Proceedings of the ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems
SMASIS2018
September 10-12, 2018, San Antonio, TX, USA
SMASIS2018-8176

DRAFT: MODELING OF THE INTERFACE OF FUNCTIONALLY GRADED SUPERELASTIC ZONES IN COMPLIANT DEPLOYABLE STRUCTURES

Jovana Jovanova
Assistant professor
Faculty of mechanical engineering
Ss Cyril and Methodius University in Skopje
Skopje, Macedonia

Simona Domazetovska
Research and teaching assistant
Faculty of mechanical engineering
Ss Cyril and Methodius University in Skopje
Skopje, Macedonia

Mary Frecker
Professor
Dept. of Mechanical and Nuclear Engineering
The Pennsylvania State University
University Park, PA, USA

ABSTRACT

Functionally graded compliant mechanisms can be fabricated with additive manufacturing technology by engineering the microstructural and compositional gradients at selected locations resulting in compositionally graded zones of higher and lower flexibility. The local compliance depends on the geometry of the structure as well as the material property in the selected region. As Nitinol (NiTi) well suited for applications requiring compliance, the critical transformation stress and the superelastic modulus of elasticity are crucial parameters for defining the local compliance. To understand the behavior at the interface between two different material compositions, three models of gradient change between the alloys are analyzed: step change, linear and polynomial gradients. This paper will address a methodology for modeling and parametrization of material properties and transition at the interface. The combined effort in the interface of the functional grading and the geometry will be used for the design of monolithic self-deployable structures, initially folded in compact shape. The design motivation comes from the self-deploying mechanisms inspired by insects' wings.

I. NOMENCLATURE

E_A	Young's modulus of austenite phase
E_t	Young's modulus of martensite transformation
σ_s^{AS}	Starting stress value for the forward phase transformation
σ_f^{AS}	Final stress value for the forward phase transformation
θ	Folding angle
M	Applied moment

II. INTRODUCTION

Bio-inspired design is a multidisciplinary research field, seeking for inspiration in the similarities between nature and design for creating structures, with the potential for remarkable scientific impact [1]. Recent research merging origami and bio-inspired engineering results in the design of trendy and unique designs in various applications. Inspired by the wings of insects, including the use of origami design, monolithic self-deployable structures with the ability to fold and unfold can be designed.

In [2], the focus of investigation are the elastic deformations in order to expand origami-inspired design for morphing structures. Detailed processes of wing-unfolding and folding of beetles providing new possibilities for design of deployable structures were introduced in [3]. Based on beetle-inspired patterns, design of rigid foldable wings are purposed in [4]. Considering the geometry of rigid origami as important parameter for designing transformable and deployable structures is analyzed in [5].

Compliant mechanisms are monolithic flexible structures that use elastic deformation of the structure, providing various advantages over rigid-body mechanisms in many applications, including micro scale [6, 7]. The use of smart materials in compliant mechanisms design could result in novel devices with improved performance.

Nickel Titanium (NiTi) has been widely used in adaptive structures applications by exploiting the shape memory effect for actuation. NiTi can also be used in applications requiring localized large recoverable deformations by exploiting the superelastic effect. This material is beneficial for compliant mechanism design. One of the main properties of NiTi shape memory alloy (SMA) is the superelastic effect that provides high flexibility and large deformations capable of being recovered.

In this paper we focus on spatial distribution of the superelasticity within NiTi compliant mechanisms through functional grading. The integration of functionally graded materials in the monolithic structure directly affects the performance of the design. Two types of functionally graded structures, step change structure and continuous change in the interface of the material, have been considered [8]. The gradients directly affect the spatial distribution of the material properties.

Using topology optimization method for design of functionally graded structures have been used in [9-11]. The effects of the material interface properties in the optimization of structures were purposed in [12, 13]. The influence of material gradation and layout in the overall stiffness behavior of functionally graded structures is exposed in [14].

Compliant mechanisms made of NiTi have a wide range of uses in various bio-inspired applications, origami structures, bio-medical and space devices. The concept of optimizing the geometry and mechanical properties by implementing the superelastic phenomenon of nonlinear NiTi SMA material is proposed in [15-17]. A geometric modeling method is applied to design compliant mechanisms, allowing spatial distribution of two materials in [18]. Topology optimization for effective design of functionally graded compliant mechanisms is developed in [19], using numerical multi-phase materials. In [20] it is shown the combined optimization of a compliant mechanism of piezoelectric stack actuator for efiicient energy conversion. Elastomer hinges were analyzed in [21] to achieve high localized flexibility at compliant joints. SMA flexures and wires [22] have been used by researchers to exploit high local superelastic behavior in compliant mechanisms.

