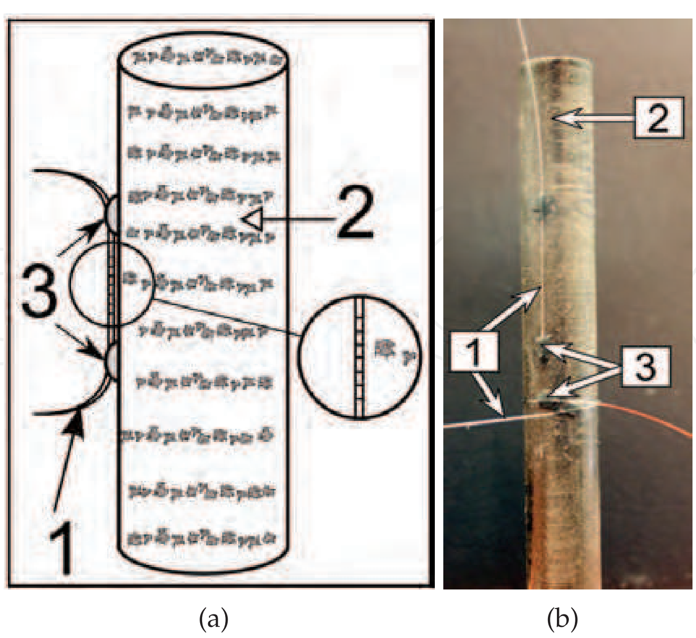


Fig. 22. The way of strain sensors distribution at a specimen: a) schematic diagram: 1 - sensor, 2 - composite, 3 - glue b) photo of the real object.

The reason for using the FBG sensors for strain measurement was their small geometric size and resistance to electromagnetic disturbance. This has a key meaning in case of tests in the conditions of stimulation with strong magnetic field (the results from other sensors, such as strain gauges and others, in which the electric quantities are recorded, are not reliable because of the high disturbances). The measurement method with the FBG use has been presented in the work Blazejewski et al. (2011).
Next, the magnetostriction value $\Delta\lambda_{max}$ was determined for the composite at the maximum intensity of the magnetic field H=158 kA/m. Figure 23a and b presents the comparison of the obtained results for the composite materials and the solid Terfenol-D, at the initial load equal to σ_0=1 MPa and σ_0=7 MPa correspondingly. Among the manufactured composite

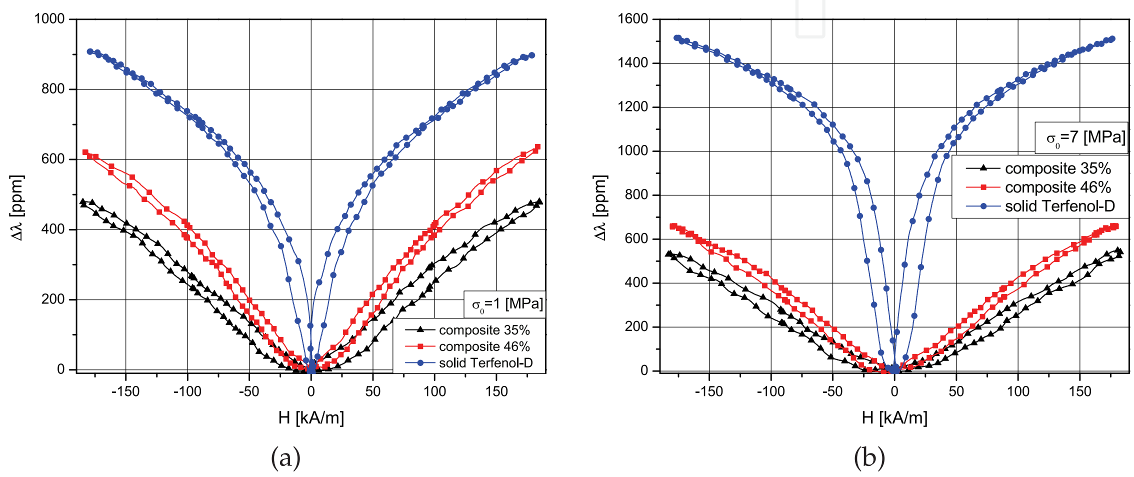
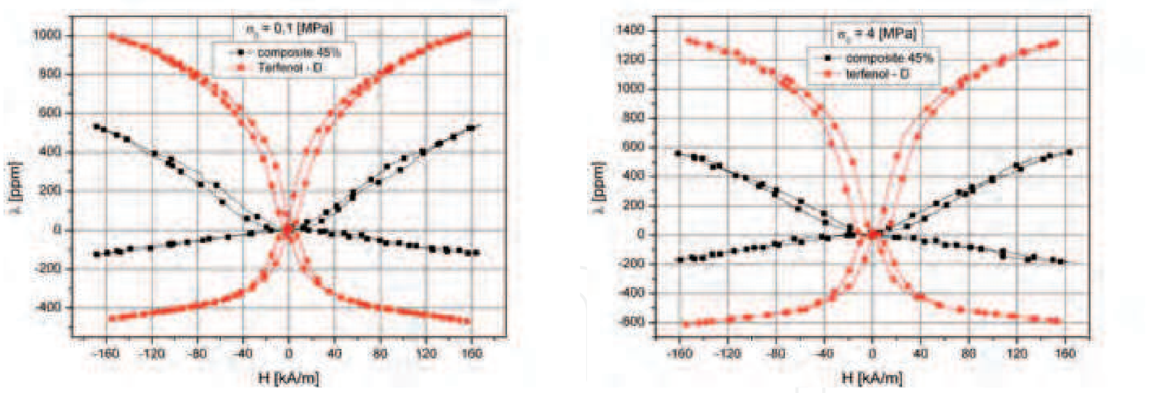


