Revealing defect-induced spin disorder in nanocrystalline Ni

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We use magnetic small-angle neutron scattering to study the magnetic microstructure of a nanocrystalline Ni bulk sample, which was prepared by straining via high-pressure torsion. The neutron data reveal that the scattering is strongly affected by the high density of crystal defects inside the sample, which were created by the severe plastic deformation during the sample preparation. The defects cause a significant spin-misalignment scattering contribution. The corresponding magnetic correlation length, which characterizes the spatial magnetization fluctuations in real space, indicates an average defect size of 11 nm. In the remanent state, the stray fields around the defects cause spin disorder in the surrounding ferromagnetic bulk, with a penetration depth of around 22 nm. The range and amplitude of the disorder is systematically suppressed by an increasing external magnetic field. Our findings are supported by micromagnetic simulations, which, for the particular case of nonmagnetic defects (holes) embedded in a ferromagnetic Ni phase, further highlight the role of localized spin perturbations for the magnetic microstructure of defect-rich magnets such as high-pressure torsion materials.

1. Introduction

Ultrafine-grained and nanocrystalline magnetic materials have attracted considerable interest over the last decades owing to their large potential for technological applications. Among the most well-known and efficient techniques for synthesizing such materials are inert-gas condensation and high-pressure torsion (HPT), the latter being a severe plastic deformation method. For a brief overview of the main techniques for the preparation of bulk ultrafine-grained and nanocrystalline materials, we refer the reader to the article by Koch; a detailed review on the HPT technique can be found in Ref.

Since the magnetic properties will ultimately determine the performance of ultrafine-grained materials, a precise knowledge of the relationship between the microstructure and the magnetic properties, i.e., the correlation between e.g., the saturation magnetization, coercive field, and magnetic anisotropy and the average grain size or crystallographic texture is crucial. Previous studies have reported that the magnetic properties of strained nanocrystalline materials produced by HPT strongly differ from polycrystalline samples with larger grain sizes; in particular, a reduction of the saturation magnetization (by 5%) and a significant increase of the coercive field (~ 50 times larger) were observed in HPT Ni using magnetometry. These features were qualitatively explained, respectively, by the decrease of the exchange energy in the vicinity of defects and by the increase of the dislocation density within the grain boundaries. The investigation of the magnetic domain structure of HPT materials with the aim to clarify the magnetization reversal mechanism has been mainly performed using Lorentz electron microscopy. Although these studies reported that the domain structure (i.e. shape and size) is not strongly affected by the grain size, the influence of a high density of lattice defects (e.g., vacancies, dislocations, grain boundaries, pores) induced by HPT on the spin structure still needs to be further clarified. As previously demonstrated, HPT can be used to modify the structure and thus to control the macroscopic magnetic properties of magnetic materials. Therefore, in the context of defect-engineering of advanced materials using severe plastic deformation, a better understanding of the influence of the defects on the magnetic properties at different length scales is necessary.

In this paper we employ magnetic small-angle neutron scattering (SANS) to investigate the magnetic microstructure of HPT Ni on the mesoscopic length scale. Magnetic SANS is a powerful technique which provides volume-averaged information about the perturbation of the magnetization vector field on a length scale of about 1 – 500 nm (see Refs. for reviews of the magnetic SANS fundamentals and applications). This technique was recently used to demonstrate that in HPT Fe defects act as a source of an anomalous effective magnetic anisotropy field. Here, we go a step further in the neutron data analysis. We determine the real-space magnetic correlation lengths from the magnetic SANS data to obtain estimates for the average defect size as well as for the spatial extent of the surrounding spin disorder within the bulk of the sample. Our experimental results are supported by micromagnetic simulations. This specific neutron data analysis of the spin-misalignment brings additional information which is important for the understanding of the role played by the defects in magnetic systems.
2. Experimental details
The HPT process for the preparation of the strained Ni sample used in this study is similar to the one described in Ref. 19. For the neutron experiments two disks of HPT Ni with a diameter of 10 mm and a thickness of 0.5 mm were stacked together, resulting in a total sample thickness of 1.0 mm. The neutron measurements were conducted at the instrument D33 at the Institut Laue-Langevin, Grenoble. The measurements were done using an unpolarized neutron beam with a mean wavelength of \( \lambda = 4.6 \) Å and a wavelength broadening of \( \Delta \lambda / \lambda = 10\% \) (full width at half maximum). The measurements were performed at room temperature and within a \( q \)-range of about 0.04 nm\(^{-1} \) \( \leq q \leq 0.45 \) nm\(^{-1} \). A magnetic field \( H_0 \) was applied perpendicular to the incident neutron beam \( (H_0 \perp k_0) \).