A comparative study was proposed in [23], analyzing the free deflection angle and blocked force of a compliant articulation structure with implemented superelatstic nitinol and stainless steel. Fabrication of NiTi through additive manufacturing (AM) exploring the spatial characteristics and properties are considered in [24-27]. The microstructure and superelasticity in AM NiTi shape memory alloy using laser directed energy deposition were investigated in [28]. An analytical approach for a SMA beam modeled with FEA was developed for solution of the displacement as a result of the applied force in [29].

The difference between folding and bending of origami-inspired structures using active materials is defined in [30]. Different smart materials can result in multi-field responsive origami structures as showed in the modeling and experiments in [31].

This paper is focused on the impact of the functional grading and interface modeling on the performance of a compliant mechanisms. The interface model will affect the stress distribution and deformation by using three different types of gradients: step, continious linear and polynomal change. To analyze the stress and deformations, the compliant mechanism is modeled using finite element analysis (FEA). The combination of functionally graded materials and the proper design of the geometry of compliant mechanism define the performance and facilitate folding and self-deployment of the structure.

The remainder of the paper is structured as follows: section 3 analyzes bio-inspired complex 3D self-deployable structures. Section 4 gives overview of the gradient of the interface for functionally graded material for compliant mechanism design. Section 5 shows the FEA predictions of the dependence of the folding angle from the combination of changing the geometric shape of the interface and functional grading of the material. The last section concludes the work and proposes further steps.

III. NiTi FOR BIO-INSPIRED COMPLIANT MECHANISMS DESIGN

Nickel Titanium is one of the most attractive and widely used shape memory alloy material because of its unique functional properties including superelastic (SE) behavior and shape memory (SM) effect, biocompability, low stiffness, corrosion behavior and damping characteristics. NiTi materials have superelastic behavior that enable restoring large strains up to 8% theoretically by unloading and heating established from a phase transformation between martensite and austenite [32].

The fabrication of NiTi elements is quite challenging and specific due to its sensitivity to processing parameters. Recently, powder metallurgy (PM) and additive manufacturing processes are being developed for NiTi components. Additive manufacturing techniques are implemented for direct fabrication of complex structures, having the potential of wide use in many applications. Powder preparation, optimum laser parameters and fabrication chambers conditions are influential parameters when considering producing NiTi SMA through AM.

Powder bed fusion via selective laser melting and laser-based directed energy deposition AM processes are currently being developed. Along with the processing, the microstructure and compressive shape memory effect recovery of as-built alloys [24, 25] are being characterized.

Other researchers have investigated porous NiTi structures fabricated using AM. These structures are useful in various medical applications because of desirable mechanical properties such as stiffness that can match bone stiffness [25, 26].

Functional grading of NiTi is achieved using different compositions of Ni and Ti powders in a direct energy deposition process, resulting in spatially varying material properties. This approach enables spatial control of the superelastic behavior of NiTi in a single-piece monolithic structure.

The material model for NiTi is a nonlinear shape memory alloy two-phase material, consisting of two parts: linear region of higher modulus of elasticity and a superelastic region with lower modulus of elasticity.

A standard nonlinear SMA material model for the mechanical behaviour of nitinol is being used, as shown in Figure 1. The model requires only two parameters, the starting stress value for the forward phase transformation (σ_s^{AS}) and the final stress value for the forward phase transformation (σ_f^{AS}). In Figure 1, there are shown the two regions of interest: the linear elastic part (marked with blue colour) and the superelastic part (marked with yellow colour).

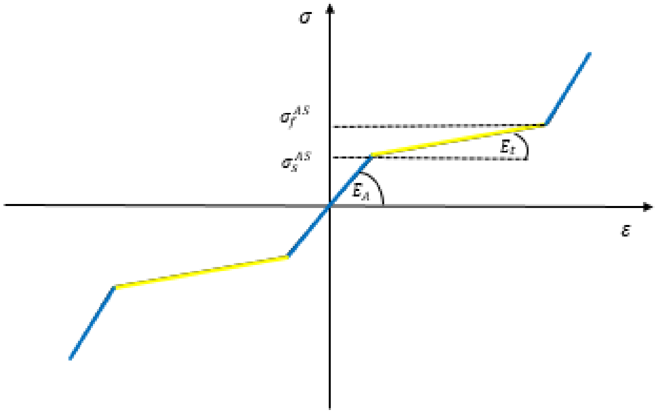
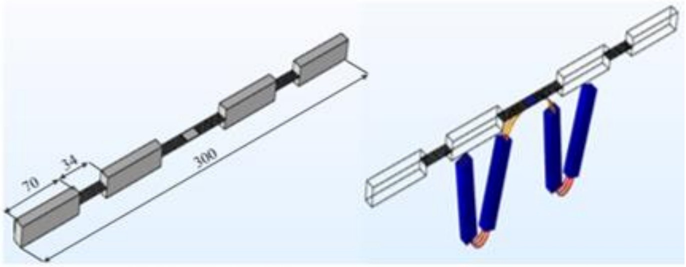


