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Organization Name : **Northwestern University, Chicago**	**09-APRA09-0113**

Proposal Title : **Improving the performance of X-ray optics with magnetostrictive films**

SECTION VII - Project Summary

The goal of this proposal is to demonstrate that shape modification can be successfully applied to thin walled (~100-400 micron thickness) replicated optics or slumped glass optics to improve the near net shape of the mirror as well as the mid-frequency ripple. The proposed process involves sputter deposition of a magnetic smart material (MSM) film onto permanent magnetic material. The permanent magnetic material would be the mirror substrate in the case of electroformed optics and would be plated onto the back of glass optics. The MSM material exhibits strains about 400 times stronger than ordinary ferromagnetic materials. The deformation process involves a magnetic write head which traverses the surface, and under the guidance of active metrology feed-back, locally magnetizes the surface to impart strain where needed. Because of the hard magnetic material, the localized shape change remains until actively demagnetized. The following tasks will be performed. Upgrade of a sputtering chamber to enable coating 10 cm and larger diameter pieces. Make sputtering targets of our baseline MSM called Terfenol-D. Make substrates onto which to sputter the MSM. Sputter onto both electroformed and and plated glass substrates. Model the magnetostrictive response for various substrate and MSM thickness combinations. Finite element modeling of the mirror based on all materials, thicknesses, boundary conditions, and magnetic field magnitude and location. The final step in year 3 will be to show that both free standing cylinders of revolution, mounted glass, and mounted cylinders can be shaped with a goal of 1" half-power diameter encircled energy as demonstrated primarily by ray tracing. The Argonne Advanced Photon Light Source will be used as well. In addition to changes in the macro figure, determine what is the smallest length (goal 100 microns) scale over which the substrates, particularly glass can be smoothed.

Table of Contents

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1. Introduction

This proposal is the resubmission of proposal that was judged good enough to fund in the previous cycle, but then no funds were available. Hence we are submitting again this year. We now begin with the X-ray astronomy motivation. The Chandra pictures have been breathtaking and show what can be done with exquisite angular resolution. It is going to be difficult, therefore, to propose future X-ray missions that don't have angular resolution comparable to Chandra's. The missions also need to have 10 to 100 times more area along with sub 1 arc second angular resolution. The resolution is important also since confusion limit becomes a problem as well. And, for example, the International X-ray Observatory (IXO) has a requirement of < 5". The Gen X mission concept (R. Brisseden, P.I.; Ulmer; Co-I; [1]) is another prime example. Since budgets are limited, however, the next generation X-ray observatories will count on the development of at least 3 capabilities: (a) lightweight optics; (b) thin walled mirrors for deep nesting and hence optimal collecting area per unit volume; and, (c) sub-arcsecond angular resolution via a process that is less expensive than grinding and polishing each separate mirror.

The key points which need to be driven home for further X-ray astronomy missions are: (a) Chandra type optics is no longer affordable, especially if the area is to be increased more than 10 fold over Chandra; (b) No form of replication optics or other affordable light-weight optics has come within a factor of 10 of the Chandra resolution; (c) Thin (< 400 μm) walled optics are the future of X-ray astronomy; (d) The only conceivable way at this time to make affordable optics is not brute force grind and polish to sub arc second each mirror (or mirror segment); (e) the only plausible solution at this time is to modify the shape of the thin walled optics via some adaptive optics technique, rather than via post figuring and polishing. Since the mirrors are to be deeply nested, the image adjustments should be done with something that is as thin or thinner then the walls of the mirrors; (f) Active shaping in orbit will be daunting, and it therefore behooves us to see first how far we can go with permanent static figure adjustment so as to make life much simpler. (g) With sufficiently thin write heads, however, it is possible that the technique we propose can be used actively, if necessary. *(h) For cases where the launch loads are such that significant post launch deformation will not occur, though, a passive approach is definitely preferred, and our approach offers hope of being the solution.*

Here is an outline of our proposal. We first discuss the basic concepts, next in shape changes that apply to any deformable X-ray optics work, and then follow a discussion that is specific to the concept we propose. We follow with some background on magnetic smart materials (MSMs) We next give a report of the work we have done to date to learn how to both deposit the film and to determine the size of the deflections we could produce on flats. This is then follow by a technical plan.

The end product of a 3 year project will be to have developed the technology to carry out the modification of both Wolter I and full scale IXO-sized glass segments that will be used to demonstrate TRL 6 or higher maturity of the technology for Wolter I full shells (with < 2″ angular resolution) and glass segments. The project will investigate macro figure changes on length scales of 5 mm or more, but also the ability of the film to smooth out mid-frequency ripple. The ability to remove mind-frequency ripple is particularly important for commercially available glass.

2. Concept

2.1 Basics of the concept: The proposed process involves sputter deposition of a multilayer film consisting of a magnetic "smart" material (MSM) – a material that exhibits strain in a magnetic field – and other hard and/or soft permanent magnet materials. A magnetic write head then traverses the surface, and under the guidance of active metrology feedback, magnetizes the layers locally and imparts strain where needed. Because of the hard magnetic material, the localized shape change remains until actively demagnetized, as it is with magnetic recording medium, as illustrated in Figure 1. Typical magnetic fields used are 5G-500G.

