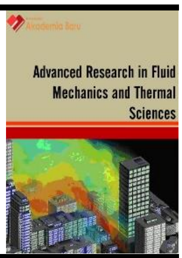
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Experimental Analysis of The Thermal Effect of The Magneto-Mechanical Behavior of Viscoelastic Elastomer

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ARTICLE INFO

Article history:
Received 25 September 2018
Received in revised form 24 October 2018
Accepted 11 November 2018
Available online 8 January 2019

ABSTRACT

This paper is devoted to an experimental of the thermal effect of the magneto-mechanical behavior of elastomer; the latter is loaded with 25% of ferromagnetic particles of micrometric size; developed under the action of a magnetic field. The characterization of the rheological properties and the interaction between the micron size ferromagnetic particles as a function of the intensity of the magnetic field are studied under the effect of different temperatures. The results obtained clearly show the high energy dissipation properties of the composite, accentuated by the structure modified under the thermal effect, which gives properties of viscoelastic structures that can be adjusted as a function of the intensity of the magnetic field.

Keywords:
Thermal effect, Magneto-mechanical behavior, Rheological properties, Viscoelastic elastomer

1. Introduction

Research on the use of Magneto-Rheological Elastomer (MRE) is one of the essential domains most important and attractive areas among the structural materials with new and improved rheological properties. These are intelligent composite materials with properties sensitive to the effect of the magnetic field.

The aim is to understand the significant energy dissipation of the structured composite, further according the magnetic field [1]. The 1980s saw the birth of an interest for the materials with a properties variables under the influence of an external factor as the temperature, the electric or magnetic fields; and where are included the magnetorheological elastomer (MRE) [2]. These materials (MRE) are composed of micron-size ferromagnetic particles polarizable and dispersed in a matrix made generally in the silicone oil. During these last years, research work has focused on the study of the magnetorheological properties of the elastomers. Usually elastomers for flexible silicone or polyurethane are used for the matrix polymer. They are filled with a significant part of micron-size ferromagnetic particles, often 30% of its volume. The composite MRE of flexible matrices of silicone or polyurethane show a significant magnetic field response, but their poor

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mechanical properties are often not appropriate for use in engineering [3]. It is intended that these materials, although in the development phase, will be very useful in solving the vibration problems. The damping properties are fundamental for MRE applications. The identification of the damping MRE properties depends of the magnetic field intensity. To determine these latter, an experimental set-up is used and the test samples are prepared to obtain the desired damping characteristics. To obtain the magnetic hysteresis curve of the MRE, the experimental studies were performed [4]. In recent years, the scientific community has focused on the knowledge of rheological behavior materials. Valery *et al.,* [5] studied the vibrations isolation by the use of magnetorheological elastomer. Their experimental work presents in exclusivity the parameters of the most important active shock absorber. Mirosław Bocian *et al.,* [6] developed a mechanical structure based on a magnetorheological elastomer. This elastomer has been designed for the absorption of energy and the attenuation of vibratory amplitudes reaction of an impact shocks excitation. An adequate mathematical model was made by Mateusz Kukla *et al.,* [7]. This work presents the analysis results in compression of the mechanical behavior material under the effect of the magnetic. Guojiang [8] studied the radiation influence on the magnetorheological elastomer shear modulus. The experimental results show that the initial shear modulus and the induced magnetic field shear modulus increase firstly and then decrease with increasing the radiation intensity. Two factors are considered to explain the experimental results. The first is the reticulation reaction and the degradation induced by the radiation, the second is the change of saturation magnetization of the carbonyl iron particle. Bunoiu *et al.,* [9] studied the hybrid magnetorheological elastomers made of silicone oil and carbonyl iron in 10%, 30% and 60% volume fraction. They showed that the dielectric and elastic behavior of MRE are influenced by the applied magnetic field and depends on the micron-size ferromagnetic particles loading rate. The obtained results presented and discussed in terms of dipolar approximation. Schümann and Odenbach [10] used the X-ray microtopography to analyze the microstructure of particles. Furthermore, the characterization of the microstructure of under the magnetic field impact has been combined with the application of mechanical stresses. A significant impact of magnetic field and strain on the rotation and radial distribution of the particles has been verified. Mateusz *et al.,* [7] developed an appropriate mathematical model to describe the response of the material under the applied forces and the magnetic field effects. This model expresses the behavior of the material at the macroscopic scale under the impact of a controlled magnetic fields excitation. Ismail *et al.,* [11] presented the simulation of magnetorheological elastomers (MRE) as engine support. Four parameters was used to modeling the MRE dapping support and compared to the performance of the dapping rubber support. The comparison shows that 50% of vibration reduction is obtained. Bastola *et al.,* [12] developed a novel hybrid magnetorheological elastomer by 3D printing method. In such a hybrid MR elastomer, a controlled volume of a MR fluid was encapsulated layer by layer in an elastomeric matrix using a 3D printer and each layer was a composite structure consisting of a MR fluid and an elastomer. Xuan Bao Nguyen *et al.,* [13] studied a magnetorheological elastomer (MRE) based isolator was investigated to mitigate excessive vibrations in structures during seismic events. The model consists to the viscoelasticity of host MRE, magnetic field-induced property, nominal viscosity as well as high stiffness in low excitation frequency. Schümann *et al.,* [14] treated a mechanical characterization on multiple time scales to get an insight on the short and long-term electrical and mechanical behavior of this novel material. The results show a complex resistivity behavior on several timescales, sensitive to magnetic fields and strain velocity. Yanfen Zhou *et al.,* [15] investigated the equi-biaxial fatigue behavior of the fabricated MREs by using the bubble inflation method in silicone rubber based MREs samples. The relationship between fatigue life and maximum engineering stress, maximum strain and strain energy density were studied. The results showed that maximum engineering stress and stored energy density can be used as reliable fatigue life predictors.