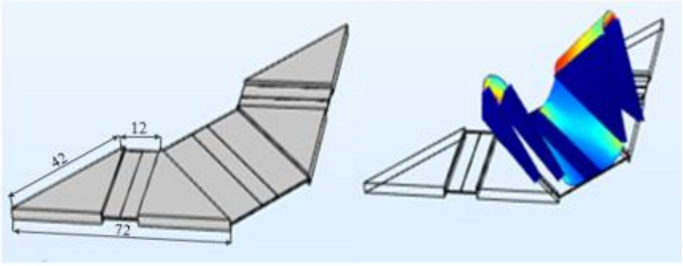
Figure 1. SMA nonlinear material model

σ_s^{AS} = Starting stress value for the forward phase transformation
σ_f^{AS} = Final stress value for the forward phase transformation
E_A = Young's modulus of austenite phase
E_t= Young's modulus of martensite transformation

Different 3D structure shapes can be designed with functional grading and tailoring of the moduli of elasticity of NiTi to obtain highly flexible regions. Some species of insects, for example, ladybug, have wings that deploy in large area surfaces when needed, and fold compactly when the insect is steady. The design of such mechanisms (Figure 2) can be achieved by modeling the geometry and functional grading of the material properties of NiTi, showing the benefit of the combined effort. It is expected to be able to achieve complete folding of a multi-segment 3D compliant mechanism.



a. Initial structure b. Folded structure



a. Initial structure b. Folded structure

Figure 2. FEA models of superelastic compliant mechanisms inspired by insects' wings. The dimensions are given in mm.

To get better understanding of the interface between two different NiTi SMA alloys in one monolithic structure, the gradient has been investigated. The overall performance of the mechanism is defined with a folding angle, and the potential of getting as close as possible to a complete fold. To achieve the fold, a flexure is designed in the interface, to localize the flexibility of the mechanism.

IV. ANALYSES OF THE MATERIAL GRADIENT OF THE INTERFACE BETWEEN TWO ALLOYS

Two different NiTi alloys are introduced in a simple cantilever beam structures in order to analyze the interface impact to the overall performance of the compliant mechanism. Additive manufacturing enables different grading of the interface, which could be advantageous for different types of applications [33]. To understand the behavior of the interface between the two different material compositions, 3 different models of gradient are analyzed: step change, linear gradient and polynomial gradient, schematically shown in Figure 3. Mathematical representation of the gradients as a function is schematically shown in Figure 3 on the right.

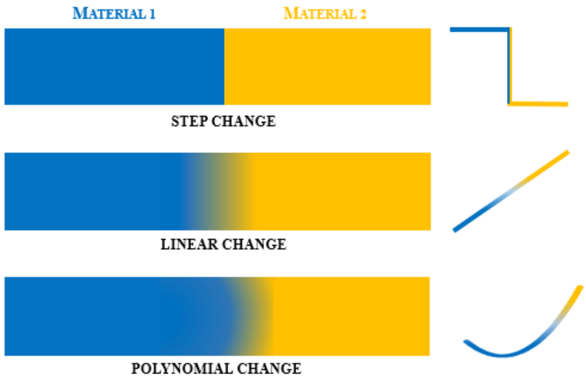


Figure 3. Types of functional grading of the material curve

The moduli of elasticities as material properties of the two alloys used for this compliant mechanism are given in Table 1. This values for the linear elastic and superelastic NiTi material properties are parametrically chosen, based on the experimental work on NiTi samples produced with the method of direct energy deposition in [28]. For the materials used in this particular paper $\sigma_s^{AS} = 300\ MPa$.

TABLE 1.

NiTi material properties		
	E_A (GPa)	E_t (GPa)
MATERIAL 1	50	10
MATERIAL 2	80	30

The nonlinear material models are implemented in the finite element analysis. The COMSOL software is used for FEA model and analyses, showing the distribution of the stresses, deformations and angle of folding of the compliant mechanism. The geometry of the compliant mechanism is given on Figure 4, showing the dimensions in mm. The analyzed mechanism is cantilever beam, fixed on the left end with a moment load applied on the other end of the beam. Different material curves are applied in the parts at the end as shown on the figure. The three types of functional grading of the curves, step change, linear change and polynomial change are applied on the interface in the middle of the mechanism. In of this research, material 1 is considered to be more flexible than material 2. In the polynomial change of the interface, material 1 is more present than material 2, and is expected to result in higher folding angle.

