Recent Advances in Magneto-active Polymers: Experiments, Modelling and Simulations

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ABSTRACT: The last decade has witnessed the emergence of magneto-active polymers (MAPs) as one of the most advanced multi-functional soft composites. An MAP consists of a soft elastomeric matrix filled with micron- or nano-sized magnetisable rigid particles. These magneto-responsive particles are generally classified into two main groups: soft-magnetic particles and hard-magnetic particles. When soft-magnetic particles are used in an MAP, these can be magnetised by an external field. However, such a magnetisation will disappear as soon as the external magnetic field is switched off. In the case of hard-magnetic particles, their magnetisations will largely retain even after the removal of the applied magnetic field. When designing such responsive materials, the choice of both (soft matrix and rigid particles) phases is crucial. In this regard, the stiffness of the polymeric matrix determines the composite resistance to deform under an external magnetic field, i.e., the softer the matrix, the stronger the magnetostriction response. Polymeric materials are widely treated as fully incompressible solids that require special numerical treatment to solve the associated boundary value problem. Furthermore, both soft and hard magnetic particles-filled soft polymers are inherently viscoelastic. In this talk, we will at first present a wide range of experimental studies conducted on soft-and hard-magnetic polymers. Afterwards, we propose a unified simulation framework for magneto-mechanically coupled problems that can model hard and soft MAPs made of compressible and fully incompressible polymers, including the effects of the time-dependent viscoelastic behaviour of the underlying matrix. Finally, using a series of experimentally-driven examples consisting of beam and robotic gripper models under magneto-mechanically coupled loading, the versatility and benefits of the proposed framework are demonstrated. The effect of viscoelastic material parameters on the response characteristics of MAPs under coupled magneto-mechanical loading is also studied.

1 INTRODUCTION

In the mid of the last century, the notion of so-called smart or intelligent materials has emerged in the science and engineering fields. These materials can respond to more than one external fields. Such an external field may tune material properties and also may change their sizes or shapes. While in the early days, stimuli-responsive materials were largely metallic and hard composites in which an external field may generate small deformations or stresses, in the recent years, stimuli-responsive soft materials demonstrate large deformations resulting in gaining unprecedented attention in the research arena. These external fields could be electric field, magnetic field, temperature, moisture, pH, light, sound, chemical potentials or their combinations. Similarly, the bulk soft materials could either polymers, hydrogels and their composites. Soft responsive materials are ideal candidates that are in compliant with human bodies and are most suitable for developing human-machine interfaces. These newly emerged soft materials can be used in manufacturing actuators for soft robotics and stretchable electronics, energy harvesters from ambient motions, stretchable sensors for wearable devices and flexible sensors for structural health monitoring,

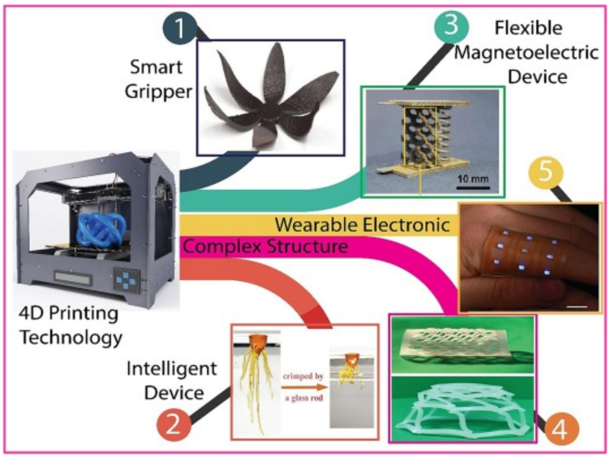

Figure 1: Recently 4D printing technology with magneto-active soft materials was used for various advanced sensors and robotics applications

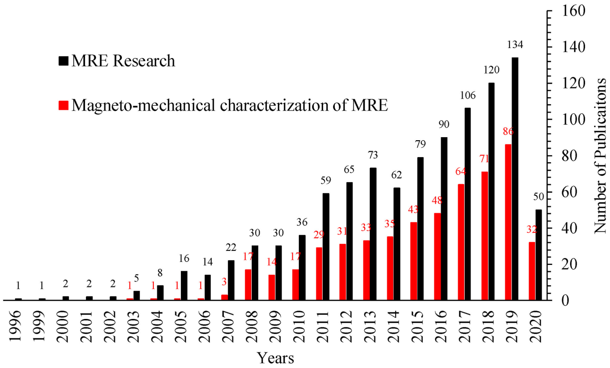

Figure 2: Publications on the magneto-mechanical characterizations of MAPs/MREs compared with various aspects of MRE-based research from 1996 to the mid of 2000. All Scopus archived documents (Journal articles, Conference proceedings, and books) are considered. The keyword "magneto-mechanical" is used to filter the research works that are focused on the magneto-mechanical characterizations of MAPs/MREs.

see Fig 1.

