# Idaho Incubation Fund Program

Final Report Form

**Proposal No.** **IF15-003**

**Name:** **Peter Mullner**

**Name of Institution:** **Boise State University**

**Project Title:** **Integral 3D Strain Sensor Phase II**

**Information to be reported in your final report is as follows:**

1. Provide a summary of overall project accomplishments to include goals/milestones met, any barriers encountered, and how the barriers were overcome:

    a) *Activities for identifying industry partners*: We organized a business development event at the 4th International Conference on Ferromagnetic Shape Memory Alloys. Following this event, we initiated an international network "MSM-Net" for connecting researchers and industrial developers and bringing our technology to the market. The kick-off meeting of MSM-Net was held at the ACTUATOR 2014 conference on June 25, 2014, in Bremen, Germany. Müllner co-chaired this meeting. MSM-Net will meet again on September 20, 2015 at the SMASIS conference in Colorado Springs, CO.

       In January 2015, Müllner registered Shaw Mountain Technology LLC (SMT) with the State of Idaho. SMT aims to commercialize technology developed in the field of magnetic shape memory alloys and to produce this technology in Idaho. In July 2015, SMT hired Dr. Aaron Smith who is a BSU alumnus. Müllner considers pursuing some outcomes of this project for commercialization.

    b) *Research activities*: We produced Ni-Mn-Ga single crystal powders by crushing single crystals and annealing the powders. With X-ray diffraction, we demonstrated the desired crystallographic structure. With magnetization experiments, we demonstrated successfully a low switching field of 200 mT, which is clearly below the specified upper limit of 300 mT ensuring high twin mobility. We identified and purchased elastomer matrix material, produced Ni-Mn-Ga/elastomer composites, and performed preliminary mechanical experiments. We made double-coils for 1-D sensor tests and measured the strain-induced change of coil inductance at a single crystal.

Figure 1a) shows a single crystal powder particle with one set of twin boundaries. The particle was oriented in a magnetic field, embedded in a raisin, and then polished. To orient the samples, we built a set of Helmholtz coils which we run with a 1500 W power supply. The x-ray diffraction pattern (Fig. 1b) demonstrates that the polished surface was within a few degrees parallel to {100}.

a) b)

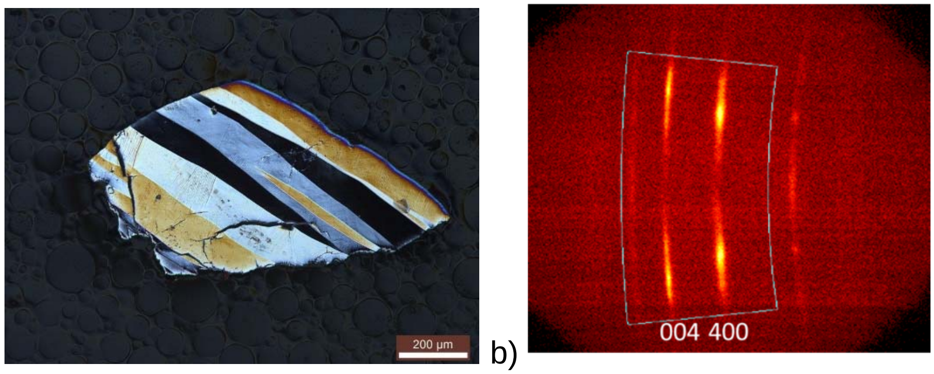


*Figure 1: Single crystalline Ni-Mn-Ga powders . (a) Optical micrograph of a powder particle with one set of twin boundaries. (b) x-ray diffraction results from a single powder particle demonstrating successful orientation.*

We improved the resolution of the sensing apparatus with an analog to digital converter (U2542A) with high resolution and four channels to measure the induced voltage. Figure 2 shows the new experimental set-up and a diagram with input and output variables.

