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Effects of Embedded Depth of Internal Printed Ferromagnetic Cell on Data Clarity of Rewritable 3D Objects

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Abstract

We proposed the method for non-destructively embedding information inside a 3D fabricated object very clearly by the process of re-magnetization. Our strong points are that the 3D object is finished (ready to use) after only a printing process, and is able to be reused by re-writing information many times. In this paper, we investigated the effects of the depth (positions inside the object) of the storage cell, which is printed as a ferromagnetic filament, on the clarity of the embedded information. Our purpose: we need to find the conditions that gave the most benefit in both obtaining high magnetic strength and protecting the embedded information. With this advantage, the method leads to the production of creating the high-quality household 4D object, the personal interactive 3D object, in the near future.

Keywords: 4D printing, Re-writable information, 3D printing, Ferromagnetic, Embedded information, Re-writable digital tag

Introduction

4D objects, the interactive 3D objects, is the very new topic of this decade [1]-[2]. They are the fabricated objects that have the functions of themselves changing when they are activated by some specific actions. On the other hand, this means that these objects are not just permanent objects. After the 3D printing process is finished, something of them can still be changed when the as time passes, such as shapes, tastes, flexibility, physical properties, chemical properties, and embedded information.

Information changing can also be referred to as data storage also. However, the production of data storage nowadays still needs a post-process, an additional process after printing, in order to combine the data storage cell with an object. This is not compatible with the household manufacturing in the future, which should be able to easily to produce the IoT at the household level. So it would better if we could use the 3D printing to produce a complete data storage object without using a post-process. It will be of benefit for the IoT tools creation in the near future a lot.

A 3D object that can keep some data has many advantages. For example, it can be used as a tag for identifying a person, an individual object as a gift, or an object watermarked for copyright protection. [3]. Furthermore, if the object is a re-writable 3D object, it will be close to a complete data storage object, such as the digital tag, IC card, RFID, etc.

We have continued to study the topic of embedding information inside a 3D object for a while. Initially, we have successfully permanently embedded information into objects during 3D printing [4]-[8]. These kinds of work can show the specifications and prove the originality of objects, ensuring they do not need to be changed anymore. Furthermore, in the last few years we have developed 3D objects that can keep non-destructively re-writable data. This means that the 3D object can keep the data for a period and we can change the data anytime as we need. The entire information-writing process is already finished after the printing.

We had proposed the method to create the re-writable information 3D objects by embedding the ferromagnetic storage cell (FSC) inside, using a dual-extrusion 3D-printer [9]-[10]. We have proved that our technique can make a re-writable 3D-object can store the information as the magnetic flux inside the object, using the ferromagnetic filament. The information can be written by magnetization and can be deleted by demagnetization. Furthermore, we have proved that the strength of magnetic flux kept inside the object varies with the volume of the storage cell.

However, we need to balance the magnetic power needed to make the information will be clearer to read well and the tactfulness needed for hiding the information. The clearness of distinguishing information from each signal is necessary because it makes the system for reading faster and more accurate. On the other hand, protecting the storage cell from being seen is necessary also because it can prevent attempts to destroy the storage area inside to the object. Moreover, it makes the 3D-object more beautiful. This is necessary for the designer to make the 3D object tiny, exquisite, high-quality, and valuable.

In this paper, we aim to study the effect of the depth at which the storage cell is embedded in a 3D object. From our study, we found that the different depth of hiding embedded storage cell (inside a 3D object) affect to the strength of magnetic

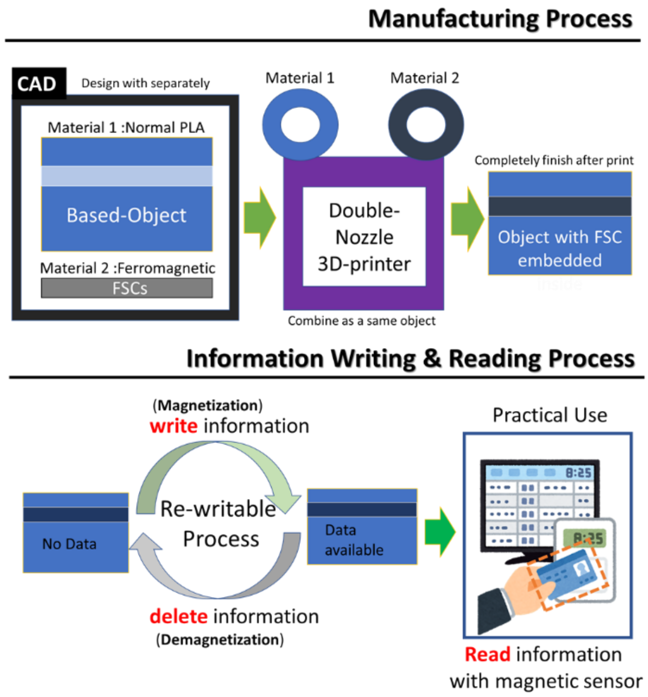

Figure 1. The workflow of the process of manufacturing 3D object with an embedded FSC and the process of information recording in practical use.

power keeping inside. Anyway, the depth of embedding also affects the hidden levels, which can protect against attempts to attack, and thus make the [information? cell?] not easy to destroy. So we have to balance between the hidden levels and the strength of storage of magnetic power if we are to get the 3D object that can hide information most effectively.