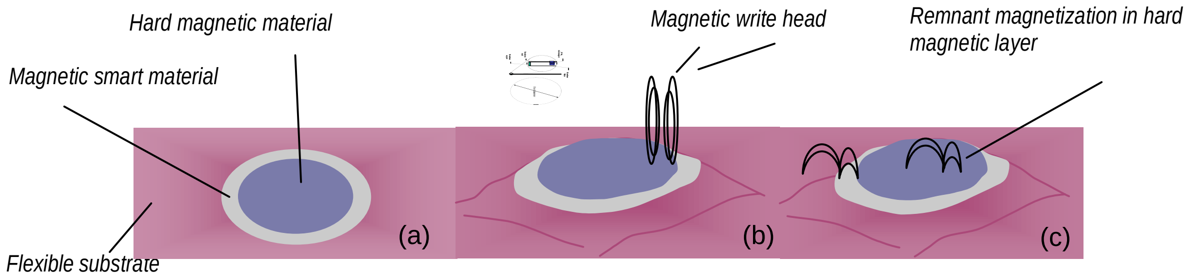

Figure 1. Illustration of shape control of a flexible substrate with a smart magnetic bilayer. (a) Nominally flat substrate with deposited films. (b) Magnetic field applied locally. (c)Magnetic shape memory layer expands and hard magnetic layer becomes magnetized.

Because of their higher stress and strain capability, magnetic films are expected to be superior to piezo-based solutions. Furthermore, magnetic films can be made to retain their corrected shape (in our proposed version of the application) without continuous application of power. In contrast, piezoelectric materials return to their former unstressed state once the applied voltage is removed.

2.2 Magnetic "Smart" Material: "Smart" materials are a special class of materials that are frequently used to perform sensing and actuation functions and are increasingly used in applications that imitate living systems. Smart-material actuators are increasingly replacing conventional systems because they are more compact, more energy efficient, and respond faster than classical actuation methods. Magnetic "smart" materials (MSM) change their shape when exposed to a magnetic field, and include magnetostrictors, which reorient their magnetic moments in response to a magnetic field, and ferromagnetic shape memory alloys (FSMA), which undergo a phase transformation in response to the field.

Magnetostriction is a very commonplace phenomenon whereby ferromagnetic materials expand or contract based on the presence of a magnetic field. This is why transformers hum, which also demonstrates that relatively high audio frequencies are obtainable by magnetostriction, i.e., 8kHz-10kHz. Studies of the basic phenomenon have long been carried out for the ferromagnetic elements and their alloys, but the magnitude of the achievable strains is typically less than 100 ppm. In recent decades, it was discovered that certain special compositions exhibited "giant magentostriction" with strains that exceed 1000 ppm. These materials typically contain rare earth elements such as Tb, Dy, Sm, etc. In a specific development program that lead to commercial application, the Navy developed a material (Terfenol-D) that optimizes the giant magetostrictive performance for actuator applications. Other researchers have investigated the magnetic-mechanical response of various rare-earth-ferromagnetic compositions, including materials deposited as coatings and including materials that do not have the ideal crystalline structures. Even with amorphous films, significant magnetostrictive response can be observed, and although it may be as small as 10% that of the crystalline phase, it can still be functional for the application we are considering here. Deposition methods that enhance the performance of thin films, for example, by strongly texturing/orienting the film crystal growth, or by incorporating nanolayers of magnetic materials have also been investigated with some success.

For the purposes of sputter depositing thin films of MSM, the targets (source material) can be fabricated as composite structures of the individual elements or obtained from commercial sources in proven compositions and structures. For example, the MSM material can be made by companies such as Etrema (producers of Terfenol D) for assembly into targets in sputtering systems such as are available at Northwestern University. This will be done by making tiles from boule (or casting) slices and then bonding them to a backing plate to form the sputtering target. We have successfully sputter deposited similar material and effectively confirm the work of Quandt and Seemann [2] who reported sputtering of Terfenol-D. They characterized the magnetization response as a function of the sputtering conditions and noted an especially strong dependency on the bias voltage, which controls film density, crystallographic orientation, and internal stress (generally compressive). They demonstrated the behavior of small cantilevers (copper and silicon substrates) to magnetization, including reversing fields at 500 Hz. They reported “no degradation” of behavior after 10^7 operations, and deflections as large as 200 μm were achieved with about 800 G fields (high but are possible with our set up). Others [3-8] have also investigated thin film behavior and the effect of structure and composition on the magnitude of response. The advantages of amorphous films (as deposited) and annealed (recrystallized) films have also been investigated, as have nanolayered films. As each structure has some advantage, it appears that it is important to achieve a balance between coercivity and magnitude of response for a specific application, and we will have to explore the various structural factors to best meet our needs.

2.3 Conceptual Design and Non-Volatile Shape Memory: A conceptual design of a membrane mirror that exploits the novel properties of an MSM/ high-coercivity material bilayer is shown in Figure 2. The film stack is simplified in the figure, but would consist of the MSM, the high-coercivity ferromagnetic material (such as Ni-Co) and appropriate adhesion layers and diffusion barriers, possibly repeated multiple times in thin layers. A small electromagnet on a translation track selectively

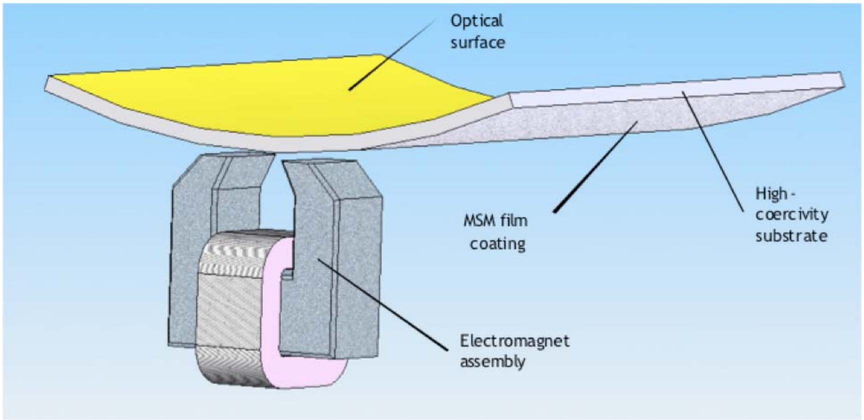

Figure 2. Mechanism for writing shape information onto the optic. The high coercivity substrate also provides structural support, e.g. Ni or Ni-Co in the case of X-ray optics.

magnetizes areas of the membrane in response to commands from a control system. The MSM in the activated regions expands (or contracts, depending on the choice of MSM), while the high-coercivity material becomes magnetized. When the write magnet moves away and the power is turned off, remnant magnetization in the high-coercivity material continues to apply a field to the MSM, which therefore remains in its deformed state until actively demagnetized. We call this property non-volatile shape memory.