This paper is devoted to an experimental of the thermal effect of the magneto-mechanical behavior of elastomer; the latter is loaded with 25% of ferromagnetic particles of micrometric size; developed under the action of a magnetic field.

2. Physico-Mechanical Identification

In this work, we will see that the generalized Maxwell model is suitable for describing the mechanical behavior of our elastomer; this model consists of a spring and N models of Maxwell arm assembled in parallel. The elasticity moduli are denoted by G_0, G_1 , G_2 ,..., G_n while viscosity coefficients are designated by η_1, η_2 ,..., η_n .

Considering two functionally graded layers bonded by viscoelastic elastomer wich can be modelled by Maxwell-Wiechert model [8, 16]. This model contains a series of spring-dashpot units and a hookean spring. The time-dependent shear modulus $G(t)$ of the viscoelastic elastomer varies with time and can be expressed as Prony series

$$G(t) = G_\infty + \sum_{i=1}^{N} G_i e^{-t/\tau_i} \tag{1}$$

where G_∞, G_i and τ_i are the long-term shear modulus, the relaxation shear moduli and the relaxation time.

The strain of the model is the sum of the strains of the two elements, represented by the spring element and the dashpot such as

$$\tau = E\varepsilon + \gamma\dot{\varepsilon} \tag{2}$$

Based on Boltzmann superposition principle, the shear stress $\tau(x,t,T)$ can be expressed as:

$$\tau(x,t,T) = G(t)\gamma(x,0) + \int_0^t G(t-\xi)\frac{\partial\gamma(x,\xi)}{\partial\xi}d\xi = G^*(t)d\gamma(x,t) = \gamma^*(x,t)dG(t) \tag{3}$$

where the (*) denotes convolution. The equation above describes relaxation constitutive relationship. After Fourier transform, this can be expressed as

$$\tau(x,\omega) = i\omega G(\omega,T).\gamma(x,\omega,T) \tag{4}$$

where $G(\omega,T)$ is the Fourier transform of shear modulus $G(t,T)$ and i denotes $\sqrt{-1}$, and this equation can also be written as

$$\tau(x,\omega) = G^*(\omega,T).\gamma(x,\omega,T) \tag{5}$$

To take account of the duality between viscosity and elasticity, we frequently use complex numbers (two components) when a material is subjected to a dynamic solicitation, the complex modulus $G^*(t)$ for a shear solicitation, is given by

$$G^*(\omega,T) = G'(\omega,T) + iG''(\omega,T) = G'(\omega,T) \times (1 + i\eta) \quad (6)$$

G' is the real part, called storage modulus, that characterizes the rigidity of the elastomer and G'' the imaginary part, called loss modulus, which characterizes the viscous behavior.
T is the Temperature and ω is the frequency.

