ISSN: 3063-8720, DOI: https://doi.org/10.70935/4v17g706

Review

Influence of Carbonyl Iron Particles on the Structural and Mechanical Performance of Magnetorheological Elastomers

Kacuk Cikal Nugroho[1]*

[1]Department of Manufacturing Engineering Technology, Akademi Inovasi Indonesia, Salatiga 50721, Central Java, Indonesia
* Corresponding: kacukcikal@inovasi.ac.id

ARTICLE INFO

Submitted 29 May 2024
Revised 9 Jun 2024
Accepted 20 Jun 2024
Published 31 Jul 2024

Abstract.
This study investigates the effects of different types of carbonyl iron particles on the structure and performance of magnetorheological elastomers (MREs). The mechanical performance of both anisotropic and isotropic MREs was analyzed using various experimental methodologies, including frequency and strain-dependent testing. Results indicate that the spatial location of particle chains, frequency, dynamic strain amplitude, and restrain substantially influence the MREs' mechanical behavior. Particular focus was given to integrating nanoparticles, which significantly enhanced performance metrics. Comparisons were made between MREs based on epoxy, silicone rubber, and polyurethane/Si-rubber hybrids, emphasizing their rheological and morphological properties post-natural weathering in a tropical climate. Additionally, the study highlights the potential applications of MREs in automotive components and sensor technologies, with particular attention to the magnetic and mechanical properties mediated by the inclusion of carbon black and cobalt. The findings provide a comprehensive understanding of the adaptive magnetoelastic characteristics of MREs, contributing to their development and deployment in various smart material applications.

Keywords: Magnetorheological elastomers (MREs); Carbonyl iron particles; Nanoparticles.

INTRODUCTION

Magnetorheological elastomers (MREs) are intelligent materials of magnetic particles dispersed within an elastomeric matrix. These materials have the ability to significantly alter their mechanical properties when exposed to a magnetic field, making them highly useful in various applications requiring adaptive control and rapid response to environmental changes. MREs were developed in the early 1990s as a result of research into magnetorheological fluids (MRFs), which were previously known for their ability to alter viscosity under the influence of a magnetic field [1]. In this context, MREs offer additional advantages due to their solid form, allowing them to maintain structural integrity while providing unique magnetorheological properties [2]. Over the past few decades, MREs have attracted

ISSN: 3063-8720, DOI: https://doi.org/10.70935/4v17g706

significant attention due to their broad potential applications in fields such as automotive, robotics, and biomedicine. The diversity in MRE composition and structure enables the adjustment of their material properties to meet specific application needs, enhancing the systems' functionality and performance [3]. The development of these materials continues to evolve alongside our increasing understanding of their complex magnetic and mechanical properties.

The development of MREs originated from research on magnetorheological fluids (MRFs), which are materials consisting of magnetic particles dispersed in a fluid medium. However, MREs offer several advantages over MRFs, such as long-term stability and shape maintenance [4]. With advancements in material technology and a better understanding of their magnetic and mechanical properties, MREs have found applications in various fields such as automotive, robotics, and biomedicine [5]. In the automotive industry, MREs are used in adaptive suspensions that can adjust stiffness according to road conditions, providing enhanced comfort and control [6]. In robotics, MREs create actuators that can change stiffness and shape, enabling robots to interact more effectively with their environment [7]. Ithe biomedical field, MREs have been used in rehabilitation devices and prosthetics that adjust stiffness to improve comfort and functionality [8]. Recent advancements in production technology and a deeper understanding of the material properties have opened new opportunities for broader and more innovative applications of MREs [9].

This essay explains the working principles of MREs, their benefits and advantages, and their various practical applications. Furthermore, the essay will identify the main challenges in developing and applying MREs and opportunities for further research. By understanding the basic principles of MREs and how they interact with magnetic fields, we can better appreciate their potential applications across various fields. This essay will provide a comprehensive overview of the mechanical and magnetic properties of MREs, including how these properties can be tailored through different compositions and production techniques [10]. Moreover, the essay will discuss the primary challenges in using MREs, such as long-term stability issues and production costs, and opportunities for further research to address these challenges. By presenting this information, the essay aims to understand MREs and their potential for future technological innovation comprehensively.