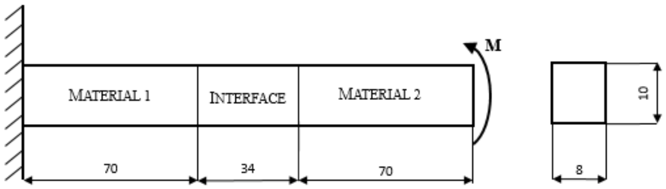


Figure 4. Geometric properties of the compliant mechanism. The dimensions are given in mm.

The folding angle θ is defined by researchers in [34], defined as the angle between the two tangent lines at the mid points of the two body panels.

The folding angle has been analyzed for the compliant mechanism over the range of applied moment from $10Nm$ to $70Nm$, as shown in Figure 5. It is noticeable that the maximum folding angle values are higher in the polynomial change of the curve than the linear and step change. At moment of $70Nm$, the folding angle of the beam with polynomial change reaches up to 25°.

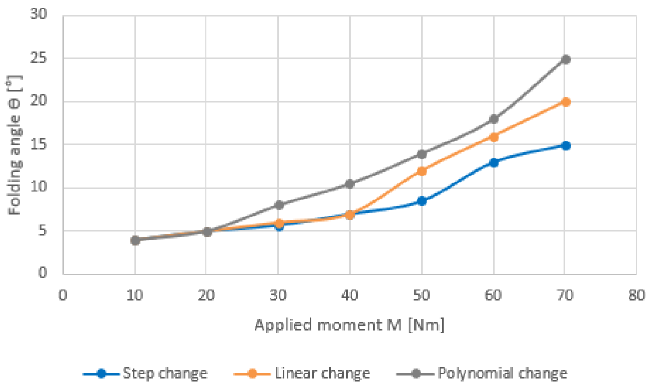


Figure 5. Folding angle for different types of gradient in the interface

The difference in folding angle is more noticeable as the applied moment increases from 10 to $70Nm$ for different gradients in the interface. At the maximum applied moment, the folding angle for the step change of the interface is 15°, for linear change is 20°, whereas with the polynomial change of the gradient of the interface the angle reaches 25°. Since the cross section is constant along the beam, the stress applied due to a constant moment cannot create high local compliance in a monolithic structure. Figure 6 shows the deformation of the FEA model for applied moment $M = 70Nm$ with applied material polynomial change of the interface. Because of the uniform geometry of the mechanism, sharp fold could not be established.

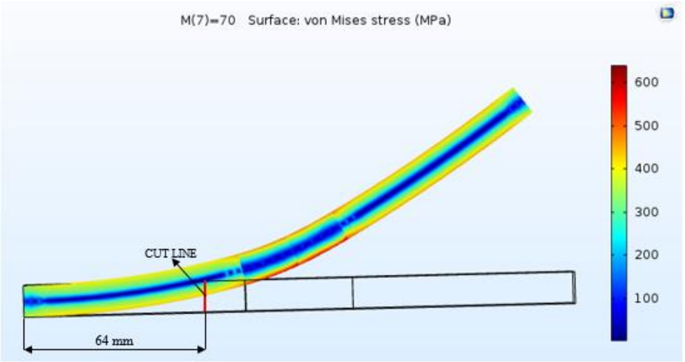


Figure 6. FEA model with material polynomial change of the interface

Based on the material curves introduced at the beam, at the moment of $M = 70Nm$ the compliant mechanism adopts superelasticity at the outer layers of the cross section, since the critical transformation stress is achieved. The interface influence on the stress distribution goes up to $5mm$ into material rigid sections. The stress distribution for a cut plane at $64mm$ from the fixed end in the Material 1 segment is presented in Figure 7, where the nonlinearity of the material curve, translates into nonlinear stress distribution at the critical transformation stress. The peak stress is at $436.8MPa$.

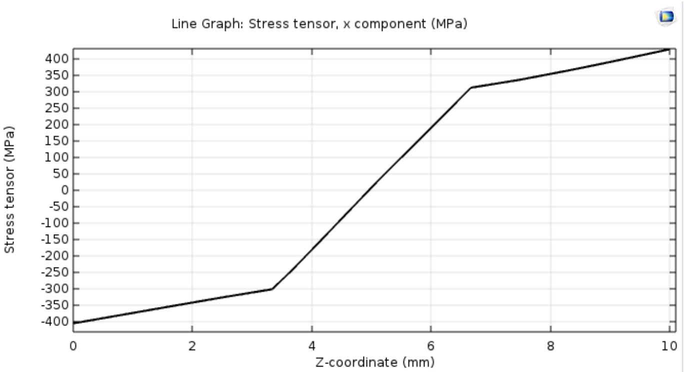


Figure 7. Stress distribution for FEA model with material polynomial change of the interface for cut line at 64mm

To get closer to a complete fold, a flexure was introduced in the interface of the compliant mechanism. Different flexure designs were analyzed with the same nonlinear materials in order to determine the best combination of interface gradient and flexure design as a combined effort to maximize local compliance.