It is evident that our concept borrows from hard disc drive construction and operation in the sense that we want a thin layer of magnetic material that will respond with high spatial resolution to the action of a magnetic write head. Major differences exist however, in that our resolution requirements are not on the order of nanometers, but hundreds of nanometers and we don't have high-speed access issues to deal with. Thus, our job should actually be made easier because of the existing hard drive technology. The materials properties we want in the high coercivity material are in fact very much like those we find in hard disc design. A permanent magnetization of a localized area will induce magnetization of the magnetostrictive material. As these two layers will be tightly joined, the expansion or contraction of the MSM will cause a proportional change in local curvature of the foil.

In a collaborative and parallel effort we will be learning to characterize the surface figure, and to use that data in FEA/FEM to model the local stress/strain adjustments needed to correct the mirror figure. An experimental setup will be used to mimic this step, by demonstrating predictable changes in shape of flats and conical sections with programmed application of a magnetic write head.

2.4 Existence Proof: Here is an existence proof of why the concept will work. Start with a "perfect master." The electroformed piece when removed will deviate from the master due to internal stresses caused by the electroforming process. Since the mirror came from a perfect master there must be a way to map this mirror figure back to where it came from by applying canceling stresses to the mirror. This is an existence proof of itself, and is consistent with Dr. William Zhang's idea of depositing a "stressy" iridium coating to a free standing glass mirror shell to counteract the stresses that come about due to the thermal gradient generated while the glass segment cools.

As pointed out by Will Zhang of GSFC, and we agree, a FEA should be able to tell us [to first order] where the stresses are that have caused this deformation and where to impose stresses to counteract these deformation stresses. Further note that we plan to apply our technology to Will Zhang's slumped glass segments (both free standing and mounted) for the IXO, and the application of our technology to glass segments, is part of our proposal.

Based on our preliminary work, plus a study of the literature, we are convinced that our idea will work. Therefore our proposal is to demonstrate the effectiveness MSM films for shaping X-ray optics and further to explore the smallest length scales for which surface improvement can be affected. Given the size of magnetic domains and the ability to write magnetic structures on sub-micron scales, it is quite likely that we can effect surface improvement down to at least 100 microns.

3. Deformable Mirrors

3.1 In General: The concept of a deformable mirror is not new. The basic concept was applied to synchrotron X-ray mirrors as early as 1995 [8]. Furthermore, a Dec 2006 conference attended by Ulmer was devoted entirely to adaptive X-ray optics [9], where bi-morph systems for synchrotron beam lines were shown to be quite mature. Other recent applications for optical use include: the secondary optics of the refurbished Multiple Mirror Telescope which has 336 voice coil actuators as described in Brusa, et al. [10], and space optical/IR mirrors as described by Trauger et al. [11]. The Trauger, et al. article demonstrates the concept of using a "dense" pack of actuators to achieve extremely high contrast imaging. Thus, the basic concepts of active (time scale of seconds) or passive/slow (time scale of days) have been applied for over 20 years.

What is unique about our approach using a thin (micron in thickness) magnetic thin film is that it holds at least two significant promises compared to the piezo approach such that it deserves to be tried and compared to theory. The promise is to be able to remove mid-frequency ripple as well as to hold the shape once power is turned off. However, if active, post-launch figure modification is necessary, then thin magnetic write-heads and write-head manipulators are available

3.2 In General Finite Element Analysis, Boundary Conditions and Zernike Polynomials, and Grazing Incidence Optics

There are at least two groups that we know of that are working on deformable X-ray optics for astrophysical applications. One group is in the UK (our contact Dick Willingale), the other at Harvard Smithsonian Center for Astrophysics (contacts Paul Reid and Roger Brissiden). Both groups are using the bi-morph approach, but the baseline substrates are different. The UK group is using electroformed Ni and the CFA group is using glass. Both groups will do some finite element analysis (FEA)/FEM finite element modeling (FEM) work. Neither group has published or conveyed to our group any detailed work regarding boundary conditions. The UK group did, however, write to Ulmer that their preliminary FEA work indicates the UK group will need 200μm of piezo material attached to a 400μm thick electroformed Ni to achieve the deflections they believe are necessary (Dick Willingale, private communication). The bottom line is that well funded and much larger groups than ours have not yet fully addressed the FEA/FEM necessary to prove beyond the shadow of a doubt that deformable mirrors will work for X-ray optics. Yet, both the groups are proceeding with full confidence this can be done. Given our hypothesis about being able to counteract stress in electroformed mirrors, we are also confident that our process will work as well.

We reiterate, the key difference between our approach and the piezo approach is that the piezo approach guarantees there must be wires and powered-on circuits in place to maintain figure. While in contrast, our approach has the potential to affect shape changes that need no continuous power as well as affect surface changes on a scale as small as 100 microns, such as the mid-frequency ripple, the bane of commercially available flat panel glass.

Returning to the issue of existence proof, any method of deforming the mirror, be it bi-morph, uni-morph, or magnetostriction needs to be concerned first with how to shape a free-standing mirror, and then how to support the mirror such that the mirror shape is not adversely affected. Applying stress or material removal (e.g. the classic case of grinding and polishing a glass mirror) in certain locations on the mirror will cause other related stresses elsewhere. This is a general problem, not peculiar to mangetosctriction.

