Conductive Magnetorheological Fluid-Based Flexible Sensor with Magneto-Mechanical Dual-Response and Adjustable Stiffness

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Abstract. Traditional flexible electronic sensors based on rigid conductive materials are prone to damage to the conductive network due to the modulus difference between them and the elastic substrate. In this work, using the “filling and sealing” process, we develop conductive magnetorheological fluid (cMRF) filled Ecoflex soft elastomer composite (cMFEC) based on liquid conductor by encapsulating cMRF into Ecoflex substrate. Due to the conductivity and magnetorheological effect of liquid conductor cMRF, cMFEC not only possesses the tensile sensing performance and perception ability of bending angle of conventional flexible sensors, but also manifests magnetic response properties with magnetic induced stiffness enhancement and magnetic actuation behavior. This work provides a simple strategy for manufacturing multi-functional sensors based on liquid conductors. It can be expected that this kind of sensor based on cMRF will be a promising candidate in flexible electronic sensor.

Possible Sessions

5. Condition Monitoring, 21. Soft matter, 24. Testing of composite materials

Introduction

With the development of electronic technology and artificial intelligence, functional flexible electronic sensors have aroused increasing interest in a variety of applications, such as soft robots, electronic skin, wearable devices, environmental monitoring and so on. Sensitive materials for flexible sensors are usually graphene, carbon nanotubes, metal nanomaterials and other rigid conductive materials. At present, most of the reported flexible sensors are prepared by dispersing sensitive materials into the elastomer substrate or coating on the surface of flexible elastomer [1,2]. Due to the difference in Young's modulus between flexible elastomer and sensitive material, damage such as fracture and sliding of the conductive network can be caused after multiple strains, resulting in a decrease in the stability of the flexible sensor [3]. Liquid conductors, such as liquid metals (LM), salt solutions, conductive inks and ionic liquids (IL), can be assembled with flexible elastomer substrates of low Young's modulus to prepare flexible sensors by filling and sealing processes [4]. Inspired by the process, a novel flexible sensor called cMFEC is developed by using cMRF as liquid conductor and encapsulated by Ecoflex (Fig. 1a).

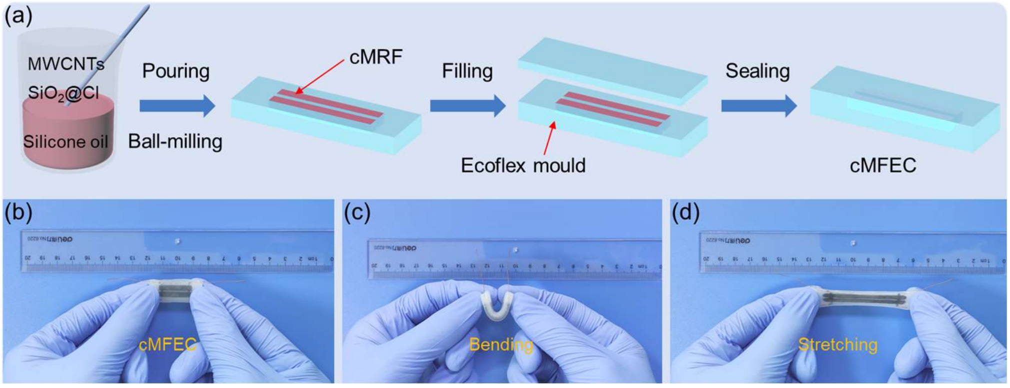

Fig. 1. (a) Flow chart for the preparation of cMRF and cMFEC. Flexible properties of cMFEC: (b) initial state, (c) bending state, (d) stretching state.

Results and Discussion

Magneto-mechanical Dual-response. The sensing response of cMFEC to different tensile strains indicates that it can be used as a strain sensor to distinguish tensile deformation (Fig 2b). After applying a transverse magnetic field during the stretching of cMFEC, the relative resistance increases significantly (Fig. 2c), which shows the magneto-mechanical dual response characteristics of cMFEC. cMFEC possesses excellent sensing stability, and its relative resistance change remains almost unchanged after 1000 cycles of stretching (Fig. 2d). Moreover, cMFEC also exhibits sensing characteristics to bending deformation due to its good flexibility (Fig. 1b-d). Finally, the cMFEC was pasted onto the human finger joint to monitor its movement. When the finger joints are bent at different angles, cMFEC produces a corresponding electrical response (Fig. 2e), indicating its promising applications in human motion detection.

Stiffness Enhancement and Magnetic Actuation. The ultimate load-bearing capacity of the load-bearing platform is tested under different magnetic flux densities (Fig. 2g). When no magnetic field is applied, the ultimate load-bearing capacity of the load-bearing platform is 21 g. As the applied magnetic field gradually increases, the ultimate load-bearing capacity of the load-bearing platform also gradually increases. When a 165 mT magnetic field is applied, the ultimate load-bearing capacity of the load-bearing platform reaches 42 g, which is 100% higher than when no magnetic field is applied. The ultimate load-bearing experiment indicates that due to the formation of particle chains along the magnetic field direction by magnetic particles in cMRF (Fig. 2h), magnetic-induced stiffness enhancement occurs during the compression process of cMFEC. Furthermore, the bending deformation of the magnetic actuated gripper is investigated using finite element simulation. The permanent magnet is placed inside the hollow ABS square cylinder, and can be moved down or up through a connecting rod to control the gripper to grasp and release objects. As the magnet gradually moves downwards, the magnetic induction intensity of cMFEC increases, and the bending deformation caused by magnetic force is also larger (Fig. 2k). As the magnet moves upwards, the magnetic force on the gripper gradually decreases to disappear, and the clamped cMFEC recovers due to its own elasticity, thereby releasing the object being grabbed (Fig. 2l). A cMFEC-based four-finger gripper was also demonstrated for grasping a heavier doll toy (Fig. 2m).

