KOSTYANTYN MALUKHIN
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EDUCATION (Total GPA = 3.7/4.0)

Northwestern University, Evanston, IL, PhD candidate, Mechanical Engineering 2000-present
(Expected graduation date: 2008)
www.northwestern.edu

Course work: Residency credit accepted toward PhD – 1 Quarter from Zhukovskiy Aviation Institute; Mechanical Behavior of Solids; Biomaterials; Electron Microscopy; Introduction to MEMS; Deformation and Fracture; Advanced Electron Microscopy; Selected Topics in Mechanical Engineering (Advanced Materials); Metal Cutting; Selected Topics in Mechanical Engineering (Nanotechnology); Introduction to Digital Control; Manufacturing Automation; Metal Forming.

Dissertation: “Shape Memory Alloy Based Micro-Meso Scale Manipulator”
Scientific Advisor: Prof. Dr. K.F. Ehmann
Qualifying Exam Committee: Prof. Dr. Kornel F. Ehmann, Prof. Dr. L. Catherine Brinson, Prof. Dr. Chi-Haur Wu

National Aero-Space University, Kharkov, Ukraine
(Kharkov Aviation Institute “KhAI”, named after Zhukovskiy)
www.khai.edu

Candidate for the Technical Sciences degree 1997-2000
Dissertation:” Modeling of Heat Transfer Loops of Spacecraft Thermal Control Systems”
Scientific Advisor: Prof. Dr. G.A. Gorbenko
Scientific Opponents:Prof. Dr.V.A. Maliarenko, Dr. E.N.Shevchuk

Specialist in Mechanical Engineering degree (BS and MS) 1991-1997
(1997 *Suma Cum Laude* Graduate)
Thesis: “Experimental Facility – Functional Analogue of the International Space Station “Alpha”

PROJECTS

1) Shape Memory Alloy (SMA) Micro/Meso Scale Monolithic Manipulator (current PhD research)
2) Micro-Tool Clamping using SMAs
3) Advanced WC-Co and Al_2O_3 Coatings
4) Experimental and Numerical Modeling of the Ground Functional Prototype (test bed) of the Two-Phase Flow Thermal Control System of the International Space Station
5) Numerical Modeling of the Bubble Condenser of a Nuclear Power Plant (NPP) Test Facility
6) Numerical Modeling of a Capillary Pumped Loop (CPL)

EXPERIENCE

Northwestern University, Mechanical Engineering Department, Evanston, IL 2000-present

- **Research Assistant**:
  - Collaborated in developing a new method of processing of commercially available SMA (NiTi) powders by laser based Direct Metal Deposition (DMD) with researchers at Southern Methodist

University (RCAM/SMU). Identified parameters (laser power, powder feeding rate, and coolant flow rate through a heat exchanger) for the deposition of NiTi powders by DMD using a factorial design of experiments.
- Performed material (NiTi) preparation and characterization: heat treatment (annealing) using a vertical oven with argon protective atmosphere; polishing and grinding; microscopy analysis using scanning electron microscope and optical microscope; tensile testing of dog-bone specimens water-jet machined from commercially available NiTi metal sheets using a tensile machine; differential scanning calorimetry measurements and analysis; secondary ion mass spectroscopy measurements and analysis; X-ray diffraction measurements and analysis, optical profilometry and analysis.
- Established a One-Way Shape Memory Effect (OWSME) thermo-mechanical treatment procedure for material fabricated by DMD from NiTi powder.
- Established a Two-Way Shape Memory Effect (TWSME) thermo-mechanical treatment procedure for a commercially available NiTi alloy used in the micro-tool clamping device.
- Developed a mathematical model based on a system of 0-D equilibrium differential equations to describe the austenitic phase fraction evolution in SMAs (NiTi). Derived an analytical phase transformation function based on the model. Experimentally verified the model.
- Developed a mathematical model of SMA properties based on a 3-D differential equation. Wrote a user material subroutine in Visual Fortran that implements the model.
- Developed a motion control model of a monolithic micro/meso-scale manipulator. Wrote the corresponding "Simulink" program. Experimentally verified the model.
- Designed, and experimentally and numerically modeled a monolithic micro/meso-scale manipulator prototype.

- **Teaching Assistant:**
  - Prepared and/or conducted laboratory exercises and/or lectures in 4 engineering undergraduate and graduate courses (Experimental Engineering ME-224, Mechanics of Materials CE-216, Manufacturing Automation ME 340-3 and computer Integrated Manufacturing ME 340-2), supervised student projects.
  - Completed the Teaching Excellence Program. 2000-2001

Center of Technical Physics of National Aero-Space University, Kharkov, Ukraine 1995-2000
(www.khai.edu)

- **Engineer-researcher:**
  - Performed numerical non-stationary simulations and analysis of a ground test prototype of a two-phase flow thermal control system for the International Space Station. Modified the provided Fortran subroutine that was based on a mathematical model consisting of a system of equilibrium stiff partial differential equations with constant coefficients. Experimentally verified the transient simulations using the ground functional analogue – test facility.
  - Created an input file and performed numerical simulations and analysis of thermal hydraulic processes in a bubble condenser of an NPP test facility using a provided numerical code "RALOC".
  - Developed a Fortran subroutine to conduct non-stationary numerical simulations of Capillary Pumped Loop (CPL) operation. Performed numerical simulations to predict instabilities in the CPL.

Elektrogorsk Research Engineering Center (EREC), Elektrogorsk, Moscow reg., Russia February-May, 1999
(www.erec.ru)

- **Part-time engineer:**
  - Performed a data reduction on the bubble condenser of the NPP (WWER - 440) test facility to use in the input file for the numerical simulations using code "RALOC"

AWARDS

Edmund S. Muskie and Freedom Support Act Graduate Fellowship Program 2000

- Awarded an educational fellowship ($60,000/2years)

GRANTS

National Science Foundation (NSF) 2004-present

- Graduate Research Assistant under the NSF (USA) grant #DMI-0400316 - "Shape Memory Alloy Based Micro/Meso Scale Manipulator" (Principal Investigator: Prof. Dr. Kornel Ehmann)

HARDWARE SKILLS

Scanning electron microscope (SEM-3500), optical microscope, tensile machine, differential scanning calorimeter (DSC), optical profilometer ("MicroXAM", ADE Phase Shift), secondary ion mass spectrometer (SIMS), transmission electron microscope (TEM-8100), X-Ray diffractometer (SCINTAG)

COMPUTER SKILLS

Visual FORTRAN, C, MatLab, Simulink, Unigraphics NX and NX3, ProEngineer, SolidWorks, ABAQUS (FEM based simulation package), RALOC, LabVIEW, MS Office (Excell, Word, Power Point, etc.), HTML

LANGUAGES

Native: Russian, Ukrainian. *Fluent*: English.

PUBLICATIONS

A). List of publications on the project "Shape Memory Alloy (NiTi) based Micro/Meso Manipulator"
*(Department of Mechanical Engineering, Northwestern University, Evanston, IL, USA, **www.northwestern.edu**)*

Published:

1. K. Malukhin, K. Ehmann, 2006. "Material Characterization of NiTi Based Shape Memory Alloys Fabricated by the Laser Direct Metal Deposition Process." *Journal of Manufacturing Science and Engineering*, Vol. 128, pp. 691-696.

2. K. Malukhin, K. Ehmann, 2006. "Manufacturing of Shape Memory Alloy Based Monolithic Functional Structures with Shape Memory Effect Properties." *Transactions of the North American Manufacturing Research Institution of SME*, Vol. 34, pp.261-268.

3. K. Malukhin, K. Ehmann 2006. "Direct Metal Deposition of Shape Memory Effect Driven Actuators – Functional Parts of a Monolithic Shape Memory Alloy Based Micro/Meso Manipulator." *Proceedings of 2006 NSF Design, Service, and Manufacturing Grantees and Research Conference, St. Louis, Missouri, July 24-27, 2006.*

4. K. Ehmann, K. Malukhin, 2005. "Monolithic shape memory alloy based micro/meso manipulator: manufacturing and material characterization," *Proceedings of NSF Design, Service and Manufacturing Research and Grantees Conference, Scottsdale, Arizona, 2005.*

5. K. Malukhin, K. Ehmann, 2006. "A Monolithic Shape Memory Alloy Based Micro/Meso Scale Manipulator," *Proceedings of the 5th International Workshop on Microfactories (IWMF'06), Besancon, France, October 25-27, 2006.*

6. K. Malukhin, K. Ehmann, 2006. "The Possibility of the Development of a "Self-Sensing" Shape Memory Alloy Based Actuator", *Proceedings of the 1st International Conference on Micromanufacturing – ICOMM 2006*, pp. 231-236.

7. K. Malukhin, K. Ehmann, 2007. "Identification of Direct Metal Deposition (DMD) Process Parameters for Manufacturing Thin Wall Structures from Shape Memory Alloy (NiTi) Powder", *Transactions of the North American Manufacturing Research Institution of SME, Vol. 35, pp.481-488.*

8. K. Malukhin and K. Ehmann, 2007. "Model of Motion of an Actuator Based on a NiTi Shape Memory Alloy". *Proceedings of the 2nd International Conference on Micromanufacturing ICOMM 2007, Greenville, South Carolina, September 10-13, 2007, pp.247-251.*

Accepted for publication:

1. K.. Malukhin, K. Ehmann, 2008. "Development of a "Smart" Monolithic Shape Memory Alloy Manipulator", *Accepted for publication in the Proceedings of the Fourth International Precision Assembly Seminar, IPAS'2008.*

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Submitted:

1. K. Malukhin, K. Ehmann, 2007. "An Experimental Investigation of the Feasibility of "Self-Sensing" Shape Memory Alloy Based Actuators", *Submitted for publication to the Journal of Manufacturing Science and Engineering.*

B). List of publications on the project on advanced WC-Co and Al_2O_3 coatings
*(Department of Mechanical Engineering, Northwestern University, Evanston, IL, USA, **www.northwestern.edu**)*

Published:

1. F. Barthelat, K. Malukhin, and H.D. Espinosa, 2002. "Quasi-static and Dynamic Torsion Testing of Ceramic Micro and Nano-Structured Coating Using Speckle Photography", E.E. Gdoutos (ed.) *Recent Advances in Experimental Mechanics. In honor of Isaac M. Daniel, Sacaucus, NJ, USA: Kluwer Academic Publishers,* pp. 75-84.

