LONG-TERM MULTIMODAL LOADING OF FIBER-BASED MAGNETIC SCAFFOLDS FOR HYPERTHERMIA APPLICATIONS

KARL SCHNEIDER, IOANA SLABU

RWTH Aachen University, Institute of Applied Medical Engineering, Aachen, Germany
schneider@ame.rwth-aachen.de, slabu@ame.rwth-aachen.de

We designed and tested an experimental setup intended for medical device quality assurance, capable of multimodal loading of fiber-based magnetic scaffolds. These magnetic scaffolds are promising for hyperthermia treatment of hollow organ cancers. To approximate the physiological conditions during magnetic hyperthermia treatment, a multimodal load consisting of a thermal load, a hydrodynamic load, and a mechanical load was considered. The effect of the multimodal load on polypropylene fibers with embedded magnetic nanoparticles was analyzed to assess changes in the mechanical properties of the fibers. We demonstrate that the nanomodified PP fibers relax according to the Poynting-Thomson model.

DOI
https://doi.org/
10.18690/um.feri.4.2025.45

ISBN
978-961-286-986-1

Keywords:
magnetic scaffolds,
multi-modal loading,
magnetic hyperthermia,
tensile test,
flow chamber

University of Maribor Press

I Introduction

Fiber-based magnetic scaffolds, polymer matrices with embedded magnetic nanoparticles (MNP), enable a myriad of clinical applications, such as magnetic hyperthermia tumor therapy. MNP generate the therapeutically necessary heat when exposed to alternating magnetic fields through non-linear magnetic relaxation processes. For hollow organ tumor treatment, nanomodified stents are implanted to reopen the occluded organ and to prevent restenosis through hyperthermal induction of cell death by application of an alternating magnetic field. The magnetic scaffold is subject to a thermal load as well as to the physiological loads during the magnetic hyperthermia treatment. To ensure patient safety and the functionality of the magnetic scaffold, i.e., the nanomodified stent, knowledge of the impact of the multimodal load on the nanomodified stent is necessary.

In this study, we investigate the impact of a long-term multimodal load on the mechanical properties of nanomodified polypropylene (PP) fibers.

II Materials and methods

The experimental setup consists of a thermal load, a hydrodynamic load, and a mechanical load. The thermal load is generated by the interaction between the MNP and the alternating magnetic field as well as through the fluid temperature. The physiological conditions in a hollow organ are approximated by the mechanical and hydrodynamic loads by placing the magnetic scaffolds under a cyclic uniaxial tensile load and exposing them to fluid flow. The main parameters of the multimodal load are given in Table 1.

Furthermore, simulations of the heating process within the magnetic scaffold were performed using COMSOL Multiphysics®. The magnetic scaffold was modeled as described in [1] with an additional fluid domain surrounding the magnetic scaffold to incorporate the cooling effect due to the hydrodynamic load. The specific loss power (SLP), i.e., the volumetric heat source of the MNP, was set to 20 W/g based on preliminary experiments.

The temperature distribution resulting from the simulations are analyzed according to the maximum, minimum and average increase in surface temperature of the nanomodified PP fiber, as well as the maximum increase in MNP temperature.

Table 1: Main parameters of the experimental setup

Parameter	Value	Unit
Magnetic field strength	5.5	kA/m
Magnetic field frequency	80	kHz
Fluid flow rate	5	ml/min
Fluid avg. pressure	1300	Pa
Fluid temperature	37	°C
Tensile load frequency	0.24	Hz
Tensile load max. strain	1	%
Tensile load min. strain	0.1	%

The mechanical properties of the nanomodified PP fibers are investigated through tensile tests using a ZwickiLine Z2.5 universal tensile testing machine and an adhesion based clamping system after EN ISO 5079:2020 [2].

III Results and discussion

The maximum surface temperature of an individual fiber strand, as shown in Figure 1, increased by 0.067 °C, with the average surface temperature increasing by 0.051°C. The maximum temperature increase of the MNP was 0.247 °C. The small temperature increase, compared to [3, 4], is due to (A) the cooling effect of the fluid flow, and more importantly, due to (B) the comparatively weak magnetic field strength at a low frequency produced by the used solenoid. Geometric constraints in the experimental setup prohibited the use of a different, stronger solenoid. As the temperature difference between the achieved fiber temperature (~37 °C) and the glass transition temperature (~-25 °C) or the melting temperature (~170 °C) of polypropylene is sufficiently large, no further nano heating effects are expected even for a therapeutically effective increase in fiber temperature [5].

In Figure 2, the stress-strain hysteresis curves from the long-term multimodal loading of the nanomodified PP fibers are shown. The maximum stress per cycle decreases from 14.77 N/mm² to 6.00 N/mm² over the course of the long-term multimodal loading. The decrease in the maximum stress is further shown in Figure 3.

The Poynting-Thomson model (equation 1), also known as the standard linear solid model, was fitted to the data showing the decrease in maximum stress per cycle [6]. The resulting parameters are given in Table 2.

