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# **3D PRINTING OF MAGNETORHEOLOGICAL ELASTOMERS(MREs)SMART MATERIALS**

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## **ABSTRACT**

The purpose of this research work is to explore manufacturability of a variety of smart materials using additive manufacturing (AM) process and a specific kind of smart material; the Magnetorheological Elastomers (MREs) is investigated in depth in this paper. A multi-material 3D printing process was designed and set up to manufacture this kind of smart materials and the preliminary results are reported. The experimental device involves a double nozzle print head which integrates dry powder printing and extrusion freeforming method to make MREs with completely arbitrary distributions of magnetic particles within the matrix material. A LabVIEW program was developed to control the printing process. Using the process developed, a number of MRE samples were produced using silicone (as matrix material), iron and copper powders. Finally, the printed samples were analyzed and the process was evaluated accordingly.

## **INTRODUCTION**

The broad category of smart materials is an exciting and relatively young field of research in material science. The possible applications for smart materials are very wide in industry, medicine and many other areas. In industry, smart materials may be used for measurement or control purposes. A material which reacts to a certain chemical by changing its colour can be a good tool to monitor chemical reactions and detect unwanted by-products. Materials with shape memory may be used in surgery to open constricted blood vessels while doing as little damage as possible to the patient's organs.

Although it is not easy to determine what makes a material 'smart', there exists a wide range of different smart materials and many believe that those will significantly drive the technological advance in future. Smart materials have great potential, but are usually very difficult to manufacture and therefore expensive. Chances are that 3D printing is the key for at least some of those materials to be fabricated easily and efficiently. As 3D printing technologies advance and become more and more affordable, we may soon be able to produce smart materials at only a fraction of today's costs.

While the term 3D printing is often used as if it describes a single process, it is a rather generic term for a variety of automated additive processes. Additive in this context means that an object is built up by gradually adding material to it. The object is therefore 'growing' during production. Because of this, 3D printing generally has a very good material utilization. 3D printing is very versatile and the list of materials that can be produced is constantly growing. So, will this list soon be expanded with a few smart materials? As it will be shown in this paper, this may actually be the case.

The so called magnetorheological elastomers (MREs) are one of the newest types of smart material. The term magnetorheological comes from "magnetic" and "rheology"; the latter means

the study of deformation and the flow of matter. Hence MREs can be defined as elastomers (flexible polymers) that change their deformation properties (e.g. stiffness) under the influence of magnetic fields. They fall under the category of smart materials because an external magnetic field can be utilized to directly control the materials stiffness. This makes MREs particularly useful for applications that involve the damping of vibrations (Lokander, 2004).MREs are sometimes referred to as “the solid analogue of magnetorheological fluids”. Magnetorheological fluids (MR-fluids) are a type of 'smart fluid' that changes its viscosity when subjected to magnetic fields. While MR-fluids are already used in certain real life applications (e.g. in adjustable shock absorbers for race cars), its solid analogue has not made it into commercial products yet. This is the case, not least because an appropriate production process is yet to be found.

In general, MREs consist of a flexible matrix material interspersed with magnetic particles. Common matrix materials can be natural rubber as well as silicone. The magnetic particles in a MRE are almost always iron particles, but other kinds may emerge in future (Naimzad et al., 2011).There are two categories of MREs which are distinguished by the distribution of magnetic particles within the elastomer. Isotropic MREs have a homogeneous distribution of magnetic particles. The particles are evenly spread throughout the volume of the matrix material. This category, while of limited practical use, is fairly easy to produce by simply mixing iron powder with silicone and pouring the mixture into a mould. Because this process is sufficient and simple already, there is no need to make use of 3D printing to fabricate those isotropic MREs. 3D printing is much more interesting for the fabrication of the second category – the anisotropic MREs. Every MRE in which the magnetic particles are not distributed homogeneously is anisotropic. Fabricating this category is far more difficult as magnetic particles have to be dispersed in the elastomer in a particular pattern. Theoretically, using 3Dprinting allows the creation of MREs with completely arbitrary distributions of magnetic particles within the matrix material. In practice however, this has not been accomplished yet.

## MATERIALS AND METHODS

Using two different materials in 3D printing requires the use of a double nozzle print head. For MREs for example, an extruder for silicone and a dispenser for iron powder is necessary. It is important to consider how those two printing heads can work together. Ideally both heads could work simultaneously and move independently from each other. This would make it possible to start the powder printing at any point and any time we want – even on freshly printed silicone while the same silicone layer is not even finished. Figure 1 depicts schematic of the overall multi-material 3D printing process used to print MREs.