The best way to address further proof that figure corrections are possible via applied stress is to begin by noting the process will be applied to grazing incidence optics. Therefore, the important issue is the slope error, on length scales of 100 microns and higher. Thus, the size of the deflections that make a noticeable difference are on the order of 1 micron over 20 cm to produce or correct for a 1 arc second deflection. Changes of this magnitude are easily possible as shown in the FEA/FEM work below.

A simple approximation that gives the total encircled energy scattered out of the reflected beam versus the incident beam is $I/I_0 = \exp(4\pi\theta\sigma/\lambda)^2$ where σ is the average surface roughness and λ is the wavelength, and θ is the grazing angle in radians. For our purposes, however, we will use ray tracing code, including our own and those available from the Gen X and the IXO programs to derive the requirements on slope error in the mid-low frequency range.

The need to consider boundary conditions is indeed important when active, in-orbit mirror adjustments are needed, and we will work with collaborator Will Zhang on aspects of mounting and boundary conditions as they especially pertain to glass segments. We also note that some FEM work on 1 m x 1m glass segments that includes boundary conditions was begun by CFA for Gen X (Paul Reid, private communication).

With regard to referee comments that our group should pay more attention and get help from the AO community: Ulmer has attended both a X-ray synchrotron optics AO conference, an extremely large telescope conference that contained an entire session on AO, and he already had and still has on his team a consultant, Dr. Mike Smutko, who got his Ph.D. in AO from renowned AO expert, Dr. Edward Kibblewhite. Thus, our team is well acquainted with normal incidence optics AO. We also have a co-investigator to carry out FEA/FEM. Mechanical Engineering Prof. Jian Cao of Northwestern Univ. will supervise a graduate student to apply her current analysis methods, already applied to a very similar problem, which is “spring back” in sheet metal that has been cut. Professor Cao also has laboratory facilities that can be utilized for the magnetic write-head experiments. Her laboratory has a laser texturing system that has a programmable stage with three-axis linear motion plus two rotation axes and spatial resolution in the nanometer range. The laser beam delivery tube can be replaced with the write head for our work.

The coupling of theoretical work and experiment is the very essence of our proposal, and we have put together a team that is well suited to carry out all the aspects of the project.

3.3 Specific Issues:

3.3.1 Mirror Thickness and Stiffness: The issue of stiffness is tricky as the mirror has to be stiff enough to maintain its shape, but not so stiff as that the MSM can't effect the desirable shape change. In this regard we note that: (a) the baseline for Gen X (which has carried out studies) is for 200 micron glass (Dan Schwartz for the Gen X team private communication); (b) the typical thickness of Wolter I Ni mirrors that have been flown on XMM are about 470 μm-1.07 mm; and (c) the Italian Wolter I group for the Hard X-ray Telescope proposed making extremely thin and flexible shells of 80 μm thickness. Thus, we will be able to find a proper balance between stiffness and the ability to deform the mirrors. It should be relatively straightforward to apply MSM to affect shape changes over the mm length scale (i.e., in the plane or curve of the mirror surface). Static or low frequency adaptive optics are particularly well suited as the place to begin since a permanent magnetic field that is written into a magnetically hard material that is coated with a MSM is the simplest and conceptually easiest way to start. A preliminary design concept and modeling result have already been presented in sections 2.1 and 2.2, plus preliminary FEA work is presented here (see also our progress report, section 4.0).

3.3.2 Magnetic material considerations: If the mirror is electroformed Ni or Ni-Co, then it will already be made of a high coercivity/magnetically hard material and the MSM will be applied to one side of this thin "foil". To be most effective, however, it would be best if the Ni were highly crystalline and highly oriented (crystallographically textured) to take advantage of the asymmetry of the magnetic response. This will involve some investigation of electroforming conditions on such properties. It may also be the case that we cannot get the maximum effect by this forming method, so alternatives may also be investigated. It is known from the hard drive fabrication that Co-based magnetic films can be oriented by the use of a base layer of Cr and appropriate adjustment of deposition (sputtering) conditions. Therefore, we are also considering the use of such Co-alloy (e.g., Co-Cr) layers, interleaved with the MSM layers in nanolayer construction (on the Ni or glass substrates/mirrors). The concept is visualized in Figure 3. This should help provide a hard magnetic (write) layer with the right orientation adjacent to the MSM layer, which may also be better oriented for efficient magnetization and maximizing of strain. The nanoscale structure (10-100 nm) of the crystal and magnetic domains should help in this regard, and also make the process more reproducible and predictable, since the total response will be averaged over a very large number of grains as opposed to the case of large grained structures commonly found in bulk cast materials. This approach will be especially useful with the thin glass mirrors, which may or may not need the electroformed Ni (or Ni-Co) layer.

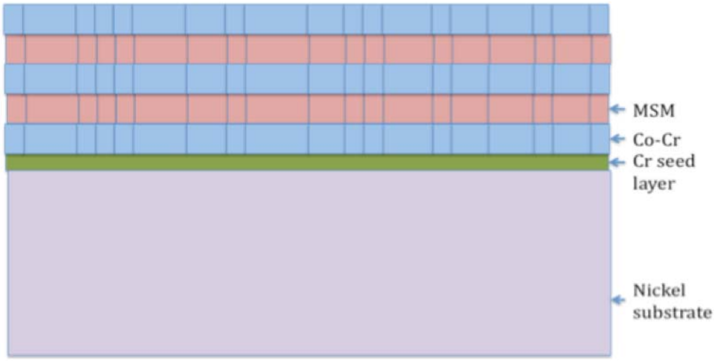

Figure 3. Cartoon of coating with columnar, textured structure on nickel.