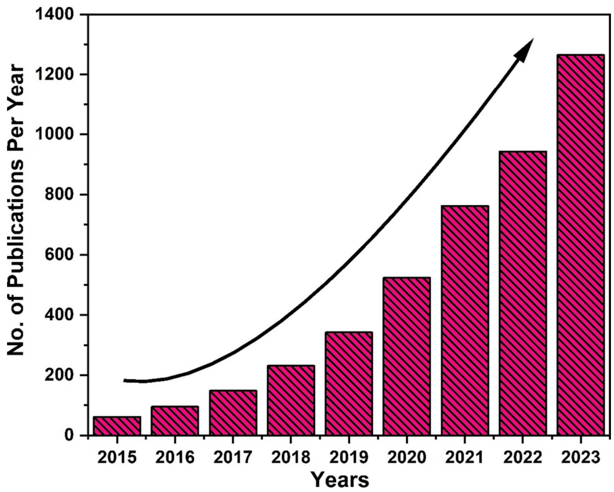

Figure 3: 3D Printing/additive manufacturing of magnetic actuated materials publication trends across the different years (Figure drawn based on the information from Scopus database using "3D printing", and "magnetic responsiveness" as keywords).

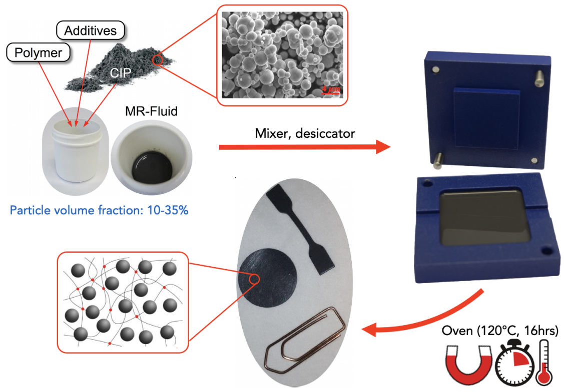

Figure 4: The key steps of an ideal/traditional synthesis process of soft-magnetic magneto-active polymers (MAPs)

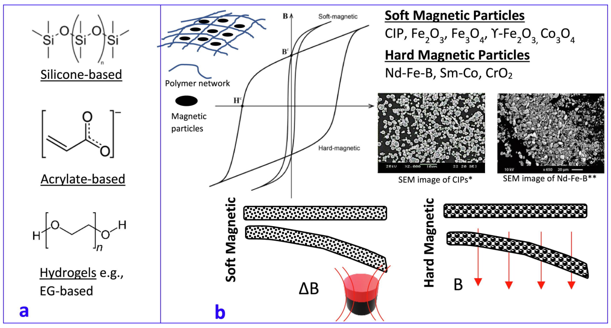

Figure 5: The key differences between hard-magnetic MAPs and soft-magnetic with respect to filler particles, residual magnetisation

2 MAGNETO-ACTIVE POLYMERS (MAPS): APPLICATIONS

Among various stimuli-responsive materials, magneto-active polymers (also known as magnetorheological polymers/elastomers, MRPs/MREs) attract a great attention in the research arena due to their untethered actuations, fast response and large actuation capabilities. Thanks to their untethered nature, magneto-driven actuations are best suitable for creating soft robots in applications for biomedical sciences such as controlled drug delivery, surgical robots, actuated cell culture or creating smart bone/cell scaffolds. Recent years have observed an unprecedented interest in MAPs with great potentials for a wide range of applications. Such growing interests are reflected in an exponential rise of the numbers of journal publications. For instance, the experimental studies on soft-magnetic MAPs are increased in ten to twenty folds in the last twenty years, see Fig 2 while the use of MAPs in the so-called 4D printing is also increased ten folds, see Fig 3.

3 MAGNETO-ACTIVE POLYMERS (MAPS): SYNTHESIS

An MAP can be defined as a filled polymer in which magneto-responsive particles of nano to micro sizes are embedded in a soft polymeric matrix, cf. Fig 4. Based on the residual magnetisation characteristics, a MAP can be termed either a hard-magnetic or a soft-magnetic material. In a hard-magnetic MAP, when

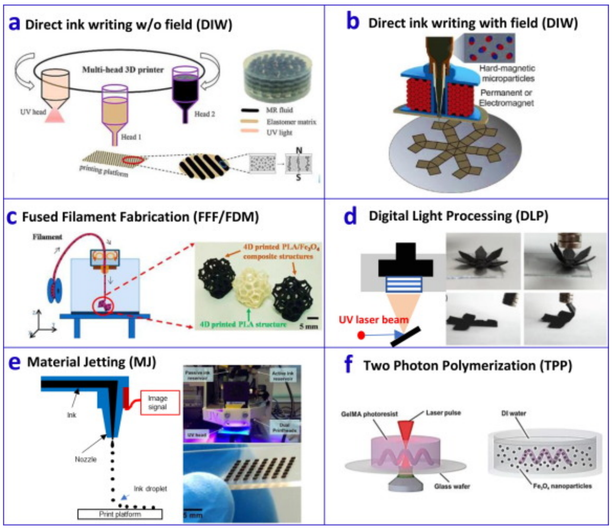

Figure 6: All major 3D printing processes can be applied to manufacture complex and intricate 3D magneto-active soft polymers