Neutron data were recorded by decreasing the field from the maximum field available of 6.7 T to 0.1 T. The neutron-data reduction (correction for the empty sample holder and background scattering, sample transmission, and detector efficiency) was conducted using the GRASP software package20. Further neutron conditions similar to those described in Ref. 19 were performed at the QUOKKA instrument at the Australian Nuclear Science and Technology Organization (ANSTO). We determined the (over 2\( \pi \)) azimuthally-averaged purely magnetic SANS cross sections \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \) by subtracting the total (nuclear + magnetic) SANS cross sections \( d\Sigma / d\Omega \) measured at the highest field of 6.7 T (approaching saturation) from the \( d\Sigma / d\Omega \) measured at lower fields. This SANS cross section data analysis was previously used to study the magnetization profile of magnetic nanoparticles23.

3. Magnetic SANS Analysis
3.1. Magnetic correlation function
The normalized magnetic correlation function \( C(r, H_0) \) was numerically computed by a direct Fourier transformation of the experimental data for \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \) according to24:

\[
C(r, H_0) = \frac{\int_0^\infty d\Sigma_{\text{mag}}(q, H_0) / d\Omega \cdot j_0(qr) q^2 dq}{\int_0^\infty d\Sigma_{\text{mag}}(q, H_0) / d\Omega \cdot q^2 dq},
\]

where \( j_0(qr) = \sin(qr) / qr \) is the zeroth-order spherical Bessel function. For this purpose, the experimental data \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \) beyond \( q_{\text{max}} \) were extrapolated to infinity using a power law, \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \propto 1 / q^n \) with \( 4 \leq n \leq 7 \) (compare inset in Figure 1b), and the extrapolation from \( q_{\text{min}} \) to \( q = 0 \) was done according to \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \propto a + bq^2 \).

3.2. Magnetic correlation length
The magnetic correlation length \( l_c(H_0) \) characterizes the distance over which perturbations in the spin structure around a lattice defect are transmitted by the exchange interaction into the surrounding crystal lattice25,26. Several procedures for obtaining \( l_c \) are discussed in the literature, e.g., \( l_c(H_0) \) can be defined as the value of \( r \) for which \( C(r, H_0) = C(0) e^{-1} \), or \( l_c \) can be found from the logarithmic derivative of \( C(r, H_0) \) in the limit \( r \to 0 \) (Ref. 25). Here, we determined the magnetic correlation length \( l_c(H_0) \) from the \( C(r, H_0) \) data at a particular field according to:

\[
l_c(H_0) = \int_0^\infty r C(r, H_0) dr / \int_0^\infty C(r, H_0) dr.
\]

The field dependence of the \( l_c \) data was then fitted using the following expression:

\[
l_c(H_0) = L + \frac{2A_{\text{sat}}}{\mu_0 M_s(h_0 + H^*)},
\]

where the field-independent parameter \( L \) is of the order of the defect size, \( A_{\text{sat}} \) and \( M_s \) are the exchange-stiffness constant and the saturation magnetization, respectively; the field \( H^* \) describes the contribution of the magnetostatic and magnetic anisotropy field to the internal magnetic field. This phenomenological model is based on micromagnetic theory27,28 and expresses the relationship between the nuclear and magnetic microstructure of a material. Equation (3) has already been successfully used to describe the spin misalignments in several nanocrystalline bulk ferromagnetic materials29,30.

