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Improved mechanical properties of magneto rheological elastomeric composite with isotropic iron filler distribution

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Abstract

In this work, mechanical property of magneto rheological elastomeric (MREs) composite is investigated using iron as filler distribution. The MREs composite were fabricated using irregular shaped iron particles with size range varies from 50 -150 µm in matrix of elastomeric polymer. The matrix such as ZA22 was considered with 1:1 catalyst ratio as the binder with 30 Vol % of filler content. The fillers were incorporated within the matrix of elastomer using silicon oil as additive binder in the composite. The open circuit solenoid coil was designed as the magnetic circuit for magnetic flux intensity. Various magnetic field intensities were induced to observe the mechanical properties of the MREs composites. Hysteresis loss was observed in MRE samples due to dissipation of energy during compression of the composite material. Improved engineering strength of the MRE is observed on varying magnetic field of intensity and constant at 0.3 Tesla.

Keywords: iron filler; magneto rheological elastomer; magnetic field intensity; isotropic distribution.

1. Introduction

Magneto rheological elastomeric composite are the new group of smart materials that can alter the properties under the influence of external stimulus [1]. These materials can characterize by reversible change of mechanical and rheological properties under the influence of external magnetic field. These behaviors of changeable properties are known as magneto rheological effect. Traditionally it is composed of MR fluids and foams [2]. The magneto rheological composite materials primarily consist of non-magnetic matrix and with magneto active particles such as iron as filler. In MR fluids the matrix is liquid fluid, which contains magnetic particle such as iron in suspended form. The main obstacles with these materials are the settlement of particles with respect to time [3]. However, the MR with foam like matrix are solid state materials with very low intrinsic modulus [4]. MREs are composite with magnetic particles are incorporated inside the elastomer matrix.

Elastomers are soft polymers with high expansion, widely used in numerous application including gaskets and vibration damping materials [5]. The key properties of elastomer are the hardness that opens up wide flexibility on various applications. The hardness can be preferred on choice of elastomeric matrix and the cross linking factor. The main advantage is that control of mechanical properties of the MRES composite at the time of application. The most suitable example in this is the vibration-mitigating effect of material that can vary in frequency [6]. The most interesting option of this material is to feel the touching surface of elastomer through haptic sensation by modifying the hardness.

MRE are composite materials that consist of elastomer matrix with magnetized particles such as iron filler. When magnetic field is applied, the filler particles are polarized and induce magnetic force of attraction towards each other as a result the materials stiffen [7]. When the magnetic field is switched off,

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the material comes back to original state and it becomes softer in nature. The magnetic interactions between particles in MRE composite depend on the magnetization orientation of each particle and their spatial relationship in coupling the strain and magnetic intensity of materials. This leads to magneto-mechanical phenomena of MRE composite materials. Earlier researchers [8] have studied the effect of volume fraction of filler particles within elastomer of the matrix. According to the investigation the optimal volume fraction of the filler contents is 35 %. Although MR materials have analogous mechanical behaviors, still MREs have unique properties that differ from others. MREs have a controllable field dependent variable, very short response time. MREs have application in developing adaptive tuned vibration absorbers.

In this article an attempt is carried out for the investigation on mechanical properties of MREs with isotropic filler distribution of iron particles within elastomer of the matrix. The mechanism behind the isotropic distribution and magnetic induced forces within the MREs under the application of external magnetic field is discussed here.

2. Experimental Section

2.1. Materials and methods

The matrix of the MREs composite silicon elastomer (ZA 22) is supplied by Czech chemical company. The reactant and catalyst are silicon based with ratio 1:1. This matrix is room temperature based material with viscosity 4000 mPa.S and tensile strength of 4 MPa with 380 % of the elongation at rupture. The chemical cross linking of the matrix ZA 22 is shown in Fig.1 (a) and (b). Heat resistant of the elastomer exists in the range of -50 to 180 °C.

The filler is chosen as iron filler with irregular shape and the size range from 50 to 150 µm. The microscopic image of filler and particle distribution is shown in Fig 2 (a) and (b).

The MRE composites were fabricated with 30 V % of filler content within silicon elastomer of the matrix. Silicon oil is used as additive for iron particles well mixing in the elastomer matrix. The samples were cylindrical shaped with diameter of 16 mm. The filler particles were mixed with silicon oil and stirred slowly for about 5 min before mixing with the matrix. Silicon oil induces better homogeneity and good dispersbility of filler particles within the elastomer of the matrix.

