HoMMage

Hysteresis design by nanostructural-engineering through continuous forming processes

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Duration	January 2020 – December 2023
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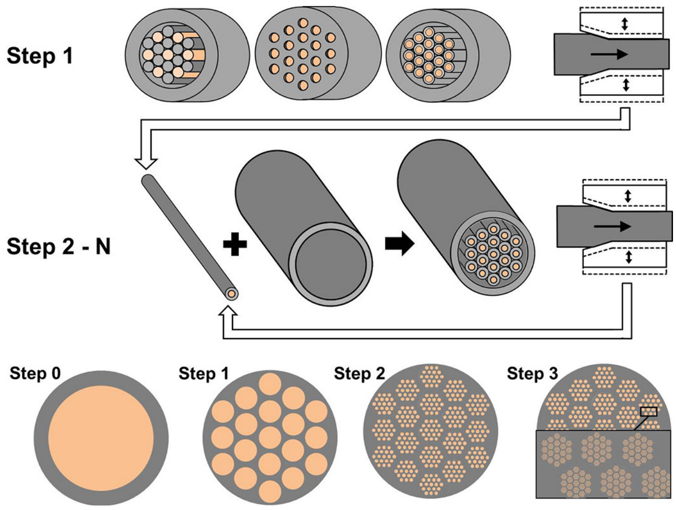
Funded by	SFB/TRR 270 – A09 (DFG)

Abstract
The microstructure of the material is decisive for optimal permanent magnetic properties. The main phase (grains) should be surrounded respectively magnetically decoupled by another phase (grain boundary). Both phases should have certain properties to induce magnetization mechanisms, such as domain-wall-pinning or nucleation. In addition, numerous parameters, such as the orientation and size of the grains and the thickness of the grain boundary, have an effect on the magnetic properties. Current approaches of investigating and manufacturing micro- or nano-structural functional materials are based on melt or powder metallurgy as well as chemical synthesis. These methods are only applicable for specific alloys or material combinations, as they are depending on the phase diagram or chemical properties. Dimensions of the microstructures are also limited by these methods. In order to improve the properties of permanent magnets, the HoMMage project is generating the microstructure by forming metal-matrix composites.

Project description
Forming of so-called Metal-Matrix-Composites (MMCs) presents a promising solution to overcome these limits. MMCs consist of a matrix and at least one other different material embedded into the matrix. The MMCs studied in the project are composed of wires and a surrounding matrix material. The wires have the composition of the main phase of the magnetic material and are transferred to the desired nanostructure during the forming operations. They are surrounded by a shell material in the form of bundled wires, matrix or coating, which represents the second phase or rather grain boundary phase in the targeted nanostructure. The initial rods will be continuously formed into wires with significantly smaller diameters. These new wires are bundled into rods and formed into wires again. This step will be repeated until the microstructures of the wires have reached the desired dimension, as shown in Fig. 1.

The approach of engineering the nanoscale MMC cross-sectional structure opens a novel route to investigate in detail the curing mechanisms of nucleation and domain-wall-pinning through the scalability of nanostructure design. At the same time, the mechanisms of plastic deformation and grain refinement of non-conventional forming materials are investigated.



[1] Concept of forming metal-matrix-composite for magnetic materials

Results
Within the scope of initial work in this project with NdFeB, it was shown that the material flow during the first step of rotary swaging of composite rods with material pairings of strongly differing flow curves does not permit stationary process conditions. This leads to problems with high forming degrees, which are necessary for the production of MMC. Thus, as a prerequisite for the implementation of the process, the material flow during rotary swaging of two component rods must first be understood as a function of the process and material parameters. For this purpose, analytical and numerical models were built within the framework of the project, on the basis of which suitable parameters for the transformation can be found.

