SMST™ 2024: Extended Abstracts from the International Conference on
Shape Memory and Superelastic Technologies
May 6–10, 2024 , Cascais, Portugal
https://doi.org/10.31399/asm.cp.smst2024p0125

Laser-induced nanostructures on shape memory actuators for strain detection

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Introduction

The activation behavior of nitinol actuators is typically examined in test rigs equipped with sensors for measuring mechanical and electrical parameters [1]. However, these test rigs allow for measurements only under laboratory conditions; assessing the actuator behavior in real-world applications is not feasible. Therefore, a non-invasive, optical measurement method for relative strain detection of shape memory actuators is presented in this work. It is based on the diffraction of a laser beam by an optical grating applied to the surface of the actuator. While the grating period changes with the strain state of the actuator during activation, a camera captures the interference pattern to detect the diffraction angle of the maxima spots.

A common method to apply gratings to a surface is laser marking. In order to prevent unwanted heat treatment of the shape memory alloy caused by the laser energy input, ultrashort pulsed lasers are preferable, as they are known to allow so-called cold processing [2]. When applying multiple low fluence ultrashort laser pulses to a surface, laser-induced periodic surface structures (LIPSS) appear on the surface [3]. LIPSS are characterized by an ablation depth below 1 µm. Thus, they are ideal for marking small samples almost without affecting their mechanical properties. As shown in prior work [4], Bessel beams have proven to be an excellent tool for generating narrow LIPSS-covered lines with constant width due to their diffraction-free nature.

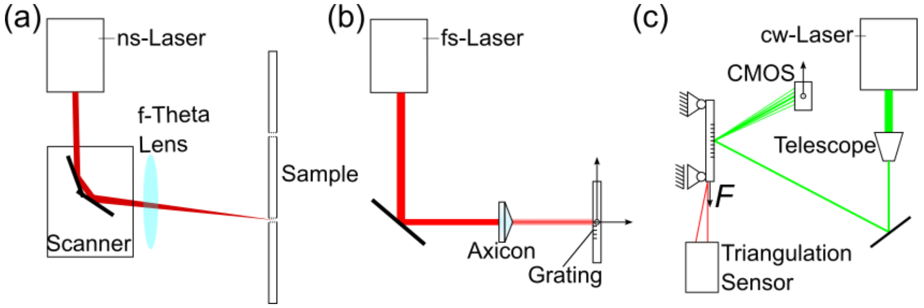

Figure 1: Experimental setup for (a) cutting actuators from nitinol sheet, (b) applying the grating to the actuators, (c) optical detection of the strain state.

Experimental Setup

Superelastic nitinol sheet cutouts (55 Wt-% Ni, niti-foil2-fx, Nexmetal Corp) were employed for the experiments instead of wire actuators. Using a flat surface is preferable for optical measurement as opposed to a wire surface, where the laser beam used for measurement would experience significant defocusing on the curved surface. As an initial manufacturing step, rectangular samples (2 x 25 mm²) were cut from a 190 µm thick sheet using a 1064 nm nanosecond laser (FLR-50-SC-OEM, SWS-Laser Solutions GmbH). Subsequently, the samples were polished and afterwards nanostructuring was performed using an 800 nm femtosecond laser (Spitfire Ace, Spectra-Physics). The pulse width was 110 fs, the repetition rate was 5 kHz, and the average laser power was set to 0.2 W. The 8.3 mm raw beam ($1/e^2$) was focused by a 5° axicon (Thorlabs AX255-B) to form a Bessel beam having a central core diameter of 11.2 µm. Thus, the peak fluence used in the nanostructuring process was calculated to 0.35 J/cm². The samples were placed on an xyz-stage (M-521.DD for x- and z-axes, M-521.DG for y-axis, Physik Instrument (PI)) to perform the relative movements between the beam and the samples. An area of 2 x 2 mm² in the center of the sample was covered with lines having a hatch distance of 10 µm.