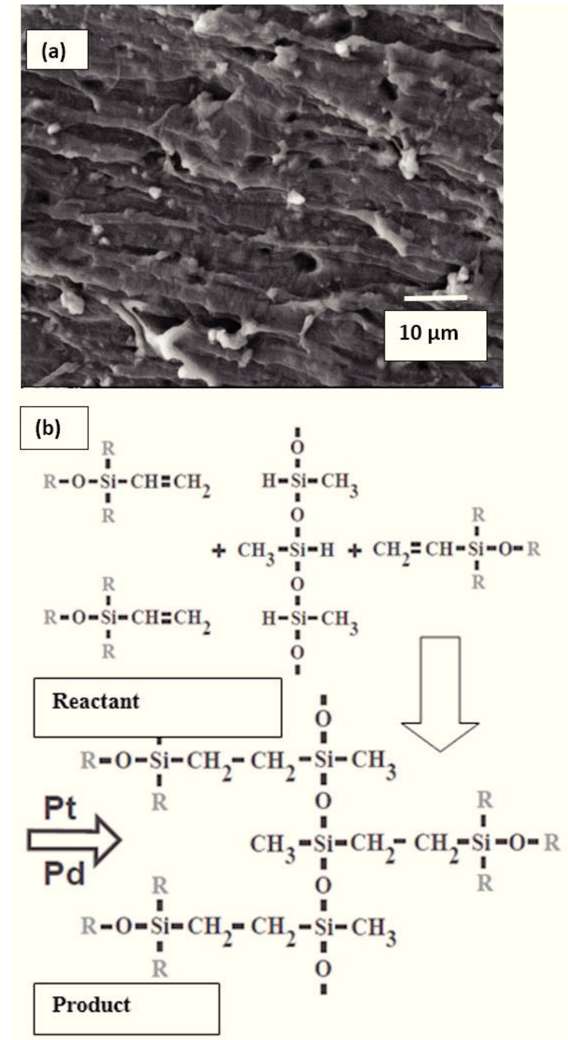

Fig. 1. (a) Scanning electron microscope image of elastomer matrix. (b) Polyaddition chemical reaction product (ZA 22 elastomer matrix). R is the alkyl group radical with catalyst platinum and palladium.

The fabrication of composite formation is shown in Table 1. Average 5 samples were fabricated for each category of specification.

The mechanism of formation and mixing of each components of MRE composite is shown in Fig. 3 (a). After stirring well for 30 min slowly and then after homogenization, samples were cured at room temperature without and with influence of magnetic field. The magnetic lines of force of attraction for sample fabrication are shown in Fig. 3 (b). The photographic image, sample dimension of MREs composite is shown in Fig. 3 c.

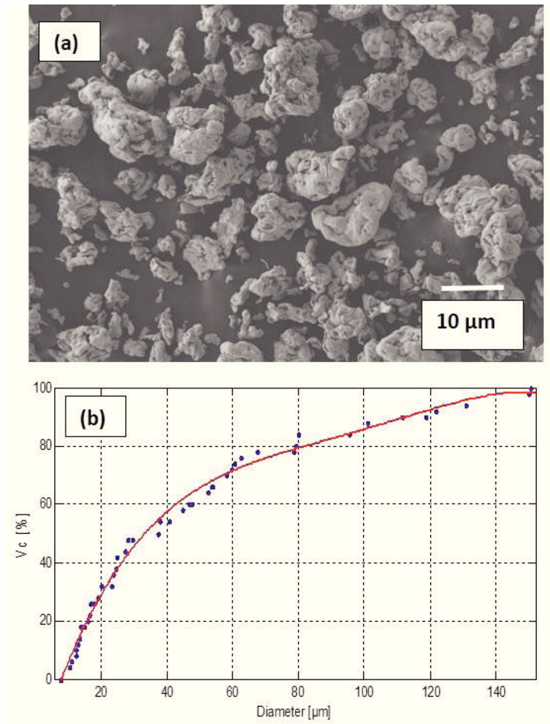

Fig. 2. (a) Scanning electron microscope image of iron filler. (b) Dependence of volume fraction (cumulative frequency) as the function of particle size for iron particles.