3.3.3 Preliminary magnetostrictive material FEA/FEM : In order to determine how much stroke could be expected from a MSM film, a simple model was constructed by a former employee of Dr. Chad Joshi, a former collaborator with our group. The model was based on a 0.1-µm layer of KelvinAll$^{®}$, Joshi's patented magnetic "smart" material, and was represented in the model deposited onto a 200-µm thick glass substrate. The layer was magnetized with a unidirectional magnetic field source below the substrate. Dr. Joshi supplied the magnetostriction curve for the model obtained from in-house measurements. Substrate geometry and results are shown in Figure 4. The Finite Element grid is represented on the left and strain plot is on the right side of the figure. The computation indicates that this film, while only 0.1 µm thick, can apply 1.6 µm of stroke at the center of the mirror to correct unwanted bumps on the optical surface. The magnitude of this deformation in comparison to the layer thickness is very promising.

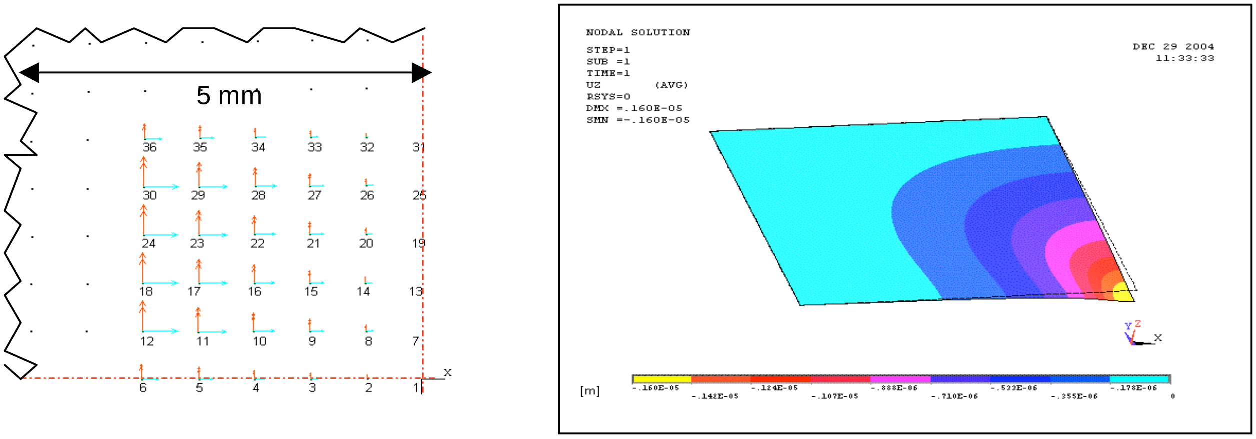

Figure 4. Magnetomechanical modeling results for 0.1 µm of KelvinAll® deposited onto a 200 µm thick 1 cm^2 glass substrate.

3.3.4 FEA/FEM - Stress-strain modeling

In our currently proposed work, Prof. Jian Cao will provide the theoretical modeling needed to interact with and guide the experimental development of the mirror structure. Applicable codes have already been developed that work for springback determinations in mechanical defomation of materials. Springback is referred to as the change of part shape that occurs upon removal of external constraints after forming. The phenomenon is due to the occurrence of primarily elastic recovery of the material at the unloading stage. The amount of springback is highly coupled with the stress distribution in the formed part prior to unloading, the applied boundary condition and material deformation behavior. This problem can be corrected by adjusting the tooling shape to the appropriate shape, i.e., the "springforward" method [13-17], and/or using active process control of external forces during the loading stage [18-20].

Several numerical methods [13-16] have been proposed aiming to reduce the number of iterations in the springforward process while achieving the desired tooling shape. In the work of Cao et al [17], we put all of those proposed methods [13-16] under the same mathematic framework. Additionally, built upon existing methods, a new methodology was proposed by incorporating pure geometry correction with fundamental mechanics analysis. As a consequence, the convergence becomes much faster and more certain. The algorithm was tested in the case of sheet metal forming under constraint. Numerical simulations using the Finite Element code, ABAQUS, were used to yield the desired tooling design, which was then used in experiment to validate our predictions. Note that gravity can be added as an external load in finite element simulations (FEM). The default setting is gravity-free. Our past work on the springback of an automotive body panel (unpublished work with General Motors) has shown that gravity needs to be considered in order to have an accurate prediction. Fortunately, with the well-established understanding of the physics law, such effect can be well captured in FEM.

In this proposed work, characterization of the mechanical behavior of the material response subjected to the magnetic field will be conducted first in one-dimensional loading and then in the bi-axial loading mode as our ultimate surface will have double curvatures in the main plane of the lens. The stress field subjected to the magnetic field will be analyzed using the finite element method. Results of the final geometry, first under the normal gravity condition, will be compared to the experimental data. Based on this knowledge, our springforward algorithm will be integrated into the design process to consider the normal gravity load on the Earth during the fabrication process, the extra gravity load during the launching process and the gravity-free condition in Space. Ultimately, the all-inclusive simulation tool will yield the desired shape.

3.3.5 Stability: Adding a high coercivity ferromagnetic layer to the MSM film creates a completely new paradigm for low-power figure control of X-ray optics. High-coercivity materials are those that retain their magnetization after the externally applied field has been removed. They are used extensively in magnetic storage technology, and the term active optics represents a lower-bandwidth or quasi-static subcategory of adaptive optics, which can be used to correct for manufacturing errors or slowly-varying undesirable mirror deformations.

Two issues that will be addressed in regards to stability are how the material reacts to vibration, and radiation. Both of these issues will be addressed by specific tests, making use of test facilities that NASA uses both for vibration and radiation. Facilities are available for both these tests at GSFC, but we have found that GSFC also uses a facility at the University of California, Davis at which Ulmer has been able to have electronics tested in parallel with other tests that GSFC has carried out. Thus, both kinds of testing will be relatively straightforward.