The loss factor or damping factor is written as

$$\tan(\delta) = \frac{G''(\omega,T)}{G'(\omega,T)} = \eta \quad (7)$$

A charge q that moves with a velocity $\vec{v}$ in a magnetic field characterized by the vector $\vec{B}$ undergoes a magnetic force called Lorentz force $\vec{f}_m$ given by

$$\vec{f}_m = q.\vec{v} \wedge \vec{B} \quad (8)$$

3. Material and Experimental Analysis

The objective of this work is dedicated to understanding the role of microstructure on the macroscopic response of the polymer when it's subjected to the magnetomechanical loading conditions. The first part of the work aims is to set up the polymer manufacturing process from different ingredients (silicone oil, magnetizable iron particles, RTV141); the second part consists to determine the rheological characteristics as well as the strength of attraction between the micron-size ferromagnetic particles as a function of the excitation frequencies.

3.1 Elaboration Process of the Elastomer

The elastomer is elaborated by the following steps

i. Mixing the silicone oil and the RTV141A polymer in a glass bowl and proceed with a manual mixing during 15 minutes to obtain an elastomeric gel with good homogenization. A second bowl containing a quantity of iron particles of micrometric size of average diameter of 1.8-2.3 µm, to loading the elastomer is prepared.
ii. A quantity of this gel obtained by silicone and RTV141A is mixed during 30 minutes with a quantity of iron particles until obtaining a homogeneous paw. By this process, an elastomer loaded with 25 % of ferromagnetic particles is obtained.
iii. In order to have a healthy structure for the experimentation, the degassing of the obtained paw under vacuum during 10 minutes to eliminate air bubbles infiltrated during the mixing is performed. Because of the temperature influence, which can cause the reticulation of the elaborate paw, the obtained elastomer is hermetically preserved at low temperature (0°C).

After the preparation of the experimental set-up (switching on the Metravib DMA + 450, the rectangular inner form aluminum mold and the two coils generating the magnetic field, Figure 1), RTV 141B which acts as a catalyst, is added to the paw, for increase the constituents adhesion in this latter; then injected in the aluminum mold so that it fills its entire volume. This must be done rapidly to avoid the reticulation. 10 specimens are elabored and each sample has a rectangular shape of 30mm of length, 28mm of width and 2 mm of thickness, loaded with 25 % of ferromagnetic particles of its total volume.

Experimental tests depicting the shear strain on an elastomer sample are conducted at a variable frequency from 0 to 100 Hz with and without the magnetic field. MER material is maintained under these experimental conditions during 24 hours and at the ambient temperature of 27°C until the reticulation.

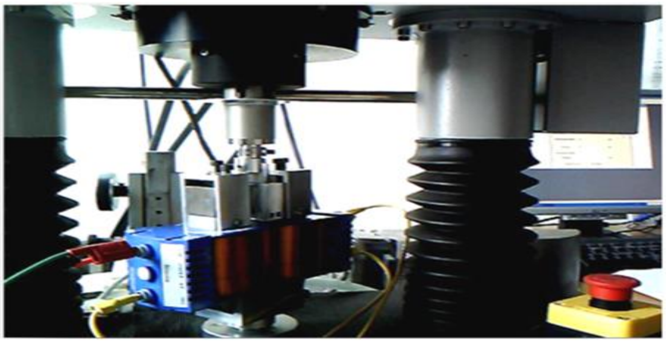

Fig. 1. Dynamic Viscoanalyseur DMA+450

Without a magnetic field, the iron micro particles are randomly distributed in the elastomer volume (isotropic structure, Figure 2a). When the elastomer is subjected to a sufficient constant magnetic field, the alignment of magnetic particles until the complete elastomer reticulation is obtained as form of the chains (anisotropic structure, Figure 2b); which significantly increases the viscosity in the direction perpendicular to the direction of the magnetic field.