2. F. Barthelat, K. Malukhin, and H.D. Espinosa, 2002. "Quasi-static and Dynamic Torsion Testing of Nano-Coatings Using Speckle and High-speed Photography", *Proceedings of 2002 Annual meeting of the Society of Experimental Mechanics,* June 10-12, Milwaukee, Wisconsin.

C). List of publications on the project on Experimental and Numerical Modeling of the Ground Functional Prototype of the Two-Phase Flow Thermal Control System of International Space Station
*(National Aero-Space University "Kharkov Aviation Institute" (KhAI), Center of Technical Physics, Kharkov, Ukraine **www.khai.edu** , together with Rocket-Space Corporation "ENERGIA", Russia)*

Published:

1. V. M. Cykhotsky, A. N. Sementsov, Y. I. Grigoriev, Y.M. Prokhorov, G. A. Gorbenko, C.A. Malukhin, E.P. Ganja, 1999. "Development and Analysis of Control Methods of the International Space Station "ALPHA" Russian Segment Central Two-Phase Thermal Control System Parameters"**,** *Mohamed S. El-Genk (ed.), Space Technology and Applications International Forum, AIP Proceedings,* Vol. 485, pp. 848-853.

2. Y. I. Grigoriev, E.I. Grigorov, V. M. Cykhotsky, Y.M. Prokhorov, G.A. Gorbenko, V.N. Blinkov, N.A. Brus, C.A. Malukhin, E.P. Ganja, 1997. "Control of Parameters of the International Space Station ALPHA Russian Segment Two-Phase Thermal Control System", *Mohamed S. El-Genk (ed.), Space Technology and Applications International Forum STAIF-97, AIP Proceedings*, Vol. 387, pp. 587-592.

3. Y.I Grigoriev, E.I. Grigorov, V.M. Cykhotsky, Y.M. Prokhorov, G.A. Gorbenko, V.N. Blinkov, I.E. Teniakov, C.A. Malukhin, 1996. "Two-phase Heat Transport Loop of Central Thermal Control System of the International Space Station "Alpha" Russian Segment", *Mohamed S. El-Genk (ed.), Heat Transfer, AIChE Symposium Series,* Vol. 92 (310), pp.9-18.

4. G.A. Gorbenko, E.P. Ganja, K.A. Malukhin, A.A. Prokopenkov, Y.M. Cykhotsky, A.N. Sementsov**,** I.Y. Linkova, 1998. **"**Engineering synthesis of Central Two-Phase Thermal Control System of International Space Station "ALPHA" Russian Segment", *1997 Transactions of a National Aero-Space University "Kharkov aviation institute" (KhAI) named after N.E. Zhukovskiy, Kharkov, Ukraine,* pp.168-176.

5. V.M. Cykhotsky, A.N. Sementsov, Y.I. Grigoriev, Y.M. Prokhorov, G.A. Gorbenko, K.A Malukhin, 1999. **"**Two-phase central thermal control system (TPS) of international space station "ALPHA" Russian Segment", *Thermal and Fluids Analysis Workshop (TFAWS-98) Proceedings, NASA Lewis Research Center, Cleveland, Ohio, August 30- September 3,* pp.69-81.

6. Prokhorov Y.M., Sementsov A.N., G.A. Gorbenko, E.P. Ganja, C.A. Malukhin, A.A. Prokopenko, 1997. **"**Condensation and capillary transport of liquid on the profiled surfaces", *Proceedings of the International Symposium on the Physics of Heat Transfer in Boiling and Condensation and 11th International School-Seminar of Young Scientists and Specialists, May 21-24, Moscow, Russia,* pp. 551-555.

7. V.N. Blinkov, P.G. Gakal, G.A. Gorbenko, E.D. Domashev, K.A. Malukhin, 2000. "Methodology of System Modeling and Engineering Synthesis of Complex Thermal Power Systems", *Industrial Heat Engineering (ISSN 0204-3602), Vol. 22 (2), pp.71-77.*

8. K. A. Malukhin, 2000. "Modeling of Thermal Power Modes of the Advanced Objects of Aero-space and Ground Industries", *Integrated Engineering and Power Saving Technologies (ISBN 5-7763-2106-9, ISBN 5-7763-2107-7), Vol.2, pp.19-24.*

D). List of publications on the project on Numerical Modeling of the Thermal Control System (Bubble Condenser) of a Nuclear Power Plant (NPP)

*(National Aero-Space University "Kharkov Aviation Institute" (KhAI), Center of Technical Physics, Kharkov, Ukraine, **www.khai.edu** together with Gesselschaft fur Anlagen und Reaktorsicherheit (GRS), Berlin, Germany, **www.grs.de** and Electrogorsk Research Engineering Center (EREC), Electrogorsk, Moscow reg., Russia, **www.erec.ru**)*

Published:

1. V.N. Blinkov, G.A. Gorbenko, P.G. Gakal, K.A. Malukhin, N.I. Ivanenko, S. Arndt, 1998. "Better estimation system codes for analysis of designed and severe accidents in Nuclear Power Plants (NPP). *Transactions of State aerospace university "Kharkov aviation institute" (KhAI) named after N.E. Zhukovskiy, Kharkov, Ukraine, Vol.6,* pp.220-224.

Submitted:

2. K.A. Malukhin**,** 1998. **"**Pre-test calculations for the EREC Bubble Condenser Test Facility", *Report for TACIS UK/TS/04, DB5, GRS, Berlin, Germany, December 1998.*

PROFESSIONAL DEVELOPMENT

RISKAUDIT company, Kiev, Ukraine July 1997

- In the frame of the European Union TASIC project (Contract No.: 95-2155-WW 9306.0205.B009), participated in a series of international workshops and obtained practical training on better estimation system codes/software (“ATHLET”, “RALOC”) that are used to perform numerical simulations aimed at analysis of thermal-hydraulic processes in NPPs.

Gesselschaft fur Anlagen und Reaktorsicherheit (GRS), Berlin, Germany January/February 1998
(www.grs.de)

- Obtained practical training in the frame of the European Union TASIC project (missions UK/TS/04 DB3 and DB5) in usage of “RALOC” code/software. Developed an input data file to perform pre-test calculations of thermal-hydraulic processes in a bubble condenser of an NPP test facility, using the provided numerical code/software “RALOC”.

Gesselschaft fur Anlagen und Reaktorsicherheit (GRS), Berlin, Germany December 1998
(www.grs.de)

- Obtained advanced practical training in the frame of the European Union TASIC project (missions UK/TS/04 DB3 and DB5) in usage of “RALOC” code/software. Developed an advanced input data file to perform pre-test calculations of thermal-hydraulic processes in a bubble condenser of an NPP test facility, using a provided numerical code “RALOC”. Analyzed severe accidents modes of the bubble condenser with the leakage of the coolant in the main contour of the containment.

TALKS AND LECTURES

“Model of Motion of an Actuator Based on a NiTi Shape Memory Alloy”.
2nd International Conference on Micromanufacturing (ICOMM) *September 10-13, 2007*
Clemson University, Greenville, South Carolina, USA.

“Identification of Direct Metal Deposition (DMD) Process Parameters for Manufacturing Thin Wall Structures from Shape Memory Alloy (NiTi) Powder”.
North American Manufacturing Research Conference NAMRC 35 of SME May 22-25, *2007*
University of Michigan, Ann Arbor, MI, USA.

“The Possibility of the Development of a “Self-Sensing” Shape Memory Alloy Based Actuator”.
1st International Conference on Micromanufacturing (ICOMM) September 13-15, 2006
University of Illinois at Urbana-Champaign (UIUC), IL, USA.

“Manufacturing of Shape Memory Alloy Based Monolithic Functional Structures with Shape Memory Effect Properties”.
North American Manufacturing Research Conference NAMRC 34 of SME May 23-26, 2006
Marquette University, Milwaukee, WI, USA

“Monolithic shape memory alloy based micro/meso manipulator: manufacturing and material characterization”.
NSF Design, Service and Manufacturing Research and Grantees Conference July 24-27, 2006
St.-Louis, Missouri, USA

“Shape Memory Alloy Based Micro/Meso Scale Monolithic Manipulator”.
NIST Advanced Technology Program *June 30, 2005*
INGERSOL Machine Tools Company, Rockford, IL, USA

REFERENCES

- Prof. Dr. Kornel F. Ehmann
  Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-3111. Work phone: (847) 491 3263, fax: (847) 491 3915.
  Email: k-ehmann@northwestern.edu

- Prof. Dr. L. Catherine Brinson
  Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-3111. Work phone: (847) 467 2347, fax (847) 263 0540.
  Email: cbrinson@northwestern.edu

- Prof. Dr. Henry W. Stoll
  Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-3111. Work phone: (847) 467 2676, fax: 491 3915.
  Email: hstoll@northwestern.edu

- Prof. Dr. Jian Cao
  Department of Mechanical Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208-3111. Work phone (847) 467 1032, fax: (847) 491 3915.
  Email: jcao@northwestern.edu

- Prof. Dr. Chi-Haur Wu
  Department of Electrical Engineering & Computer Science, 2145 Sheridan Road, Evanston, IL 60208-3111. Work phone (847) 491 7076, fax: (847) 491 4455.
  Email: chwu@ece.northwestern.edu

RESEARCH INTERESTS

Currently I'm active in the PhD program in the Department of Mechanical Engineering of Northwestern University in Evanston, IL, under the supervision of Prof. Dr. Kornel F. Ehmann. I will obtain my PhD degree in Winter 2007.

- Future (proposed) research.

My current and previous research encompasses several multidisciplinary research problems involving material science, mechanical engineering, manufacturing, mechatronics, control theory and heat transfer. Therefore, there is a great potential in development of new research and academic disciplines due to the created unique multi-disciplinary research foundation. Some of the proposed research areas are listed as follows.