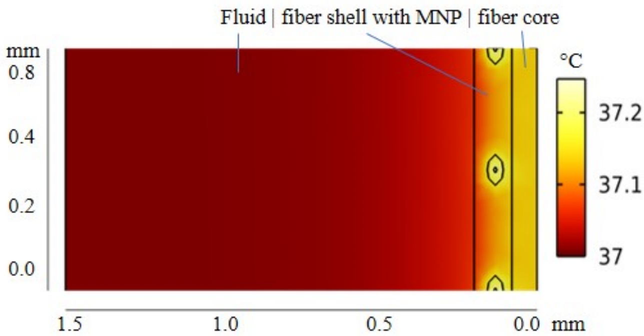

Figure 1: Simulation of the temperature distribution after application of the thermal and hydrodynamic load. The fluid domain with fluid flow is on the left, the shell of the PP fiber with the embedded MNP in the middle, and the core of the PP fiber is on the right.

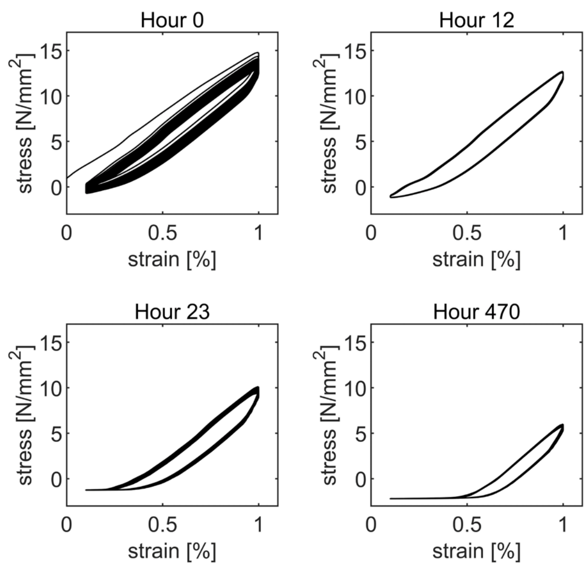

Figure 2: Stress-strain curves of the nanomodified PP fibers during multimodal loading.

$$\sigma(t) = \sigma_\infty + \bar{\sigma} \cdot e^{-\frac{t}{\tau}} \tag{1}$$

After 73.3 hours of multimodal loading 95% of the final maximum stress is achieved.

Table 2: Parameters of the poynting-thomson model

Parameter	Value	Unit
σ_∞	5.97	N/mm^2
$\overline{\sigma}$	5.82	N/mm^2
τ	93927.77	s

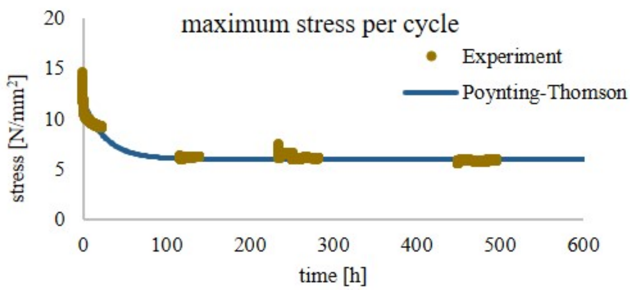

Figure 3: Decrease in maximum stress per cycle over time.

IV Conclusions

We demonstrated that nanomodified PP fibers behave according to the Poynting-Thomson model of relaxation. Figure 3 demonstrates that the maximum stress due to a 1% tensile load decreases over time and reaches saturation. Thus, preloading of the nanomodified PP fibers before implantation can prevent significant changes in the mechanical properties of the nanomodified PP fibers.

Considering the therapeutic application of magnetic hyperthermia, higher thermal loads are expected. The generation of these conditions was limited by the geometric constraints of the experimental setup. This can be solved by the utilization of a solenoid capable of producing a more powerful AMF.

Acknowledgments

We gratefully acknowledge financial support by the German Research Foundation (grant no. 467959793), and by the Federal Ministry of Education and Research (grant no. 03VP10971). We gratefully acknowledge the financial support by the by the European Union (ERC, MAD Control, 101076174). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

References

[1] K. Schneider, I. Slabu, "Heating of fiber-based magnetic scaffolds for hyperthermia applications: Maintaining simulation accuracy with reduced model complexity," in *XXVII Symposium Electromagnetic Phenomena in Nonlinear Circuits*, Hamburg, pp. 40–41, 2022.
[2] DIN Deutsches Institut für Normung e. V., DIN EN ISO 5079:2021-02, Textilfasern Bestimmung der Höchstzugkraft und Höchstzugkraftdehnung an einzelnen Fasern (ISO 5079:2020); Deutsche Fassung EN ISO 5079:2020, Berlin, 2021.
[3] B. Mues et al., "Assessing hyperthermia performance of hybrid textile filaments: The impact of different heating agents," *Journal of Magnetism and Magnetic Materials*, vol. 519, 2021.
[4] B. Mues et al., "Nanomagnetic Actuation of Hybrid Stents for Hyperthermia Treatment of Hollow Organ Tumors," *Nanomaterials* Basel, vol. 11, no. 3, 2021.
[5] J. P. Greene, *Automotive plastics and composites: Materials and processing*. Oxford, William Andrew, 2021.
[6] H. T. Banks, S. Hu, Z. R. Kenz, "A Brief Review of Elasticity and Viscoelasticity for Solids," *Adv. Appl. Math. Mech.*, vol. 3, No. 1, pp. 1-51, 2011.