Principle of embedding the ferromagnetic storage cell (FSC) in a 3D object

This section will explain the steps of how to embed the ferromagnetic storage cell (FSC) in a 3D object. Figure 1 illustrates our technique to make an information storage 3D object.

The most important thing for our interactive 3D object is the ferromagnetic filament because this material has the property of keeping the magnetic flux inside itself after it is magnetized. In addition, with the variation of magnetic flux, we can assign the flux to a signal. It means that if we would like to write signals or information to the object, we can control by vary the magnetic values inside the object instead.

To control the magnetic values inside the object, we can vary by designing the storage area of the object for containing the ferromagnetic filament. Hence, the step of object design is very important because the shape, volume, and embedding depth of the storage area all affect to the clarity and strength of magnetic flux remaining after magnetization. The process begins with a computer-aided design (CAD) program. Normally, we use CAD software to create a 3D model. Furthermore, we can make what would otherwise be a normal 3D fabricated object a data storage 3D object by adding small cells for data storage. Each of these cell is called a ferromagnetic storage cell (FSC). Thus, the step of file preparation is essential for creating a data storage 3D fabricating model, especially with our technique.

For adding the FSC to a 3D object, we have to spare a storage cell area separately from the original 3D object but inside the same 3D model. Then we can design and create the size, shape, and volume of each FSC as we need. These factors have effects to the clarity of data, which will be kept in this 3D model also. We had proved by our works about the effect of volume of FSC to the strength of magnetic flux in [10]. Moreover, we can also set the embedding depths of FSCs throughout the object to keep them from being seen from the outside. Finally, we have to set each FSC as a separate part of an object (but still inside the object).

After the CAD process, we move to the 3D-printer station. We have to set the g-code to print out the 3D model and the storage cell with different nozzles by different materials. The storage cell has to be printed as a ferromagnetic filament. Anyway, both parts are combined together with the same object in order to obtain an object with FSC embedding that will be completely finished after printing.

In the process of printing, both materials will print out such a same time. Hence, the storage cell is hidden inside the 3D object automatically, depending on the embedding depth that we have designed in CAD. Finally, we obtain a 3D model which has a data storage cell completely hidden inside as soon as the printing is finished. (No any post-process). This is the first of our prominent points.

Secondly, although, we cannot see and touch the storage cell from the outside, the magnetic power, which is referred to here as information, still can be detected from the surface of the object by a magnetic sensor. We found that the ferromagnetic filament can maintain the magnetic fields far beyond the period

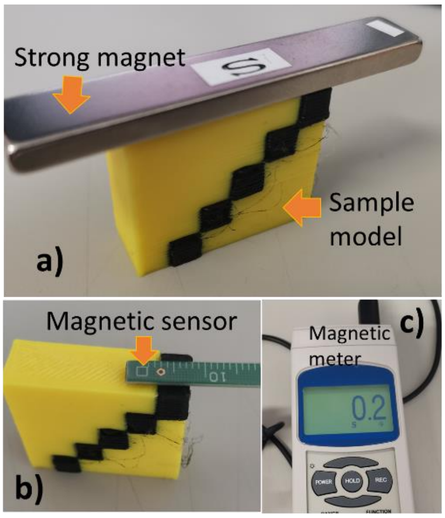

Figure 2. *Steps of experiment methodology: a) place the strong magnet on the sample, b) measure the magnetic flux by placing a magnetic sensor on the surface of the sample, c) read the magnetic flux and polarity.*

after which we use the strong magnet. This is the way to write data to the storage cell. On the other hand, demagnetization is the way to eliminate the magnetic fields in the FSC. Thus, we can delete the data this way. Moreover, the advantage and strong point of our technique is that the FSC can be demagnetized and magnetized many times. This means that the object can be reused by having some data changed and/or by having new kinds of information added. In addition, we can vary magnetic flux, value, and polarity [10].

This is the benefit and is suitable for application to the real-using because we can easily write, read, and change the information stored in a 3D object by interacting with the object's surface. (such as by touching an object to sensors). Furthermore, we can fabricate this object by using a household 3D printer as an FDM printer. So it is convenient for practical home-use in the future.

Experiments investigating the effect of FSC embedding depth

Balance between the hiding from seeing (making the object look tiny and elegant) and the clarity of data (still reading information well) is necessary for the CAD process designing the 3D model because both are important.