4. Results and discussion
Figure 1a displays the (over 2\( \pi \)) azimuthally-averaged total (nuclear + magnetic) SANS cross section \( d\Sigma(q, H_0) / d\Omega \) measured at applied magnetic fields. As can be seen, at the smallest momentum transfers \( q \) the cross section \( d\Sigma(q, H_0) / d\Omega \) increases by more than two orders of magnitude when \( H_0 \) is decreased from 6.7 T to 0.1 T. Since the nuclear scattering is field independent, the strong field dependence of \( d\Sigma(q, H_0) / d\Omega \) observed in figure 1a originates from spin-misalignment scattering caused by mesoscale spin disorder (i.e., the failure of the spins to be completely aligned along \( H_0 \)). Figure 1b shows the corresponding purely magnetic SANS cross sections \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \), which were obtained by subtracting the total scattering at 6.7 T (approaching saturation) from the data at lower fields. The magnitude of \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \) is of the same order as \( d\Sigma(q, H_0) / d\Omega \). The asymptotic power-law exponent \( n \) in \( d\Sigma_{\text{mag}}(q, H_0) / d\Omega \propto 1 / q^n \) was found to be larger than the value of \( n = 4 \) (see inset in figure 1b); \( n = 4 \) would correspond to scattering from particles with sharp interfaces or from exponentially correlated fluctuations. The finding of a field-dependent \( n > 4 \) supports the notion of dominant spin-misalignment scattering, for which exponents \( n = 4 \)–8 are theoretically predicted and experimentally found27,28.

Figure 2 shows the normalized magnetic correlation function \( C(r, H_0) \) which was numerically computed according to equation (1). Increasing the field from 0.1 to 4 T, results in a decrease of \( C(r, H_0) \) at a given \( r \). This observation reflects the decrease of the spin-misalignment fluctuations and the suppression of the amplitude of the static disorder with increasing field. Furthermore, the correlations do not decay exponentially (see the log-linear plot in the inset
of figure 2), in agreement with the absence of a corresponding \( n = 4 \) power-law exponent observed in figure 1b. Moreover, for the lowest applied fields, the absence of a finite slope of \( C(r, H) \) in the limit \( r \to 0 \) is consistent with the absence of sharp interfaces in the magnetic microstructure and with the presence of a continuous magnetic scattering length density variation.

Figure 3 presents the field dependence of the magnetic correlation length \( l_c(H) \) determined from the \( C(r, H) \) using equation (2). As can be seen, \( l_c(H) \) increases from about 14 nm at the highest field of 4 T to 26 nm at the lowest field of 0.1 T. Moreover, for all fields investigated, the values of \( l_c(H) \) remain much smaller than 100 nm, which is the typical grain-size value reported in HPT Ni\(^{10}\). This latter observation thus indicates the presence of spin misalignment on a scale smaller than the grain size, as previously suggested by the analysis of experimental data to equation (3) (dashed line in figure 3), the following best-fit parameters are obtained: \( L = 11.3 \pm 0.1 \) nm and \( \mu_0 H^* \approx 71.2 \pm 3.0 \) mT. We reemphasize that \( L \) can be regarded as an estimate of the average defect size and \( H^* \) models the influence of the magnetostatic and magnetic anisotropy field contributions to the internal magnetic field. The estimated ‘defect size’ \( L \approx 11 \) nm suggests that the origin of the spin misalignment observed in HPT Ni results from a high density of crystal defects on a scale smaller than the grain size, as previously suggested in HPT Fe\(^{16}\). In the remanent state, we estimate the penetration depth \( \delta = l_c(H = 0) - L \) of the spin disorder into the ferromagnetic Ni-phase to be about 22 nm (figure 3).

To support and graphically illustrate our experimental findings, we simulated the real-space distribution of the magnetization vector field \( \mathbf{M}(r) \) around a spherical nonmagnetic defect embedded in a ferromagnetic Ni-phase (magnetic hole or pore). The open-source software package MuMax3 (Ref. 22) was used for this purpose. Figure 4 displays the simulation results for two selected applied fields, namely 0.05 T and 2 T. As can be seen, a localized perturbation of the magnetization (top panel) is observed around the defect at 0.05 T. This magnetization inhomogeneity is caused by the magnetodipolar stray field which is related to the jump of the magnetization magnitude at the pore-matrix interface (\( \mu_0 \Delta M \approx 0.62 \) T). In our experimental results the spatial extent of such a magnetization gradient is at (a given field) represented by \( l_c \). An applied field of 2 T largely suppresses the stray-field-torque related spin disorder. This can be seen in the bottom panel of figure 4, which compares the perpendicular component \( M_y \) at both fields. The scenario which is displayed in figure 4 illustrates how the nanoscale magnetization inhomogeneity, which is associated with a particular lattice defect, is related to a contrast for magnetic SANS. In real HPT samples, in addition to magnetostatic stray fields around voids, the magnetic anisotropy field generated by other microstructural defects such as vacancies, dislocations, and grain boundaries may contribute to the spin-misalignment scattering\(^{32,33}\).