- **"Use of super-elastic NiTi materials in automobiles as materials that can recover large stress-induced deformations".**
  Motivation for this project serves the capability of the super-elastic NiTi alloys to recover large stress-induced deformation without failure. The magnitude of recoverable deformation strains is at least two orders more than can be recovered by the conventional steel or aluminum alloys. The "rubber-like" behavior of the super-elastic NiTi alloys can be used in manufacturing parts of an automobile that undergo large stress regimes of operation.
- **"Manufacturing of advanced small-scale shape memory effect driven monolithic SMA (NiTi) robots and related fabrication, processing and modeling methodologies".**
  Motivation for this project lies in the current trends in the industries towards miniaturization and batch production. The micro/meso scale SMA robots can be used in

biomedical applications due to the biocompatibility of the SMAs (NiTi). They can complement the existing MEMS devices.

- **“Laser assisted polishing techniques capable of large material removal rates and producing low or no impact on the quality of the polished parts”.**

  Motivation for this project lies in the existing problems of presence of high surface roughness (several microns) in metallic parts fabricated by laser assisted manufacturing processes. Laser assisted polishing techniques can potentially be used in finishing of the parts that cannot be post-processed by conventional methods, such as milling, grinding, and mechanical polishing.

- **“Combined non-destructive methods for evaluation of the quality of metallic parts fabricated by laser assisted manufacturing processes”.**

  A combination of several non-destructive inspection techniques, e.g., optical and ultrasound methods, can be a used to evaluate a quality of the material (porosity, cracks, contamination) and geometry of the fabricated parts in-situ and provide an active feedback information during the fabrication process.

- Current Research - **“Shape Memory Alloy (NiTi) Micro/Meso Scale Manipulator (mMM):”**

  My current research is dealing with the development of a Shape Memory Alloy (NiTi) Micro/Meso Scale Manipulator (mMM). The need for low-cost robust meso-scale “smart” robots (manipulators) that have no moving parts (monolithic), no sensors (“self-sensing”) and can be used in space-constrained systems, e.g., in microfactories, biomedical applications, etc., was the motivation for the current research. This research includes the design, fabrication and analysis of such a smart robot – a monolithic mMM, fabricated from Shape Memory Alloy powders (NiTi) by the laser assisted Direct Metal Deposition (DMD) process, where the NiTi powder is layer-by-layer deposited, melted and solidified into the required geometry of the mMM. The DMD equipment was landed to us at the Southern Methodist University (RCAM lab, SMU). Characterization of the DMD fabricated NiTi material was done using Differential Scanning Calorimetry (DSC), Secondary Ion Mass Spectroscopy (SIMS), Energy Dispersive Spectroscopy (EDS), Scanning Electron Microscopy (SEM) and optical microscopy. A new mathematical model of the NiTi material properties (kinetics of temperature-induced phase transformation) and its experimental verification was developed. A new mathematical model of motion of the SMA wire and spring actuator was developed. The details and publications on this research topic are listed in my curriculum vitae.

- Previous Research – **“Modeling of Heat Transfer Loops of Spacecraft Thermal Control Systems:”**

My previous research dealt with the modeling of complex heat transfer loops of spacecraft and on-ground objects, while pursuing and receiving the degree of Candidate of Technical Sciences at the National Aero-Space University in Kharkov, Ukraine (Kharkov Aviation Institute “KhAI”, named after Zhukovskiy) under the supervision of Prof. Dr. G.A. Gorbenko and Prof. Dr. V.N. Blinkov. I performed numerical non-stationary simulations and analysis of an on-ground test prototype of a two-phase flow thermal control system of the International Space Station. I experimentally verified the transient simulations using the on-ground functional analogue – test facility. I participated in the development of a Fortran subroutine to conduct non-stationary numerical simulations of Capillary Pumped Loop (CPL) operation and performed numerical simulations to predict instabilities in the CPL. I have developed an advanced input data file and performed pre-test calculations and analysis of thermal-hydraulic processes in a bubble condenser of an NPP test facility, using the provided numerical code "RALOC" in the frame of the European Union TASIC project (at Gesselschaft fur Anlagen und Reaktorsicherheit (GRS) company, Berlin, Germany). The details and publications are listed in my curriculum vitae.

TEACHING INTERESTS

Currently I'm active in the PhD program in the Department of Mechanical Engineering of Northwestern University in Evanston, IL, under the supervision of Prof. Dr. Kornel F. Ehmann. I will obtain my PhD degree in Winter 2007.

The undergraduate courses, I'm capable of instructing are (and not limited to): **"Heat transfer**", **"Thermodynamics"**, **"Mechatronics"**, **"Computer-aided design (CAD)"**, and other mechanical engineering related subjects.

During my previous teaching experience I prepared and/or conducted laboratory exercises and/or lectures in 4 engineering undergraduate and graduate courses (Experimental Engineering ME-224, Mechanics of Materials CE-216, Manufacturing Automation, ME 340-1 and Computer integrated Manufacturing, ME 340-2) in the Department of Mechanical Engineering at Northwestern University. I supervised student projects. I have also completed a Teaching Excellence Program at Northwestern University (Evanston, IL) as my curriculum vita indicates.

I have conducted a broad range of research tasks in the area of advanced materials (NiTi shape memory alloys) and their applications as well. I have also conducted research in the area of experimental and numerical modeling of complex thermal-hydraulic loops for space applications.

Therefore, it will be advantageous to develop new interdisciplinary graduate courses that would integrate all the above-mentioned teaching and research areas into the graduate disciplines tentatively titled as **"Advanced manufacturing processes using advanced materials"**, **"Experimental and numerical approaches and techniques in modeling of behavior of complex automated systems"**.

SELECTED PUBLICATIONS

Material Characterization of NiTi Based Memory Alloys Fabricated by the Laser Direct Metal Deposition Process

K. Malukhin

K. Ehmann

Department of Mechanical Engineering,
Northwestern University,
2145 Sheridan Road,
Evanston, IL 60208-3111

Shape memory alloys (SMAs) are used in a wide variety of applications including medical stents, couplings, actuators, jointless monolithic structures for actuation and manipulation, etc. Due to the SMA's poor machinability it is advantageous to use rapid prototyping (RP) techniques for the manufacturing of SMA structures. However, the influence of the RP process on the properties of the SMA is not fully explored yet. A laser based direct metal deposition (DMD) RP process was used in this work to manufacture NiTi SMA samples and to investigate their physical properties using optical microscopy, differential scanning calorimetry (DSC), chemical analysis with secondary ion mass spectrometry (SIMS), and energy dispersive x-ray spectrometry (EDS) with a scanning electron microscope (SEM). DSC analysis has shown that the thermally treated parts possess smooth and pronounced reversible martensite-austenite transformation peaks that are the prerequisite for the shape memory effect (SME) in SMAs. DSC has also shown that quenching affects the peaks. The density of the produced parts was close to the theoretical density of the material as determined by porosity measurements. Finally, SIMS depth profile analysis has shown very low amounts of contamination in the material manufactured by DMD. The major conclusion is that the DMD RP process can be used to manufacture high-quality SMA structures from SMA powders. [DOI: 10.1115/1.2193553]

1 Introduction

Shape memory alloys (SMAs) are materials that exhibit particular mechanical and thermal responses: (1) the so-called superelasticity condition when large recoverable strains (up to 8.5%) exist at a constant temperature and the SMAs exhibit a "rubber"-like behavior and (2) the shape memory effect (SME)—when SMAs can fully recover the apparently plastic strains with great force due to the austenite-martensite transformation [1]. Such behavior is frequently referred to as "pseudoplasticity." As a consequence, SMAs can produce extremely large microstrains—on the order of 10^4 or equivalently 10% strain [2]. This property of the material can be used in jointless monolithic structures for actuation [3,4] and manipulation purposes with high force output [5] in a constrained space, e.g., in microfactories [6].

The transformation temperatures (TTRs) are one of the key parameters for SMA based actuation. TTRs are the prerequisite for the material to exhibit the SME. They also define the proper application for a certain NiTi composition alloy (medical, industrial, etc.). Conventionally, SMAs are made by high-frequency induction-, argon arc-, plasma arc-, or electron beam-melting [7]. Melting is performed several times in sequence to ensure the homogeneity of the manufactured material. Melting is followed by hot/cold working and thermal treatment (annealing and quenching) [7]. Otsuka and Ren [8–10] classified NiTi alloys using their Ni content as an indicator of their performance range. Using a Landay-type model, they state that the higher the elastic modulus (larger amount of Ni) of the material the lower the TTRs are. Therefore, the effect of quenching, which increases point defects, is equivalent to a compositional change (elastic modulus increase). Since the elastic modulus can be treated as an effect caused by composition, both terms are used as synonyms in the paper. Hence, quenching lowers the TTR, since it increases the elastic modulus of the material. For example, 1 at. % (atomic percent) composition change of Ni content (plus or minus) can result in an approximately 10% change in elastic modulus (minus or plus accordingly) and decrease or increase of the TTR by as much as several tens of degrees.

The other factors that affect the composition of SMAs and, therefore, their Ni content are the level of impurities during the production process and the level of precipitation in the SMA material. In the case of impurities, the most important fact to consider is the high reactivity of Ti with oxygen at high temperature levels [7]. Precipitates (additional stable phases such as $NiTi_2$ and Ni_3Ti according to the NiTi phase diagram) present in the NiTi alloy do not exhibit the SME, but their presence alters the alloy composition, and therefore affects the TTRs. Bram et al. [11] believe that metastable precipitates Ni_4Ti_3 (ultimately transforming into Ni_3Ti precipitates) mediate martensite transformation. This conclusion came from the fact that the authors did not achieve any TTRs in solid-solution-treated NiTi samples, but obtained the TTRs in precipitation-hardened samples. In this case, solid solution was used to achieve better homogeneity of the material. Finally, it appeared that with an increase in Ni content in the NiTi (50 at. % – 50 at. %) alloy the martensitic temperature decreased almost linearly. This characteristic allows the use of the alloys in medical, biological, and other applications that require very low actuation temperatures.