Hence, we set two experiments for investigating the effects of FSC embedding depths on the magnetic flux. The first examined the maximum depths from which the sensors could read the magnetic power strength. The second continued by studying which depth is suitable for practical use: the depth at which the FSC cannot be seen from the outside but from which we could still get a strong magnetic power reading.

In every experiment we used the 3D Builder as the CAD for designing the sample models. After that, we used the CURA as a slicer program. Then we printed every sample by using a HICTOP: D3 Hero Dual-Extruders FDM 3D printer. One nozzle is for FSC printing. We used the ferromagnetic filament (black color) and another nozzle is the normal PLA for the samples' body printing (various colors). All samples were printed with infill 100%. After finishing printing, we cleared all magnetic flux of each sample by demagnetization (Hozan: HC-31). After that, we magnetized the sample by placing a very strong bar magnet (1950 Gauss) on the sample, above all of the FSCs, only 1 time,

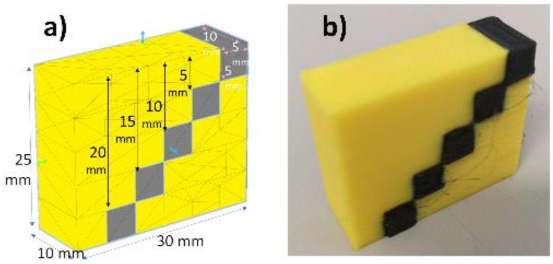

Figure 3. *Sample1: a) design, and b) real 3D model. The yellow color is PLA and the black color area are the ferromagnetic storage cells (FSCs) printed as ferromagnetic filaments. Each FSC had been embedded at a depth different by 5 mm (totally, 5 positions).*

around 5 seconds, attached to the object with *North* polarity. Then we checked the magnetic flux remaining in the samples by using a magnetic meter (Lutron: MG-3003SD). We placed the sensor on the surface of the sample, at the position upon each embedded FSC, to read the power of magnetic flux which FSC can keep. The steps of methodology in the experiments are shown in Figure 2. The details and results of each experiment are presented next.

Fining Maximum Depth of FSC Embedding

In the first experiment, we intended to find the limit of distance from the surface of the sample at which we would be able to embed the FSC.

We designed a sample as shown in Figure 3a, and Figure 3b shows the 3D model obtained after printing with a double-nozzle 3D printer. The yellow color is a based-object (PLA) and the black color areas are the ferromagnetic storage cells (FSCs) printed as a ferromagnetic filament. The size (width x length x height) of sample 1 was 10x30x25 mm. The sample was designed to vary the depths of embedding FSC in different positions inside the object. Anyway, we designed the side of the sample in such a way that we could see the positions of each FSC clearly for the advantage of easily identifying and measuring (reading) the magnetic flux in the right position.

The size (width x length x height) of each FSC was 5x10x5 mm and be embedded inside the object. They are placed vary from the surface (0 mm) deeper inside to 20 mm. Each is different with 5 mm deeper. Totally for all object are 5 positions (Figure 3.). We would like to find the maximum depth at which we can embed FSCs and have the sensor can read the magnetic flux.

The results of this experiment are presented in Table 1. We found that the maximum depth of FSC embedding in a fabricated object is 10 mm from the surface.

Table 1: Results of remaining magnetic flux in Sample 1

Embedding Depth (mm)	0	5	1 0	15	20
Magnetic Flux (Gauss)	11.8	1.5	0.2	0	0

Note: *all remaining magnetic flux is *South* polarity

Appropriate Depth Investigation

After finding the limit of embedding depth, we next investigated the appropriate depth: that at which the FSCs were completely hidden but date could be read clearly. Hence, we designed Sample 2 for this experiment.

In Sample 2 (Figure 4), we intended to keep the size of the FSC the same as in Sample 1 (5x10x5 mm) but we aimed to vary

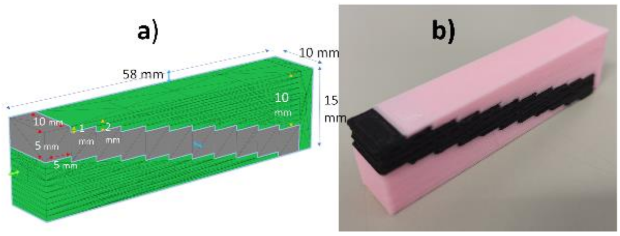

Figure 4. *Sample2: a) design, and b) real 3D model. The pink color is PLA and the black color is FSC. Each FSC has embedded depth different in 1 mm, totally 11 positions*

the embedded depth as 1 mm deeper, from the surface (0 mm) to 10 mm depth, inside the fabricated object (totally are 11 positions). The size of the sample was 10x58x15 mm. We printed out the sample as a pink color because that made it is easy to see the FSC (black) through the object. So we could determine the FSC hiding level better. The design of Sample 2 is shown in Figure 4a, and the real 3D model is shown in Figure 4b.

