Hafezi, M. and Feeney, A. (2023) Microscale Nitinol Hardness Measurements for Engineering Adaptive Ultrasonic Devices. 17th International Conference on Advances in Experimental Mechanics, Glasgow, UK, 30 Aug-01 Sept 2023.

Microscale Nitinol Hardness Measurements for Engineering Adaptive Ultrasonic Devices

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Abstract. Nitinol is arguably one of the most utilised shape memory alloys, widespread in the biomedical industry in stent designs and in the aerospace industry for damping structures. It exhibits two properties which have shown potential for enhancing the performance of ultrasonic devices. The first is the shape memory effect, the ability to switch its shape and phase microstructure in response to temperature or stress. The second is the highly reversible response to loading, known as superelasticity. The atomic crystal lattices of Nitinol are hence highly sensitive to static and dynamic loading, with the potential to revolutionise medical and industrial ultrasonics. For example, integration of Nitinol into ultrasonic devices will enable adaptive control of operational frequency in a single device, potentially across thousands of Hz. However, few of the developments made in the integration of Nitinol with ultrasonic transducers has focused on the mechanics of the material, particularly under the conditions to which Nitinol would be subjected as a component of an ultrasonic device. In this study, micro-indentation is undertaken on binary Nitinol to understand the influence of loading on mechanical characteristics such as hardness and stiffness. A square-pyramidal shaped diamond indenter has been used to apply the mechanical loading to samples cut from Nitinol sheet, where nonlinear increases in the mechanical hardness of Nitinol was measured, as the indentation load was raised. It has been found that both hardness and stiffness of Nitinol increase with load, and so there will be implications for the dynamics of ultrasonic devices fabricated using Nitinol and operating at elevated levels of dynamic stress.

Introduction

Nickel titanium, more commonly known as Nitinol, is a binary alloy of nickel and titanium which is a form of shape memory alloy. These materials exhibit shape memory, which is the ability to recover set shapes through a microstructural phase transformation which is temperature or stress dependent, and superelasticity, which is a reversible physical recovery from a relatively high applied stress. The elastic modulus of Nitinol can switch from the order of 30-40 GPa with a martensitic phase microstructure, towards 70-90 GPa when its phase microstructure is austenitic. These moduli magnitudes in part depend on the material composition and the hot and cold working applied to the material. Nitinol has traditionally been utilised in the biomedical industry, for example as the basis for a range of vascular stents. It has also been integrated into aerospace structures, for purposes including introducing mechanical damping features. More recently and particularly over the past ten years, Nitinol has been investigated for its suitability for integration in ultrasonic devices. It has most successfully been incorporated into the flextensional cymbal transducer [1,2]. The underlying rationale behind integrating ultrasonic devices like the cymbal transducer with shape memory alloys such as Nitinol, is that the change in elastic modulus of a vibrating Nitinol component embedded in the device, in magnitudes as referred to here, will thereby generate a notable shift in resonance frequency. This would have significant implications for both medical and industrial ultrasonic devices. For example, there is evidence that the optimal frequency of surgical cutting has some relationship with the properties of the material being cut [3]. Therefore a Nitinol-based device may confer advantages including removing the need to switch the cutting tip, should operations be undertaken involving both softer muscular tissues or harder bone materials. However, up to this point, little attention has been given to the mechanics of Nitinol under loads it would be subjected to when integrated in an ultrasonic device. Much of the research up to this stage has primarily focused on the dynamics of transducers fabricated using Nitinol, and thus for future design and optimisation, a more complete overview of the mechanical properties of Nitinol is required. Transducer configurations, including the Langevin stack, can be composed of multiple components, including end-masses and piezoelectric ceramics, bolted and pre-loaded together. Since it is known that the transformational properties of Nitinol are in part stress-dependent, the influence on stress on any component in an ultrasonic device which is manufactured using Nitinol is important, particularly for future dynamics applications. Specifically, understanding influences on mechanical stiffness is key for engineering a new generation of adaptive ultrasonic devices which are fabricated using advanced materials such as shape memory alloys. In this study, micro-indentation is used to understand the influence of mechanical load on the hardness and stiffness characteristics of Nitinol, and the implications for integrating such materials into medical and industrial ultrasonic devices.