Bram et al. [11] used metal injection molding (MIM) and hot isostatic pressing (HIP) to fabricate their NiTi samples and to explore the possibility of achieving SMA properties by using these two processes. The level of homogeneity of the material was not high enough to achieve smooth and pronounced TTR peaks, which could be seen from their corresponding DSC thermograms. The possible reasons for having nonsmooth peaks are contamination and the initial homogeneity of the starting powders. Another RP technique for producing NiTi SMA by thermal explosion mode

Contributed by the Manufacturing Engineering Division of ASME for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received May 29, 2004; final manuscript received December 29, 2005. Review conducted by S. G. Kapoor.

Table 1 Experimental conditions

Laser power	250–600 W for different samples
Beam spot size	Not more than 1 mm
Traverse speed (scan speed)	10.16 mm/s
Z-incremental (layer thickness)	0.381 mm
Shielding gas	Ar, at 17.5 l/min
Carrier gas	Ar, at ΔP (pressure difference) of 13.7895 kPa
Flow rate of powder (set point)	6.7 g/min
No. of layers	20 layers $\times$ 0.381 mm, or 12 layers $\times$ 0.635 mm

of combustion synthesis was tested by Yi and Moore [12]. However, in their case, the high amount of impurities increased the brittleness of the NiTi SMA due to the combustion reactions.

A novel manufacturing technique—laser-based direct metal deposition (DMD)—allows the creation of monolithic jointless metallic structures. Another advantage of the DMD technologies is in batch production that leads to a low cost of the manufactured devices. Batch production requires minimum postmachining: milling, grinding, drilling, etc., as opposed to the conventional production processes that consist of milling, grinding, drilling, etc. The possibility of building 3-D structures in parallel by DMD laser "printing" them on a substrate reduces the cost. This is why it is desirable to explore the properties of DMD manufactured SMA parts. A technique similar to the DMD technique is laser engineered net shaping (LENS). DMD and LENS processes allow the creation of fully dense metallic structures from computer-aided design (CAD) solid models [13–15]. The DMD process is aimed at using metal powders, while LENS can process nonmetallic components as well.

The present paper is primarily aimed at using the DMD process in order to achieve high-quality NiTi SMA materials made by laser melting of prealloyed SMA powder. DMD will be used to manufacture SMA powder based parts. A subsequent heat treatment procedure (annealing and quenching) of the parts will follow to impose the SME. The physical properties of the SMA part, related to the existence of SME, and the quality of the material will be also investigated. A subsidiary objective of this work is the achievement of a specific set of transition (activation) temperatures (TTRs). The desired TTRs, which need to be above room temperature due to the design requirements, are the finish of the martensite transformation peak at about 9°C, the start of the martensite transformation peak at about 18°C, the start of the reverse martensite transformation peak at about 34°C, and the finish of the reverse transformation peak at about 49°C.

2 SMA Sample Preparation

Preliminary experiments have been conducted to assess the feasibility of laser-based DMD processing by fabricating six cylindrical objects using a prealloyed UDIMET NITINOL (NiTi) powder with 55.5–56 wt. % Ni, balance Ti, and with a particle size of 10–180 μm. A Nd:YAG laser DMD machine with a feedback control system was used (courtesy of Dr. R. Kovacevic at SMU). The conditions for the DMD experiments are given in Table 1. The cylinders were 25.4 mm in diameter and 2.54 mm high. One of the cylinders (its cross section is shown in Fig. 1(*a*)) was annealed in an Ar atmosphere at 850°C for 15 min with no filling afterwards and then Ar quenched.

Five out of the six NiTi samples were DMD manufactured on a Ti substrate at laser powers of 300–600 W. Due to the difference in the thermal expansion coefficients of NiTi and Ti the samples debonded from the Ti substrate at the end of the deposition process. No melting pool in the Ti substrate was formed. The sixth NiTi sample (Fig. 1(*a*)) was made on one of the five previously manufactured samples using that NiTi sample as the substrate at a laser power of 250 W. Consequently, no debonding occurred in

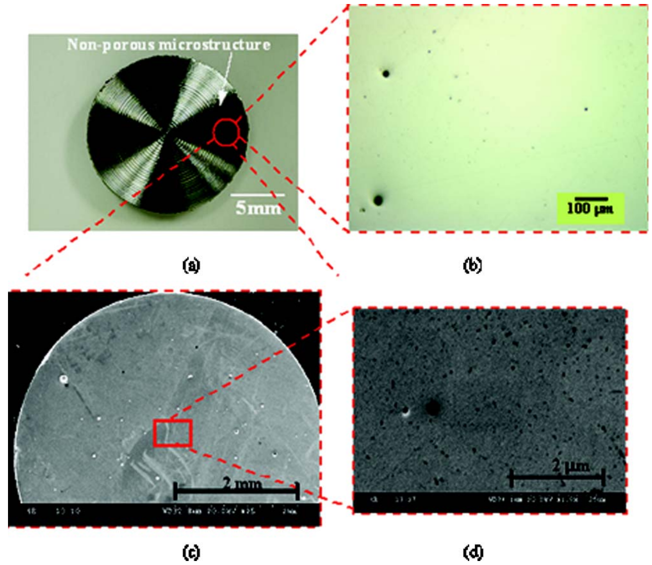

Fig. 1 (*a*) As-annealed NITINOL cylinder with turned cross section. (*b*) Optical microscope image of the ground and polished sample part of cylinder (*a*). (*c*) SEM micrograph of (*b*), sample #1. (*d*) Zoomed SEM micrograph of (*c*), sample #1.

this case. The use of the Ti substrate, in addition to Ar as the shielding gas, insures a minimal contamination of the NiTi with oxygen, since oxygen (if present) is absorbed by the Ti first and not by the melt [7]. A similar effect takes place with the NiTi premelted layer used as a substrate.

One of the reasons for the achievement of the apparently nonporous NiTi structure (Fig. 1(*b*)) was the high content of Ni (Ni—55.5%wt., Ti—balance) and low amount of oxygen due to the shielding gas environment. These conditions have also enhanced the strength of the obtained material since no additional cold work was required as in the case of the conventional manufacturing processes [7].

The raw DMD manufactured sample (a round plate 25.4 mm diameter ingot) was annealed at 850°C in an Ar atmosphere and then quenched in Ar. This was done in order to homogenize the material, since, according to the phase diagram for the current Ni and Ti composition, this is the solid-solution region. After that, two identical 5 mm diameter, 0.5 mm thick round samples (samples #1 and #2) were wire EDM cut from the DMD manufactured NiTi cylinder shown in Fig. 1(*a*). Sample #1 (Fig. 1(*c*)) was polished and used in optical microscopy, SEM imaging of the surface, and SIMS and EDS analysis of impurities in the SMA material. Both samples were used for DSC measurements. Samples #1 and #2 were heat treated differently from each other as shown in the subsequent DSC thermograms (Fig. 3). All the heat treatments were done in an oven with a protective Ar atmosphere to prevent oxidation of the material.

3 Experimental Analysis of the Samples: Results and Discussion

3.1 Optical and Scanning Electron Microscopy of the SMA Cylinder. Optical microscopy has been performed on sample #1. Figures 1(*b*)–1(*d*) show an apparently solid and nonporous microstructure. After grinding and polishing the sample, microscopy at a higher resolution revealed a negligible number of pores in the material (Fig. 1(*b*)). The largest pore had a diameter of approximately 15 μm. In the area of interest ($500 \times 700\ \mu m^2$ in Fig. 1(*b*)) the amount of area porosity was about 300 μm^2 of pores per 35,0000 μm^2 of the area or 0.086%.

Scanning electron microscopy (SEM) on sample #1 was done using a Hitachi S–3500N variable-pressure scanning electron mi-

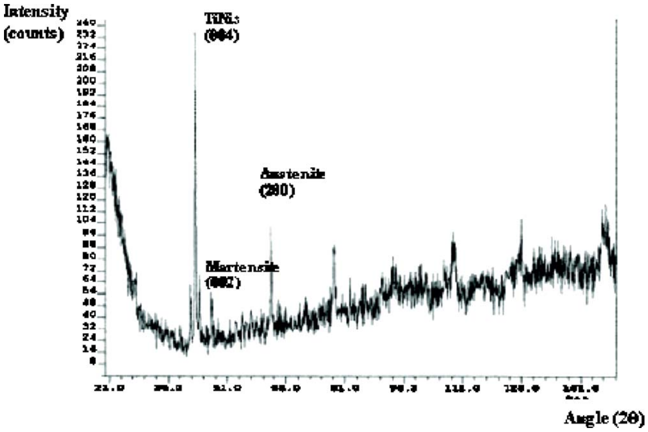

Fig. 2 XRD raw data of the 850°C annealed cylinder

croscope. The SEM micrographs representing the circled part of the optical microscopy image (Fig. 1(*a*)) are shown in Figs. 1(*c*) and 1(*d*).

3.2 X-ray Diffraction Analysis. X-ray diffraction (XRD) analysis was done on the 850°C annealed raw sample using a SCINTAG x-ray powder diffractometer. The raw XRD data are shown in Fig. 2.

The XRD analysis shows the distribution of phases in the annealed NiTi material. The XRD data are unfiltered, and therefore show the superimposed background signal on top of the meaningful peak signals. The material contains austenite, martensite, and $TiNi_3$ precipitates. The existence of the precipitates undermines the presence of the R-phase in the material, which is advantageous for having a two-way shape memory effect (TWSME).

3.3 Differential Scanning Calorimetry (DSC). The differential scanning calorimetry (DSC, TA Instruments 2920 DSC) method was used to determine the TTRs for the manufactured NITINOL samples under no stress conditions. Both samples were subject to a secondary annealing process to achieve the TTRs by exploring two ranges of temperatures: (1) from 630°C and above that corresponds to the solid-solution region according to the NiTi phase diagram and (2) below 630°C that corresponds to the precipitation-hardening region. Sample #1 was annealed at temperatures above 630°C (in an Ar atmosphere) and quenched in water. Sample #2 was annealed 11 times under different conditions to achieve the SME heat flux peaks on the DSC thermogram. The different annealing temperatures, ranging between 282°C and 500°C, annealing times, and quenching conditions are shown in the annotation to Fig. 3. The resulting DSC thermograms for different samples and different heat treatment conditions are also shown in Fig. 3.