Table 1. Fabrication of MREs composite.

Sample	Filler (iron V%)	Matrix (elastomer)	Plasticizer (Silicon Oil)	Polarized
A	0	ZA22	0	no
A1	30	ZA22	2 g	no
A2	30	ZA22	2 g	yes

2.2. Magnetic domain and magnetization

Magnetic domain is designed by using two open circuit solenoids cylinder with core material Steel 11 343 with total length of the core is 110 mm. The dimension of the core is 22 × 110 mm with length to diameter ratio is 5 mm. The no. of turns of coil is around 1000 with total resistance of the winding 1.8 Ω. The inner diameter of coil is 22 mm and outer diameter 85 mm respectively. The maximum operating temperature is 403 K with maximum current of 5 A. The schematic diagram of one solenoid core is shown in Fig. 4 (a) and the coupled two solenoids core with magnetic intensity direction is shown in Fig. 4 (b).

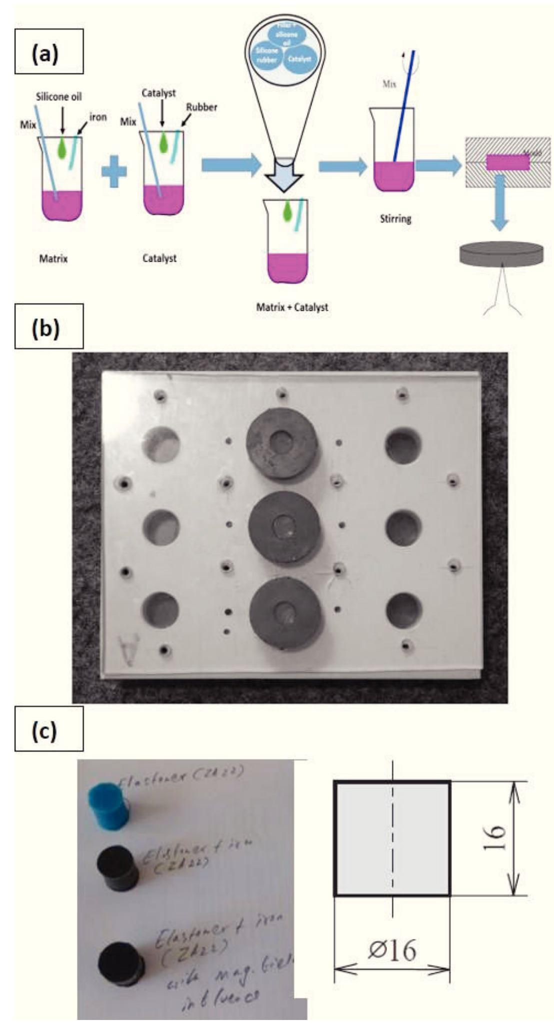

Fig. 3. (a) Schematic diagram of MREs composite formation. (b) Fabrication of sample and curing under magnetic field. (c) Photographic image and sample dimension of MRE composite.

Where N is the no. of turns in solenoids, d is the diameter of each winding, l is the coil length, H_2 is the exterior intensity, J is the magnetic flux intensity with demagnetizing factor of 0.14 %.

At the different interface the magnetic intensity H and magnetic field B are different value. Here the interface changes from air to core of solenoid steel so magnetic intensity is defined as below [9]

$$H_{2t} = H_{1t} - H_d \cdot l \qquad (1)$$

H (2t) = intensity of core solenoid, H (1t) (air) – H (demagnetization) . *l* (diameter of each coil)

$$H_d = \frac{D_f \cdot J_2}{\mu_0} \qquad (2)$$

Where D_f is the demagnetization factor with dimensionless variable having value change from 0 to 1, J_2 is the magnetic polarity and μ_0 is the refractive index of the medium.

Using equation 2 in equation 1, it can be transform into as follows

$$H_{1t} = N.I = \left(H_{2t} + \frac{D_f \cdot J_2}{\mu_0}\right) \cdot l \quad (3)$$

Where N is the no. of turns, I is the electric current, l is the coil length, H_{2t} is the exciter intensity, J is the magnetic polarity, D_f is the demagnetized factor and $\mu 0$ is the vacuum permeability.

