

# PROCEEDINGS

28<sup>TH</sup> CONFERENCE OF  
SLOVAK PHYSICISTS

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EDITORS

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28<sup>th</sup> CONFERENCE OF SLOVAK PHYSICISTS  
PROCEEDINGS

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## OPENING ADDRESS

Ladies and Gentlemen,  
Esteemed Colleagues,

It is my great pleasure to welcome you all, on behalf of the Slovak Physical Society, to the 28th Conference of Slovak Physicists here at the University of Prešov. This conference is part of a long-standing tradition of scientific exchange, and it's remarkable to have such a high concentration of distinguished physicists and researchers and researchers in one place.

Our sincere appreciation goes out to the members of the Slovak Physical Society and the entire Organizing Committee. It is their extraordinary dedication and effort that have brought this year's conference to life, providing us with a seamlessly organized and vital platform for global scientific discourse. We anticipate that the high-quality presentations and subsequent discussions will prove to be an enriching and stimulating experience for the entire physics community.

The history of this conference speaks to its importance as a hub for collaboration among scientists, university educators, and researchers from the Slovak Academy of Science, as well as professionals involved in both fundamental and applied research. Held annually, this conference not only serves as a space for exchanging ideas but also provides an exceptional opportunity for young physicists, including our PhD students, to present their work and ideas. I am especially pleased to welcome our distinguished plenary speakers, whose presentations promise to be both timely and thought-provoking, and to acknowledge the laureates of the Competition of Scientific Works of Young Physicists from Slovakia.

The exchange of knowledge and ideas constitutes the very bedrock of scientific progress. This conference represents an opportunity to disseminate latest research, foster meaningful collaborations, and contribute substantially to the continued growth of physics within Slovakia. The insights shared here will prove instrumental in advancing our field, and I am excited to see the impact of these contributions on the future of physics.

In closing, I extend my profound appreciation to all participants for their dedicated engagement and scholarly contributions. I am confident that this 28th Conference of Slovak Physicists will be a success, and that the knowledge exchanged herein will continue to significantly propel the development of physics across our nation. Thank you; I look forward to a highly productive and inspiring conference.

Jozef Kúdelčík  
President of the Slovak Physical Society

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# PHASE-RESOLVED STUDY OF MAGNETIZATION PROCESSES IN SOFT MAGNETIC MATERIALS

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## INTRODUCTION

Multiphase, so-called hybrid composites enable the fine-tuning of magnetic properties for targeted applications [1]. By appropriately combining materials of different physical natures, these composites can potentially replace conventional materials in high-frequency signal and power electronics [1, 2]. A fundamental understanding of the micro-mechanisms underlying hysteresis in such composites is essential for their effective design. While parameters extracted from the major hysteresis loop offer valuable insights into the material's overall behavior, they primarily reflect bulk properties and do not reveal the contributions of individual magnetic constituents. The intricate interactions between distributed particles and the complexity of the magnetization process often obscure intrinsic features, resulting in an averaged macroscopic response. A more detailed characterization can be achieved by analyzing successive partial hysteresis loops nested within the major loop - known as first-order reversal curves (FORCs) [3]. Although this method requires a significantly larger dataset, it provides a much deeper understanding of the distributions of coercive fields ( $H_c$ ) and interaction fields ( $H_u$ ), associated with fundamental hysteretic units - so-called hysterons - which can correspond to individual particles or even magnetic domains [4]. Using FORC analysis, we recently revealed ferrite-mediated interactions between iron particles in hybrid composites [5], as well as magnetic softening effects in shifted grain-oriented Fe-Si structures [6]. In this study, we present a phase-resolved decomposition of the major macroscopic hysteresis loop in a hybrid composite material comprising iron particles interspersed with alloy flakes.

## EXPERIMENTAL

The composite sample was prepared using commercially available coated iron powder Somaloy 700 1P (Höganäs AB, Sweden) and 5 wt% of Vitroperm 500 (Vacuumschmelze GmbH & Co. KG, Germany). Vitroperm is an amorphous Fe-based alloy supplied in the form of flakes. The mixed powders were compacted into ring-shaped samples under uniaxial pressure of 800 MPa, followed by a stress-relieving heat treatment at 550 °C for 60 minutes in an electric furnace under air atmosphere. As a result of this thermal treatment, the Vitroperm powder underwent partial nanocrystallization.

A set of 150 FORCs per sample was acquired using the point-by-point method, following the measurement protocol developed in [5], with independent measurements of magnetization states confined within the major hysteresis loop. The FORC distribution was com-

puted as a mixed second derivative of the magnetization surface with respect to the applied field and the reversal field

$$\varrho(H, H_R) = -\frac{1}{2} \frac{\partial M(H, H_R)}{\partial H \partial H_R}, \quad H \geq H_R. \quad (1)$$

This distribution can be transformed into coordinates of coercive field  $H_c$  and interaction field  $H_u$  via the following change of variables  $H_c = (H - H_R)/2$  and  $H_u = (H + H_R)/2$ .

