Use of magnetically smart films to shape X-ray mirrors

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(Dated: November 25, 2018)

In this paper, we report progress to develop adaptive X-ray mirrors using magnetically smart materials or MSM for short. These adaptive X-ray mirrors work using the stress difference a magnetically smart material (MSM) provides under the influence of an external magnetic field. We used silicon substrates coated with Terfenol-D ® (MSM), to act as the actuating layer, and NiCo as our magnetically hard material to retain the surface profile of the mirror after magnetization. Profile measurement of 5mm x 20mm films were done using a Fizcam 2000 interferometer under different conditions. The goal was to show that the samples could be shaped with the help of an external magnetic field, and that the remnant field in the NiCo holds the deflection after the external field has been removed. For this project, we measured three different samples showing a deflection up to 1.34m under 0.12 Tesla; Two of the samples successfully hold some of their deflection under the remnant magnetic field created by the NiCo layer. As a proof of concept, the tests were done with permanent magnetics located on each side of the cantilever. An X-ray beam application would use a electromagnetic/magnetic write head.
Keywords: Magnetically smart materials, X-ray optics, active or adaptive optics

INTRODUCTION

Deformable mirrors are essential for many applications in modern X-ray synchrotron facilities and X-ray astronomy [1]. For the next X-ray optics generation, there is a need for an exceptional angular resolution which modern techniques such as slumped glass or grinded and polished 3mm thick full shell glass mirrors have not been able to achieve yet [2], so an adaptive X-ray mirror approach would be ideal. There are a variety of different approaches to create adaptive X-ray mirrors, including, but not limited to mechanical benders, bimorph mirrors and voice coils actuated mirrors, our concept was the use of magnetically smart films to shape X-ray mirrors. In this project, we focused on the possibility of using magnetically smart materials to shape mirrors with future X-ray optics applications.

Ferromagnetic materials exhibit a shape modification under the influence of an external magnetic field. This shape modification can be explained by the rotation and re-orientation of small magnetic domains, which causes an internal stress and stretches the material in the direction of the magnetic field [3]. Materials that show a giant magnetostriction are called magnetically smart materials, or MSMs for short. A material that has been shown to have a high magnetostrictive response is Terfenol-D®[4]. Because of the big response that Terfenol-D® has shown, we will use it as our actuating layer in our experiment.

The idea is to coat the mirror with a MSM, and with a magnetically hard material. As the samples experience a change in the magnetic field parallel to the long axis of the sample, the Terfenol-D® wants to expand/contract, creating the stress difference which deforms the mirror [2]. This Magnetostrictive stress can be maintained by the magnetically hard material after the magnetic field is removed (this is caused by the remnant magnetic field the magnetically hard material provides after it has been magnetized), maintaining the deformation for an extended period. It is important to note that the deformation is not expected to be retained indefinitely, but rather to be retained for a minimum of a few hours, long enough to make beam line measurements.

SETUP

The setup consists of the sample being clamped at the edge with a reference flat next to it. Two movable permanent magnets, mounted on a translation stage, are to control the magnetic field strength applied to the mirror sample. The two magnets are mounted in a way so that they are always equidistant to the sample, to apply a field that is as uniform as possible to the sample. This configuration was also chosen to minimize the magnetic field component perpendicular to the sample, which can cause an undesired perpendicular force due to the pull of the magnets on the sample, giving us a false positive.

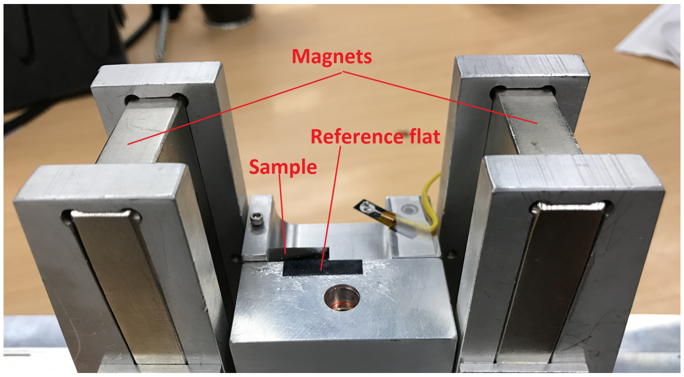

FIG. 1. Set up with magnets at their closest for maximum magnetic field. Because of the lack of degrees of freedom the reference flat has, we were not able to use it with the Fizcam interferometer