In this research work, the novel dry powder printing technology invented recently by Dr. Shoufeng Yang and his colleagues was used to print iron and copper powders with different physical properties (density, particle size and shape, etc.) on the surface of silicone layers deposited by extrusion method. ALabVIEW program was developed to control the overall printing process. Dry powder printing has been very successful in dispensing uniform ‘drops’ of powder with weights as low as 15 ug (micro gram) of a wide range of different materials, including metal, polymer and ceramics (Lu et al., 2009). In this method, a simple glass capillary filled with powder is excited by ultrasonic pulses to give uniform and variable drop size control. The use of acoustic vibrations from a piezoelectric disc aids in breaking up agglomerated powder clots by applying a distributed and initiates the flow of powder from a fine glass nozzle without using a mechanical stopper. On switching off the vibrations, particle-particle and particle-wall frictions lead to the formation of domes causing powder flow arrest in the nozzle. The efficient functioning of the device is dependent on the inter-play between different process variables such as nozzle diameter, voltage

amplitude, voltage frequency and time of vibrations. BASF Carbonyl iron Powder (CM, CAS Number: 7439-89-6) and gas atomized copper powder (OFHC Cu) supplied by Sandvik Osprey Ltd. with particle size less than 20  $\mu\text{m}$  (mean about 14  $\mu\text{m}$ ) and sieved with 50  $\mu\text{m}$  test sieve were used in this research work to dispense on the silicone layers and make sandwich structures.

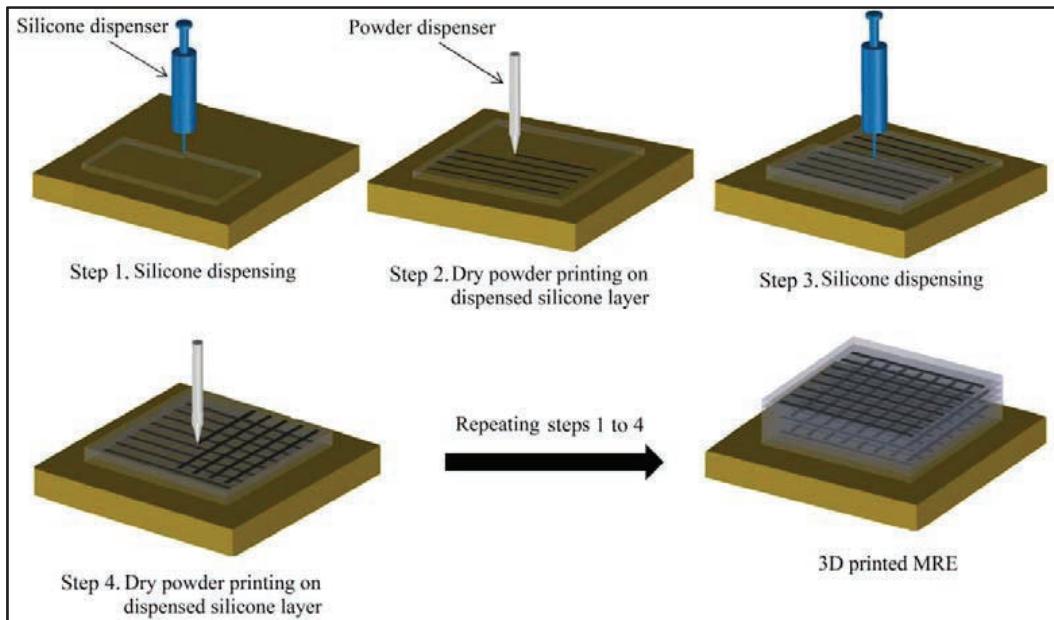


Figure 1. a) Schematic diagram of the integrated dry powder printing and extrusion freeforming method used in this work

## RESULTS AND DISCUSSION

The print of carbonyl iron powder was very problematic and the preliminary print quality achieved was not sufficient. The iron powders are very fine which make it very sticky and tend to leave the dispenser in lumps rather than in smooth and fine lines (Figure 2a). It is possible that the particle size of the used powder (8 to 10  $\mu\text{m}$  diameter) affect its flowability. Copper powders were used to compare flowability and quality of the printed samples. Any samples using copper powder should therefore be considered as test pieces to show the functionality of the printing process, rather than actual 'working' MRE samples.

Using copper, it was possible to print continuous powder lines. For high quality prints however, it is also important to have full control over flow rate of powder. The flow rate can be controlled by the magnitude of voltage (used to drive the dispenser) as well as the speed of the XY-table while following the powder paths. In practice, changing the voltage had no significant effect on the powder flow rate, thus the main control factor used was the velocity of the XY-table. The LabVIEW program for MRE-printing could allow the user to adjust the XY-table velocity separately for the print of silicone and powder layers. The dry copper powder printing nozzle clogged time to time which resulted in failure of the process. This can be due to electrostatic

charging of powders inside glass tube. The static charging is mostly between particles and found less between particle and wall of glass tube, although the overall static charging is less severe than non-metal powders.

