# The Thermomechanical Behaviour of Nitinol for Adaptive Ultrasonic Devices

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**Abstract.** In the drive towards multifunctional ultrasonic devices, the incorporation of shape memory Nitinol with ultrasonic transducers such as the Langevin and cymbal has been explored to enable active resonance tuning. This occurs via changes in Nitinol Young's modulus, between compliant martensite and stiff austenite. However, there remain challenges to understand Nitinol's mechanical performance across dynamic loading cycles. Here, the thermomechanical characteristics of bulk Nitinol under dynamic loading at different temperatures are investigated as functions of time, using dynamic mechanical analysis. In general, the results indicate that over time, storage modulus and dynamic stress are similar irrespective of phase microstructure, though the loss modulus is more dependent on the phase. There is hence evidence that Nitinol therefore exhibits potential for stable use in devices generating high cyclic motions, such as ultrasonic transducers.

## Introduction

In recent years, there has been growing activity in the integration of shape memory alloys into ultrasonic devices, predominantly for the cymbal-type flextensional and Langevin configurations [1,2]. The motivations for this include the potential to enable multi-frequency and multifunctional devices, by exploiting the phase transformations of shape memory materials. Nitinol has been the material of choice for these studies, given its prevalence and relatively inexpensive status, and its success in both industrial and medical applications [3]. Nitinol is a binary alloy of nickel and titanium which undergoes a phase transition between a martensitic microstructure at comparatively low temperatures, and an austenitic microstructure at higher temperatures. Associated transformation temperatures can be tailored in the alloy depending on factors such as hot or cold working applied to the material, or the alloy composition [1]. The phase microstructure of the material can be switched through a trigger, typically either temperature or load. The key behaviours of this material, common to many shape memory alloys, are the shape memory effect (the capacity of the material to recall a set shape recoverable with temperature upon deformation) and superelasticity (a highly reversible recovery to an appropriate level of applied stress). Fundamentally, and why multi-frequency or tuneable (adaptive) frequency ultrasonic devices are possible, the different phase microstructures possess different Young`s moduli. Therefore, it is possible to construct an ultrasonic transducer which will resonate at different frequencies depending on the phase microstructure generated in the Nitinol component. Nitinol in its superelastic form is that which exists with the temperature of the material above its final austenitic transformation temperature. The shape memory effect is produced by instigating a phase transformation via the transformation temperatures associated with the martensitic and austenitic microstructures. The Young's modulus of martensitic Nitinol can exist in the 30-40 GPa range, whereas that for austenite can be in the order of 70 GPa or higher [2]. There have been several studies demonstrating the thermomechanical characteristics of Nitinol [4,5], but they tend to be limited to the study of wire configurations, popular in robotics or biomedical stents. A more complete understanding is required of the time-dependent thermomechanical properties of Nitinol to inform future design strategies for ultrasonic devices incorporating this material. The core aim of this study is to measure the loss and storage moduli of bulk Nitinol, analysing the energy balance in the material microstructure over time, instructive for the integration of Nitinol in devices utilising cyclic dynamics like ultrasonic transducers.

## Material and Methods

Nitinol sheets were acquired (SAES Smart Materials, Inc., NY, USA), with a nominal transition temperature to austenite of 55ºC. This means that above this temperature, the phase microstructure of the Nitinol should be fully austenitic, having completely reoriented from the martensitic phase microstructure at lower temperatures. Test specimens were machined based on standard sizes of load cell from these Nitinol sheets, each with length, width, and thickness measurements of (24.66, 5.94, 1.53) mm respectively. An abrasive waterjet (MAXIEM 1515, OMAX Corporation, WA, USA) was used to create the test specimens, with a linear position accuracy of ± 0.076 mm. In a range consistent with practical ultrasonic applications, such as surgical cutting of soft and hard tissues, or some drilling processes, the Nitinol test specimens were subjected to a series of complex strain measurements at three different temperatures, 25ºC, 45ºC and 55ºC, with fixed strain magnitudes from 0.01 mm to 0.70 mm. For this reason, a Dynamic Mechanical Analyzer (DMA 8000, Perkin Elmer, MA, USA) was used. Specifically, sets of parameters were measured as functions of time, up to 140 s, consisting of dynamic stress, and loss and storage moduli. Dynamic stress is a key parameter in the context of Nitinol's thermomechanical characteristics for ultrasonic devices since the material is typically subjected to high levels of cyclic motion when embedded in these devices. The stresses from such loading conditions are

therefore critical to the transformation behaviours in Nitinol since stress is closely linked to transformation temperature. Here, dynamic stress is considered in conjunction with the loss and storage moduli, which are measures of the dissipated energy and resistance to deformation, respectively. Using these three parameters, a more detailed picture of the thermomechanical response of Nitinol to dynamic loading can be produced, and therefore be used to inform future designs of ultrasonic device incorporating Nitinol.