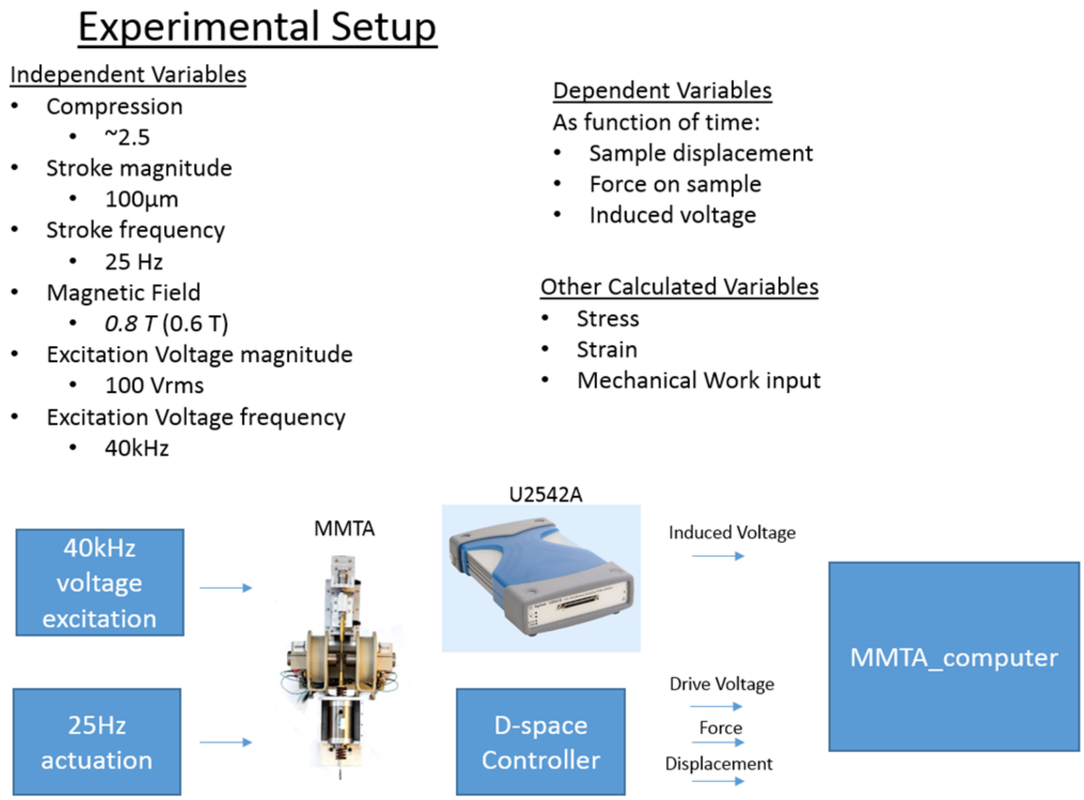


*Figure 2: Experimental setup: a drive coil sends a 40 kHz signal which is sensed by the pick-up coil.*