## MAGNETIC FINGERPRINT IN FORC DIAGRAM

Figure 1a presents the FORC diagram obtained for the hybrid composite consisting of Somaloy insulated iron powder and 5 wt% Vitroperm flakes. This diagram offers valuable insight into the internal magnetic structure of the material. In contrast to compacted iron, where the FORC diagram typically features a single, well-localized distribution [5], the composite exhibits two distinct features: one broadly distributed around  $H_c \approx 250$  A/m, and another at lower coercive fields, with significant broadening along the interaction field axis  $H_u$ . The high- $H_c$  feature can be primarily attributed to the Somaloy component, while the low- $H_c$  feature likely originates from the magnetically softer Vitroperm alloy flakes. The pronounced vertical spread of the latter feature is consistent with the presence of strong local demagnetizing fields, which arise due to the flake-like morphology of Vitroperm particles. These flakes possess high demagnetizing factors perpendicular to the flake plane, contributing to the observed vertical broadening.

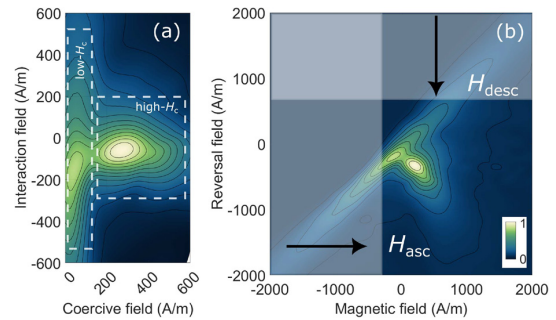


Fig. 1. FORC diagram of the composite material: (a) in  $(H_c, H_u)$  coordinates and (b) in  $(H, H_R)$  coordinates after extension into the  $H < H_R$  half-plane.

## PHASE-DECOMPOSED BEHAVIOR

Before decomposing the major hysteresis loop into phase-related components, it is necessary to fully re-

cover the reversible contributions. This requires extending the measured FORC distribution into the half-plane defined by  $H < H_R$ , which is not experimentally accessible. To achieve this, a linear extrapolation of individual FORCs was applied, following the approach proposed in [7]. By selectively integrating the low- and high-coercivity features in the FORC distribution, represented in  $(H, H_R)$  coordinates as shown in Fig. 1b, the corresponding descending and ascending branches of the phase-related hysteresis loops can be reconstructed

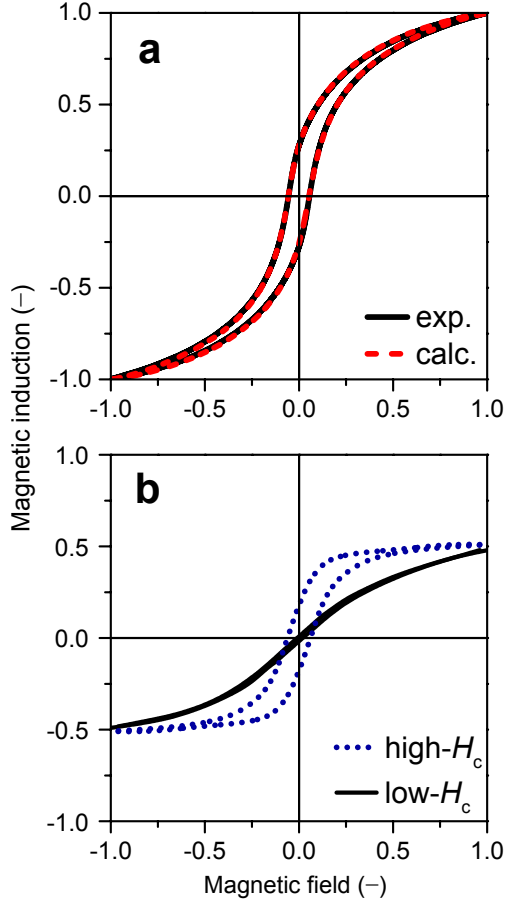


Fig. 2. (a) Measured major hysteresis loop of the composite compared with its reconstruction obtained by summing the two decomposed loops. (b) Phase-specific hysteresis loops.

$$M(H_{desc}) = 1 - 2 \int_{-\infty}^{\infty} \int_{H_{desc}}^{\infty} \varrho(H, H_R) dH_R dH, \quad (2)$$

$$M(H_{asc}) = -1 + 2 \int_{-\infty}^{H_{asc}} \int_{-\infty}^{\infty} \varrho(H, H_R) dH_R dH. \quad (3)$$

Using this approach, the major hysteresis loop of the Somaloy/Vitroperm composite (Fig. 2a) was decomposed into two components associated with the low- and high- $H_c$  features identified in the FORC diagram (Fig. 2b).

Both phases exhibit similar peak magnetization values under the applied conditions. However, the low-

$H_c$  component, attributed to the Vitroperm flakes, displays reduced permeability and a more linearized response. This behavior is consistent with the broad distribution of local demagnetizing fields caused by the flake-shaped morphology of the Vitroperm particles (as also reflected in Fig. 1b). The two decomposed hysteresis components were subsequently summed and compared with the experimentally measured major loop. As shown in Fig. 2a, the reconstructed loop exhibits excellent agreement with the experimental data.

## CONCLUSIONS

The decomposition of the major hysteresis loop of a soft magnetic composite material into phase-specific components - each governed by distinct dominant coercive fields - has been demonstrated using a selective integration technique applied to the FORC diagram. This approach enables the investigation of phase-resolved magnetization processes and offers valuable insights for analyzing loss mechanisms associated with the individual phases of the composite.

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