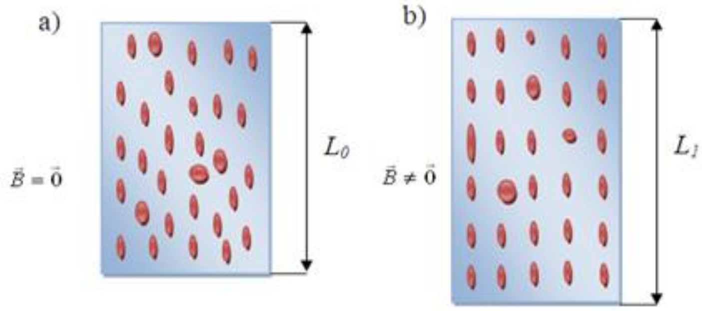

Fig. 2. MRE under the magnetic field. (a) Without a magnetic field, (b) With a magnetic field (whatever the value of the temperature)

The ingredients of specimen in magnetorheological elastomer loaded with 25% of iron particles of its total volume are given in Table 1.

Table 1
Constituents of the magnetorheological elastomer

Loaded elastomer to 25% ferromagnetic particles				
Time of reticulation in Hours	$m_{Silicon\ Oil}$(g)	$m_{RTV(A)}$(g)	m_{Fe} (g)	$m_{RTV(B)}$ (g)
24h	1.23	1.193	5.339	1.191

4. Results and Discussion

The curves modulus-strain of isotropic composites charged to 25% with and without magnetic field subject to different temperatures is compared (Figure 3.a, b). On this figure, it is observed that the storage modulus and the loss modulus decrease as a function of the increase of shear strain, we distinguish, a sudden change of the storage modulus and the loss modulus for a shear deformation less than 5%, then a slow change for a shear strain greater than 5%.

The explanation of this stiffening of the material submitted to a field is the following: at the microscopic level, the magnetic field creates an attractive inter-particular force whose consequence is to strongly stiffen the chains of particles, which then act as real small fibers. Then, when put under different temperatures, the thermo-mechanical stress will exceed the magnetic stress and it will break the fibers gradually into increasingly short elements. On the other hand there is a significant increase in these moduli under the influence of the magnetic field.

