Detection and quantification of crystal structure transformations in stainless steel and nitinol by use of spin echo MRI

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Introduction

Stainless steel and nitinol are commonly used materials in medicine, e.g. in orthodontics, orthopedics and cardiovascular and interventional radiology. They can be brought safely into the MR suite, on condition that a non-ferromagnetic stainless steel is used. Inside the body of a patient, both materials cause susceptibility artifacts in the surrounding tissue. In the case of stents and filters, also local signal enhancement of loss can occur. The size of the susceptibility artifact depends on the image sequence, orientation of the imaging plane, quantity of the material and the susceptibility difference between the foreign material and the surrounding tissue. For stainless steel and nitinol, the magnetic susceptibility depends on the exact composition of the alloy and the thermo-mechanical pretreatment and state. We investigated and quantified the dependence of the latter by use of a spin echo technique. We used mechanical deformation of stainless steel wire and thermal treatment of nitinol wire to induce a crystal structure transformation. We started with stainless steel 304L, because its magnetic response is the largest [1].

Materials & Methods

Stainless steel – At cold deformation, stainless steel 304L undergoes a crystal structure change from an austenitic into a martensitic structure. Austenite is paramagnetic, while martensite is ferromagnetic. Stainless steel 304L wire of 1 mm diameter (Lastek, Lexmond, The Netherlands) was drawn to lower diameter wires to initiate a crystal structure change, while keeping its cylindrical form. The lowest diameter was 0.131 mm. A phantom, filled with a $MnCl_2 \cdot 4H_2O$ solution and containing a fixation mechanism, was used to place the wires perpendicular to B_0. Coronal spin echo images (FOV 150, MTX 256, TR/TE 100/30 ms, TH 10 mm, G_R 2.6 mT/m) were obtained at a clinical 0.5 and a clinical 1.5-T scanner (Gyroscan, Philips, Best, The Netherlands). The position difference in read direction between the maxima of the spearheaded artifact of these images is a measure of the magnetization of the disturbing cylinder [2,3]. The susceptibility is than found to be:

$$\chi_1 = \left(\frac{H}{2.829}\right)^3 \frac{2\pi G_R}{B_0 A} + \chi_2 \qquad (1)$$

with χ_1 the magnetic susceptibility of the wire, H the distance between the maxima, A the cross-sectional area of the wire, G_R the read gradient and χ_2 the susceptibility of the surrounding media.

Nitinol – In Nitinol, we induced a crystal structure change by heating. Austenite is the high temperature structure. NTC04 (@ Medical Technologies, Herk-de-Stad, Belgium) is a nickel titanium alloy containing little copper to increase the transformation temperatures of the alloy. The austenite start (A_s) and austenite finish (A_f) temperatures are 21 °C and 46 °C respectively. A NTC04 0.66-mm diameter wire was fixed in a phantom containing a $MnCl_2 \cdot 4H_2O$ solution and a heat exchanger spiral. The spiral was connected to a heat pump (Tamson TC03, Labovisco b.v., Zoetermeer, The Netherlands) to increase the surrounding temperature. Four fluoroptic temperature probes (Luxtron 790, Luxtron Corporation, Santa Clara CA, USA) were positioned close to the wire to measure the temperature every two minutes. Also every two minutes, a spin echo image was obtained at the 1.5T scanner (FOV 150, MTX 256, TR/TE 100/40 ms, G_R = 1.4 mT/m, TH 10 mm). The temperature dependence of the susceptibility was determined with equation 1.