V. GEOMETRIC ANALYSIS OF THE INTERFACE

The geometry of the interface plays crucial role in the mechanism performance. In order to get folding, a flexural hinge is introduced in the interface section, in order to get localized high flexibility. The methodology for design of the flexural hinges, as well as different flexure geometries are elaborated in [35]. The different geometries analyzed here are shown in Figure 8. The volume of all interfaces is constant for the 3 different geometric shapes. The length of each geometry is the interface length shown in Figure 4. The width of the flexures is constant with the rest of the beam. The minimum thickness in all flexures is 5mm.

Figure 8. Flexure design: A. Step change, B. Linear change, C. Elliptical change

The step change is just a reduced height of the beam cross section. The linear change and the elliptical change show smoother transition in the cross section area along the beam.

The same material gradients were introduced for each of the flexures, and the folding angle as the compliant mechanism performance was measures and compared. Figure 9 shows the analysis of the folding angle for the geometric step change of the shape of the interface. It can be immediately noticed that a bigger folding angle is achieved with the flexures, compared for the same applied moment with the constant cross section case, Figure 5. The maximum folding angle reaches the value of 55° for the material polynomial change of the interface as shown in Figure 9. When the interface is thinner the compliant mechanism reaches large localized deformations in this part, increasing the folding angle.

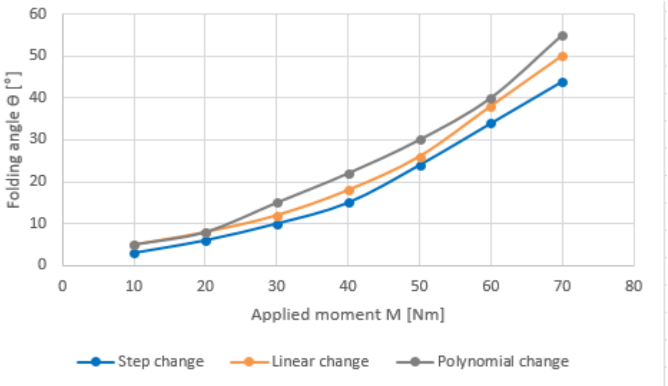


Figure 9. Folding angle for different gradients for the geometric step change of the interface

The geometric linear change combined with the three material gradients and the results from the folding of the compliant mechanism are shown on Figure 10. From the figure showing the folding angle of the linear shape interface, it can be concluded that the maximum value of the folding angle is again for the polynomial change of the material curvature, where for applied moment of $70Nm$, the predicted angle is 60°. This indicates that the geometrical transition should be smoother for improving performance.

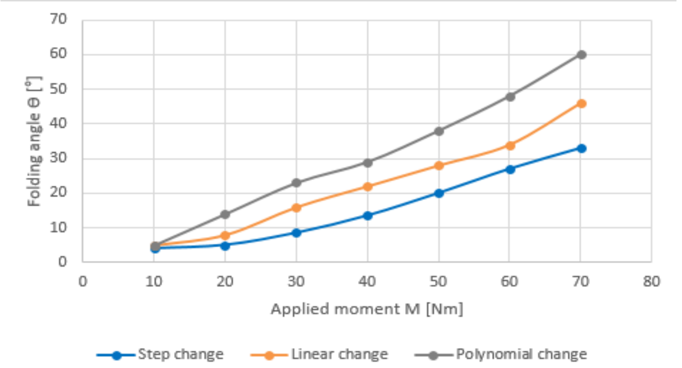


Figure 10. Folding angle for different gradients for the linear geometric change of the interface

At the end an elliptical flexure was designed and the same material gradients were again introduced. Figure 11 shows the results of the performance analysis of the compliant mechanism with an elliptical flexure. As it can be noticed, the folding angle has the maximum value as expected for the polynomial material change, and the folding angle is 97° for moment of $70Nm$.

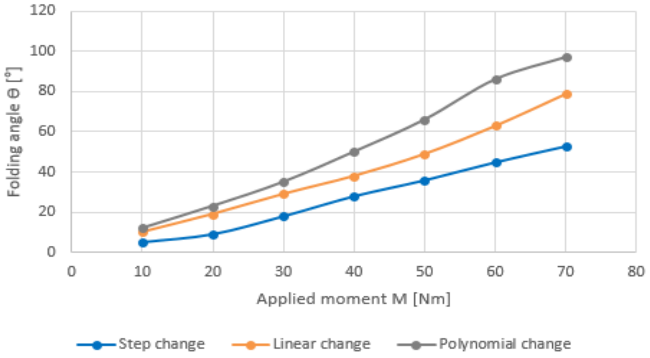


Figure 11. Folding angle for different gradients for the elliptical geometric change of the interface

The deformation for the elliptical flexure and polynomial gradient is shown in Figure 12.