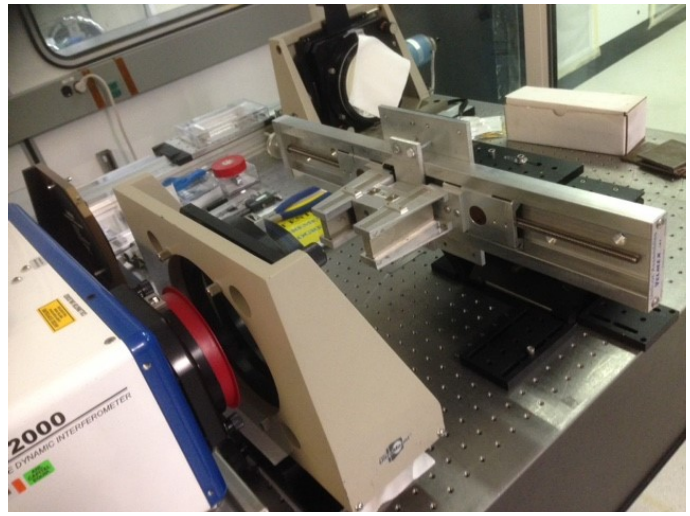

FIG. 2. Fizacm interferometer (right), and setup (left)

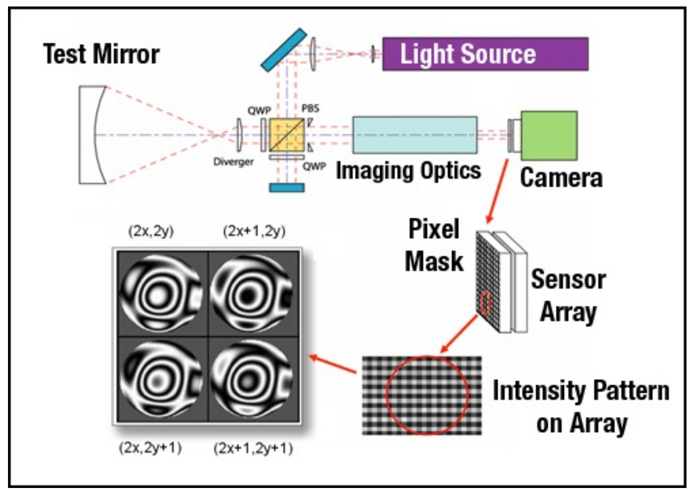

FIG. 3. schematic of how the Fizcam interferometer works (image can be found at https://www.4dtechnology.com/products/dynamic-interferometry/)

The samples start as a polished 200 um thick silicon wafer which is cut into strips (20 mm x 5 mm wide), and then sputtered with a 1.6um layer of Terfenol-D® (creating the actuating layer). The deposited films have non-zero stress, causing the sample to bend. We are currently working on controlling the amount of stress in the films, which will allow us to set the initial shape of the mirror before applying additional corrections via the MSM layer. After the samples have been sputtered with Terfenol-D®, the samples are then coated with a thin layer of NiCo 20nm, which serves the purpose of providing a magnetically hard material, and protecting the Terfenol-D® from oxidizing.

The deflection of the samples were measured using a broadband 4D Technology Fizcam 2000 interferometer, which is a type of a Fizeau interferometer.

MAGNETIC FIELD MEASUREMENTS

To correlate the deflections of the samples to the strength of the magnetic field, measurements and analysis of the magnetic field at different separations of the magnets were done (figure 4).

The measurements done of the magnetic field of the setup (figure(4)) were taken using a Hall probe at the APS magnetic device laboratory. We started by setting the magnets as far apart as the setup allowed, which for this case was 366mm, and measured the magnetic field perpendicular to the surface of the magnets, the probe moved also in the direction perpendicular to the magnets, setting our x-axis to be zero where the center of the sample is located. We then decreased the distance between the magnets to be 200mm and measured the magnetic field in the same way. Finally we got the magnets as close as the setup allowed, which was 70mm, and measured the magnetic field.

To get the graph shown in figure(5), we took all the data points at x=0 from figure(4), and plotted it as a function of distance between the magnets. The fitted curve (in red) is described by the exponential equation shown in the graph. An exponential function was chosen for a best fit because it naturally tends to 0 as x approaches infinity (which is what one would expect the magnetic field to behave like), and the function fits the data accurately.