Fig. 23. Comparison of the magnetostriction results for the composite materials and the solid Terfenol-D, at the initial loads of: a) σ_0=1 MPa and b) σ_0=7 MPa correspondingly.

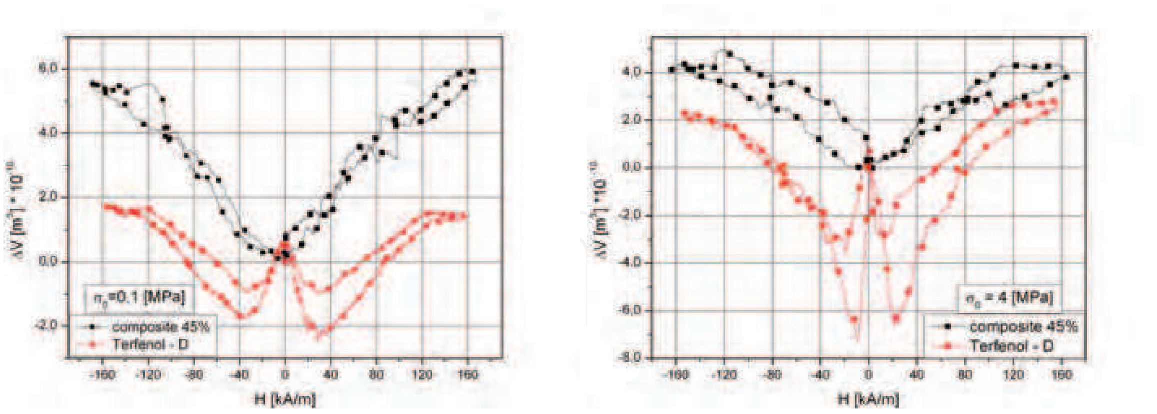
materials the best results were obtained for the specimen containing the highest content by volume (46%) of the Terefenol-D powder. Then, for the initial stress of σ_0=1 MPa, the magnetostriction of composite material is lower by only 280 ppm from the magnetostriction of the solid material, that is by 30%. Whereas, at the higher value of the initial load σ_0=7 MPa, it is lower from that for the solid material by 700 ppm, that is by 45%. However, it has to be noted, that by applying the composite the eddy currents phenomenon was almost eliminated and the tensile strength increased.
Figure 24a and b present measurement results for the composite material and the solid Terfenol-D, both, along the specimen axis, and in the circumferential direction. The FBG sensors glued up in both directions were used in the measurements (see Figure 22b). That way, it has been shown that both, in the solid material and in the composite, the volume magnetostriction does not appear. Moreover, the influence of the initial stress (prestress) at magnetostriction of both materials has been shown. It could be noted that increase in the σ_0 (prestress) to the value of 7 MPa significantly increases magnetostriction of the solid Terfenol-D, and it has no practical influence at the magnetostriction of composite.
Subsequent graphs in Figure 25a and b present the change in volume, which happened in case of both tested specimens depending on the magnetic field intensity and for the different values of prestress, to which the specimens were subjected during the tests, and which amounted to 0,1 MPa and 4 MPa correspondingly. From the obtained results it could be unequivocally stated that in case of the solid material, as well as in case of the manufactured composite materials, the Berrett effect is marginally small, hence one could attempt the



(a) (b)

Fig. 24. Comparison of magnetostriction results in the longitudinal and circumferential directions for the composite material with content of 46% by volume of the Terfenol-D powder and the solid material. The prestress amounted to: a) σ_0=0,1 MPa and b) σ_0=4 MPa, correspondingly.

statement that the effect in these materials could be neglected during the tests. Large magnetostriction of the Terfenol-D has caused that the application works concern mainly the actuators Shaffer & DeChurch (2004). It has been known however, that in the GMM materials, the reverse magnetostriction (the Villari effect, i.e. the alteration in material magnetisation influenced by the applied mechanical load) assumes large values. This allows using the GMMs for a construction of sensors Quattrone et al. (2000). Therefore, an attempt to study the Villari effect in the composites manufactured with the GMM powder was undertaken. For that aim, the proper preparation of specimen surfaces was necessary so, as to be able to make measurements of the magnetic field intensity at a constant distance from a specimen. The composite containing 46% volume fraction of Terfenol-D particles was selected for the tests.