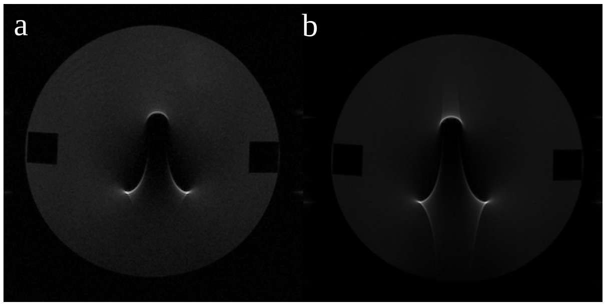

Figure 1: *Spin echo images of the 0.515 mm diameter stainless steel wire at a) 0.5T and b) 1.5T*

Results

Figure 1 shows the spin echo images at both scanners of a 0.515-mm diameter stainless steel wire. The distance between the maxima is only slightly larger at the 1.5-T scanner. This indicates nonlinear, ferromagnetic behavior, which is confirmed in the Figures 2a and 2b. The susceptibility is higher at 0.5 T and the ratio is constant, which implies magnetic saturation and that martensite was already present in the undeformed material. The susceptibility increases at larger deformations, denoting an increase of the ferromagnetic martensitic crystal structure. In Figure 2c, the temperature dependence of the susceptibility of the NTC04 wire is depicted. It shows that the nitinol austenitic structure has a larger susceptibility and that the susceptibility increased by 20% at a temperature increase of 50°C.

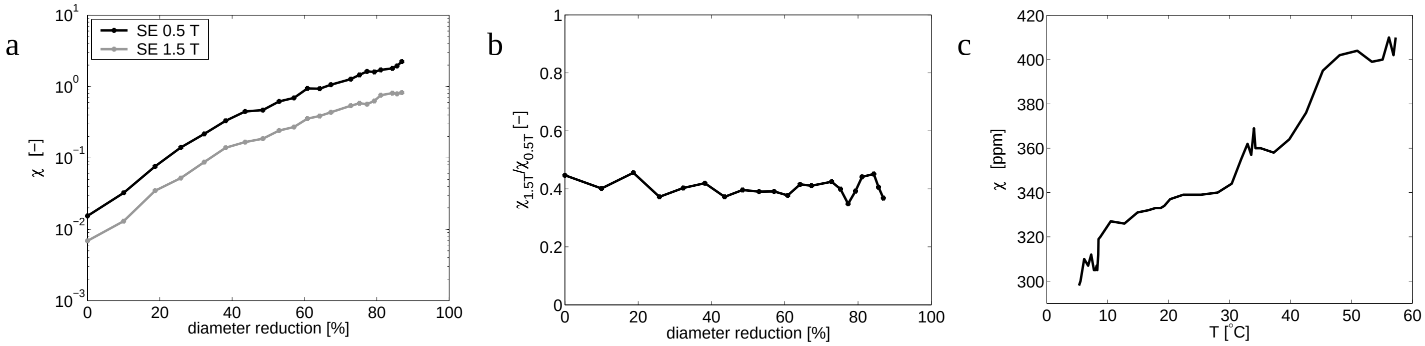

Figure 2: *a) Relative susceptibility of the stainless steel wires at 0.5T and 1.5T, b) Fraction of the relative susceptibility at 1.5T and 0.5T, c) Relative susceptibility during temperature increase of the nitinol wire*

Conclusions & recommendations

Both stainless steel and Nitinol show a change in magnetic behavior after or during a thermo-mechanical treatment. With MRI it is possible to follow and quantify these changes. We used wires and spin echo images for quantification. However, when more complex geometries are used, other methods have to be developed. These methods may facilitate material determination or in the case of Nitinol, they may even facilitate measurements of local stresses. For the latter, the complete thermo-mechanical response of the material has to be known prior to the measurements. The crystal structure, and with that the magnetic response, will depend on the surrounding temperature and the local stress. Because of the nonlinear, ferromagnetic behavior of the stainless steel 304L wire, images artifacts did not increase linearly with field strength. The susceptibility decreases considerably with field strength at 0.5T and 1.5T and will even decrease more at 3T.

[1] Bendel LP et al., JMRI 1997; 7(6):1170-1173, [2] Schenck JF, SMRM 12th annual meeting 1993, p. 350 , [3] Beuf O et al., JMR series B 1996; 112:111-118