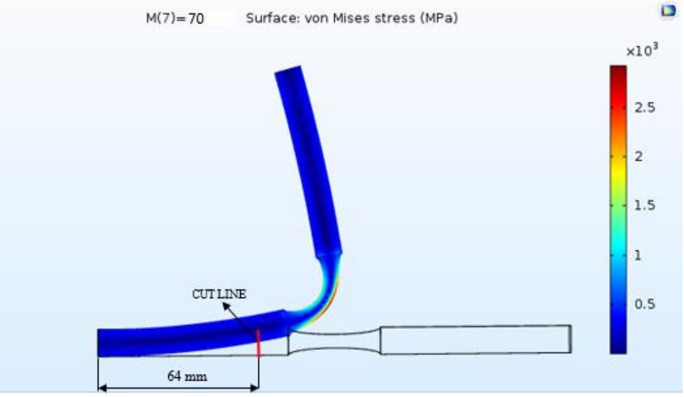


Figure 12. FEA model with material polynomial change and geometric elliptical shape change of the interface

The stress distribution of the same cut line in Material 1 is shown in Figure 13. The peak stresses here are $398.5MPa$ and are less compared to the same cross section in Figure 7, where the peak stress has the value of $436.8MPa$. The inner section of the beam with 4mm thickness in this segment is in the linear elastic part of the material curve. The external layers of $3mm$ on each side are in the superelastic region of the material, allowing much higher strains.

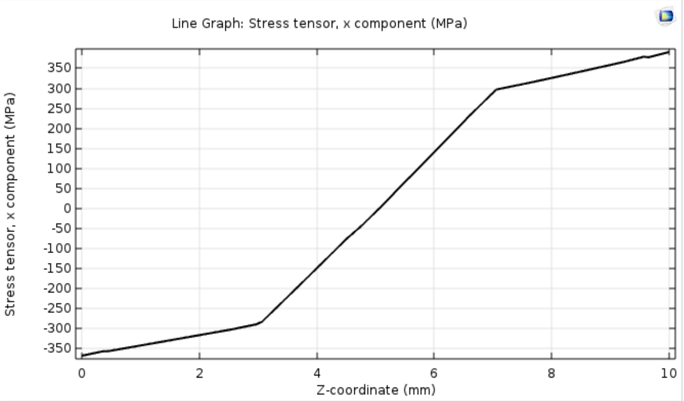


Figure 13. Stress distribution for FEA model with material polynomial change of the interface for cut line at 64mm

Even though the deformation of the mechanism is significantly higher, the peak stresses are lower, clearly indicating that a polynomial material gradient and elliptical flexure could provide the best combined effort for achieving the maximum folding angle. The results shown on Figure 14 show that the compliant mechanism has the maximum folding angle while polynomial change of the interface is applied on the elliptical shape of the geometry of the flexure. The maximum angle for the applied moment of $70Nm$ is 97° for the geometric elliptical flexure, 60° for the geometric linear shape and 55° for the geometric step shape of the interface.

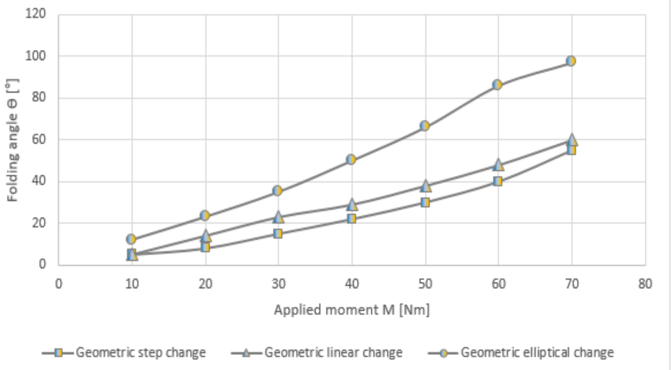


Figure 14. Folding angle of the compliant mechanism with the polynomial gradient for the three different flexure designs of the interface

For instance, for the polynomial material change for the same folding angle of $\theta = 38°$, the compliant mechanism with elliptical flexure has the lowest peak stress compared to the linear flexure, where the peak stress is 29% higher, while for the step shape change the peak stress is 57.1% higher. Reduction of the stress distribution is noticed. The elliptical geometry of the flexure with the polynomial gradient results in best compliant mechanism performance.