Sample Preparation

Shape memory Nitinol sheet has been provided from SAES Smart Materials, Inc. (New York, USA) which was tailored with an austenitic start temperature of 55ºC. This means that the temperature at which the stiffer austenitic microstructure emerges is when the Nitinol is heated to 55ºC. In short, a shape memory alloy such as Nitinol has several transformation temperatures, and each indicates the start or finish of a transformation from one microstructure phase to another. Samples of Nitinol were cut from the sheet via the water jet method (Maxiem1515, OMAX) with a linear position accuracy of ± 0.076 mm. To investigate the hardness, a Hardness Testing Machine (Micromet 5104, Buehler) has been employed, with the process undertaken at room temperature and under ambient humidity conditions. The experimental setup is shown in Fig. 1.

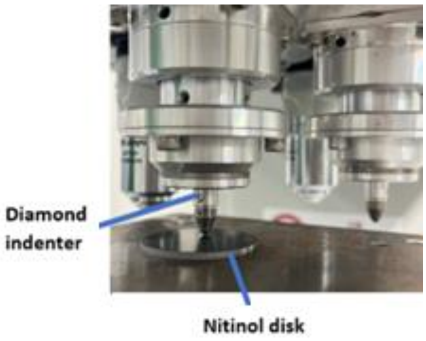

Fig. 1: The micro-indentation of Nitinol using a square-pyramidal indenter.

A square-pyramidal shaped diamond indenter has been used to indent the Nitinol surface across a range of loads from 10 to 1000 g, with a sensitivity of 10 g. A load matrix has then been designed to evaluate hardness via the applied force and the average length of the diagonals of the indent`s base.

Hardness Measurement

The hardness measurements are shown in Fig. 2, where the hardness maximum has been measured as 279.3 HV at 1000 g of load. The indentations could be recovered by stimulating the shape memory effect in the material, by raising the temperature of the Nitinol above 55ºC.

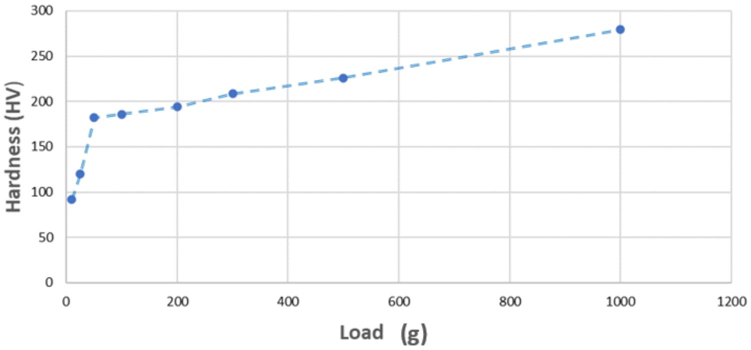

Fig. 2: Hardness as a function of load for shape memory Nitinol.

Interestingly, there can be observed nonlinear increases in hardness with a linear rise in loading, suggesting that there should be care taken in the operation of adaptive ultrasonic devices which incorporate Nitinol. There will be changes to the mechanical stiffness and hardness at the interfaces between vibrating components fabricated from Nitinol, which will then undergo localised phase transformations and impart influences on the dynamics on the device. Critically, it appears that this will not occur linearly with load.

Conclusion

In this study, micro-scale mechanical indentation has been undertaken to demonstrate the influence of indentation load on the mechanical characteristics of Nitinol, including hardness and stiffness. There is a nonlinear relationship between hardness and applied load, where stiffness rises with load. These behaviours generate phase transformations, which will directly impact the dynamics of an ultrasonic device fabricated using this material. Future research will focus on deeper understanding of these mechanisms.

References

[1] A. Feeney and M. Lucas: *Differential Scanning Calorimetry of Superelastic Nitinol for Tunable Cymbal Transducers*, J. Intell. Mater. Syst. Struct. Vol. 27 (2016), p. 1376-1387.

[2] S. Smith, X. Li, M. Hafezi, P. Barron, M. Lucas and A. Feeney: *Enhanced Resolution Phase Transformations in a Nitinol Cymbal Ultrasonic Device*, In: 2022 IEEE International Ultrasonics Symposium (IUS), IEEE, p. 1-4.

[3] M. Lucas and A. Mathieson: *Ultrasonic Cutting for Surgical Applications*, In: Power Ultrasonics (2015), p. 695-721.