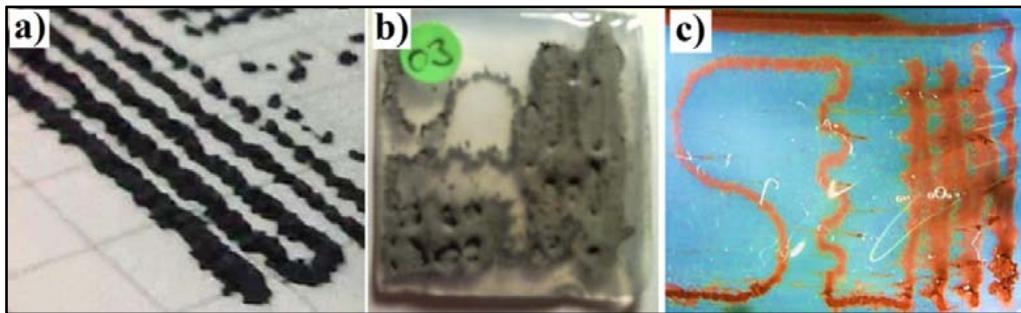


Figure 2. Different problems occurred during printing of MRE samples a) iron powder tend to leave the dispenser in lumps rather than in smooth and fine lines b,c) Sandwich structures: double layer silicone with iron and copper printed lines with width of 400  $\mu\text{m}$ . The printed iron and copper patterns washed away after printing of the top silicone layer.

It is important to keep the thickness of printed powders as less as possible with desireline width which affects quality of the printed sandwich structures. The thickness and width of printed powders could be controlled by powder flow rate and offset distance (the distance between powder dispensing nozzle and silicone layer). It was observed that problems occurred once a layer of silicone was printed on previous layers including silicone and printed copper lines with too big thickness so that while some of the powder (which was dispensed on top of a still sticky layer of silicone) was held in place, excess powder tended to be 'washed away' or 'smear away' by the new silicone layer printed on top (the powder was carried by the flowing silicone). This could be seen in some samples using both iron and copper powder (Figure 2b and c), but even more in any of the iron powder samples, where the original powder path is unrecognisable due to this issue (Figure 2b). General speaking, as contact surface between printed powder and silicone layer get more the silicone/powder bonding get more which results in less unwanted scattering of printed powders during next silicone layer dispensing. In addition, smaller silicone needle with lower silicone dispensing speed can be used to make silicone layers with less interaction on the dispensed powders. It could be also useful to give the printed powder some time to sink into the lower silicone layer before covering it with a new one to reduce the smearing problem. In order to do this, adjustable time delays or 'timeouts' have been incorporated into the LabVIEW program. Those timeouts pauses the printing process between each change from silicone to powder layers and vice versa. This allows for some control over the curing state of the silicone when powder is laid on top of it and over the time we allow the powder to sink into the lower silicone layer. Sandwich structures with copper powder lines as fine as 250  $\mu\text{m}$  could be printed with no smeared with the top silicone layer by proper adjustment of process parameters (to control powder thickness and width) and applying timeouts pause. This indicates that the copper powder was sticking to the lower silicone layer as desired when the second silicone layer was printed on top of it. With the powder dispenser provided, the finest continuous copper lines achieved, although the powder layer is slightly distorted and some particles spread unexpectedly toward direction of top

layer silicone dispensing (as can be seen in rectangle areas in Figure 3a and b). This means that the copper powder has moved with the silicone flow of the lower silicone layer. Hence, the lower silicone layer had not enough time to set before the next layer of silicone was added. Samples had better printing quality and printed line uniformity with thicker lines of powder.