VI. CONCLUSIONS

Having different compositions of nickel and titanium in one monolithic structure during fabrication allows tailored compliant mechanism designs to different beneficial behavior. Using additive manufacturing for fabrication allows design beyond conventional processing including shape and material complexities, in order to achieve better performance of the compliant mechanism.

Bio-inspired deployable structures could be designed based on origami engineering approach exploiting NiTi superelasticity for high localized compliance. Additive manufacturing allows functional grading and the interface between to different NiTi alloys could be modelled with a step change, linear or polynomial change. Using FEA, the mechanism performance was analyzed based on a different grading. To maximize local flexibility, geometrical nonlinearity was introduced in the form of flexure, to achieve combined effort of the interface grading and the geometry. The results showed that applying polynomial grading in combination with elliptical geometry of the hinge, the best performance is achieved. Self-deployable, bio-inspired origami active structures could potentially improve their performance in applications when designed in this manner.

Further research includes expanding this approach with optimization of the polynomial gradient and the flexure in the interface to improve the performance of compliant mechanisms.

REFERENCES

[1] Lepora, N. F., Verschure, P., & Prescott, T. J. (2013). The state of the art in biomimetics. *Bioinspiration & biomimetics*, *8*(1), 013001.

[2] Tsukahara, A., & Okabe, Y. New Deployable Structures Based on an Elastic Origami Model

[3] Saito, K., & Okabe, Y. (2015, August). Elastic Wing Deployments in Beetles and Their Folding Mechanisms. In *ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V05BT08A033-V05BT08A033). American Society of Mechanical Engineers

[4] Saito, K., Tachi, T., Niiyama, R., & Kawahara, Y. (2017, August). Design of a Beetle Inspired Deployable Wing. In *ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V05BT08A045-V05BT08A045). American Society of Mechanical Engineers.

[5] Tachi, T. (2010, November). Geometric considerations for the design of rigid origami structures. In *Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium* (Vol. 12, No. 10, pp. 458-460).

[6] Vijayan, V., & Karthikeyan, T. (2009). Design and Analysis of Compliant Mechanism for Active Vibration Isolation Using FEA Technique. *International Journal of Recent Trends in Engineering*, *1*(5), 77.

[7] Kota, S., & Ananthasuresh, G. K. (1995). Designing compliant mechanisms. *Mechanical Engineering-CIME*, *117*(11), 93-97.

[8] Udupa, G., Rao, S. S., & Gangadharan, K. V. (2014). Functionally graded composite materials: an overview. *Procedia Materials Science*, *5*, 1291-1299.

[9] Paulino, G. H., & Silva, E. C. N. (2005). Design of functionally graded structures using topology optimization. In *Materials science forum* (Vol. 492, pp. 435-440). Trans Tech Publications.

[10] Carbonari, R. C., Silva, E. C., & Paulino, G. H. (2007). Topology optimization design of functionally graded bimorph-type piezoelectric actuators. *Smart Materials and Structures*, *16*(6), 2605.

[11] Radman, A., Huang, X., & Xie, Y. M. (2013). Topology optimization of functionally graded cellular materials. *Journal of Materials Science*, *48*(4), 1503-1510.]

[12] Faure, A., Michailidis, G., Parry, G., Vermaak, N., & Estevez, R. (2017). Design of thermoelastic multi-material structures with graded interfaces using topology optimization. *Structural and Multidisciplinary Optimization*, *56*(4), 823-837.

[13] Vermaak, N., Michailidis, G., Parry, G., Estevez, R., Allaire, G., & Bréchet, Y. (2014). Material interface effects on the topology optimizationof multi-phase structures using a level set method. *Structural and Multidisciplinary Optimization*, *50*(4), 623-644.]

[14] Almeida, S. R., Paulino, G. H., & Silva, E. C. (2010). Layout and material gradation in topology optimization of functionally graded structures: a global–local approach. *Structural and Multidisciplinary Optimization*, *42*(6), 855-868.

[15] Jovanova, J., & Frecker, M. (2017, September). Two Stage Design of Compliant Mechanisms with Superelastic Compliant Joints. In *ASME 2017 Conference on Smart Materials, Adaptive Structures and Intelligent Systems* (pp. V002T03A019-V002T03A019). American Society of Mechanical Engineers.

[16] Jovanova, J., Frecker, M., Hamilton, R. F., & Palmer, T. A. (2016, September). Target Shape Optimization of Functionally Graded Shape Memory Alloy Compliant Mechanism. In *ASME 2016 Conference on Smart Materials, Adaptive Structures and Intelligent Systems* (pp. V002T03A006-V002T03A006). American Society of Mechanical Engineers.