WORKING PRINCIPLES OF MAGNETORHEOLOGICAL ELASTOMERS

Magnetorheological elastomers (MREs) are intelligent materials of magnetic particles dispersed within an elastomeric matrix. The elastomeric matrix is typically made of flexible polymeric materials such as silicone rubber or polyurethane, allowing the material to change its shape and mechanical properties

ISSN: 3063-8720, DOI: https://doi.org/10.70935/4v17g706

easily. The MRE morphology can be seen in Figure 1. The magnetic particles commonly used in MREs are iron particles due to their strong magnetic properties. Combining the elastomer matrix and magnetic particles enables MREs to respond significantly to magnetic fields, making them suitable for applications requiring rapid and controllable changes in mechanical properties [11]. In practical applications, the distribution and size of magnetic particles within the elastomer matrix are crucial for determining the MRE’s response to magnetic fields. These particles must be evenly dispersed to ensure that the mechanical properties of the MRE can be effectively altered under the influence of an external magnetic field.

Additionally, the type of elastomer used as the matrix plays a vital role in determining the material's flexibility and resistance to deformation. For example, silicone rubber is often used for its high flexibility and thermal stability, while polyurethane is chosen for its superior mechanical strength and abrasion resistance [3]. By optimizing the combination of magnetic particles and the elastomer matrix, MREs can be tailored to meet the specific needs of applications such as vehicle suspensions, vibration dampers, and adaptive medical devices.

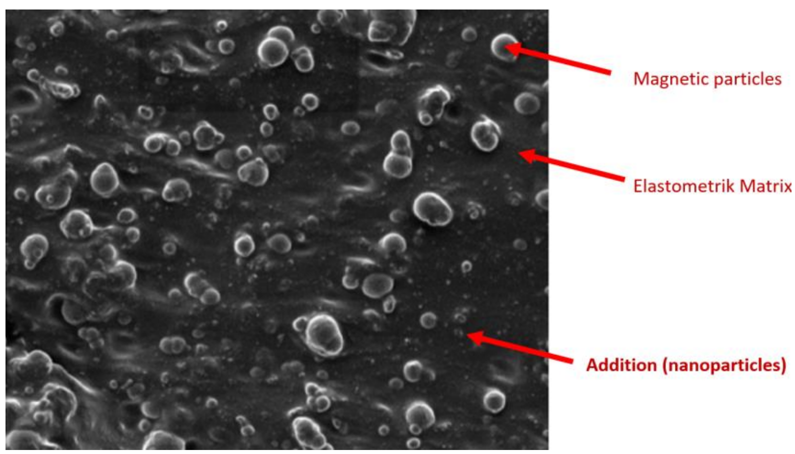

Figure 1. SEM micrographs of MRE sample crosssection [12]

The working principle of MREs is based on the interaction between magnetic particles within the elastomer matrix and an external magnetic field. When a magnetic field is applied, the magnetic particles within the MREs induce magnetic moments, causing the particles to interact and form chain-like or columnar structures within the elastomer matrix. This structuring significantly alters the mechanical properties of the MRE, such as elasticity modulus and viscosity [13]. This process is typically reversible, meaning that when the magnetic field is removed, the magnetic particles return to their random positions, and the mechanical properties of the MRE revert to their original state. The mechanical properties of MREs can be controlled by varying the strength of the applied

ISSN: 3063-8720, DOI: https://doi.org/10.70935/4v17g706

magnetic field. For instance, increasing the magnetic field strength can increase the elasticity modulus of the MRE, making the material stiffer. This is particularly useful in applications such as vehicle suspensions, where the suspension stiffness can be adjusted in real-time based on road conditions to enhance ride comfort and stability [6]. Moreover, MREs exhibit adjustable viscoelastic properties, making them suitable for controllable damping applications, such as vibration dampers [9], [10]. These property changes occur on a very short timescale, allowing almost instantaneous response to changes in the magnetic field, making MREs highly effective in applications requiring dynamic control. The illustration of MRE working principle is shown in Figure 2.