All thermograms show three heating and cooling cycles. The mass of NiTi sample #1 was 65 mg and that of sample #2 was 66.47 mg. The DSC of the raw NITINOL powder used for sample fabrication is given in Fig. 3(*a*).

3.3.1 Effect of Thermal Treatment With Quenching on TTRs. Sample #1 was solid-solution treated under different temperatures (above 630°C). One of the corresponding thermograms (shown in Fig. 3(*b*)) shows very small peaks upon heating at −14°C and −9°C in the measuring range of the DSC apparatus. A further increase in the annealing temperature slightly increased the corresponding temperatures of the peaks (to −3°C and +2°C, not shown here), but the intensities of the peaks remained insignificant.

Sample #2 was precipitation hardened at lower temperatures than sample #1. The resulting thermogram for sample #2 (Fig. 3(*c*)) shows significantly larger intensity peaks at −10.35°C (cooling) and 6.26°C (heating) than the peaks for sample #1. The peaks correspond to the martensite and reverse martensite transformations in the material. This suggests that the phase transformations in the SMA material are mediated by precipitation (Ni_4Ti_3) growth, which takes place at the annealing temperatures lower than 630°C according to the NiTi phase diagram. In order to shift the TTRs to the right (or to increase the TTRs), the annealing temperature has been decreased to 450°C (Fig. 2(*d*)). Then, the annealing temperature has been decreased gradually from 450°C to 282°C. The corresponding shifts in the transition temperatures very closely approached the desired room temperature range (see Figs. 3(*d*)–3(*k*)).

The cumulative trend of the TTR peaks versus the annealing temperature is shown in Fig. 4, where Ta, Tr, and Tm correspond to the reverse martensite, R-phase, and martensite transformation peaks, respectively. Figure 4 contains three curves corresponding to the different phase transformations that take place in the SMA material. The curves were approximated using MatLab's curve fitting toolbox. A quadratic polynomial has been used to fit the eight experimental points. It can be seen that the lower the annealing temperature is the higher the TTRs are for the martensite, the reverse martensite, and the intermediate R-phase transformation. Such behavior was found in the temperature range from 282°C to 500°C. Beyond an annealing temperature of 500°C the TTRs did not exist. Below an annealing temperature of 360°C the TTRs tended to decrease.

As indicated before, Bram et al. [11] have used hot isostatic pressing (HIP) and metal injection molding (MIM) in order to manufacture SMA materials using a mixture of raw Ni and Ti powders and a prealloyed NITINOL powder, respectively. A comparative analysis shows that the samples manufactured by DMD exhibit much more pronounced and completely uniform peaks (Figs. 3(*c*)–3(*k*)) than those achieved by the HIP and MIM processes [11]. This is an indication of the high quality and homogeneous structure (Ni, Ti distribution) of the DMD manufactured material. The successful achievement of the TTR peaks in sample #2 proves that the DMD process is an efficient RP method for fabricating high-quality SMA-based structures. It also shows that precipitation growth is one of the most important factors in obtaining the SME. The peaks (during the three DSC cycles) on each thermogram exhibit very little shift with respect to each other, implying no or very little degradation of the SME.

The TTRs can be further fine tuned by modifying the thermal treatment, NiTi composition (including point defects introduced by quenching), and contamination with oxygen and carbon. The first two factors were named by Ren and Otsuka [9] to be the key issues in the strong dependence of the martensite transformation temperatures on composition. Also, according to the same authors [8] and other references on NiTi alloys, the TTRs linearly decrease in the SMA (NiTi) alloys with an increase of Ni content starting at 50 at.% (equivalent to 55 wt.%), Ti balance.

3.3.2 Effect of Thermal Treatment With No Quenching on TTRs. In order to study the effect of quenching on the TTRs, sample #2 was heat treated under the same conditions as shown in Figs. 3(*k*) and 3(*l*), but no quenching was applied. The sample was naturally cooled down in the oven. The results are shown in Figs. 3(*l*) and 3(*m*). Comparison with the data from Fig. 3(*k*) shows that Tm and Tr decreased by almost 1.5°C from 14.91°C and 42.42°C (quenched sample, Fig. 3(*k*)) to 13.28°C and 41.37°C (nonquenched sample, Fig. 3(*l*)). The temperature Ta increased by 1.5°C from 58.65°C (quenched sample, Fig. 3(*k*)) to 60.24°C (nonquenched sample, Fig. 3(*l*)). Comparison between Fig. 3(*e*) (quenched sample) and Fig. 3(*m*) (nonquenched sample) shows the same behavior—decrease in Tr and Tm and an increase in Ta. The aim of removing quenching was to increase all TTRs above room temperature, but the opposite effect occurred with Tm and Tr. In addition, the quality of the nonquenched material, namely,

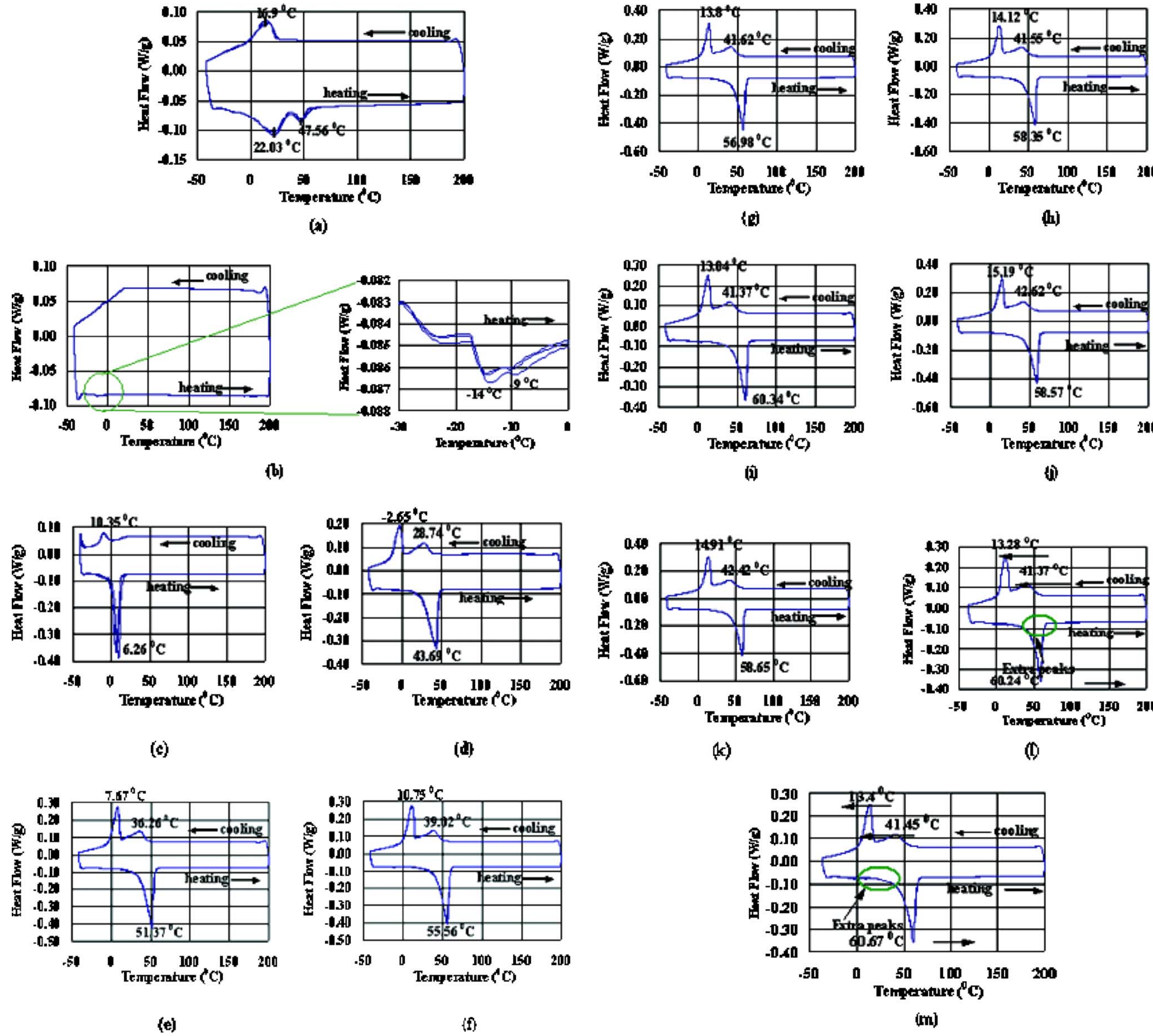

Fig. 3 DSC thermograms obtained under different heat treatment conditions (annealing temperatures)—(*a*) as-is raw (prealloyed) NITINOL powder used for fabricating the samples; (*b*) sample #1: $T=820°C$, time=1 h, room temperature water quenched; (*c*) sample #2: $T=500°C$, time=1 h, room temperature water quenched; (*d*) sample #2: $T=450°C$, time=1 h 30 min, room temperature water quenched; (*e*) sample #2: $T=424°C$, time=1 h 30 min, room temperature water quenched; (*f*) sample #2: $T=408°C$, time =1 h 30 min, room temperature water quenched; (*g*) sample #2: $T=396°C$, time=1 h 30 min, room temperature water quenched; (*h*) sample #2: $T=358°C$, time=1 h 30 min, room temperature water quenched; (*i*) sample #2: $T=331°C$, time=1 h 30 min, room temperature water quenched; (*j*) sample #2: $T=309°C$, time=1 h 30 min, room temperature water quenched; (*k*) sample #2: $T=282°C$, time=1 h 30 min, room temperature water quenched; (*l*) sample #2: $T=282°C$, time=1 h 30 min, no quenching; (*m*) sample #2: $T=424°C$, time=1 h 30 min, no quenching.

its homogeneity, became worse—new small peaks appeared during the heating cycle (Figs. 3(*l*) and 3(*m*)). Because the removal of quenching tends to decrease Tm and Tr, quenching should be retained during the heat treatment procedure of the SMA material.