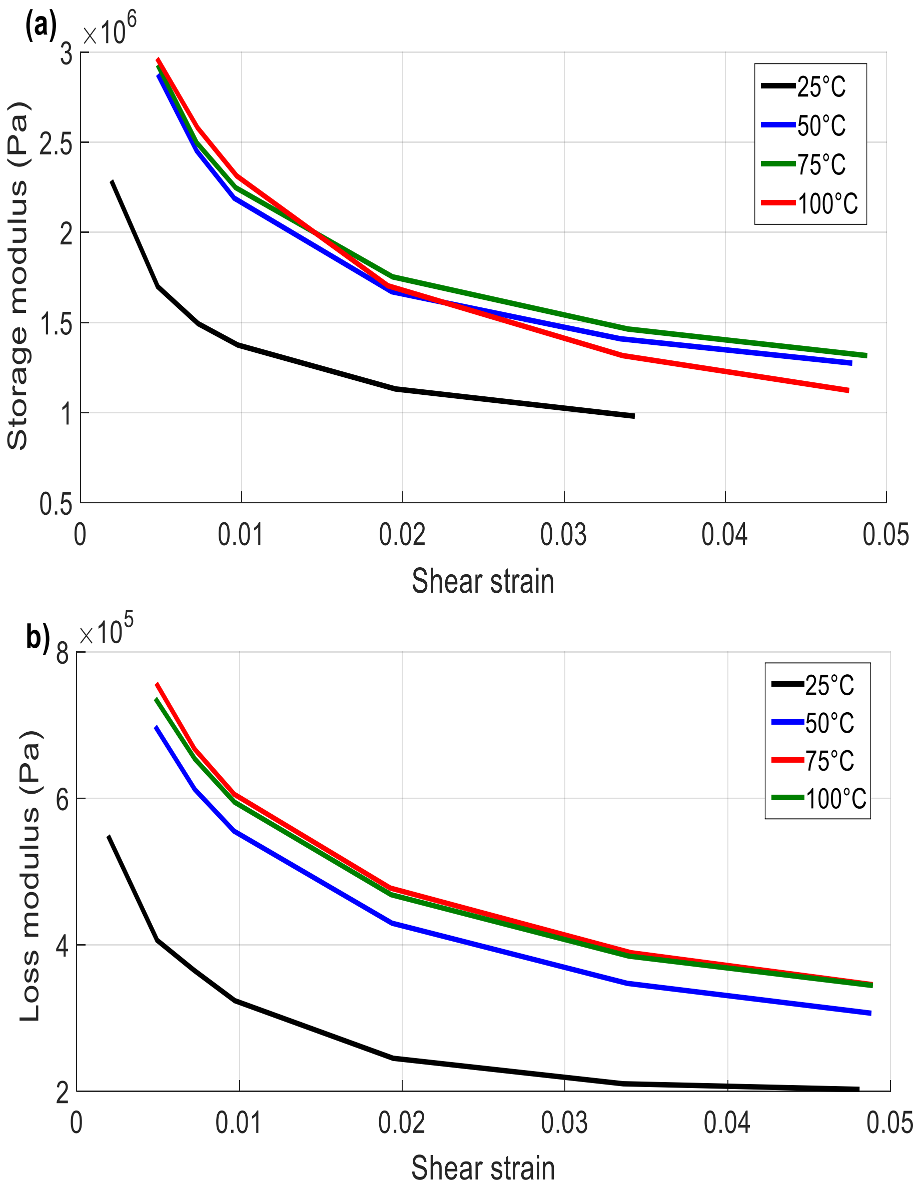

Fig. 3. Variation of rheological properties as a function of shear strain under different temperatures, a) Storage modulus, b) Loss modulus

The Figure 4 shows the evolution of the loss factor according to the shear deformation, as this figure show, thermal effect plays an important role in the energy dissipation and it notes that the loss factor is growing very strongly with the increase in the temperature. However, the angle of loss shows clear differences (Figure 4): The fraction of the dissipated energy increases with the field and with the creation of the pseudo-fibers formed by the ferromagnetic particles.