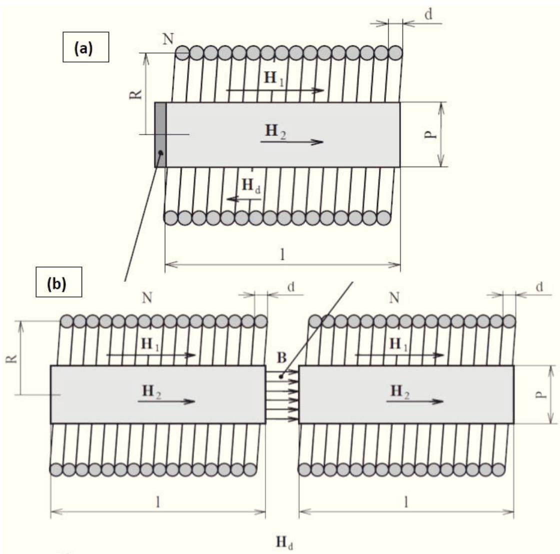

Fig. 4. (a) Schematic diagram of solenoid core. (b) Coupled magnetic core domain.

Fig. 5 displays the magnetic flux intensity versus solenoid core exciter intensity. The number of turns of the coil in the magnetic core is calculated using selected magnetic flux intensity of B = 0.5 T to seek the core exciter intensity of H = 533 A/m. The known power source to obtain maximum voltage of 20 V with maximum current of 10 A with selected current values of 5 A.

The coil length is chosen of 0.1 m. Substituting the known values in the equation 3, the no. of turns is calculated as

$$N.5 = \left(533 + \frac{0.14.0.5}{4\pi.10^{-7}}\right) 0.1 \quad (4)$$

$$N = 1124.7 \quad (5)$$

The each parameter for the experimental measurement of measuring coil is calculated and shown in Table 2. Fig. 6 shows the schematic picture of measuring coil with number of turns and length of inner and outer diameter.

A digital multimeter (Meter man 37 XR) with 4 digit displays was used to measure the various quantities of electrical measurement such as electrical resistance, capacitance, inductance, current with accuracy of 0.1 % of accuracy.

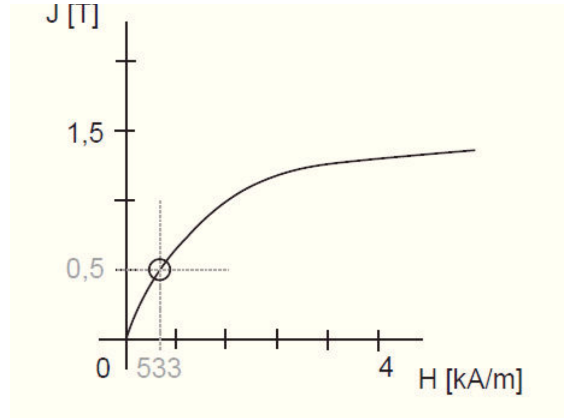

Fig. 5. Characteristic of core (steel) intensity versus magnetic induction.

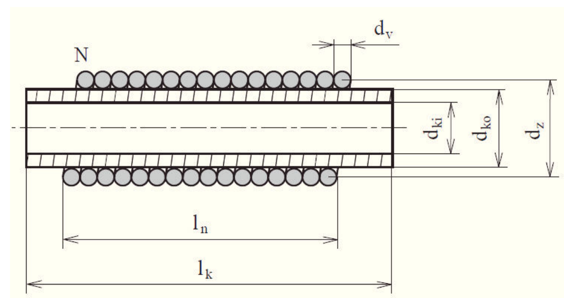

Fig. 6. Schematic diagram of measuring coil.

Table 2. Parameters of measuring coil.

Material	Cardboard
Length	$l_k = 117$ mm
Outer diameter	$d_{ko} = 18$ mm
Inner diameter	$d_{ki} = 16$ mm
Material	Wire
Average diameter	$d_v = 18.28$ mm
No. of turns	N = 300
The mean diameter thread	$d_z = 18.28$ mm
Width of the coil	$l_n = 85$ mm
Ratio	$L_n/d_z = 4.65$
Actual value of induction	$L_v = 303.57$ mH
Measured value of induction	$L_v = 263.3 \pm 0.8$ mH