A 532 nm cw-laser (Verdi G6, Coherent Corp.) was used to create the diffraction pattern of the grating applied to the sample. The diffraction pattern was captured by a CMOS camera (UI-122xLE, IDS Imaging Development Systems GmbH) mounted on a translational stage for stitched images. The sample was clamped with a free length of 10.8 mm. A load of 308 N/mm² was applied to elongate the sample by transforming the material from austenite to martensite. A triangulation sensor was used for validation of the strain state detection. Schematic illustration of the three experimental setups for the fabrication and length detection of the nitinol samples are shown in Figure 1.

Results and Discussion

A scanning electron image of a laser-generated grating can be seen in Figure 2 (a). It shows LIPSS covered lines with a width of 7 µm. Figure 2 (c-d) shows the diffraction pattern from the grating captured under an angle of 22° in a distance of 100 mm from the sample. As it can be seen, the higher order maxima spots move when load is applied to the shape memory actuator. 312 µm total displacement measured with the triangulation sensos (corresponds to 2.9 % relative strain of the niti sheet) led to clearly visible movement of the higher order maxima spots, as it can be seen in the intensity profile in Figure 2 (b). The dashed lines in the diagram indicate the theoretical positions of the spots according to the grating equation. The process is reversible; thus, the pattern spots move back after relaxation.

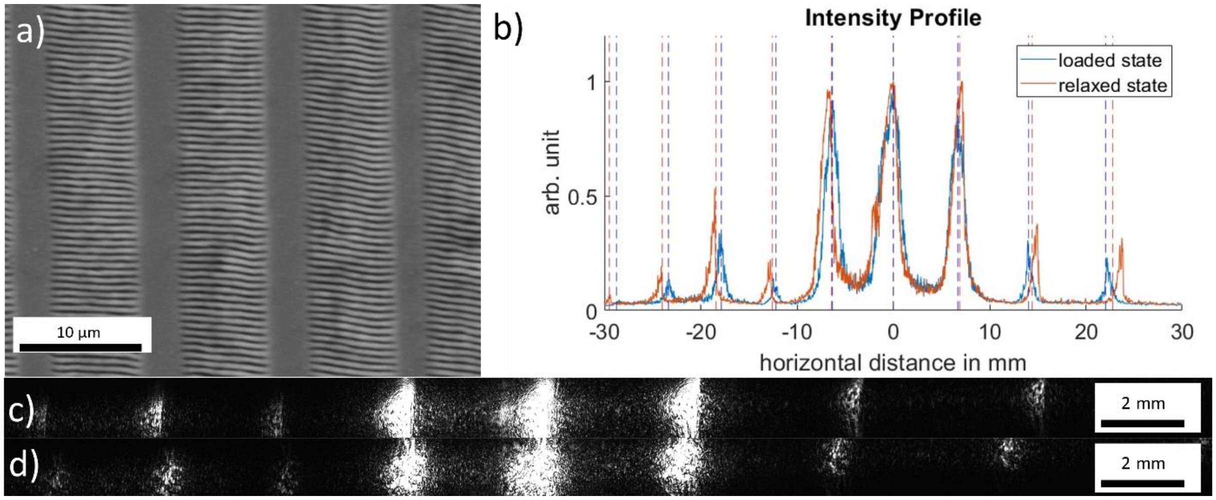

Figure 2: a) SEM image of a sample patterned with a micro-grating, b) intensity distribution of the diffraction pattern, c) stitched camera images of the diffracted laser spot in relaxed state and d) loaded state.

Conclusion

It has been successfully demonstrated that the strain state of a shape memory actuator can be determined by capturing the diffraction pattern from an exposed surface grating. The method is non-invasive and can also be applied to actuators in hard-to-reach areas. Therefore, it is an excellent approach for monitoring the functional fatigue of shape memory actuators in real-world applications.

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