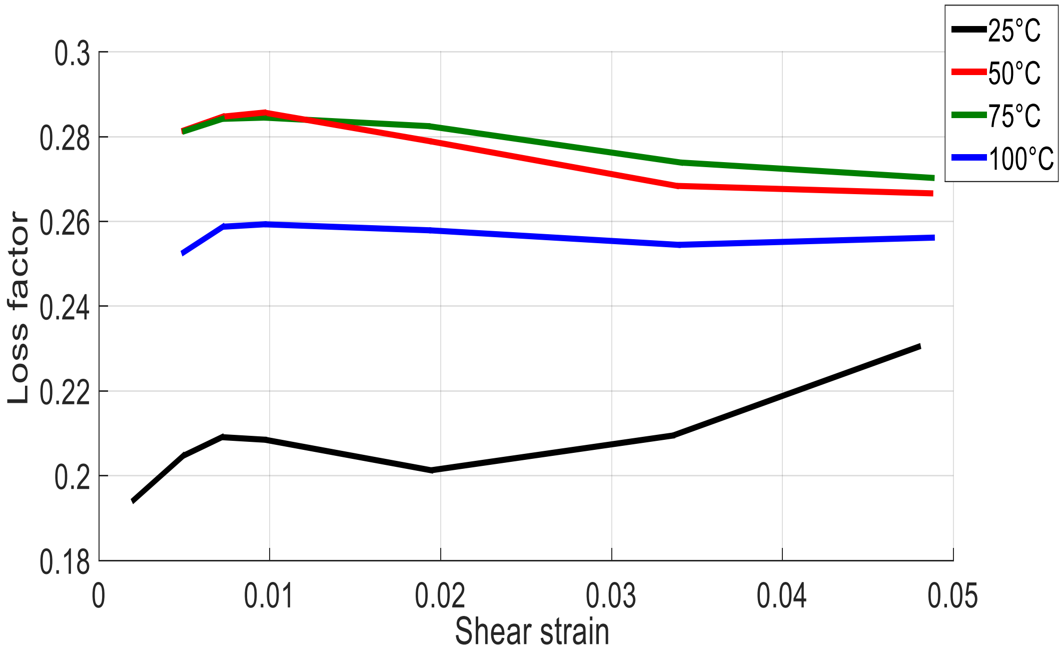

Fig. 4. Variation of loss factor as a function of shear deformation under different temperatures, a) storage modulus, b) loss modulus

The results of the quasi-static tests are illustrated in Figure 5, a strong thermal and magnetic effect is observed on the 25% loaded composite, a sign of an interaction between channels. Furthermore this figure gives a detailed overview of the influence of shear deformation on the magneto-mechanical properties, the storage and loss moduli. It is noted that the magnetic field modifies significantly the rheological properties and acts mainly on the shear deformation. In addition, the decrease and the relative increase of G' is a little more intense than for the loss modulus G''; or the addition of oil reduces strongly the local stresses and requires more strong deformations to access critical stresses.

The magnetic field despite all small defects (bad aggregates, bad alignments of chains, particulate columns very close…), which then contributes to the interaction between the neighboring chains and during the solicitations, there will be as much additional thermal effect, which are reflected at the microscopic level by the fall accentuated G' and G''.

MREs consist of micrometric particles sensitive to a magnetic field embedded in a polymer matrix. Under the effect of the field the particles are polarized and aligned in the direction of the field. Changes in the spatial distribution of particles by the field are responsible for changes in their thermal, mechanical, electrical and optical properties. The fibrillar structure makes the MRE materials very interesting in several applications, they are conductors even at low particle charge rates and are also more sensitive to pressure. Structured chains of magnetic particles dispersed in a liquid phase still elastomer creates a microstructure permitting active control of the composite properties via a magnetic field; the increase in stress in the presence of the field is limited by the quality of the microstructure and the ruptures in the chains during the solicitations.