4. Progress Report, preliminary results.

4.1 Description of sample and experimental set-up for magnetization:

The Ni-foil mirrors are circular with a diameter of 5 cm and a thickness of 100 microns. They were electroformed from a Ni plating bath. The magnetostrictive material (MSM) was deposited by sputtering to a thickness of 1 micron on the smooth side of the foil. The Dektak stylus profilometer was used to measure the curvature of the foil along a centrally located 2-cm trace along a selected diagonal of the foil circle.

4.2 Magnetization and Demagnetization

Two different methods were used to magnetize the Ni foil samples. The first was a system consisting of two NdFeB bar magnets with a 6mm separation between the two magnets. This system gave a maximum magnetic field strength of approximately 3 KGauss and was used merely to confirm that a shape change could be measured. The other setup (for which the results are presented here) was more controlled, consisting of an electromagnet (two oppositely wound iron posts) and two flat, rectangular pieces of steel to use as pole pieces. The electromagnet was connected to an adjustable power supply that could provide a maximum of 3A. This gave a maximum field strength in the range of 1-2 KGauss. The two metal bars (25 mm x 6mm cross section) were placed on top of the electromagnet with a 6mm gap between them. The 50mm dia. sample was placed on a glass slide and placed over the gap between the two pole pieces.

In order to standardize the process as much as possible, the sample was always placed on the magnet in the same direction (A-C, for example). The power supply to the electromagnet could then be adjusted to obtain the desired field strength. Once magnetization was complete, the sample was removed from the electromagnet and measured. Dektak measurements of the curvature of the sample were made before (demagnetized) and after the samples were magnetized. To demagnetize the sample, a degaussing coil was used.

4.3 Preliminary Results The most conclusive results came from comparing the changes in curvature of samples Ni-1 (not coated) and Ni-3 (coated). The idea was to compare deflection on a non-coated piece versus a coated piece. The measurement was the change in the maximum deflection of the foil, which on average for the *coated foil* a net change of 6 microns. Both samples were measured over 20mm with the Dektak and repeatedly magnetized and demagnetized with the 1KGauss electromagnet. Sample Ni-1, the uncoated nickel foil, showed relatively small changes in curvature (generally less than 1μm maximum height/depth change). These changes were generally not reversed when the sample was demagnetized and appeared to represent the error bar in this measurement due to various factors. While the experimental set up was not as precise as we would like for a controlled process, it sufficed to demonstrate the order of magnitude of the effect.

In order to estimate the stresses involved in this process, we used a modified version of Stoney's equation shown below, which is commonly used in thin film work to determine the stress induced by a deposited coating on a substrate. As long as the deflection is elastic and the coating thickness is much smaller than that of the substrate, the equation is expected to hold and provide a fairly accurate estimate of residual stress. The thicknesses of the coating (h_f) and that of the substrate (h_s) were 1 μm and 100 μm, respectively. The elastic modulus of the substrate, (E_s), is taken from the literature (for Ni-plating) to be about 170 GPa and Poisson's ratio (v) is taken as 0.31. The length of the trace (L) was 20 mm and the maximum deflection (d) was 6 microns. The calculated stress is then about 49 MPa for the 6 micron deflection. We have approximated kappa (κ) in the formula as ($1/R_2 - 1/R_1$), where R_1 and R_2 are the radius of curvature, respectively, before and after the shape change due to magnetization.

Stoney's equation [21,22]:

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

5. A Study of Schott glass: Relevant to the ability of our proposed process to smooth surfaces on small (sub mm) length scales are the surface properties of Schott Glass. Thus, we present the surface characterization done at Brookhaven National Lab by Dr. Peter Takacs. Typical surface shape errors present in a 100μm thick D263T down-draw Schott glass sample that is used in making flat panel displays are shown in the folowing figures. These measurements were made with a Keyence LT9030M Confocal Displacement Meter mounted on an Aerotech XYZ gantry translation system. Measurements were made along the direction of the draw on a 100x100 mm square sample placed unconstrained on a flat surface. The profile shown on the left in Fig. 5 is taken from a scan down the center of the glass with 0.2mm measurement sample spacing.

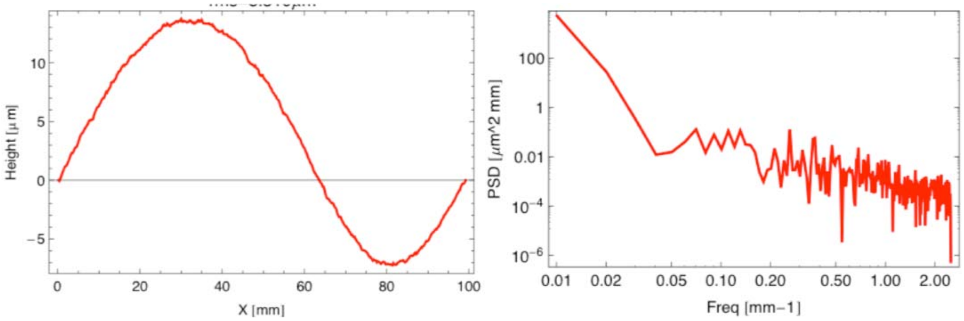

Fig 5 - Height profile of 100μm thick D263T flat panel glass (left) with typical low-order figure error. The PSD curve (right) shows that the low frequency error encompasses several low frequency harmonics before descending to the general roughness level.