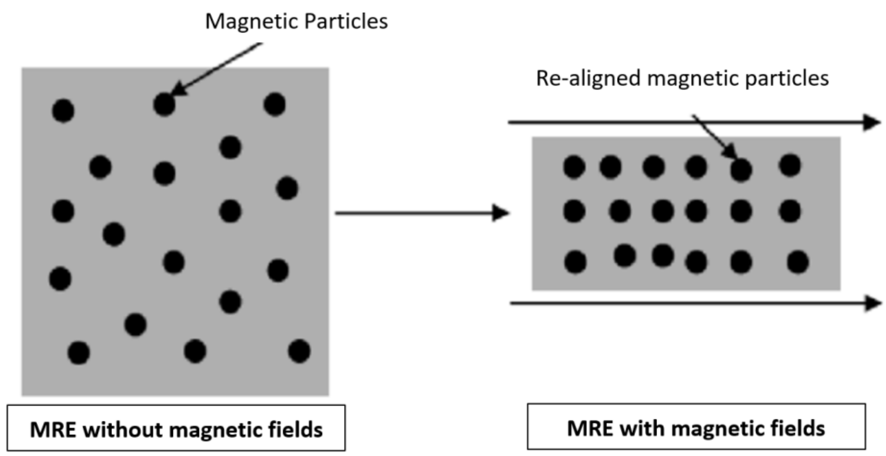

Figure 2. Illustration of MRE working principles with/without magnetic fields. [14]

MATERIALS USED IN MRE

MRE is a composite material composed of several materials. It is usually made of magnetic particles dispersed in an elastrometric material matrix. Sometimes, enhancers are added as nanoparticles or surfactants to improve the properties of MREs.

Magnetic Particles

The choice of magnetic particles significantly influences the performance of MREs. Iron, cobalt, and nickel nanoparticles are commonly used due to their high magnetic susceptibility and compatibility with elastomeric matrices (Gordaninejad et al., 2017).

Carbonyl Iron Particle (CIP)

Salem et al., [15] investigate the dynamic properties of Magnetorheological Elastomers (MREs) by studying the influence of different types, concentrations, and coatings of carbonyl iron particles (CIPs) on the rheological and mechanical properties of the elastomers. Frequency and strain-dependent measurements are conducted to analyze the storage and loss modulus and the Magnetorheological

(MR) effect and Payne effect. Results show that the MR effect is influenced by the type, concentration, and coating of CIPs, with hard particles and silica coatings enhancing the effect. The Payne effect is found to be influenced by CIP concentration, with lower values for coated CIPs and higher values for hard CIPs. The dynamic properties of MREs change with varying frequency and strain amplitudes. Frequency-dependent measurements are performed to examine the frequency dependence of the samples and highlight their MR effect. Strain amplitude tests are conducted to investigate the dependence of MREs' dynamic properties on strain. Both frequency excitations and strain amplitudes affect MREs' storage and loss modulus. These changes provide insights into selecting appropriate particle grades for MRE applications, where samples with hard and coated CIPs tend to exhibit a higher MR effect than other samples.

Co

Zainudin et al., [16] discuss the properties and applications of magnetorheological elastomers, focusing on their use in vibration control, shielding effectiveness, strain sensors, and more. Various studies highlighted in the article investigate the composition, microstructure, magnetic properties, morphology, rheological properties, and resistance properties of cobalt-based magnetorheological elastomers (MRE) in both isotropic and anisotropic forms. The studies demonstrate the significant magnetorheological effects of these materials, showing enhanced field-dependent modulus and controllable electrical resistance, making them suitable for sensor applications. Cobalt-based magnetorheological elastomers show an increase in storage modulus as the magnetic field strength increases. This is due to the attractive magnetic interaction between particles, causing the cobalt particles to align and restrict the deformation of the matrix, leading to a change in the modulus.