(a) (b)

Fig. 25. Change in the volume of specimen made of the composite material with 46% by volume content of the Terfenol-D powder and the solid material, depending on the magnetic field intensity value, for the prestress amounting to: a) σ_0=0,1 MPa and b) σ_0=4 MPa correspondingly.

The composite was divided into two parts, and cut crosswise and in parallel to the initial specimen polarisation line. The sample obtained that way was placed in the testing machine.

A magnetic field sensor was applied to its surface in three different directions, as shown in Figure 26a - c. The measurements were performed for cyclically loaded sample, with various force amplitudes.

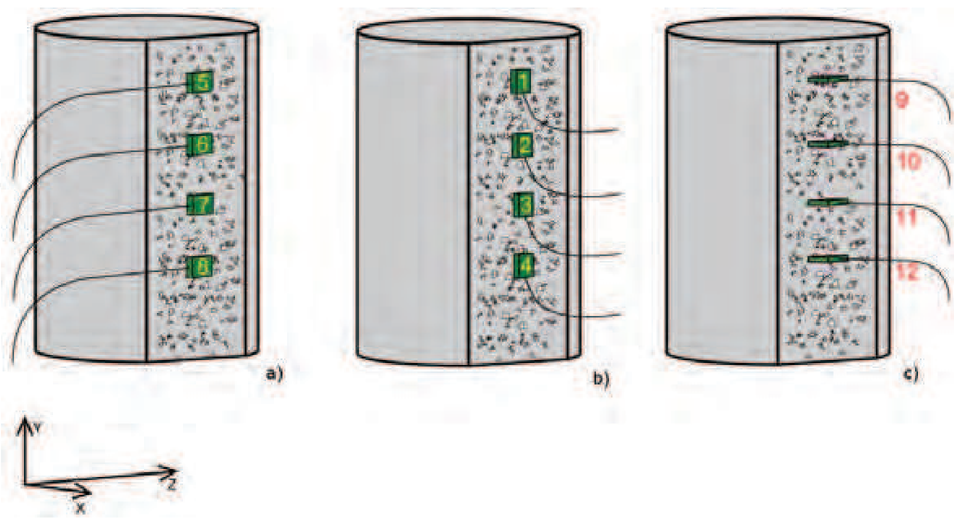


Fig. 26. The way of positioning the magnetic field sensor along the tested sample, where: a) Z component, b) Y component, and c) X component of the magnetic field.

Figure 27 presents the results obtained by means of the magnetic field sensor, for the selected sensor positioning (position 1 at Figure 26b). It could be noted that with the increase in force amplitude the magnetic response of the material measured with the magnetoresistor was growing.

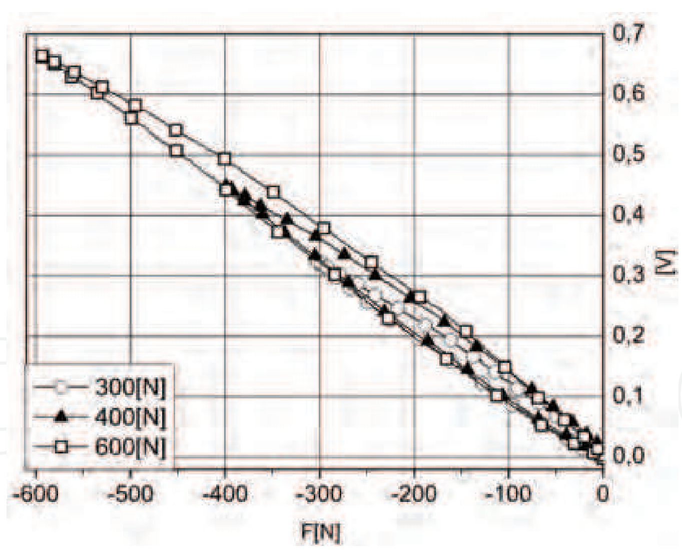


Fig. 27. Change in the magnetic field value for the sensor in position 1 (see Figure 26b).