3. Results and discussion

3.1. Mechanical testing

MREs samples were tested for compression using TIRA instrument. The frequency of vibration for compression was fixed up to 50 Hz. The MREs samples were tested at compressive stresses at various intensity of magnetic field. Fig. 7 (a) represents the compressive test of the sample with schematic presentation. Fig. 7 (b1) shows force versus axis

elongation on compression and Fig. 7 (b2) shows on strain. Fig. 7 (c1) shows the engineering stress and (c2) true stress as the function of time at various magnetic field intensity. It has been observed (Fig. 7 c2) that 0.3 [T] shows the better value of true stress 0.9 MPa in compare to other magnetic field intensity.
The configuration of magnetic domain using two open solenoid magnetic coil is designed is shown in Fig. 8. The MREs composite with iron filler were undergoes compression test. Fig. 9 shows the hysteresis curves of MREs samples in compression test. The hysteresis curve signifies the release of frictional energy of iron particles in the matrix as a result dissipation of energy to the surrounding.
Fig. 10 displays the engineering stress and true stress as the function of various magnetic intensity for MREs composite. This has been observed that magnetic field of intensity 0.3 T shows better values in both stress values. This implies that saturation magnetic field effect is observed at 0.3 T may create the small chains of iron particles within the matrix of the composite.

3.2. Microstructural observation

The magneto rheological effect is observed by the microstructural investigation of MREs sample. The isotropic distribution of iron particles within the matrix of MREs composite is observed in Fig. 11.
Small chain like assembly is observed in the MREs composite that (shown by the marker in the Fig.11) may create due to the effect of magneto rheological.
Fibrils are generated due to the strong coupling between iron particles called affine coupling effect.
The effect of size of the globular inclusion in the matrix of the composite is deduced the shear modulus of elasticity as follows [10]

$$G = G_0 (1 + 2.5Ø + 14.1 Ø^2) \quad (6)$$

Where Ø defines the packing fraction of the MREs composite. G_0 is the initial modulus of the composite.
For all isotropic composites G increases with increasing magnetic field intensity and with volume fraction. The shear deformation of the filler particles results due to shear stress σ.
The influence of magnetic field in MRE composite induces the magnetic dipole of iron particles in the filed direction of shear force that rotates the particle position and even the particle distribution. As the dipole moment rotates with particles rotation so there is effect of particle interaction with applied force.

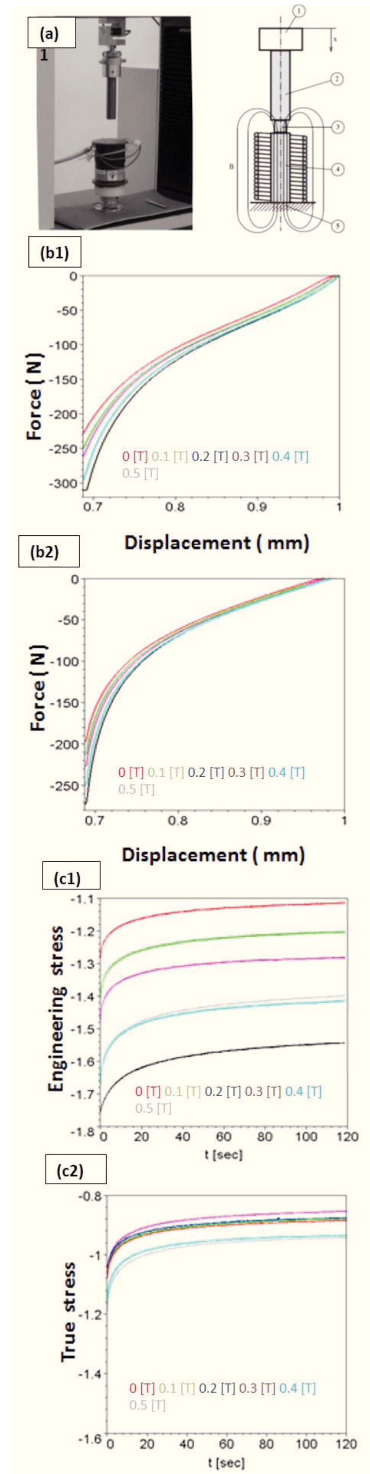

Fig. 7. (a) Photographic and schematic configuration of compression test. (1 - Dynamometer TIRA, 2 - Aluminum metal, 3 - MSE elastomer, 4 - magnetic domain, 5 - frame of TIRA). (b1) Force versus displacement for compression and (b2) relaxation stage at various magnetic intensity. (c1) Engineering stress as the function of time at various magnetic intensity. (c2) True stress as the function of time at various magnetic intensity.