An analytical model was built based on parameterized stream functions. The model parameters were determined by means of a minimization function with respect to the mechanical work done during forming (defined as a function of the geometry, material and friction parameters). Additionally, a numerical model was built to investigate the stress states for deeper analysis of the material flow. To validate the two models, experiments were carried out on a rotary swaging machine with variation of the investigated process parameters (material pairing, initial geometry and surface roughness). The materials used are 1.4301 stainless steel and 99 % ETP copper. The area ratios of the two components before and after the forming process are expressed by the parameter ΔA. Thus, $\Delta A = 1$ means stationa-

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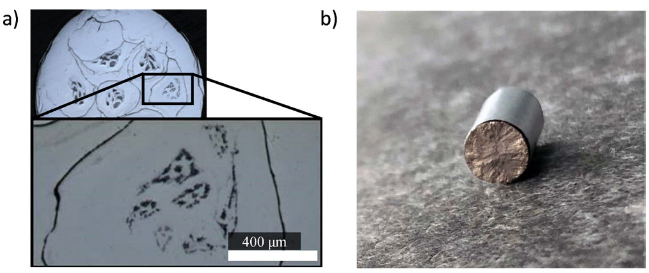
ry process conditions. By adjusting the feed rate and the ratio of the initial diameters of the components, almost stationary forming conditions can be set, even with materials of widely varying strength. These findings can be transferred to the rotary swaging of the first stage of NdFeB MMCs and thus achieve a significant improvement in formability. The findings were published in [1].

For the forming of NdFeB in the first stage, the material must be completely encased so that the brittle NdFeB material can be formed. Furthermore, oxidation can be prevented in this way and no leakage of the liquid Nd-rich phase is possible at elevated temperatures. A concept was developed to close the tube by means of rotary swaging and thus to encase the sample. Various sealing elements that can be inserted into the pipe by rotary swaging were investigated experimentally. The use of undercuts offers particularly high pressure stability of the seal [2].

In order to achieve further stages of the MMC process, preliminary tests were carried out with copper-1.4301 material pairings. In particular, the filling factor of the bundle of rods from stage 0 and the wall thickness of the tubes were varied. It can be seen that at low fill factor and thin wall thickness, no MMC honeycomb structure is formed and instead the material flows into a non-uniform shape. In order to achieve the desired NdFeB-1.4301 MMC microstructure, the filling factor of the bundles was adjusted and the rotational movement of the rotary swaging machine feed was alternated between the stages in order to reduce translational material flow. Results can be seen in Figure 2a. Based on the microsection, the difficulties encountered during the implementation of stages 1 - 3 can be seen. In particular, the wall thickness from the 1.4301 phase presents a challenge in the process. The sufficient wall thickness for problem-free process execution is > 2 mm. To achieve hard magnetic properties, an initial wall thickness in step 0 of < 0.1 mm is required, based on a target grain boundary thickness of 5 nm in the final state and the conditions of stationary processes ($\Delta A = 1$). In a further approach been pursued, the composite is extended by an additional stainless steel foil (Fig. 2b) and a separating layer. Thus, after cutting the outer stainless steel shell, the specified wall thicknesses can be achieved.



[2] a) MMC structure made of NdFeB (dark) and 1.4301 stainless steel (light) processed by rotary swaging and b) NdFeB magnet encased with stainless steel foil

Acknowledgement
The project was funded by “Deutsche Forschungsgemeinschaft” (DFG) in terms of the Collaborative Research Centre/ Transregio (CRC/TRR) 270 – Subproject A09 “Hysteresis design of magnetic materials for efficient energy conversion (HoMMage)”.

Source
[1] Groche, P., Löffler, D., Franceschi, A., & Chi, F. (2022). Continuous swaging of composite wire bundles through controlled material flow. CIRP Annals, 71(1), 257-260. https://doi.org/10.1016/j.cirp.2022.03.014

[2] Germann, T., Löffler, D., Becker, L., Heck, P., Groche, P. (2024). Axial Tube Sealing by Plastic Deformation via Rotary Swaging. In: Mocellin, K., Bouchard, PO., Bigot, R., Balan, T. (eds) Proceedings of the 14th International Conference on the Technology of Plasticity - Current Trends in the Technology of Plasticity. ICTP 2023. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/978-3-031-41341-4_13

Funded by

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Collaborative Research Center

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