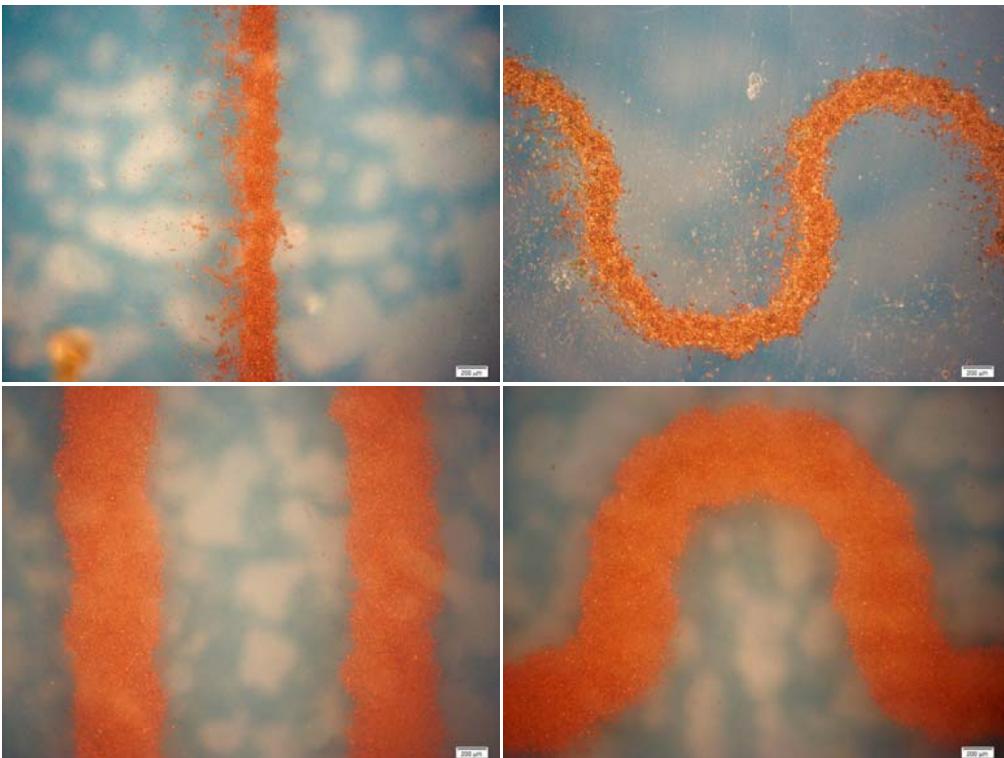


Figure 3.3D printed sandwich structures: double layer silicone with copper printed patterns (scale bar 200  $\mu\text{m}$ )

a, b) lines width of 250  $\mu\text{m}$ , silicone layer height: 0.8 mm, powder dispenser voltage: 1V, timeout SIL --> POW: 120 s, timeout POW --> SIL: 60 s

c, d) line width of 600  $\mu\text{m}$ , silicone layer height: 0.8 mm, powder dispenser voltage: 1V, timeout SIL --> POW: 120 s, timeout POW --> SIL: 3 hours

An interesting sample that should be mentioned can be seen in Figure 3c and d. Even though the powder lines are not that fine (it is 600 microns), this sample does not suffer from distortion of the powder layer. The powder layer is nearly perfect in the sense that it represents the exact shape of the powder path designed. This was achieved, by initially leaving out the print of the second silicone layer. The unfinished sample (one silicone layer plus one powder layer), was left alone for about 3 hours, giving the thin silicone layer enough time to cure. After that, all loose powder was

removed and only then a second layer of silicone was printed on top of it. As the lower silicone layer was already cured and the remaining powder was held in place, the print of the second silicone layer could not distort the powder layer in any way. While this is surely not a practical way to produce MRE samples, it shows us possible ways to improve the MRE printing process. The sample also shows that the curing state of silicone is very important when printing on top of it. However it is not practical to let each layer cure for hours before adding new layers. More experimentation should be done to figure out, how much curing time is sufficient or if the curing time required can be somehow reduced.

Examining the samples with multiple powder layers, it was found the same flaws as in samples with single powder layers. Unsurprisingly, flaws such as the distortion of powder layers are even worse as more layers of liquid silicone are stacked together. If however, the quality of samples with just a single powder layer is optimized, so that flaws like the distortion of powder layers are eliminated, a multi-layer sample could have sufficient quality as well. Increasing contact surface between printed powders and the silicone layer by adjusting offset distance and flow rate would be an asset to reduce distortion of powder as more powders can be in contact with silicone, thus better silicone/powder bonding before deposition of a new silicone layer can be achieved. Moreover as discussed earlier for single powder layer, a longer timeout between silicone layers deposition could be an efficient approach to minimize printed powder distortion and unwanted spreading in multi-layer MREs, although this increase production time.

## **CONCLUSIONS**

In this paper it was shown that it is generally possible to print MREs using a multi-step 3D printing process even though much more experimentation and optimization has to be done. The technique based on extrusion freeforming and dry powder printing showed a great potential to be served for fabrication of MREs with completely arbitrary distributions of magnetic particles within the matrix material. The optimization of curing time and other ways to speed up the curing would be worth to investigate. It is also worth to investigate more different silicon rubbers which will have different viscosity and curing time.

## **ACKNOWLEDGMENTS**

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