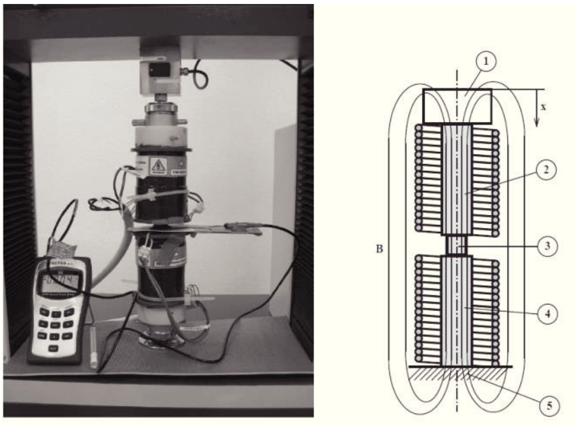

Fig. 8. Photographic and schematic diagram of compression test in closed magnetic domain. (1 - Dynamometr TIRA, 2 and 4 – ferromagnet, 3 - MRE sample, 5 - frame of TIRA).

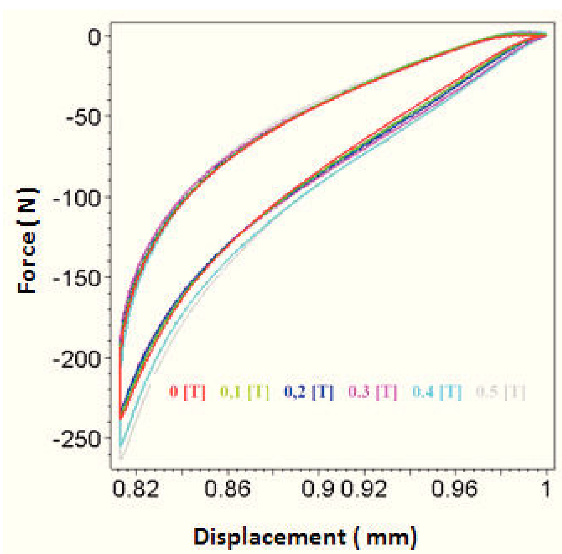

Fig. 9. Hysteresis curve in compression test for MRE samples.

The particles induces affinity coupling towards each other in the composite (except the magnetic field intensity is very strong that disturbs the inter-particle interaction). Hence the strain induced distortion of particle distribution results due to inter-particle interaction and this signifies to MR effect (Fig. 12).

The uniformly distributed particle without strain shows that inter particle distance is directly proportional to volume density of particles in the composite

$$\Delta r_x \propto V^{\frac{-1}{3}} \tag{7}$$

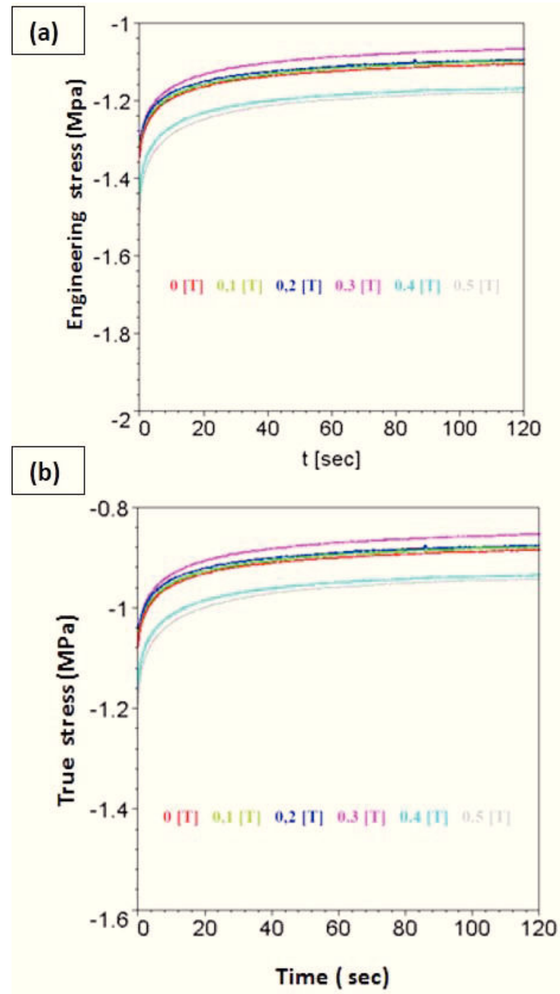

Fig. 10. (a) Engineering stress as the function of time at various intensity. (b) True stress of the MRE composite as the function of time at various intensity.