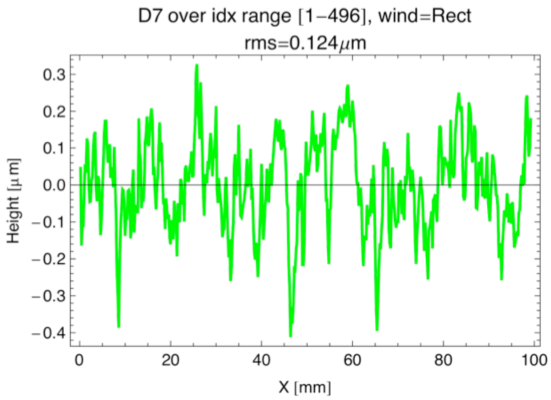

Fig 6 - Height profile after removing a LSF 7th order polynomial.

The unconstrained surface shape contains a significant third-order curvature with an RMS error of more than 8 microns. The power spectral density curve on the right in Fig 5 shows that there is significant power in several low-order spatial periods.

Removing a 7th order polynomial from the height profile eliminates all of the figure and mid-spatial frequency shape error. What remains in Fig. 6 in the residual profile is an RMS roughness of 0.124μm. This includes a system noise level of about 0.1μm, which actually masks the true high frequency behavior of the glass surface.

We can also view the surface in the slope domain by performing a Fourier differentiation on the height profile. The cumulative sum of the slope PSD curve (encircled energy) computed for this surface after removing a 3rd order height term is shown in Fig. 7. The 4th order residual contributes the initial 160μrad to the slope error. The spatial frequency range between the 4th harmonic and the 7th harmonic contributes another 25μrad to the slope error. It is slope error in the low frequency region that has the most serious effect on image quality in the telescope. This is the spatial frequency range that can be controlled most easily by the magnetostrictive film. Our work here then both shows the room for improvement that can be made and that we have the capability to measure quickly and easily the before and after effects of depositing a film on the glass and tuning the magnetic field pattern.

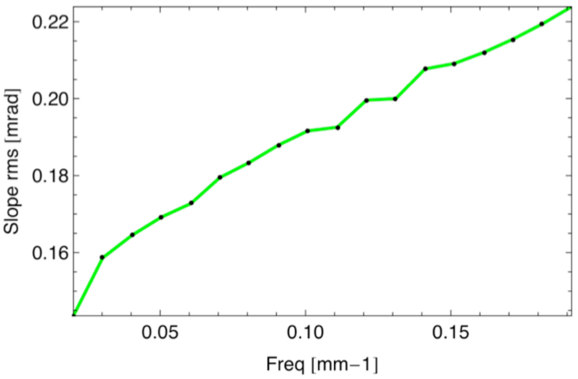

Figure 7

6. Major tasks and milestones and associated schedule:

Year 1

Task 1: Modify the large deposition chamber by adding two cathodes and substrate fixturing to deposit Terfenol D® films and the nanolayer structures using Terfenol D® and a ferromagnetic material such as iron, nickel, or cobalt alloy. Preliminary work reported here was performed in a small research sputtering system with 2” dia. targets. We will need our large chamber with two larger targets and the ability to rotate/translate our substrate in order to cover a larger area and to create multilayer structures.

Milestone: We will purchase, install and test system hardware. This phase should take about 2 months to complete.

Task 2: Develop a reliable and repeatable process for electroforming test samples with controlled stress and predictable figure. Develop technique and acquire mandrels for cylindrical mirrors. This task will involve appropriate measurements and feedback to the operation of the electroforming process. Initially, this work will be done with Nickel, with which we have significant experience, and will be extended to include Ni-Co alloy deposition.
Milestone: Protocol for the Ni deposition will be completed by month 3. Ni-Co will be undertaken in year 2.

Task 3: Carry out material comparisons, deposition schemes, and post-deposition treatments. Start with Terfenol D®, but also make nanolayer structures, interleaving selected ferromagnetic alloys with the Terfenol D® as time permits. The deposition variables and layer structures will affect the magnetic response, of course, but also the internal stress, which can also affect the mechanical response of the substrate-thin film system. We will characterize the process-structure-response relationships in order to optimize the response for our application. While focusing on a principle materials system to move the project forward, we will continue to explore nanolayer and material combinations. Post-deposition annealing will also be evaluated for its affect on structure, stress and performance.
Milestone: by the end of month 7 have decided on material and process direction for the first generation prototype structure.

Task 4: Deposit the MSM on both glass and electroformed Ni. Perform stress tests on free-standing pieces, both flats (about 2 inch in diameter) and electroformed ½ or ¼ cylinders (~ 10cm dia. by about 5cm long). Both the electroformed pieces made here at NU, and the IXO type glass provided by Will Zhang (see attached letter of support) will be coated.
Milestone: by the end of month 9 of the first year several pieces will be coated.

Task 5: In parallel with Tasks 1 and 2, carry out development of initial FEA/FEM codes and grids to guide us on the optimal thicknesses of both the MSM and the substrate. Begin to adapt models to accommodate multi/nano-layer structures as well as patterned deposition on the Ni substrate.

Milestone: Obtain the required materials property values and develop basic framework (boundary conditions, grids, etc.) for the modeling by month 9 of the year.

Task 6: Compare FEA/FEM work with measurements:
Milestone: By the end of the first year, make first pass at modification of FEA/FEM to iterate with the hardware work. This includes on one hand, guiding fabrication and on the other hand modifying the FEA/FEM to fit the observations as accurately as possible.

Task 7: Concurrent with FEA/FEM development, design initial version of hardware for magnetizing selected areas on test samples, first on flats and then on cylinders. The manufacturing group at the Department of Mechanical Engineering has designed/constructed different research equipment for various fabrication processes, e.g., laser processing, machining and forming. One common feature among all these equipment is the moving stage, which is capable of precisely controlling samples' movement in multiple degrees of freedom. In this work, we are going to select one of those systems that best meets the need of this project in terms of size and precision requirement, and then replace the tool in the z-axis with a magnetic head. Care will be given to eliminate any potential signal crossing in the new system. Ultimately, the

magnetic head can either be permanent magnetic or can be electro-magnetic. In the latter case, our position system can be seamlessly integrated with the electrical pulses, similar to what we do now for controlling the firing of the pico-second laser.
Milestone: Have initial design and some preliminary simulation data from different magnetic heads done by the end of the first year to guide the final design and fabrication.