## Results and Discussion

The Nitinol test specimens have a martensitic microstructure at 25°C and a rhombohedral microstructure at 45ºC. As temperature passes 55ºC, austenite is formed. The results in Fig. 1 show the dynamic stress and the loss and storage moduli across the three temperatures of interest, as functions of time in each case.

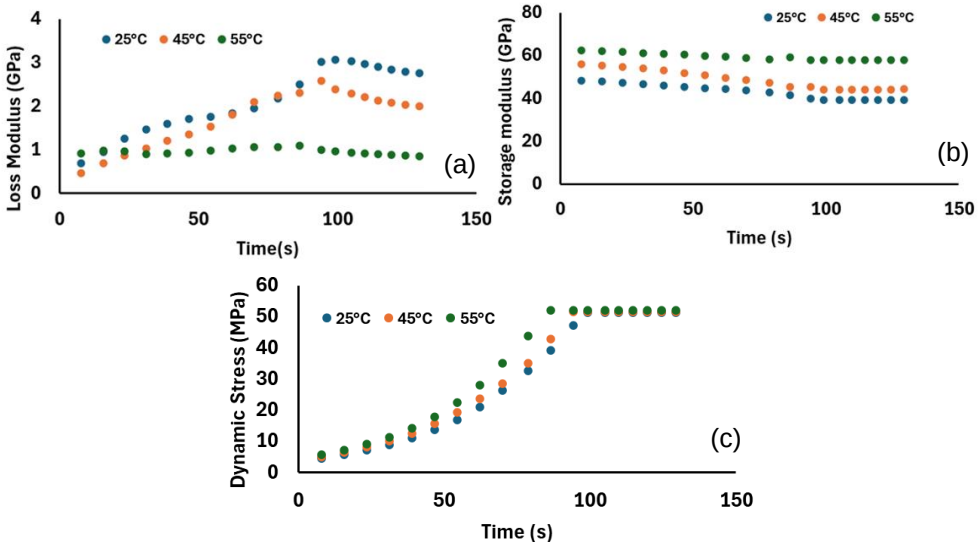


Fig 1: The time-dependent thermomechanical responses of Nitinol at temperatures of 25ºC, 45ºC, and 55ºC, for (a) loss modulus, (b) storage modulus, and (c) dynamic stress.

The time dependent characteristics under study all show similar trends of response, irrespective of the phase microstructure present in the Nitinol. Regarding dynamic stress, whether the Nitinol is martensitic or austenitic, there is a steady rise in dynamic stress present in the material as the experiment time increases, before a plateau is reached around 90 s. This plateau is reached slightly faster, the higher the temperature. Inspecting the results holistically, the maximum dynamic stress for all measured conditions is at 55°C, where the phase microstructure exhibits the lowest loss modulus and the highest storage modulus (around 65 GPa). One reason for this is that the phase microstructure of Nitinol is stiffer as face centred cubic austenite. In comparison, the test specimens at 25°C exhibited a minimum in dynamic stress, with a minimum of storage modulus (in the order of 48 GPa) and a maximum of loss modulus, where there is high energy loss in the lattices of the microstructure, around 3 GPa. The implications of these measurements are that as time progresses and Nitinol is subjected to longer periods of dynamic stress, there are greater discrepancies between the loss moduli dependent on the phase microstructure, compared to those for the dynamic stress or the storage moduli. Regarding dynamic stress, the similarity of the thermomechanical responses across the phase microstructures illustrates the feasibility of using Nitinol in ultrasonic devices over many deformation cycles.

## Conclusion

This research has investigated three thermomechanical properties of Nitinol as functions of time, comprising the dynamic stress and the loss and storage moduli. Measurements at three different temperatures aligned with different phase microstructures were undertaken. The interconnected behaviours were discussed, showing consistency in the thermomechanical response of Nitinol irrespective of the phase microstructure.

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