Stress monitoring in Nitinol by gradient echo magnetic resonance imaging

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Introduction

The functional properties of Nitinol implants, like self-expansion of stents and filters, are determined by microcrystalline transitions between the high-temperature austenite and the low-temperature martensite structure. Next to the temperature, the crystal structure depends on the internal stress (σ) of the specimen. The magnetic properties of Nitinol depend on the martensite-austenite ratio and can be detected and quantified by spin echo MRI susceptibility analysis [1]. In this study, the potential of MRI to monitor stress-induced crystal structure transitions will be investigated. Magnetization (M) changes during elongation of a Nitinol wire will be quantified by gradient echo susceptibility artifact analysis and coupled to measurements with a tensile tester, providing a relation between M and σ.

Materials and Methods

A phantom consisting of a square basin of 140x140x100 mm^3 and a mounting frame for fixation of a wire was used. A 0.66 mm-diameter Nitinol wire (NTC04, @MT, Herk-de-Stad, Belgium) was put into the mounting frame. The distance between the fixation points (L_0) was 70 mm. The basin was filled with a manganese solution (T_1/T_2 = 1030/140 ms at 1.5 T). One side of the mounting frame could be translated within the basin by turning a nut outside of the basin. The phantom was placed in a 1.5-T scanner (Gyroscan, Philips, Best, The Netherlands) with the wire placed horizontally and perpendicular to B_0. By turning the nut, the wire was elongated in nine steps of 0.5 mm. After every step, a sagittal GE scan was made with the parameters: FOV 150 mm, MTX 128 pixels, T_R/T_E = 200/30 ms, TH = 10 mm, α = 10° and G_R = 0.7 mT/m. Time domain simulation with the same sequence parameters was performed with values of M in the range 225 – 450 A/m in steps of 5 A/m and a homogeneous background [2]. The background signal of the simulated and observed images was normalized to a gray value of 100. Subsequently, the sum of squared difference was determined in a square region of interest of 25x25 pixels containing the artifact (L_2-norm). The magnetization of the wire was found by minimizing the L_2-value, giving the relation between M and strain ($\varepsilon = \Delta L/L_0$). The same wire was tested with a tensile tester (Synergy 200, MTS, Eden Prairie, Minnesota, USA) with an elongation speed of 0.2 mm/s. The measured σ-ε curve was coupled to the M-ε curve obtained with MRI, providing the relation between σ and M.

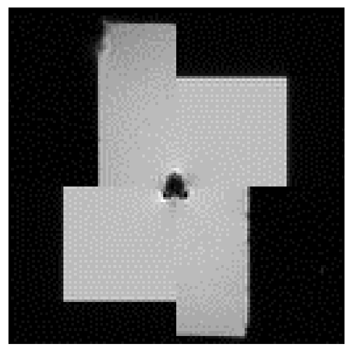

Figure 1: Gradient echo artifact of the Nitinol wire. The upper left and lower right quadrant originate from an observed artifact, the upper right and lower left from the simulated one with M = 380 Am^2.

Results

Figure 1 shows a combination of an observed and the best matching simulated artifact. It indicates the excellent agreement between the simulations with observations for the quantification of M. The relation between M and ε is depicted in Figure 2a. M decreases more rapidly at ε = 0.75%, denoting the start of the martensite transformation. At ε = 4.65%, M levels off, indicating a fully martensitic crystal structure. This complies with theory: first elastic deformation within the austenite structure occurs, then martensite transformation starts and, after full transformation, deformation within the martensite structure occurs [3]. The σ-ε curve of the tensile tester is shown in Figure 2b, which reveals the same transformation region. Combining the MR results with those of the tensile tester finally yields the relation between σ and M (Figure 2c).

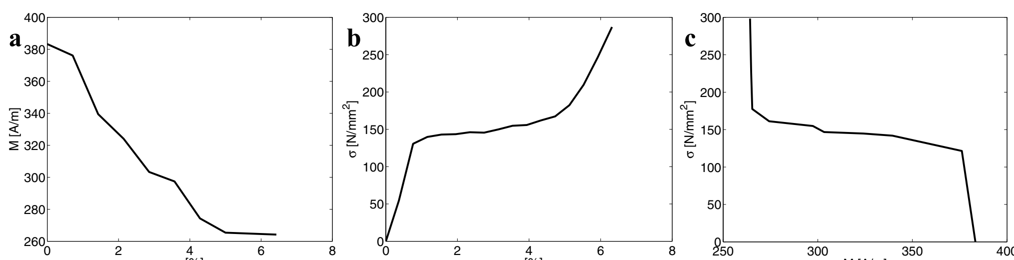

Figure 2: a) M-ε curve measured with MRI, b) σ-ε curve measured with the tension tester, c) σ-M curve after coupling of data from the MRI measurements and the tensile tester.

Discussion

Results show the potential of MRI magnetization measurements for measuring stress in an implant material. The magnetization provides direct feedback of the austenite-martensite proportion and, accordingly, of the thermal-mechanical state. Within the transformation region, MRI is sensitive for stress changes. Outside, it can only indicate the maximum tension between tissue and implant because M does not change anymore. The proposed MRI method is a general method that can be applied not only to wires, but also to more complex geometries. Then, numerical methods to model the material behavior and to calculate the field disturbance have to be used.

References

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