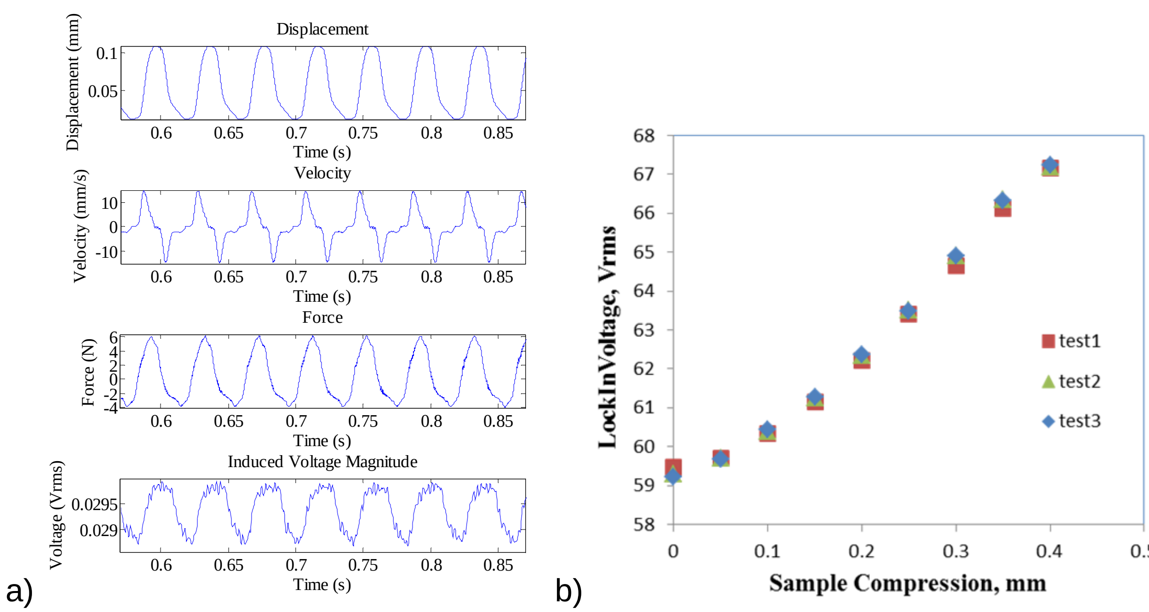


*Fig. 3: (a) Output signals recorded with the experimental set-up shown in Figure 2. (b) Plot of the displacement and voltage data shown in (a).*

Switching field experiments serve to identify twin reorientation which is a precondition for the strain sensing mechanism. Switching field tests were done alternating at 90 degree angles, switching the magnetic axis between orthogonal directions in the crystal. The graphs in Figure 4 show tests done at the same angle, with one orthogonal test done in between. We see a switching event in the first experiment (left, note the step-like increase of the blue curve around 3500 Oe) but no switching event in the second experiment (right).

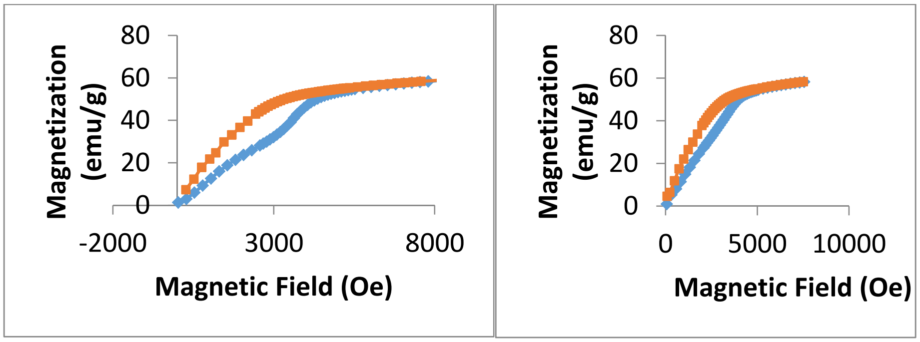


*Figure 4: Switching field tests performed at the same angle, with one perpendicular switch in between.*

To systematically characterize particles and compare their properties with bulk crystals, we grind the irregularly shaped particles into cubes with all faces parallel to {100}. For this purpose, we apply a magnetic field which orients the particles, embed the oriented particles in an epoxy, and polish one face and subsequently the opposite face. We then perform an x-ray diffraction experiment to verify that the surface is parallel to {100} (Figure 5). With additional x-ray diffraction experiments we can identify a second {100} orientation and polish that pair of faces. Finally, we polish the third pair of faces to make a cube. To date, we demonstrated the first pair of faces and are in the process of preparing finished cubes with three pairs of {100} faces.

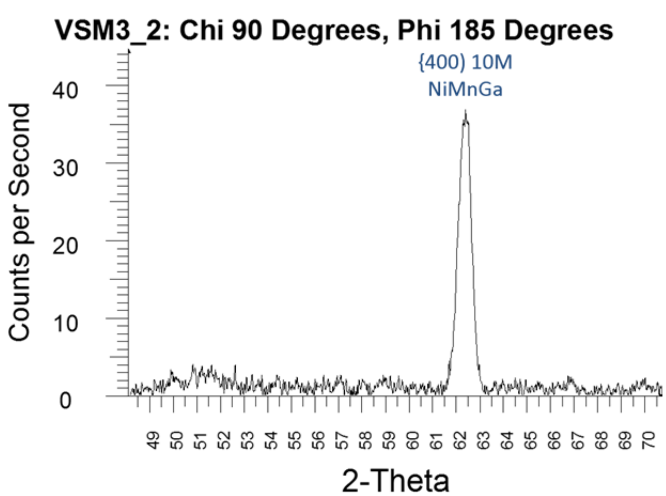

*Figure 5: X-ray trace taken from a polished surface of a particle demonstrating that the surface is parallel to {100}.*

We obtain a relationship for the root mean square (RMS) voltage from the coil vs. strain of the sample during post processing using Matlab. Figure 6 (a) and (c) display this relationship. The relationship is fitted using a 5$^{th}$ order polynomial shown as the red line. This gives voltage as a function of strain, and vice-versa. Using the equation of the fitted line, we can plot Stress vs. Strain using solely the voltage. The blue curves in Figure 6 (b) and (d) are the direct stress vs. strain curves, while the magenta curves use only the voltage and polynomial fit to approximate strain. The estimated stress vs. strain curve is very similar to that of the directly measured data.