Fe3O4

X. Liu et al., [17] use Fe_3O_4 nanoparticles to create a micro-nano magnetorheological elastomer (MRE), and its mechanical characteristics were examined. MREs with varying nanomagnetic particle concentrations were examined using a microscopic static force model. An experimental platform was constructed, and finite-element software was used to model the magnetic field flow to examine the mechanical properties. According to the findings, MREs with 10% Fe 3 O 4 nanoparticles have a maximum compressive elastic modulus of 2.89 MPa, 149% higher than a conventional MRE in the same magnetic field.

Elastomeric Matrices

Elastomers like silicone, polyurethane, and epoxy are frequently employed as matrices in MREs. These materials offer elasticity and deformability essential for the controllable mechanical response of MREs under varying magnetic fields [18].

Silicone-Based MRE

Silicone-based MREs are among the most studied and widely used types. They typically consist of silicone elastomers as the matrix material with dispersed magnetic particles. Balasoiu et al., [19] explore the magnetic structure of silicone rubber-based magnetorheological elastomers through neutron depolarization and magnetic force microscopy techniques. It details the experimental setup, sample preparation, and measurement methods used. The study reveals insights into the average microparticle diameter and the dispersion of magnetic induction in the elastomer samples. Specifically, the research compares isotropic and anisotropic samples, finding differences in microparticle size and depolarization behaviour based on sample characteristics.

Polyurethane-Based MRE

Polyurethane elastomers are another common choice for MREs. These materials offer flexibility in mechanical design and can be tailored for specific applications by varying the types and concentrations of magnetic particles embedded in the polyurethane matrix. The paper [20] discusses the fabrication of a new type of magnetorheological elastomer based on a hybrid of polyurethane and silicone rubber. The elastomer exhibited a better magnetorheological effect than elastomers based on pure silicone rubber or polyurethane matrix by optimizing preparation conditions, adjusting the PU/Si-rubber ratio, and adding a silicone oil additive. The microstructure analysis revealed a unique interpenetrating structure in the presence of polyurethane in the matrix, leading to a maximum increase in shear modulus of up to 0.5 MPa when exposed to a magnetic field of about 0.2 T. The magnetorheological effect of the elastomer was improved by optimizing preparation conditions, particularly by adjusting the PU/Si-rubber ratio and improving compatibility between PU and Si-rubber

Epoxy-Based MRE

Epoxy resins are preferred in applications requiring high mechanical strength and durability. Epoxy-based MREs combine the toughness of epoxy matrices with the responsiveness to magnetic fields provided by embedded magnetic particles, making them suitable for structural applications. The study [21] focuses on utilizing flexible epoxy as the Magnetorheological Elastomers (MRE) matrix to enhance mechanical properties and the MR effect. Results showed that the epoxy-based MRE exhibited improved mechanical properties and MR effect, with the highest absolute modulus increase recorded at room temperature and -40 °C. The MR effect was influenced by the carbonyl iron particles' content and temperature, while the morphology of the epoxy-based MRE was also examined.

ISSN: 3063-8720, DOI: https://doi.org/10.70935/4v17g706

In conclusion, the study suggests that flexible epoxy-based MRE demonstrates a favorable MR effect and mechanical properties. The use of flexible epoxy as the matrix for Magnetorheological Elastomers (MRE) improved both the mechanical properties and the Magnetorheological (MR) effect of the MRE. At room temperature, the highest absolute modulus increase was 203 MPa when the intensity of the magnetic field was 0.2T, and the carbonyl iron content was 71.4%

Additives

Additional fillers such as carbon black or silica nanoparticles are sometimes incorporated into MREs to enhance mechanical properties or achieve specific functionalities like improved thermal stability or increased stiffness. [22] The paper discusses studies on magnetorheological elastomers, focusing on their preparation, properties, and performance. Various experiments explore these elastomers' mechanical, viscoelastic, and magnetic characteristics and the impact of different additives and magnetic field intensity. The research also delves into the fabrication and characterization of isotropic and anisotropic magnetorheological elastomers using different materials and techniques. Two studies highlighted in the paper investigate the properties of CI and CI/γ-Fe_2O_3-based MR elastomers, showcasing improvements in elasticity and the MR effect with adding γ-Fe_2O_3 particles. The CI/γ-Fe_2O_3-based elastomers showed higher MR efficiency in all magnetic field strengths than the CI-based elastomers, indicating that adding γ-Fe_2O_3 particles magnifies the MR effect. Introducing γ-Fe_2O_3 additives made the MR elastomers stiffer and more elastic at non-zero magnetic fields.