Since cold work was not used on the examined specimens, its influence can be excluded from the list of the parameters that affect the TTRs. Other factors influencing the TTRs could be oxygen and carbon contamination, to be studied later.

3.4 EDS Analysis. In order to assess oxygen and carbon contamination in the fabricated NiTi sample and their influence on the TTR, an energy dispersive spectrum (EDS) analysis was conducted using the Hitachi S–3500N variable-pressure SEM. The sample used for the DSC analysis was further polished (final polishing was done by 0.05 μm microcloth). The resulting x-ray spectrum of the sample surface, shown in Fig. 5, does not show any apparent contamination with oxygen or carbon. The SEM used cannot determine contamination lower than 0.1 wt.%, so one can assume that if contamination took place it had to be at a lower level.

3.5 Secondary Ion Mass Spectroscopy (SIMS) Analyses. The contamination level can also be estimated by doing SIMS (ToF-SIMS, PHI TRIFT III, Physical Electronics), which is more sensitive than EDS. SIMS allows a chemical composition analysis of a material up to a certain depth.

Two NiTi samples have been analyzed: the manufactured NITINOL sample #1 and a commercially available NITINOL sample with known chemical composition (purchased from Special Metals Corporation with a known chemical specification, i.e., with a

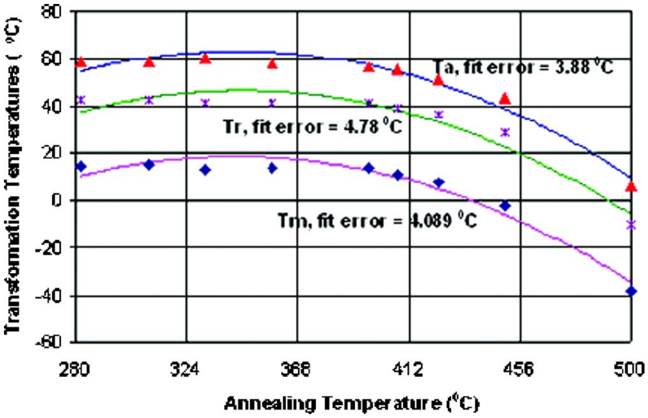

Fig. 4 Cumulative annealing curves: TTRs versus the annealing temperature (Tm, Ta and Tr are the martensite, reverse martensite (austenite), and R-phase peak transformation temperatures)

known level of impurities), both under no stress conditions. The commercially available NITINOL sample was used as a standard sample to compare the level of contamination with the manufactured sample. The depth profiling analyses (in positive ion mode—for identification of metals and oxides) for the standard and for the manufactured sample are shown in Figs. 6(*a*) and 6(*b*), respectively. The approximate material depth along which the profiles (chemical compositions) of all the elements have been built was about 940–970 nm. Ion-milling (the removal of layers of the material) was done at approximately 0.18 nm/s. Each cycle—material layer removal (ion-milling) and layer chemical analysis—lasted 300 s. Mass spectroscopy was performed after a layer of the material was removed. The ion-milling window size was about $100 \times 100\ \text{nm}^2$.

The data in Fig. 6 show that there is some contamination with O, C, TiO, K, and Na that is changing with depth. Ni is less reactive with oxygen than Ti, hence oxides are mostly formed with Ti. All the contamination data are qualitative, but it is possible to estimate the level of contamination in the manufactured sample by comparing the corresponding SIMS data (Fig. 6(*b*)) with the data from the standard NITINOL sample with known chemistry (Fig. 6(*a*)).

The commercially available NITINOL metal sample contains 185 ppm of oxygen, 310 ppm of carbon, and less than 0.01 wt.% of Na and other contaminants. The reference value for the maximum allowable amount of oxygen in SMAs is about 1000–2000 ppm. The complete information on the chemical analysis of the commercially available UDIMET NITINOL material (metal strip) was provided by Special Metals Corporation and

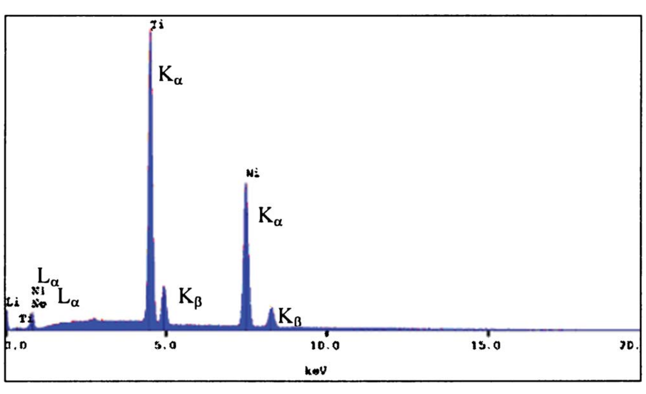

Fig. 5 EDS spectrum of the manufactured NiTi sample

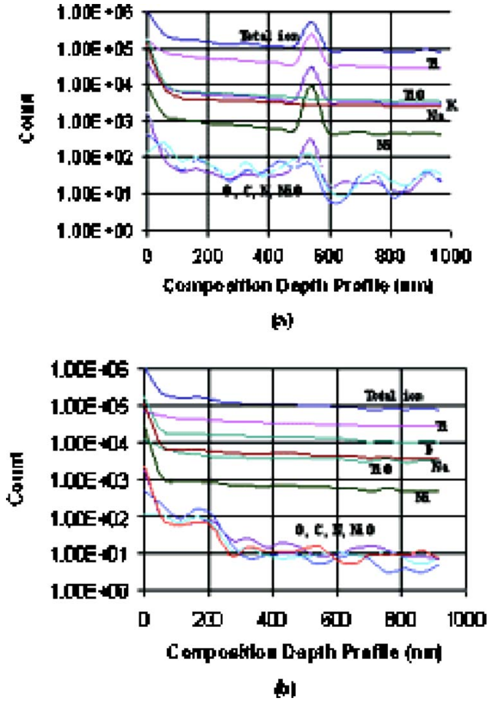

Fig. 6 SIMS depth profiles—metals, some nonmetals, and oxides (positive ion mode). (*a*) Commercially available (standard) NITINOL sample and (*b*) DMD manufactured NiTi sample.

is given in Table 2.

The plots of all the element's intensities versus depth were compared in both samples (Figs. 6(*a*) and 6(*b*)). The comparative evaluation of spectra shows an almost identical or even smaller level of contamination in the manufactured sample. Therefore, the impurities can be excluded from the list of factors that noticeably affect the TTRs in the manufactured NiTi sample.

Our experimental studies allow us to conclude the following:

1. It is important to have a sufficiently protective antioxidation atmosphere (e.g., Ar gas) when melting NiTi due to the high affinity of Ti to oxygen.
2. It is important to keep the level of impurities low in the material. Therefore, the addition of a binder and wax, such as in the MIM process, could worsen the quality of the material's homogeneity.
3. It is important to have high-quality prealloyed homogenized starting powders and the proper Ni content in them. The cited authors [8] homogenized the NiTi powders themselves from elementary Ni and Ti powders for further use in the HIP process. We obtained already prealloyed homogenized NiTi powders from the manufacturer.

Table 2 Chemical analysis of UDIMET NITINOL material provided by Special Metals Corporation

Element	wt%
Ni	55.49
Ti	Balance
C	310 ppm
O	185 ppm
Mn, Si, Cr, Co, Mo, W, Nb, Al	<0.01
Zr, Cu, Ta, Hf, Ag, Pb, Bi, Ca	<0.01
Mg, Sn, Cd, Zn, Sb, Sr, Na, As, Be	<0.01
Ba, Fe	<0.01
B	<0.001

4. It is important to postthermally treat the manufactured samples in an oven with an Ar protective atmosphere due to the high oxidation propensity of Ti.

4 Conclusions

A comprehensive set of experimental tests on DMD manufactured NiTi samples has been conducted, namely, optical microscopy, DSC, EDS, and SIMS. The following conclusions can be drawn:

- The so far obtained results have confirmed the capability of the DMD process to manufacture high-quality, almost nonporous NiTi samples out of NITINOL powder. Consequently, the samples do not require any further cold work, sintering, or filling with an additional material.
- The samples possess smooth and pronounced TTR peaks confirmed by DSC analysis. The TTR peaks are the prerequisite for the SME and are in the desired range of values. The experiments show that removing the quenching procedure tends to decrease some of the TTRs (Tm and Tr) and worsen the quality of the material, therefore, it is not desirable to remove quenching from the heat treatment procedure. It can also be concluded that quenching does affect the TTRs.
- EDS revealed no visible contamination; therefore, a more sensitive method for contamination detection needs to be used.
- SIMS depth profile analysis has shown a contamination with oxygen (TiO), Na, and K. The comparative evaluation of spectra shows almost the same or even a smaller level of contamination in the manufactured NiTi sample in comparison to the standard NITINOL sample with known chemistry provided by the supplier. Therefore, the present impurities would not noticeably affect the TTRs in the manufactured NiTi sample.

Acknowledgment

We gratefully acknowledged the help of Prof. Dr. Radovan Kovacevic at SMU in defining and implementing the DMD process and for lending us the necessary DMD equipment. We are also very thankful to Dr. James Hulvat of the Materials Science Department at Northwestern University for his help with the DSC measurements. The Keck-II facilities in the Materials Science Department at Northwestern University were used for the SIMS measurements. We greatfully aknowledged the financial support of the National Science Foundation under Grant No. DMI-0400316.

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Model of Motion of an Actuator Based on a NiTi Shape Memory Alloy

ICOMM
2007

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ABSTRACT

A mathematical model of the motion of the Shape Memory Alloy (SMA) based actuator of the agonistic-antagonistic type has been developed. The model is based on our new mathematical model of the kinetics of phase transformation in SMAs. In addition, the model uses a known model of motion of a "human muscle". The suggested mathematical model of the motion of the actuator has been verified by means of an SMA wire based experimental prototype of the actuator. The results of the numerical and experimental modeling of the step response behavior of the prototype of the actuator shows an excellent agreement at the sub-millimeter motion level. The SMA spring based experimental prototype of the actuator was designed, manufactured and tested.