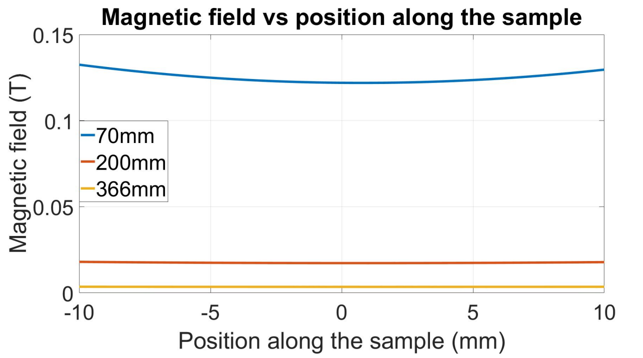

FIG. 4. Plot of the magnetic field perpendicular to the long axis of the sample at 3 different magnet separations

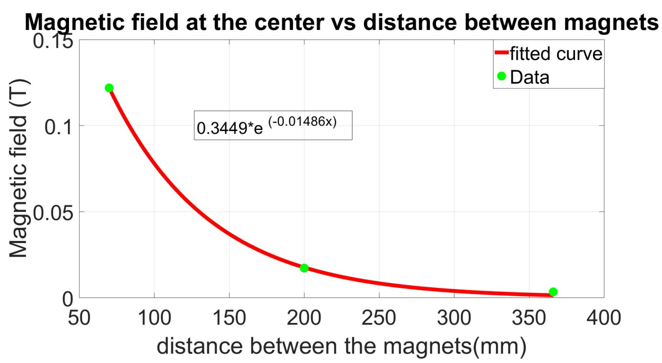

FIG. 5. Best fit curve of the magnetic field at the center of the sample as the magnets get far apart from each other

DEFLECTION AND TEMPERATURE MEASUREMENTS

Measurements of the three samples were taken at different separations of the magnets of our setup. Before doing any measurements, a degausser was used to make sure the NiCo was not magnetized. For the first measurements the magnets were as far apart as the setup allowed (366mm), to have a low magnetic field. The second measurement was taken when the magnets were as close as the setup allowed (70mm). Finally we again decreased the magnetic field to see how well the NiCo holds the deflection. The results are shown in Table 1. The temperature of the room was also measured during the experiment (See Table 2) to verify that the deflections were not caused by thermal effects.

The surface profiles where shifted in the y-axis, so that all the surface profiles would meet at x=0. Since all the samples were clamped at one end($x = 0$), there is no deflection in that area, which can tell help us reduce random source errors (such as vibrations, thermal expansions, etc.). The sift in surface profiles did not exceed 0.2um, meaning that even if there was no data analysis done, the results would show the same conclusion.

As it can be seen in table 1, all the samples had a deflection which was in the um scale, with sample 3 having the biggest response, and sample 1 having the smallest response. We can also see from table 1 that the NiCo in samples 2 and 3 was able to hold some remnant magnetic field and partially hold the deflection after they have been magnetized. From table 2 we can see that the temperature fluctuated between 22.7C and 22.9C, making a difference of only 0.2C, making it unlikely that the deflections were caused because of the change in temperature.

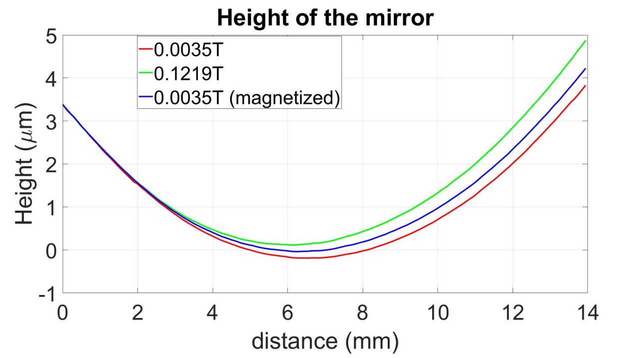

FIG. 6. comparison of the surface profiles of sample 2 before magnetization and magnets far apart (read curve), magnets close together (green curve), and after magnetization and magnets far apart(blue curve)