The change in magnetic field around the sample was causing a change in the voltage induced in the sensor. It is worth of underlining that with growing load of the sample, the shape of the hysteresis loop was not changing significantly. In addition, the changes in the material response to the mechanical enforcement depending on a sensor positioning along the sample were recorded (Figure 28). The presented results concern all sensor localizations shown in Figure 26b. The changes in the hysteresis loop shape, magnetic field sign, and what is equally important, in the value of that field for the tested sample, have been shown. This indicates that the field distribution over the tested samples length is diversified.

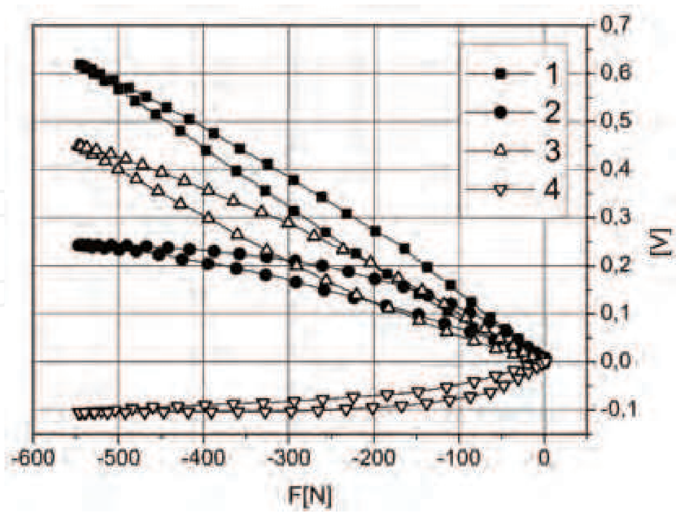


Fig. 28. Change in the magnetic field value depending on the sensor localization (for the situation as in Figure 26b).

In sum, we were able to show, that the manufactured composite materials, similarly as the solid materials, show considerable effect of the reverse magnetostriction, as well as to determine distribution of the magnetic field acting along each of the samples. That means, that composites containing powdered GMM may be used for creating the new generation sensors. The new fields of application, such as: hearing aids, extensometer systems, accelerometers, proximity detectors, momentum sensors, magnetometers and many others, could be indicated.

Study of the Villari effect in composites enabled also indicating the use of those materials in the so called harvester, which converts the mechanical energy into the electric current (known as the energy harvesting) Kaleta et al. (2010).

4.6 Justification and directions of further research

Significant advantages of the composites containing powdered GMM (elimination of the eddy currents, rise in the tensile strength), despite the lower values of magnetostriction and the Villari effect (in comparison to the solid GMM materials of the Terfenol-D type) provide for a series of applications and justify further research. As particularly valid, the following issues should be considered:

- Investigation of how magnetostriction is influenced by the powder fraction change, i.e. the use of larger grains than those used in the presented work, as well as application of grains of the up to 100 μm size. Additional parameter, that could change is the form of the powder (flakes, fibers, or the powder of oval grain shapes). The subject literature in that field is scarce and the results disputable.
- Estimation of the composite matrix influence and verification, whether there are any interactions between the matrix and the filling, as well as checking what influence has the density and hardness of the resin on the results.
- Verification of how the manufactured composite behaves during cyclic, random and pulse changes in the magnetic field intensity. Moreover, the investigation whether the use of

stronger magnetic field, over the value of 1 T, will cause saturation of the material and more non-linear distribution of the hysteresis loop field is justified.

- Verification of how the change in positioning of the magnetic field polarisation vector in relation to the main axis of a sample influences the composite magnetostriction. This could enable obtaining the optimum angle of the sample polarisation, in order to reach the highest values of magnetostriction.
- Investigation of the GMM composites magnetostriction for the case of static tension, which could enable better material characteristics and widen its application area.
- Continuation of works aimed at utilization of that composite class in the energy harvesting.

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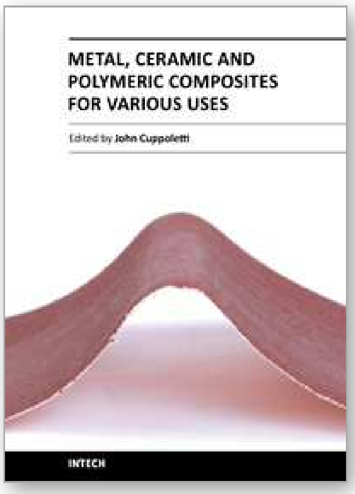

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Composite materials, often shortened to composites, are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct at the macroscopic or microscopic scale within the finished structure. The aim of this book is to provide comprehensive reference and text on composite materials and structures. This book will cover aspects of design, production, manufacturing, exploitation and maintenance of composite materials. The scope of the book covers scientific, technological and practical concepts concerning research, development and realization of composites.