INTRODUCTION

A Shape Memory Alloy (SMA) actuator of the "agonist-antagonist" type in which actuation is achieved due to the presence of bias and pulling forces of the "agonist" and "antagonist" parts, is under development (K. Malukhin, and K. Ehmann (2006a)). The actuator includes a linear X-Y stage fabricated from NiTi alloy. NiTi alloys have the property to undergo temperature and/or stress- induced phase transformations allowing recovery of large strains and stresses developed in a pre-deformed material (Brinson et al., 1996). Strain recovery in the NiTi material due to the temperature induced phase transformation is called a Shape Memory Effect (SME). As a consequence, these materials are widely used for actuation (Ikuta, K. et al., 1988; Kohl, M. et al., 2002).

The purpose of the current paper is to create a model of the motion of the SMA based actuator to be later used in the design of the motion controller of the actuator.

CONCEPTUAL DESIGN AND EXPERIMENTAL PROTOTYPE OF THE SMA ACTUATOR

The X-Y linear stage under development is a monolithic structure whose linear motion is provided by means of four (4) accordion spring type actuators as shown in Figure 1. The springs are connected to each other through the middle piece from one of their ends (Fig. 1). The other end of each spring is permanently fixed to the frame. The springs will possess the SME due to the property of the material to undergo the phase transformation when heated and/or cooled. This property will be imposed on the springs during a thermo-mechanical treatment. The SME drives their motion when the springs are heated and/or cooled. The heating/cooling of the springs will be achieved by means of the direct heating, when the electric current is applied through the springs.

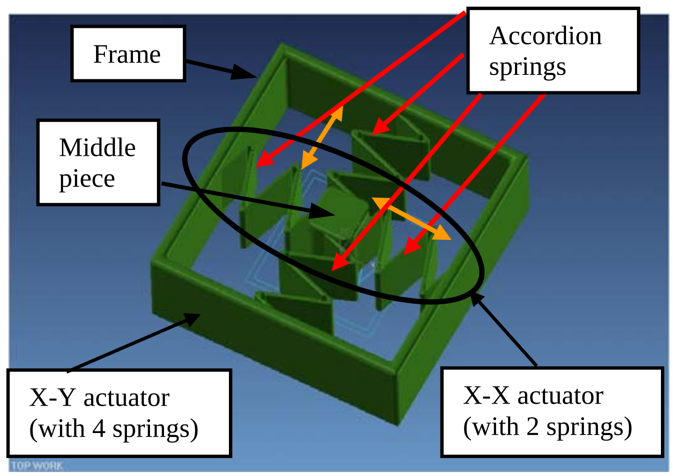


Fig. 1. SMA actuator – X-Y linear stage.

MATHEMATICAL MODEL

In our earlier un-published mathematical investigations, a new phase transformation model that describes the kinetics of the phase transformation in SMAs was developed. One of the results of the model is an analytical function that predicts the evolution of the austenite phase fraction in the material with its temperature and stress change. Skipping all the derivation steps, our analytical expression for the phase transformation function is given as:

$$\xi_A = \sqrt{\frac{2C_p}{r_A}\left(T - A_{S0}\right)} \qquad (1)$$

where: ξ_A – austenite phase fraction in NiTi,
C_p – heat capacitance, J/(kg*K),
r_A – latent heat of phase transformation, J/kg,
T – temperature of NiTi alloy, K,
A_{SO} – austenite start transformation temperature for the stress-free conditions, K.

Equation (1) allows computing the amount of the austenite phase fraction ξ_A in the material that undergoes the temperature induced phase transformation. The magnitude of the ξ_A can further be used to predict the amount of strain (or stress) the material can recover during free or constrained recovery regimes of motion.

In the current study we develop a mathematical model that describes the linear motion of our SMA actuator. For this purpose, and for simplicity, the SMA linear X-Y actuator with 2 degrees of freedom (DOF), containing 4 accordion springs (Fig. 1), will be simplified into a 1-DOF X-X actuator, having two accordion springs only as marked in Figure 1. The simplified version of the actuator is shown in Figure 2.

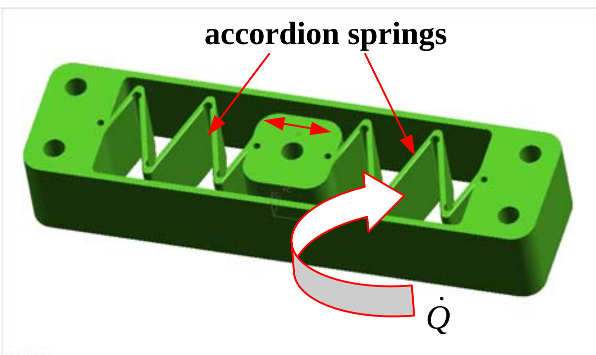


Fig. 2. 1-DOF SMA actuator

One of the accordion springs (non-heated) produces the bias force, while the other one (heated with heat flux $\dot{Q}$) produces the pulling (actuation) force in an "agonist-antagonist" manner. To further simplify the mathematical model for its verification purposes, the pulling (active) SMA spring is substituted by an equivalent SMA wire. The corresponding SMA wire actuator is described in K. Malukhin, and K. Ehmann (2006b). The schematic of the actuator's equivalent model is shown in Figure 3.

The equations of motion of the equivalent SMA wire actuator can be written, by treating it as a spring with an equivalent stiffness and damping. In order to generate the motion, the wire is initially pre-stretched. Afterwards, when a heat load $\dot{Q}$ is applied to the wire, it recovers its initial length due to the phase transformation in the NiTi material. The equivalent force, F_Q, due to this constrained recovery (SME) can be calculated using our suggested analytical expression for the phase transformation function given by Eq (1).

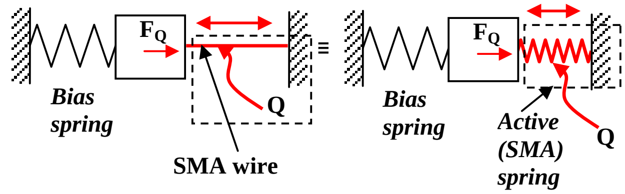


Fig. 3. The equivalent model of the SMA actuator

The system of ordinary differential equations (ODEs) that describes the motion of the actuator can be written, where the equivalent force, F_Q, plays the role of an externally applied force:

$$F_Q = f(\xi_A) \tag{2}$$

During our previous experiments (K. Malukhin, and K. Ehmann (2006b)) it was observed that SMA wires/actuators possess a non-linear damping property, similar to the dumping property of the human muscle. Human muscle behavior was extensively investigated and modeled by Wu et al., 1990. In the current paper we adopt their approach to model the non-linear damping coefficient and their way to simulate the movement of the human muscle, to model our SMA "agonist-antagonist" actuator. The schematic depiction of this model is shown in Fig. 4.

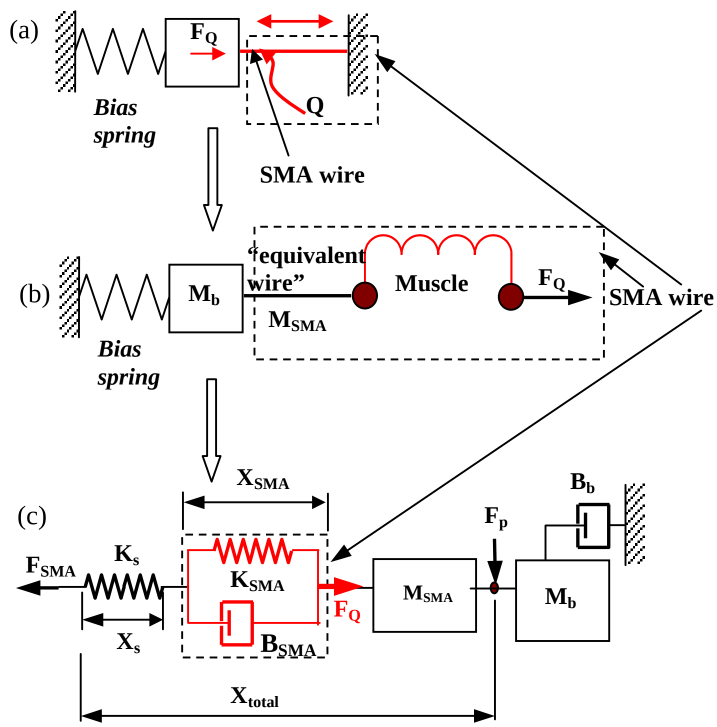


Fig. 4. SMA "agonist-antagonist" actuator: (a) equivalent model, (b) adopted model, (c) equivalent adopted model

Figure 4a shows the schematic of our SMA wire based actuator, where the bias spring and the SMA wire are connected through the moving middle block of mass Mb.

The moving block also represents a payload system with a certain damping property. In order to use the approach suggested by Wu et. al 1990, the SMA wire is substituted with its functional equivalent in Figure 4b, containing three parts: 1) a wire with the equivalent "lumped" mass M_{SMA} (no SME), 2) "muscle" element with non-linear damping according to Wu et. al 1990, and 3) the external force, F_Q, due to the SME. Figure 4c shows the final layout of the adapted SMA actuator in which the "muscle" element (from Fig. 4b) is substituted with its equivalent stiffness/non-linear damping elements – K_{SMA}/B_{SMA}; the bias spring is substituted with its equivalent stiffness element - K_S; and an additional damping B_b which together with the force F_p, represents a payload on the SMA wire actuator. The system of ODE describing the model in Figure 4c can be written as follows:

$$\left.\begin{aligned}
&F_Q - B_b\,\dot{X}_{total} - \left(M_b + M_{SMA}\right)\ddot{X}_{SMA} = \\
&= K_s\left(X_{total} - X_{SMA}\right), \\
&F_{SMA} = F_s = K_s\left(X_{total} - X_{SMA}\right) = \\
&= K_{SMA}\,X_{SMA} + B_{SMA}\,\dot{X}_{SMA}^{\;1/5}, \\
&F_p = M_{SMA}\,\ddot{X}_{total} + K_s\left(X_{total} - X_{SMA}\right),
\end{aligned}\right\} \qquad (3)$$

where:

- F_{SMA} – reaction force of the SMA wire, N;
- F_Q – applied force to the SMA wire, N;
- F_p – payload, N;
- X_{SMA} – displacement of the SMA wire, m;
- X_{total} – total displacement of the SMA wire system, m;
- X_s – displacement of the bias spring, m;
- K_s – stiffness of the bias spring, N/m;
- K_{SMA} – stiffness of the SMA wire, N/m;
- B_{SMA} – non-linear damping constant of the SMA wire, $N\cdot(s/m)^{1/5}$ (using approach from Wu et al., 1990)
- B_b – damping constant of the payload system, N·s/m;
- M_b – mass of the block, kg;
- M_w – mass of the SMA wire, kg;
- Q – heat flux applied to the SMA wire, W;
- F_Q – force applied to the SMA wire based on the heat flux magnitude Q and the new transformation kinetics function, N.