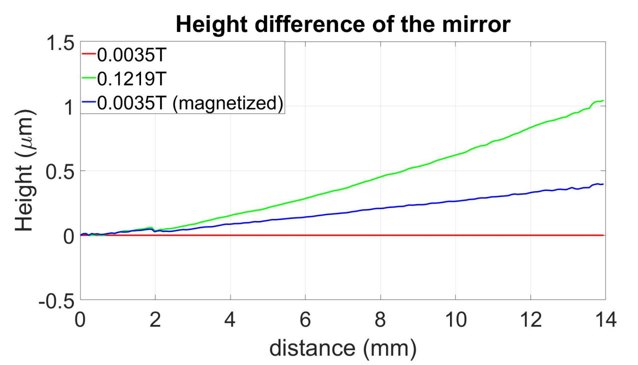

FIG. 7. Deflection of sample 2 before magnetization and magnets far apart (read curve), magnets close together (green curve), and after magnetization and magnets far apart(blue curve)

TABLE. 1. Deflection of the samples at x=14mm

Samples	Deflection at 0.12T (μm)	Deflection after magnetization (μm)
1	0.47	0
2	1.04	0.4
3	1.34	0.68

TABLE. 2. Temperature measurements of the room during the deflection measurements

Samples	1^{st} measurement (^{0}C)	2^{nd} measurement (^{0}C)	3^{rd} measurement (^{0}C)
1	22.8	22.7	22.7
2	22.9	22.8	22.9
3	22.9	22.9	22.8

MAGNETOSTRICTIVE STRESS APPROXIMATION

In this case, we are also able to calculate the stress created by the Terfenol-D, which can be described by Stoney formula (equation 1).

$$\sigma^f = \frac{E_s h_s^2 k}{6h_f(1-\nu_s)} \tag{1}$$

Where σ^f is the stress, E and ν are the Youngs modulus and Poissons ratio respectively, k is the curvature (Where $k \equiv 1/R$, R being the radius of curvature), and h represents the thickness.

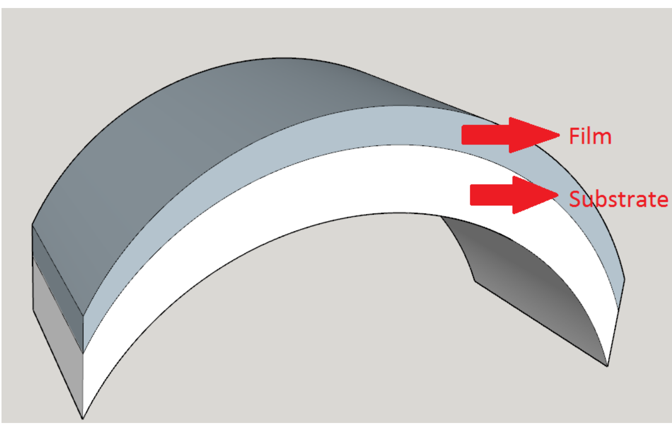

FIG. 8. schematic of a substrate and film

It is worth noting that Stoney formula works only for a thin film sample, where we define thin to be about h(s)/10 [2].

To calculate the stress in Stoney formula we need the curvature k. We can then fin k using the following formula (which will be derived in the appendix):

$$k = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \tag{2}$$

To calculate this, we need to take derivatives of the surface profile, and while this can be done numerically, we found out that a quadratic function fits the surface profile well enough to give us significant results.

FIG. 9. best fit curve of the sample before magnetization and magnets far apart (sample 2 is being used for this calculations)

For the following calculations we used equation (2). To describe the shape of the mirror we used the best fit curve (which units are in m), which equation can be found in figure (9).

$$k(relaxed) = \frac{2*0.0781/m}{\left[1-(0.001x)^2\right]^{\frac{3}{2}}}$$

Since $(0.001x)^2 << 1$ then we can approximate it to be 0, meaning that the curvature is no longer dependent on x, which means it is constant. We then arrive at the curvature of the sample.

$$k(relaxed) = 0.155/m$$

Once the curvature of the mirror is found, we can then use it in Stoney formula, for which we have used the following values:

TABLE. 3. Geometrical and mechanical parameters used for Stoney equation

E_s(GPa)	h_f (μ)	μ_s
129.5	1.6	0.27

The stress found in Stoney equation for the relaxed case in Stoney equation is then.