[17] Jovanova, J., Frecker, M., Hamilton, RF., Palmer TA., (2017). Target shape optimization of functionally graded shape memory alloy compliant mechanisms. *In Journal of Intelligent Material Systems and Structures. Special Issue Article*

[18] Zhou, H., & Ting, K. L. (2009). Geometric modeling and synthesis of spatial multimaterial compliant mechanisms

and structures using three-dimensional multilayer wide curves. *Journal of mechanical design*, *131*(1), 011005.

[19] Yin, L., & Ananthasuresh, G. K. (2001). Topology optimization of compliant mechanisms with multiple materials using a peak function material interpolation scheme. *Structural and Multidisciplinary Optimization*, *23*(1), 49-62.

[20] Abdalla, M., Frecker, M., Gürdal, Z., Johnson, T., & Lindner, D. K. (2005). Design of a piezoelectric actuator and compliant mechanism combination for maximum energy efficiency. *Smart materials and structures*, *14*(6), 1421.

[21] Vogtmann, D. E., Gupta, S. K., & Bergbreiter, S. (2013). Characterization and modeling of elastomeric joints in miniature compliant mechanisms. *Journal of Mechanisms and Robotics*, *5*(4), 041017.

[22] Bellouard, Y. R. Clavel, 2004," Shape memory alloy flexures,".*Materials Science & Engineering A, 378,* 210-215.

[23] Liu, J., Hall, B., Frecker, M., & Reutzel, E. W. (2013). Compliant articulation structure using superelastic NiTiNOL. *Smart materials and structures*, *22*(9), 094018.

[24] Elahinia, M., Moghaddam, N. S., Andani, M. T., Amerinatanzi, A., Bimber, B. A., & Hamilton, R. F. (2016). Fabrication of NiTi through additive manufacturing: A review. *Progress in Materials Science*, *83*, 630-663.

[25] Elahinia, M. H., Hashemi, M., Tabesh, M., & Bhaduri, S. B. (2012). Manufacturing and processing of NiTi implants: a review. *Progress in materials science*, *57*(5), 911-946.

[26] Taheri Andani, M., Haberland, C., Walker, J. M., Karamooz, M., Sadi Turabi, A., Saedi, S., ... & Elahinia, M. (2016). Achieving biocompatible stiffness in NiTi through additive manufacturing. *Journal of Intelligent Material Systems and Structures*, *27*(19), 2661-2671.

[27] Hamilton, R. F., Palmer, T. A., & Bimber, B. A. (2015). Spatial characterization of the thermal-induced phase transformation throughout as-deposited additive manufactured NiTi bulk builds. *Scripta Materialia*, *101*, 56-59.

[28] Bimber, B. A., Hamilton, R. F., Keist, J., & Palmer, T. A. (2016). Anisotropic microstructure and superelasticity of additive manufactured NiTi alloy bulk builds using laser directed energy deposition. *Materials Science and Engineering: A*, *674*, 125-134.

[29] Eshghinejad, A., & Elahinia, M. (2011, January). Exact solution for bending of shape memory alloy superelastic beams. In *ASME 2011 conference on smart materials, adaptive structures and intelligent systems* (pp. 345-352). American Society of Mechanical Engineers.

[30] Lauff, C., Simpson, T. W., Frecker, M., Ounaies, Z., Ahmed, S., von Lockette, P., ... & Lien, J. M. (2014, August). Differentiating bending from folding in origami engineering using active materials. In *ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V05BT08A040-V05BT08A040). American Society of Mechanical Engineers.

[31] Ahmed, S., Lauff, C., Crivaro, A., McGough, K., Sheridan, R., Frecker, M., ... & Strzelec, R. (2013, August). Multi-field responsive origami structures: Preliminary modeling and experiments. In *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. V06BT07A028-V06BT07A028). American Society of Mechanical Engineers.

[32] Elahinia, M. (2015). *Shape memory alloy actuators: design, fabrication and experimental evaluation*. John Wiley & Sons.

[33] Hofmann, D., Kolodziejska, J., Roberts, S., Otis, R., Dillon, R., Suh, J., Liu, Z. & Borgonia, J. 2014, "Compositionally graded metals: A new frontier of additive manufacturing", JOURNAL OF MATERIALS RESEARCH, vol. 29, no. 17, pp. 1899-1910.

[34] Zhang, W., Ahmed, S., Masters, S., Ounaies, Z., & Frecker, M. (2016, September). Finite Element Analysis of Electroactive Polymer and Magnetoactive Elastomer Based Actuation for Origami-Inspired Folding. In *ASME 2016 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*(pp. V001T01A001-V001T01A001). American Society of Mechanical Engineers.

[35] Lobontiu, N., 2002. *Compliant mechanisms: design of flexure hinges*. CRC press.