The linear X-X motion of the SMA "agonist-antagonist" actuator was modeled in the "Simulink" environment, by solving the system of the equations of motion (Eq. 3). The heat flux, Q, (characterizes the temperature T_{SMA}) was applied to the SMA wire in the form of a step function, thus generating the external (SME driven) force F_Q that leads to the displacement (contraction) of the pre-stretched SMA wire.

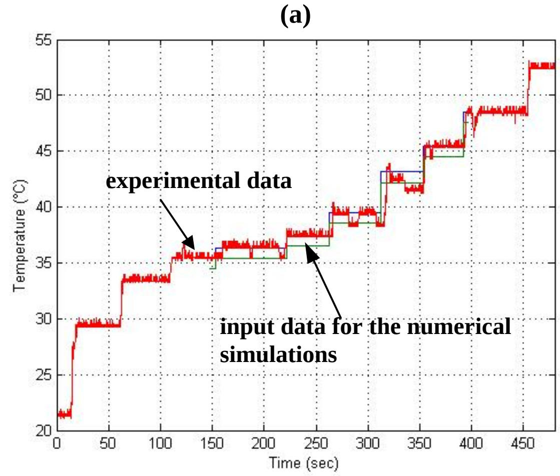
EXPERIMENTAL VERIFICATION OF THE MATHEMATICAL MODEL

The experimental verification of the mathematical model of the SMA actuator was accomplished by using our experimental setup, that simulates the SMA wire actuator (K. Malukhin, and K. Ehmann (2006b)). The SMA wire was heated and its corresponding SME driven displacements were recorded.

The results of our numerical simulations and the experimental verification of the step response of our SMA wire actuator are shown in Fig. 5. Figure 5a shows the stepped temperature input to the SMA wire, while Fig. 5b shows the corresponding displacement output of the actuator.

The numerical and experimental results show an excellent agreement.

(a)



(b)

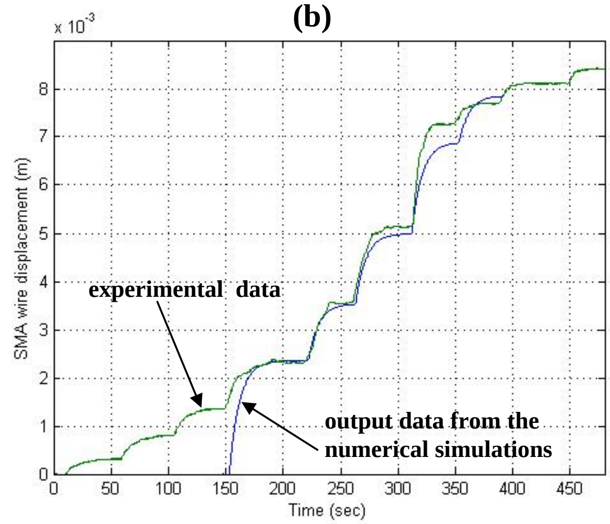


Fig. 5. Numerical simulation results and experimental results of the step response of the SMA wire based actuator: input temperature,(b) output displacement

EXPERIMENTAL PROTOTYPE

The ultimate goal of developments of the experimental prototype of the SMA spring based actuator (Fig. 2) is to achieve similar results to those, shown in Fig. 5, where the mathematical model of the motion of the actuator is in excellent agreement with the experimental measurements of the motion, developed by the SMA wire. This task is more complicated because the SMA wire based actuator develops displacements that closely resemble uniaxial strain recovery displacements, while the movement of the accordion springs represents a complex 3-dimensional strain recovery case.

A commercially available NiTi alloy in the form of a raw ingot was purchased from the Nitinol Devices and Components Company. The “as-is” NiTi material has already possessed the property to undergo temperature-induced transformation. This was verified through Differential Scanning Calorimetry (DSC) measurements of its phase transformation temperatures.

The simplified experimental prototype of the actuator (shown in Fig. 2) has been fabricated from the NiTi material by wire-Electro Discharge Machining (EDM). Afterwards, the actuator was equipped with a measurement system consisting of a Linear Variable Displacement Transducer (LVDT) and a thermocouple (K-type) connected to a data acquisition card (DAQ). A DC-source was used to apply heat to one of the accordion springs by means of resistive heating. The voltage drop due to the undergoing phase transformation in the heated spring was measured and recorded by the DAQ as well. LabVIEW software was used for the collection and recording of the experimental data through the DAQ. The experimental setup is shown in Fig. 6.

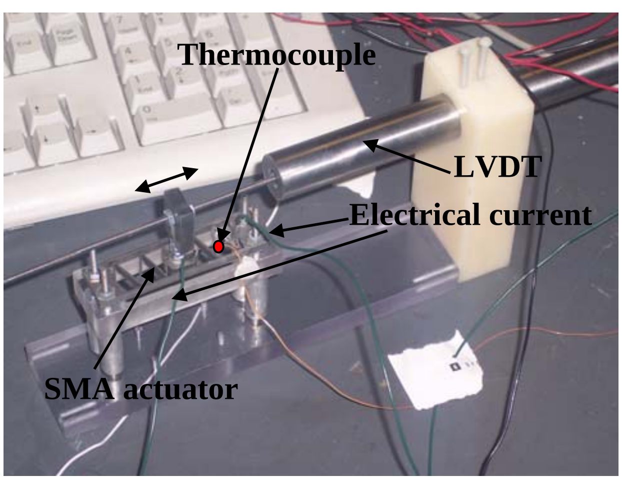


Fig.6. Experimental setup of the SMA actuator.

The NiTi SMA actuator was placed on a supporting structure as shown in Fig. 6. The LVDT was connected to the actuator to measure the displacement of the springs. The temperature of the spring that was heated was measured by the thermocouple glued to its surface.

The scenario of the preliminary experiments was the following: (1) The active spring was compressed manually, while the second (bias) spring was stretched. When the compression load was removed - both springs stayed in their deformed state. (2) Electrical current was applied to the active spring, thus heating it and causing it to return to its initial non-deformed position. (3) The corresponding displacement, temperature and voltage drop across the active spring were measured and recorded by the DAQ. (4) After the active spring recovered its non-deformed position, the electrical current was turned off.

The preliminary experimental results for four separate tests of the step response of the actuator are shown in Fig. 7. The voltage drop across the active spring was not measured during these experiments.

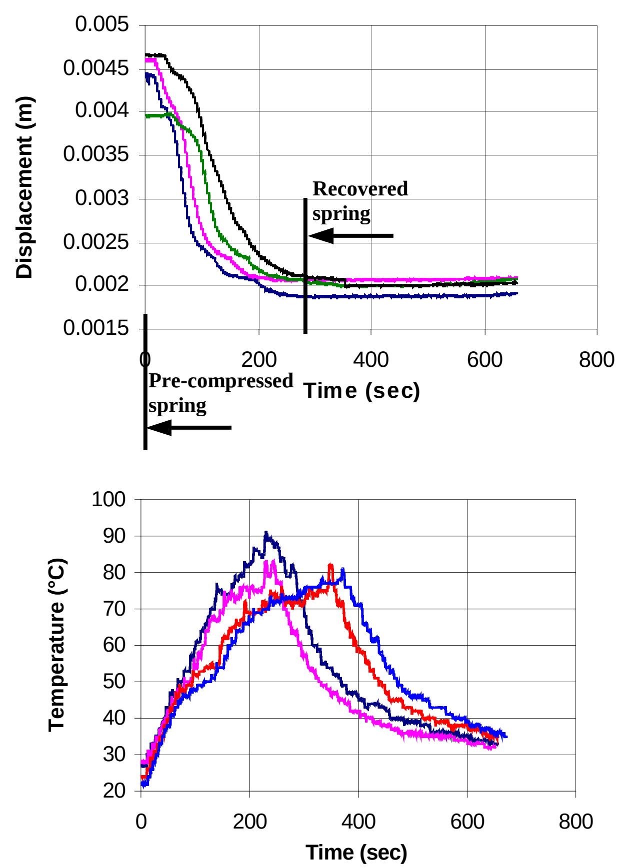


Fig. 7. Experimental results: (a)relative displacement of the active spring, (b) temperature of the active spring.

Figure 7a shows that the pre-compressed active spring recovers about 2.5 to 3 mm of its length upon heating. The range of the working temperatures was from 20 to 90 °C (Fig. 7b). The maximal temperature corresponds to the maximal recovery displacement of the active spring. Again, when the active spring recovered its initial pre-compressed position – the heat was turned off.

CONCLUSIONS

A mathematical model of the motion of a SMA NiTi actuator was developed. The model was based on the kinetics of the phase transformation in SMAs and equations of motion that describe “human muscle” behavior. The model has been verified by means of an SMA wire based experimental prototype of the actuator. It represents a uniaxial case of modeling of recovery displacements based on the Shape Memory Effect in SMAs. The results of the experimental and numerical simulations of the step response of the actuator show excellent agreement.

A more complex experimental prototype of the SMA actuator has been also designed and fabricated. The motion of this SMA prototype is driven by an active SMA spring, rather than by an SMA wire, as in the first case. Preliminary step response tests of the second prototype were conducted. The active SMA spring generated an about 2.5 to 3 mm linear motion due to the Shape Memory Effect recovery phenomenon. Future work will include the further verification of the step response experiments of the SMA spring- based actuator in accordance with the mathematical model presented by the system of equations of motion.

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