$$\sigma(relaxed) = 114.57MPa$$

Similarly we can calculate the stress of the sample under the magnetostrictive stress Terfenol-D®. Using equation (2), and the best fit equation fromfigure 10 we get the following values.

$$k(magnetsclose) = \frac{2*0.0814/m}{\left[1-(0.001x)^2\right]^{\frac{3}{2}}}$$

Similarly to the previous case, the denominator is mostly constant.

$$k(magnetsclose) = 0.163/m$$

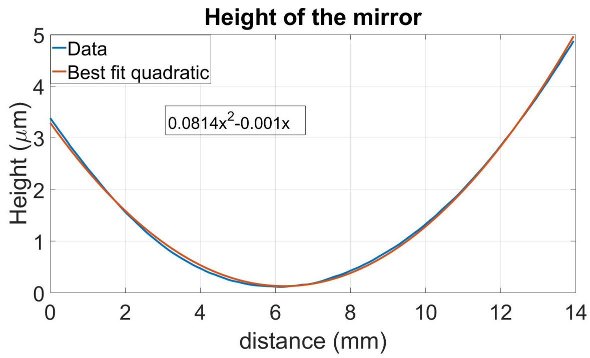

FIG. 10. best fit curve of the sample with magnets clos together (sample 2 is being used for this calculations)

Using then this value into Stoney equation we get:

$$\sigma(magnetsclose) = 120.48MPa$$

Taking then the difference of the stresses we can then find the stress produced by the magnetostrictive effect of Terfenol-D®.

$$\sigma(magneetostrictive) = 120.48MPa - 1145.57MPa$$

$$\sigma(magneetostrictive) = 5.91MPa$$

This stress due to magnetostriction seems to agree with previous research done on terfenol-D [6], where the elastic modulus has a change of about 6MPa under a magnetic field of 90kA/m (which is about 0.11T), which is close to our 0.1219T applied magnetic field.

CONCLUSION AND FUTURE WORK

Our measurement showed that magnetic smart materials could be potentially used to shape x-ray mirrors. A deflection of up to 1.34m was obtained under 0.12 Tesla, and the deflection can be partially held in place by the NiCo. We also achieved results which are within reasonable deviations from our theoretical calculations in Stoney formula. Further research is needed to determine the optimum film thickness of NiCo to preserve the shape of the mirrors. We are also interested in the effects of annealing the sample and using a thicker layer of Terfenol-D® have.

ACKNOWLEDGMENTS

I would like to give thanks to my mentor Lahsen Assoufid and Prof. Ulmer for their guidance throughout the project; to Jun Qian for providing the help and guidance for the measurements; to Rocco Coppejans, Kyle Condron, for providing the samples and the sample mounting setup; to Nikita Strelnikov and Isaac Vasserman for the help provided during the measurements of the magnetic field.

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Curvature formula derivation

The curvature is defined by the radius of curvature, which using can be written as:

$$k = \lim_{\Delta\theta \to 0} \frac{\Delta\theta}{\Delta s} = \frac{d\theta}{ds} \tag{3}$$

Where s represents the arclength function, ant θ is the angle with respect to the x-axis. By the use of the chain rule we get:

$$\frac{d\theta}{ds} = \frac{d\theta}{dx}\frac{dx}{ds} \tag{4}$$

Note that $tan(\theta) = \frac{dy}{dx}$, so $\theta = arctan\left(\frac{dy}{dx}\right)$. So we then have:

$$\frac{d\theta}{dx} = \frac{d}{dx} arctan\left(\frac{dy}{dx}\right) \tag{5}$$

Taking then the derivative of $arctan\left(\frac{dy}{dx}\right)$ we get:

$$\frac{d\theta}{dx} = \frac{\frac{d^2y}{dx^2}}{1+\left(\frac{dy}{dx}\right)^2} \tag{6}$$

Looking at equation4, we also need $\frac{dx}{ds}$.

$$\frac{dx}{ds} = \frac{1}{\frac{ds}{dx}} = \frac{1}{\sqrt{1+\left(\frac{dy}{dx}\right)^2}} \tag{7}$$

using equation (7) and (6) into equation 4 we get:

$$k = \frac{d\theta}{ds} = \frac{\frac{d^2y}{dx^2}}{\left[1+\left(\frac{dy}{dx}\right)^2\right]^{\frac{3}{2}}} \tag{8}$$

We have then concluded the proof ■