The accuracy of the purple lines in Figure 6 (b) and (d) is a measure for the strain measuring capacity of this method. This result is surprising since the range of induced voltage is only a 1% (50 $\mu$m stroke, Figure 6a,c) and 5% (150 $\mu$m stroke, Figure 4b,d) of the measured value. Work is needed to improve the RMS voltage range.

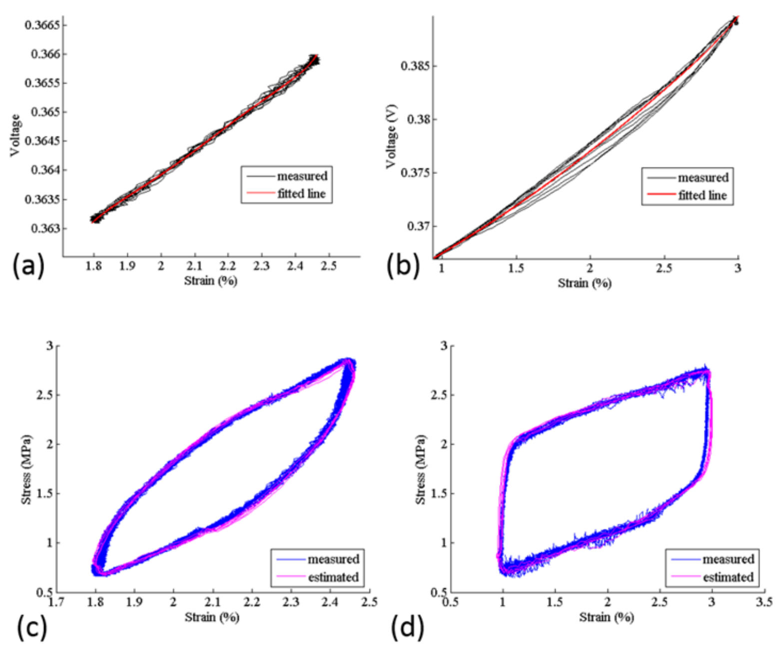


*Figure 6: Experimental setup using the magneto-mechanical testing apparatus. The sample is dynamically actuated, the stress, strain, input and output voltage are acquired using the Agilent U2542A 14-bit analog to digital converter.*

In summary, we demonstrated the fabrication of Ni-Mn-Ga single crystal particles with faces parallel to {100} with suitable magneto-mechanical properties. We also demonstrated the sensing capability. Though the stress-strain curves can be reconstructed well using the RMS voltage values, the resolution is limited by the comparatively small range of the voltage response (Fig. 6a,b).

2. Describe the current state of the technology and related product/service:

   We have demonstrated:

   a) the concept of strain sensing (Figure 6)
   b) the feasibility of producing powder particles exhibiting a switching field (Figure 4)

   Research will continue on characterizing powder particles. Three scientific publications are currently in preparation.

3. List the number of faculty and student participants as a result of funding:

   Faculty involved: Dr. Peter Müllner (PI), Dr. Nader Rafla (co-PI)
   Students involved: Tony Hobza (PhD student), Charles Link Patrick (undergraduate student), Miranda Buttram (undergraduate student), Andrew Morrison (undergraduate student), Eric Rhoads (undergraduate student)

4. What are the potential economic benefits:

   - Direct economic benefits: The creation of SMT has generate one tax-paying job.
   - Indirect economic benefits: The work performed through this project has spurred further ideas for using magnetic shape memory alloys for the generation of electrical power from heat sources (including solar energy). Boise State University plans on pursuing a patent on this technology with potentially very high economic benefits for the State of Idaho.