an external magnetic field is applied, particles are magnetised and a significant amount of residual magnetisation retains despite the withdrawal of the applied magnetic field. In contrast, in a soft-magnetic MAP, if an external magnetic field is applied, particles are magnetised and a complete demagnetisation occurs when the external field is switched off, cf. Fig 5. Both hard-magnetic and soft-magnetic MAPs have a wide range of applications with related merits and demerits. The synthesis process of an ideal soft-magnetic MAP is presented in Fig. 4 in which carbonyl iron particles (CIP), widely considered as the soft-magnetic particles are used. In order to design more complex and intricate geometries/devices with MAPs, additive manufacturing (AM) aka 3D printing techniques are widely accepted. In this case, all major 3D printing processes can largely be applied to synthesis MAPs, e.g. Fused Filament/Deposition Modelling (FFM/FDM), Digital Light Processing (DLP), Stereolithography (SLA), Selective Laser Sintering (SLS) and Ink Jet Printing etc., see Fig 6. Similar to applications of MAPs, the experimental study in the literature is also increasing exponentially in the last decade, see Fig 2. One of the key characteristics of the addition of soft-magnetic particles is that they create tuneable mechanical properties such as the change of stiffness and loss moduli. In this case, we, for the first time, mix soft- and hard-magnetic particles to obtain the maximum tuneable properties, see Fig 7.

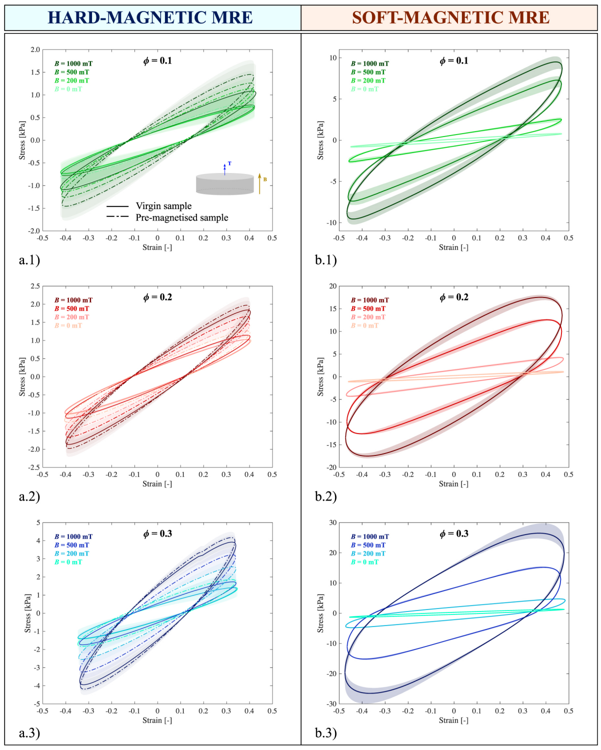

Figure 7: The change of rheological properties in the case of mixture of soft- and hard-magnetic particles in MAPs under a wide range of magnetic fields

REFERENCES

[1] Bastola A K, Hossain M, *The shape-morphing performance of magnetoactive soft materials performance*, Materials & Design, 211:110172, 2021

[2] Bastola A K, Hossain M, *A review on magneto-mechanical characterizations of magnetorheological elastomers*, Composites Part B: Engineering, 200: 108348, 2020

[3] Lucarni S, Hossain M, Gonzalez-Garcia D, *Recent advances in hard-magnetic soft composites: Syntheses, characterisations, computational modelling, and applications Ultra-stretchable and skin-mountable strain sensors using carbon nanotubes-Ecoflex nanocomposites*, Composite Structures, 279:114800, 2022

[4] Khalid M Y, Arif Z U, Tariq A, Hossain M, Umer R, *3D printing of stimuli-responsive polymeric hydrogel materials: Literature review and emerging applications* , GIANT, 17:100209, 2024

[5] Khalid M Y, Arif Z U, Tariq A, Hossain M, Khan K A, Umer R, *3D printing of magneto-active smart materials for advanced actuators and soft robotics applications*, European Polymer Journal, 205:112718, 2024

[6] Moreno-Mateos M A, Hossain M, Steinmann P, Gonzalez-Garcia D, *Hard magnetics in ultra soft magnetorheological elastomers enhance fracture toughness and delay crack propagation*, Journal of the Mechanics and Physics of Solids, 173:105232, 2023

[7] Moreno-Mateos M A, Hossain M, Steinmann P, Gonzalez-Garcia D, *Hybrid magnetorheological elastomers enable versatile soft actuators* , Nature Computational Materials, 8:162, 2022

[8] Moreno-Mateos M A, Hossain M, Steinmann P, Gonzalez-Garcia D, *Effects of soft and hard magnetic particles on the mechanical performance of ultra-soft magnetorheological elastomers*, Smart Materials and Structures, 31(6): 065018, 2022