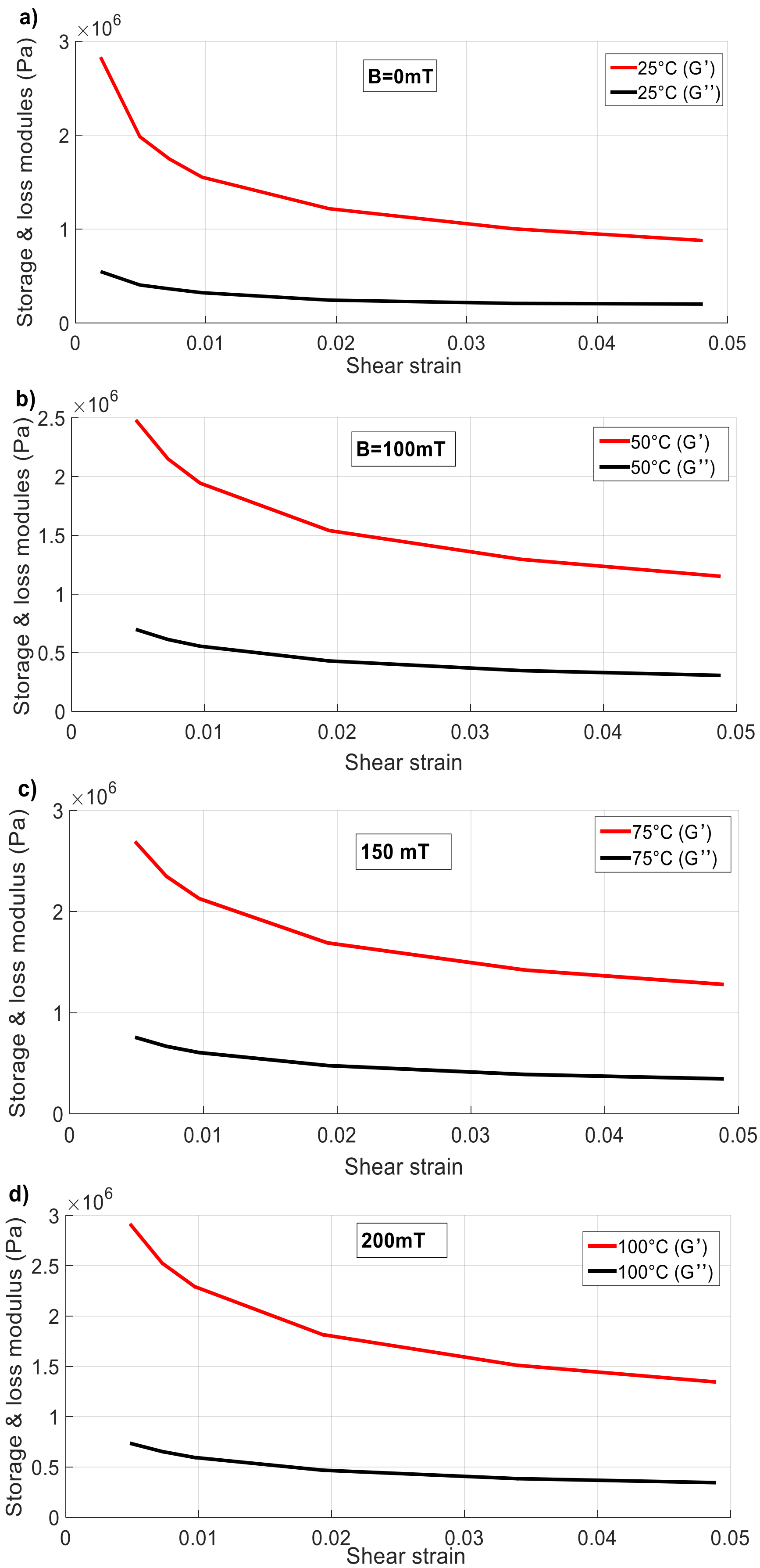

Fig. 5. Variation of rheological properties according to shear deformation with different temperatures and magnetic field

5. Conclusions

The magnetorheological elastomer charged with 25% of iron particles is prepared under different temperature (25°C, 50°C, 75°C and100°C) and magnetic fields (0mT, 100mT, 150mT and 200mT); the microstructures are greatly affected by the magnetic field intensity during the preparation. The MRE viscoelastic properties are also tested by a thermo-magneto-mechanical coupling dynamic mechanical analyzer (DMA).

The realization of a structured composite elastomer cannot be done under any conditions. First, the elastomer must have good mechanical properties but also a low viscosity before crosslinking to facilitate the dispersion and structuring of the charges. Therefore, the conditions of preparation play an important role in the rheological properties of the composite elastomer; the conclusions drawn are given below:

The thermal effect plays an important role in the variation of the properties of the magnetorheological elastomer, but a large increase in temperature results in a decrease in the tensile strength and the angular tearing resistance of the MRE.

The interparticle attractive force generated by the magnetic field approximates the particle and modifies the resistivity of the elastomer composite.

Rheological properties increase with the applied magnetic field intensities during testing. The rheological properties of the elastomer also depend on the arrangement of their particles and the thermal effect.

The application of magnetic field leads to an important increase in elastic modulus. The results show a non-linear change in the rheological properties according to the variation of the magnetic field intensity, it is due to the magneto-rheological effect.

An essential advantage of this type of elastomer is to develop shock absorbers capable of damping vibrations in a wide range of frequencies.

Finally, it can be seen that the magnetic field has a considerable effect on the effect of temperature on the behavior of the MRE [16].

Acknowledgement
Thanks to Laboratory of Condensed Matter Physics (LPMC) University of Nice - Sophia Antipolis - France, for providing various supports for this study. We are also grateful to Messrs George Bossis Research Director Emeritus and Dr. Kuzhir Pavel of LPMC, for their help.

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