The results of remaining magnetic flux in each FSC are shown in Figure 5. The magnetic flux in FSCs is inversely proportional to the embedding depth. The equation fitting the graph is presented here as Equation 1, where y is the magnetic flux in the FSC (Gauss) and x is the embedding depth (mm) of the FSC ($R^2 = 0.9939$).

$$y = -0.0316x^3 + 0.6626x^2 - 4.7017x + 12.097 \qquad (1)$$

From Figure 5, in 3mm depth (from the surface), the remaining magnetic flux decreases dramatically. However, after 3mm depth, the remaining magnetic flux decreases as little, (flux on surface=12G, 1mm depth=8.4G, 2mm depth=5G, and 3mm=2.5G). This implies that if we would like to make a sample that can keep the magnetic flux and show the magnetic flux (information) clearly, we should be able to embed the FSCs at depths ranging from 0 mm (i.e., on the surface) to 3 mm. We noticed from our experiments that the non-active FSCs (No information or just incomplete demagnetization), it can also store a little magnetic flux inside and it can be detected around or less than 2G. So, we should not use a small flux value ($\leq$ 2G) to define as the information.

In addition, the results in Experiment 2 conformed to the results of Experiment 1 (Table 1) in having the same magnetic values (compare flux at the FSC at same depth between sample 1 and sample 2), we notice at the depths 0 mm (surface), 5 mm, and 10 mm, two samples showed as the same flux. It referred to

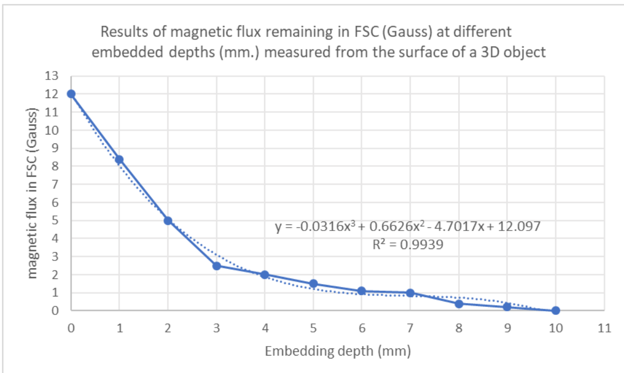

Figure 5. *Results of magnetic flux remaining in FSC (Gauss) in different embedding depth (mm) measured from the surface of a 3D object*

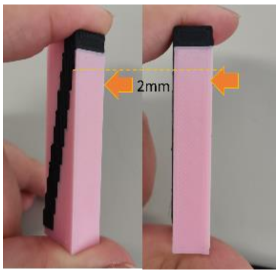

Figure 6. *At the embedding depth of 2 mm, the FSC is completely hidden. So we can embed the FSC 2 mm deep and get clear information reading.*

the stability of FSC to keep the magnetic flux. These results confirmed that whenever FSCs of the same size is printed out and magnetized with the same magnetic strength, they keep the same magnetic flux. This is another advantage if we will apply it in practical also.

Moreover, we confirmed with Sample 2 the level of depth at which the FSC was completely hidden (at which we could not see the black color through the object). In Figure 6, with the depth at 2 mm, we cannot see the color of the ferromagnetic filament, which is black, completely. Hence, in conclusion, we could say that the appropriate depth of FSC embedding should be 2 mm from the surface of a fabricated object. With this depth, we cannot see the embedded FSC and the data reading and writing is clear.

Conclusion

We proposed the technique to embed the ferromagnetic storage cell (FSC) into a 3D fabricated object. With our technique, the 3D fabricated object can be a storage to keep information inside and can be non-destructively readout clearly. In addition, two strong points of our method are: firstly, the object can be reused by re-writing data again and again many times by the process of magnetization and demagnetization. We can change the information inside after finishing the production process. And secondly, our technique has no post-process for embedding the storage part into the object. So, with these advantages, we will be able to make a 3D interactive object (a 4D object) in the near future by using a normal household 3D printer, such as a double-nozzle FDM 3D printer. In this paper, we investigated the appropriate depth for embedding the FSC into the object. We found that FSC should be embedded between 2 and 10 mm (1 cm) from the object's surface These distances are the depths that able to hide the FSC completely and at which the data reading and writing will still be clear. Moreover, with confirming results of 2 experiments (two samples, at the same embedded depth, they got the same flux), it referred that the FSC has the stability for keeping the information also. Hence, in practical use, the user will use this knowledge to design and make interactive products that can be manufactured by a household process. We hope that all those products will support the IoT system with 4D objects in the future well.

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