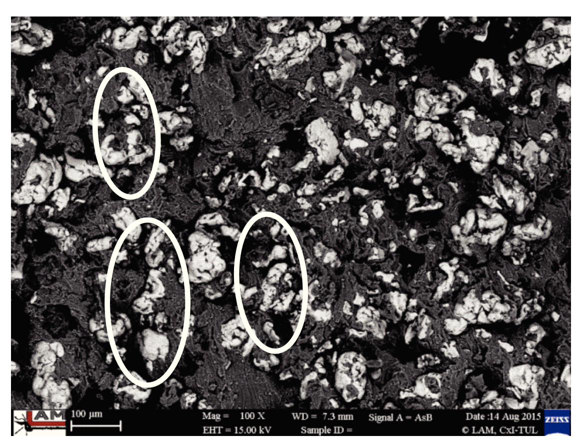

Fig. 11. SEM image of fillers arrangement in elastomeric matrix composite.

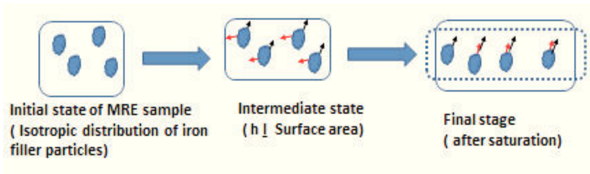

Fig. 12. Schematic distribution of pair effect.

Furthermore on considering the pair wise magnetic interaction of between particles the potential Φ created by the induced magnetic dipole μ of each particle,

$$\emptyset \propto \mu \Delta r^{-3} \quad (8)$$

And the corresponding force is expressed as follows

$$\bar{F}_y = \mu\emptyset \propto \mu^2 \Delta r^{-3} \propto \mu^2 v \quad (9)$$

In addition $\sum_{\alpha,\beta}(\neq \alpha)$ is considered as ~ v^2 for pair of particles. Thus the equation 7 will be transform into as follow

$$\sigma\mu^2 v^{8/3} \propto \mu^2 \emptyset_{iron}^{8/3} \quad (10)$$

Therefore here we consider the proportionality between v and the volume fraction of particles $\emptyset$.

The equilibrium modulus of MREs composite arises from the interaction effect of particle is deduced as follows

$$\Delta G_e(\Psi) = G_e(\Psi) - G_e(\Psi \neq 0) \quad (11)$$

Here $G_e(\Psi)$ is the effective modulus of composite in isotropic composite measured under magnetic field is contributed from the elastomer matrix and filler interaction effect. $G_e(\Psi \neq 0)$ is the effective modulus without any effect and absence of magnetic field. $\Delta G_e(\Psi)$ is the change in effective modulus from the influence of magnetic field to without any magnetic field.

This strongly suggests the effect of MR in the isotropic composites results from magnetic interaction of iron particles. Iron particles with low T are not arranged into chain like structure under influence of magnetic field because of embedment inside the elastomer matrix. This makes a remarkable difference between MRE composite from MR fluid, as the latter allows plastic flow behavior under magnetic field.

4. Conclusions

Mechanical properties of iron filler incorporated elastomeric matrix were investigated in the absence and presence of external magnetic field. The isotropic composite containing uniformly distributed particles shows the improved behavior of force and engineering stress of the MREs composite under the influence of 0.3 T magnetic field. The equilibrium modulus deduced from the result showed increased value than the elastomeric matrix. The filler particle interaction plays the crucial role in increased force and stress of the material. The magneto rheological effect is attributed towards the contribution of magnetic interaction between the isotropic distributions of iron particles within the elastomer of the composite. The change in modulus from the combination of equation 11 and 12 leads to the assumption of $\Delta G_e \propto \emptyset_{iron}^{8/3}$ for isotropic distribution of MREs composite.

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