TYPES OF MRE BASED ON MAGNETIC PARTICLE ORIENTATION

Magnetorheological Elastomers (MRE) are materials of an elastomeric matrix embedded with magnetic particles that respond to external magnetic fields. Depending on how the magnetic particles are oriented within the elastomeric matrix, MRE can be classified into two main types: isotropic and anisotropic. The isotropic and anisotropic MRE can be seen in Figure 3.

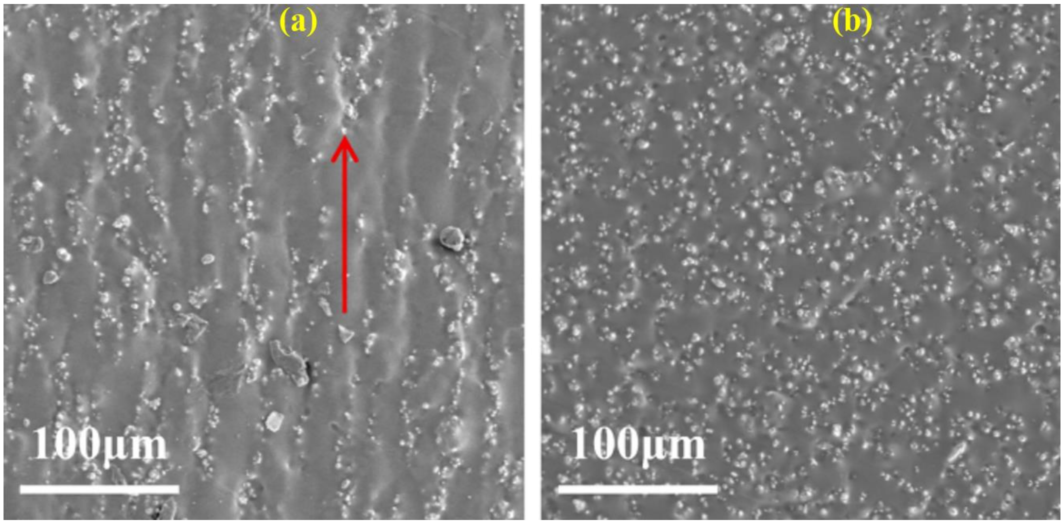

Figure 3. (a) anisotropic MRE (b) isotropic MRE [23]

Isotropic MRE

Isotropic MRE features randomly distributed magnetic particles within the elastomeric matrix, resulting in a material with homogeneous properties in all directions and no dominant magnetic orientation. The main advantage of isotropic MRE lies in the ease of manufacturing and uniform distribution of particles throughout the material. This makes it suitable for applications where specific magnetic orientation control is not required. For instance, in vehicle suspension systems or vibration isolators, isotropic MRE can significantly enhance dynamic response to magnetic fields without added complexity in design or production.

However, a major drawback of isotropic MRE is the lack of specific control over mechanical responses to magnetic fields. Due to the randomly dispersed particles, there is no consistent orientation in response to magnetic fields, limiting its application in systems that require precise control. Research by Smith et al. [24] evaluated the effect of particle orientation on the mechanical and magnetic properties of isotropic MRE. They used experimental approaches to compare variations in magnetic particle distribution and found that while uniform distribution facilitates the production, magnetic field responsiveness is suboptimal compared to anisotropic MRE.

Anisotropic MRE

Conversely, anisotropic MRE contains magnetic particles that are regularly or structurally oriented within the elastomeric matrix. Particle orientation can be controlled during manufacturing, creating programmable magnetic patterns. The main advantage of anisotropic MRE is their ability to provide more directional mechanical responses and responsiveness to magnetic fields according to the particle orientation pattern.