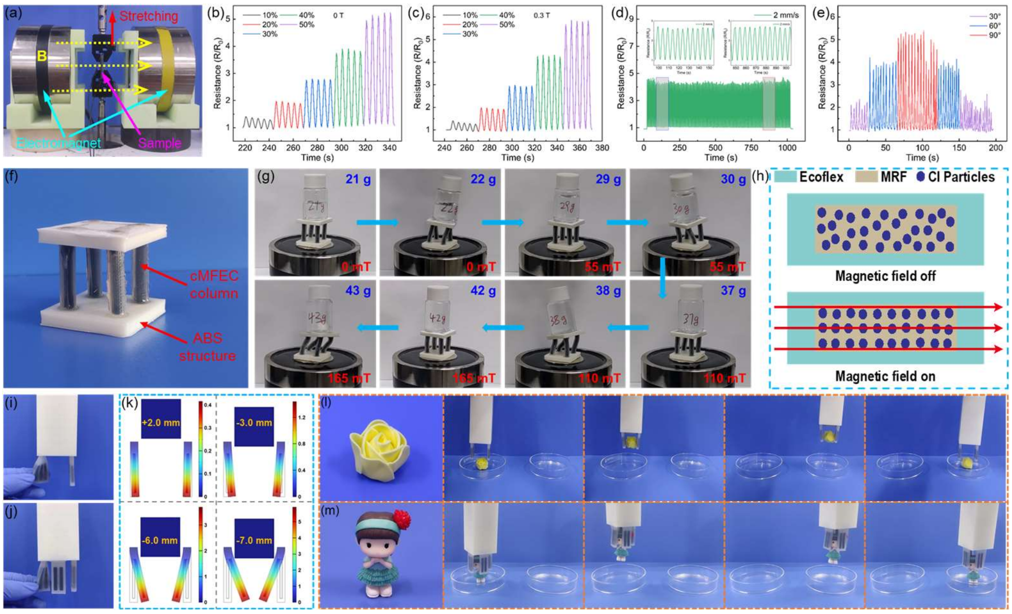

Fig. 2. (a) Tensile test fixtures and electromagnets. Relative resistance of cMFEC with different tensile strains (10%~50%) at magnetic field of (b) 0 T and (c) 0.3 T. (d) Electrical stability of cMFEC during 1000 stretching cycles at a stretching rate of 2 mm/s. (e) Variation in relative resistance of fingers at different bending angles when pasting cMFEC onto finger joints. (f) Four hollow Ecoflex hoses are filled with cMRF and connected to two 3D printed ABS plates to assemble a magnetic induced variable stiffness load-bearing platform. (g) The ultimate load-bearing capacity of the bearing platform under different magnetic flux densities. (h) Schematic diagram of magnetic induced stiffness enhancement in cMFEC under magnetic field. magnetic actuated grippers with (i) two fingers and (j) four fingers. (k) Simulation results of the grippers deformation when the permanent magnet moves downwards to different positions (The position parameter represents the distance from the lower surface of the permanent magnet to the upper surface of the cMFEC, and the legend represents the deformation size of the cMFEC in mm). (l) Two-finger and (m) four-finger grippers grasping, transferring, and releasing objects.

Conclusion

In summary, a cMRF-based soft sensor cMFEC was developed to achieve magneto-mechanical dual-response characteristics. As a strain sensor, cMFEC can recognize 10-50% tensile strain and exhibit electrical stability, while it is frequency-insensitive. Furthermore, it can sense bending angle and be used for assembling variable stiffness load-bearing platform and intelligent magnetic actuated gripper.

References

[1] X. Cao, J. Zhang, S. Chen, R.J. Varley and K. Pan: *1D/2D nanomaterials synergistic, compressible, and response rapidly 3D graphene aerogel for piezoresistive sensor,* Adv. Funct. Mater., Vol. 30 (2020), p 2003618.

[2] Y. Jiang, Y. Wang, Y.K. Mishra, R. Adelung and Y. Yang: *Stretchable CNTs-Ecoflex composite as variable-transmittance skin for ultrasensitive strain sensing*, Adv. Mater. Technol., Vol 3 (2018), p 1800248.

[3] G. Lu, H. Yuan, J. Zhou, F. Chen, C. Li, T. Xue, X. Shu, Y. Zhao, J. Nie and X. Zhu: *Patterned magnetofluids via magnetic printing and photopolymerization for multifunctional flexible electronic sensors*, ACS Appl. Mater. Interfaces, Vol 14 (2022), p 30332-30342

[4] A. Ahmed, I. Hassan, I.M. Mosa, E. Elsanadidy, M. Sharafeldin, J.F. Rusling and S. Ren: *An ultra-shapeable, smart sensing platform based on a multimodal ferrofluid-infused surface*, Adv. Mater., Vol 31 (2019), p 1807201.