5. Description future plans for project continuation or expansion:

   - Continuing research on Ni-Mn-Ga powder particles
   - Publishing three articles
   - Filing a patent on electrical power generation using magnetic shape memory alloys
   - Commercialize technology through SMT

6. Please provide a final expenditure report (attached) and include any comments here:

7. List invention disclosures, patent, copyright and PVP applications filed, technology licenses/options signed, start-up businesses created, and industry involvement:

K. Ullakko, K. Sasaki, P. Müllner, “Sensor Device”, Non-Provisional Application for United States Letters Patent.

8. Any other pertinent information:
   - Shaw Mountain Technology LLC
     - 891 W. Gettysburg St., Boise, ID, 8370
     - President: P. Müllner
     - Number of employees: 1

**FINAL EXPENDITURE REPORT**

| A. FACULTY AND STAFF | | |
|---|---|---|
| Name/Title | $ Amount Requested | Actual $ Spent |
| Peter Mullner, Professor | $3,523 | $3,526.82 |
| Nadar Rafla, Professor | $2,419 | $2,419 |
| Paul Lindquist, Senior Lab Engineer | | $3,933.12 |
| **B. VISITING PROFESSORS** | | |
| Name/Title | $ Amount Requested | Actual $ Spent |
| | | |
| | | |
| **C. POST DOCTORAL ASSOCIATES/OTHER PROFESSIONALS** | | |
| Name/Title | $ Amount Requested | Actual $ Spent |
| | | |
| | | |
| **D. GRADUATE/UNDERGRADUATE STUDENTS** | | |
| Name/Title | $ Amount Requested | Actual $ Spent |
| Graduate Student: Anthony Hobza | $18,000 | $15,337.52 |
| Undergraduate Students: | $6,580 | |
| Charles Patrick | | $4,966.70 |
| Andrew Morrison | | $709.20 |
| Eric Rhoads | | $1,027.02 |
| Miranda Buttram | | $1,992.65 |
| **E. FRINGE BENEFITS** | | |
| Rate of Fringe (%) | $ Amount Requested | Actual $ Spent |
| Peter Mullner | $915 | $893.43 |
| Nader Rafla | $798 | $631.93 |
| Paul Lindquist | | $1,518.64 |
| Anthony Hobza | $990 | $317.68 |
| Charles Patrick | $389 | $165.54 |
| Andrew Morrison | | $4.78 |
| Eric Rhoads | | $6.53 |
| Miranda Buttram | | $104.77 |
| **PERSONNEL SUBTOTAL:** | **$33,650** | **$37,555.33** |
| **F. EQUIPMENT: (List each item with a cost in excess of $1000)** | | |
| Item/Description | $ Amount Requested | Actual $ Spent |
| 1.Precision Wire Saw, Model No | | $2,488.75 |
| 2. | | |
| 3. | | |
| 4. | | |

| | | |
|---|---|---|
| **EQUIPMENT SUBTOTAL:** | | $2,488.75 |

**G. TRAVEL**

| Description | $ Amount Requested | Actual $ Spent |
|---|---|---|
| 1.Visiting industrial partners | $600 | |
| 2. | | |
| 3 | | |
| **TRAVEL SUBTOTAL:** | $600 | |

**H. PARTICIPANT SUPPORT COSTS:**

| Description | $ Amount Requested | Actual $ Spent |
|---|---|---|
| 1. | | |
| 2. | | |
| 3 | | |
| **PARTICIPANT SUPPORT COSTS SUBTOTAL:** | | |

**I. OTHER DIRECT COSTS:**

| Description | | $ Amount Requested | Actual $ Spent |
|---|---|---|---|
| 1. Materials and Supplies | | $3,500 | $1,533.58 |
| 2. Publications and dissemination | | $300 | |
| 3.BCSMC Fees 120 hours at $35 | | $4,200 | $673.34 |
| 3. Graduate Student Remission | | $7,750 | $7,749 |
| **OTHER DIRECT COSTS SUBTOTAL:** | | $15,750 | $9,955.92 |

| | | |
|---|---|---|
| **TOTAL COSTS (Add Subtotals):** | $50,000 | $50,000 |
| **TOTAL AMOUNT REQUESTED:** | | $50,000 |
| **TOTAL AMOUNT SPENT:** | | $50,000 |