Year 2

Task 1: Use refined FEA/FEM.
Milestone: To show that the theory not only fits observations, but also makes accurate (sub micron deflections normal to the surface) predictions by month 4 of year 2.

Task 2: Test various measurement systems (optical and mechanical) as a means of ***characterizing*** the figure of larger pieces and the non-flat pieces to be coated in year 3. **Milestone:** Use experimental data to begin validation of feed back loop between magnetizing the substrates and the FEM/FEA.

Task 3: Develop the Ni-Co deposition process for flat and cylindrical parts. Characterize stresses and structures of the electroformed shells.
Milestone: Achieve successful deposition and control of process by month 4 of year 2.

Task 4: Build the basic system for magnetizing the selected areas of the samples. **Milestone:** By month 4 in year 2, have operational model of magnetic patterning device for flats and concepts developed for cylindrical parts. Have operational models for both flat and cylindrical mirrors by year end.

Task 5: Based on the FEA/FEM predictions and experimental results, modify the coating and the substrates for optimized performance. Even if it is not possible to modify the basic glass, the coating can be modified.
Milestone: complete the task prior to the end of year 2.

Task 6: Test permanency of the effect by relating stability to structure and materials. Is Ni-Co better than Ni? Are layered structures beneficial?
Milestone: Compare results over time and set direction for optimized design by year end.

Task 7: Carry out vibration and radiation tests.
Milestone: Year end - Based on results of this year, modify fabrication facilities as needed. e.g., convert baths to Ni-Co, modify sputtering compositions and hardware, etc.

Year 3

Task 1: Use result of years 1 and 2 to make optimally formed and coated pieces, both flat glass segments and Ni-Co cones (10 cm diameter and 10 cm long with a draft angle of about 30 arc min (about 9 milli-rad)).
Milestones: Verify concept and produce a technical report useful for IXO, Gen X and for other programs that could use the technology. Done 6 months prior to the end of the project

Task 2: Produce a follow-on plan that would make a full scale Wolter I optics with the goal of 1 arc sec (~ 4.9 micro-radians**).**
Milestone: Completion of task 2 by 6 months prior to the end of the project.

Task 3: Write a final technical report.
Milestone: delivered within 60 days of the end of the award.

7. **Key Project personnel**

Professor Mel Ulmer – P.I.

Professor Ulmer will have overall responsibility for the management of the project, and will coordinate all the activities. He is an expert in electroforming design as well as X-ray optics design and metrology. He is also an X-ray astronomer who understands the requirements of the final product. He will supervise a student who will carry out ray tracing to predict the mirror performance. Ulmer along with Takacs has experience running ray tracing codes such as OSAC, which we have budgeted to purchase.

Research Professor Semyon Vaynman – Co-I

Dr. Vaynman will be responsible for the electroforming activity at Northwestern University, collaborating with Dr. Graham and Energen personnel. Also he will be involved in characterization of the mirrors materials. Dr. Vaynman has extensive experience in electroforming, electrochemistry and materials characterization through SEM and XRD.

Research Professor Michael Graham – Co-I

Dr. Graham will be responsible for the sputter coating activity at Northwestern, collaborating with Dr. Joshi in the development of the MSM coating and working with Dr. Vaynman as needed to develop seed layers for enhancing directional nickel growth. Dr. Graham has been working in thin film deposition for nearly 30 years and has much experience developing process-structure-property relationships in the sputter deposition process.

Prof. Jian Cao- Co-I Prof. Cao has expertise in mechanics analysis and process control of deformation processes and laser processes. She and her graduate student(s) will modify the existing positioning system in her lab for the proposed magnetizing system, and will further develop her springforward algorithm to incorporate the effect of magnetizing onshape change, and therefore reaching the desired shape with a minimum number of iterations.

Senior Lecturer Michel Smutko –Collaborator

Dr. Smutko did his Ph.D. on adaptive optics at the Univ. of Chicago under Prof. Ed Kibblewhite. Dr. Smutko will provide a very important local source of knowledge of and experience with adaptive optics and issues such as actuator creep, which is a known concern with mechanical actuators.

Dr. Peter Takacs – Brookhaven National Lab (BNL)- Collaborator

Dr. Takacs is director of the BNL optics lab. He is an expert in metrology of optical elements, and he will provide the key support for evaluating the ability of the MSM to shape our mirrors.

8. Applications Outside of X-ray Astronomy: Besides the typical bi-morph mirror being used now, our mirror technology could play a role in synchrotron facilities where a nested system is necessary to collect as much light as possible. X-ray optics is being explored more and more for lithography related to super high density ASICs, and a less expensive method of mirror manufacture will be important. Solar physics needs true (as opposed to coded aperture) imaging above 10 keV. The typical relatively short focal length (<2 m) designs then call for such small diameter mirrors (<12 cm), that electroformed mirrors with multilayers on the inside surface as pioneered by Ulmer et al [22] is the best approach. However, without the figure modification we propose to develop, the required 1 arc second (or better) angular resolution will not be achievable. Finally, the Bragg crystals needed for the next generation National Light Source (NSL2) could due to the heat load they will experience, make use of our technology and Ulmer has made a trip to Brookhaven National Lab to begin exploring this option.

In conclusion, then, the use of MSM has great potential usefulness both inside and outside of X-ray astronomy. The concept ought to be pursued, and we have assembled an excellent team to do this.

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