Studies by Johnson et al. [25] developed anisotropic MRE for adaptive stabilization applications. They employed specialized processing techniques to achieve desired particle orientations within the elastomeric matrix, enabling material adaptability to varying external magnetic fields. Their research findings demonstrate that anisotropic MRE offers better control over mechanical characteristics in diverse operational conditions, such as active suspension systems or adaptive actuators.

CONCLUSION

This study elucidates the significant influence of carbonyl iron particles on the structural and rheological properties of magnetorheological elastomers (MREs). The mechanical performance of both anisotropic and isotropic MREs is substantially affected by particle chain alignment, frequency, dynamic strain amplitude, and restraint factors. Additionally, the incorporation of nanoparticles markedly improves the overall performance. The research findings underscore the potential applications of MREs in sectors such as automotive and sensor technologies, driven by their adaptive magnetoelastic characteristics and enhanced performance metrics.

REFERENCES

[1] Y. Li, J. Li, W. Li, and H. Du, "A state-of-the-art review on magnetorheological elastomer devices," Smart Mater Struct, vol. 23, no. 12, p. 123001, 2014, doi: 10.1088/0964-1726/23/12/123001.

[2] W. H. Li, X. Z. Zhang, and H. Du, "Magnetorheological Elastomers and Their Applications," in Advances in Elastomers I: Blends and Interpenetrating Networks, P. M. Visakh, S. Thomas, A. K. Chandra, and Aji. P. Mathew, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 357–374. doi: 10.1007/978-3-642-20925-3_12.

[3] L. Chen, X. L. Gong, and W. H. Li, "Effect of carbon black on the mechanical performances of magnetorheological elastomers," Polym Test, vol. 27, no. 3, pp. 340–345, 2008, doi: https://doi.org/10.1016/j.polymertesting.2007.12.003.

[4] R. L. Harne, Z. Deng, and M. J. Dapino, "Adaptive magnetoelastic metamaterials: A new class of magnetorheological elastomers," J Intell Mater Syst Struct, vol. 29, no. 2, pp. 265–278, Jul. 2017, doi: 10.1177/1045389X17721037.

[5] H. You, Q. Bai, Y. C. Liu, and L. W. Ning, "Preparation and Mechanics Properties of MR Elastomers Based on Silicone Rubber," Applied Mechanics and Materials, vol. 34–35, pp. 942–945, 2010, doi: 10.4028/www.scientific.net/AMM.34-3S5.942.

[6] S. H. Kim et al., "A feasibility work on the applications of MRE to automotive components," IOP Conf Ser Mater Sci Eng, vol. 333, no. 1, p. 012013, 2018, doi: 10.1088/1757-899X/333/1/012013.

[7] A. K. Bastola and M. Hossain, "A review on magneto-mechanical characterizations of magnetorheological elastomers," Compos B Eng, vol. 200, p. 108348, 2020, doi: https://doi.org/10.1016/j.compositesb.2020.108348.

[8] X. Zhu, X. Jing, and L. Cheng, "Magnetorheological fluid dampers: A review on structure design and analysis," J Intell Mater Syst Struct, vol. 23, no. 8, pp. 839–873, Mar. 2012, doi: 10.1177/1045389X12436735.

[9] T. Liu and Y. Xu, "Magnetorheological Elastomers: Materials and Applications," in Smart and Functional Soft Materials, X. Dong, Ed., Rijeka: IntechOpen, 2019, p. Ch. 4. doi: 10.5772/intechopen.85083.

[10] W. H. Li, X. Z. Zhang, and H. Du, "Magnetorheological Elastomers and Their Applications," in Advances in Elastomers I: Blends and Interpenetrating Networks, P. M. Visakh, S. Thomas, A. K. Chandra, and Aji. P. Mathew, Eds., Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 357–374. doi: 10.1007/978-3-642-20925-3_12.

[11] H. Böse, J. Ehrlich, and T. Gerlach, "Magnetorheological Elastomers–Material Properties and Actuation Capabilities," IEEE Trans Magn, vol. 58, no. 2, pp. 1–5, 2022, doi: 10.1109/TMAG.2021.3081016.

[12] M. A. F. Johari et al., "Natural Weathering Effects on the Mechanical, Rheological, and Morphological Properties of Magnetorheological Elastomer (MRE) in Tropical Climate," Int J Mol Sci, vol. 23, no. 17, Sep. 2022, doi: 10.3390/ijms23179929.

[13] A. Boczkowska, S. F. Awietjan, S. Pietrzko, and K. J. Kurzydłowski, "Mechanical properties of magnetorheological elastomers under shear deformation," Compos B Eng, vol. 43, no. 2, pp. 636–640, 2012, doi: https://doi.org/10.1016/j.compositesb.2011.08.026.

[14] M. N. H. Hadzir, Z. A. Norfaidayu, M. S. M. Sabri, and M. H. Abu-Bakar, "Investigation of Damping Coefficient for Magnetorheological Elastomer," in MATEC Web of Conferences, EDP Sciences, Oct. 2018. doi: 10.1051/matecconf/201821702003.

[15] A. M. H. Salem, A. Ali, R. Bin Ramli, A. G. A. Muthalif, and S. Julai, "Effect of Carbonyl Iron Particle Types on the Structure and Performance of Magnetorheological Elastomers: A Frequency and Strain Dependent Study," Polymers (Basel), vol. 14, no. 19, 2022, doi: 10.3390/polym14194193.

[16] A. A. Zainudin et al., "Rheological and resistance properties of magnetorheological elastomer with cobalt for sensor application," Applied Sciences (Switzerland), vol. 10, no. 5, Mar. 2020, doi: 10.3390/app10051638.S

[17] X. Liu et al., "Normal Stress of a Micro–Nano Magnetorheological Elastomer," IEEE Magn Lett, vol. 13, pp. 1–4, 2022, doi: 10.1109/LMAG.2022.3184259.

[18] Y. Cao et al., "The dynamic mechanical properties of magnetorheological elastomer: Catalytic effect of carbonyl iron powder," J Intell Mater Syst Struct, vol. 31, no. 13, pp. 1567–1577, Jun. 2020, doi: 10.1177/1045389X20930090.

[19] M. Balasoiu, S. V. Kozhevnikov, Y. V. Nikitenko, G. E. Iacobescu, M. Bunoiu, and I. Bica, "Silicone rubber based magnetorheological elastomer: Magnetic structure tested by means of neutron depolarization and magnetic force microscopy methods," in Journal of Physics: Conference Series, Institute of Physics Publishing, Jun. 2017. doi: 10.1088/1742-6596/848/1/012016.

[20] Y. Hu et al., "New magnetorheological elastomers based on polyurethane/Si-rubber hybrid," Polym Test, vol. 24, no. 3, pp. 324–329, May 2005, doi: 10.1016/j.polymertesting.2004.11.003.

[21] X. Wang, H. Y. Ge, and H. S. Liu, "Study on epoxy based magnetorheological elastomers," in Advanced Materials Research, 2011, pp. 852–856. doi: 10.4028/www.scientific.net/AMR.306-307.852.

[22] G. W. Kim, S. Kim, and H. J. Choi, "Enhanced performance of nano-sized maghemite added carbonyl iron-based magnetorheological soft elastomer," J Magn Magn Mater, vol. 560, Oct. 2022, doi: 10.1016/j.jmmm.2022.169659.

[23] B. Wang et al., "The influence of particle chain-magnetic field spatial location, frequency, dynamic strain amplitude and the prestrain on the mechanical performance of anisotropic magneto-rheological elastomer," Polym Test, vol. 104, Dec. 2021, doi: 10.1016/j.polymertesting.2021.107411.

[24] X. L. Gong, X. Z. Zhang, and P. Q. Zhang, "Fabrication and characterization of isotropic magnetorheological elastomers," Polym Test, vol. 24, no. 5, pp. 669–676, Aug. 2005, doi: 10.1016/J.POLYMERTESTING.2005.03.015.

[25] J. Kaleta, M. Królewicz, and D. Lewandowski, "Magnetomechanical properties of anisotropic and isotropic magnetorheological composites with thermoplastic elastomer matrices," Smart Mater Struct, vol. 20, no. 8, p. 085006, 2011, doi: 10.1088/0964-1726/20/8/085006.