To systematically correlate the macroscopic magnetic properties (e.g., the coercivity) to the outcome of the neutron data analysis (e.g., defect size, range of the correlation) one should perform a series of measurements for different degrees of deformation (HPT straining). Such experiments are underway and could further establish the SANS technique as an important pillar for the characterization of ultrafine-grained materials in the bulk and on the relevant mesoscopic length scale; for instance, one might then link the observed increased coercivity of HPT Ni\(^{2} \) to the defect density.

A final comment relates to the role of unpolarized versus polarized neutrons for the study of magnetic materials. The present results clearly demonstrate that for nanocrystalline defect-rich materials, which exhibit a strongly field-dependent SANS signal, it is not necessary to resort to polarized neutrons, if the aim is to study the (polarization-independent) spin-misalignment scattering. Polarized neutrons only provide additional information via the chiral scattering term in the cross section. A recent paper\(^{19} \) suggests that the local symmetry-breaking at defect sites gives rise to an asymmetric polarization-dependent contribution to the SANS cross section. In this respect, it would of interest to carry out half-polarized SANS experiments or even a one-dimensional polarization analysis on HPT samples.

5. Conclusion

We employed magnetic SANS to investigate the influence of crystal defects on the magnetic microstructure of nanocrystalline Ni prepared by HPT. The analysis of the field-dependent magnetic SANS data suggests the presence of strong spin misalignment on the mesoscopic length scale. In fact, the computation of the magnetic correlation function and the correlation length confirmed the presence of spin disorder on a scale smaller than the grain size. The phenomenological model [equation (3)] provides an excellent description of the field dependence of the spin-misalignment correlation length. We estimated the defect size to be around 11 nm and the penetration depth of the spin misalignment into the pure Ni phase in the remanent state to be around 22 nm. Our findings are supported by micromagnetic simulations which highlight that microstructural defects (such as pores) can induce significant nanoscale spin disorder, representing a contrast for magnetic SANS. The presented neutron-data analysis procedure is particularly useful for defect-rich materials, which exhibit a large magnetic SANS signal in response to an applied magnetic field.

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Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

References
1. A. Makino, T. Hatanai, Y. Naitoh, T. Bitoh, A. Inoue, and T. Masaunoto, IEEE Trans. Magn. 33, 3793 (1997).
2. M.E. McHenry, M.A. Willard, and D.E. Laughlin, Prog. Mater. Sci. 44, 291 (1999).
3. J. Petzold, J. Magn. Magn. Mater. 242–245, 84 (2002).
4. Y. Huang and T.G. Langdon, Mater. Today 16, 85 (2013).
5. C.C. Koch, J. Mater. Sci. 42, 1403 (2007).
6. K. Edalati and Z. Horita, Mater. Sci. Eng. A 652, 325 (2016).
7. K.Y. Mulyukov, G.F. Korznikova, R.Z. Abdulov, and R.Z. Valiev, J. Magn. Magn. Mater. 89, 207 (1990).
8. K.Y. Mulyukov, S.B. Khapzhov, and R.Z. Valiev, Phys. Status Solidi 133, 447 (1992).
9. G.F. Korznikova, K.Y. Mulyukov, V.N. Timofeyev, and R.Z. Valiev, J. Magn. Magn. Mater. 135, 46 (1994).
10. G.F. Korznikova, J. Microsc. 239, 239 (2010).
11. C.M. Cepeda-Jímenez, J.I. Beltrán, A. Hernando, M.A. García, F. Ynduráin, A. Zhilyaev, and M.T. Pérez-Prado, Acta Mater. 123, 206 (2017).
12. S. Scheriau, M. Kriegisch, S. Kleber, N. Mehboob, R. Grössinger, and A. Michels, J. Phys. Condens. Matter 26, 383201 (2014).
13. S. Mühlbauer, D. Honecker, E.A. Pérgo, F. Bergner, S. Disch, A. Heinemann, S. Erokhin, D. Berkov, C. Leighton, M.R. Eskildsen, and A. Michels, Rev. Mod. Phys. 91, 015004 (2019).
14. Y. Oba, N. Adachi, Y. Todaka, E.P. Gilbert, and H. Mamiya, Phys. Rev. Res. 2, 033473 (2020).
15. A. Lak, S. Disch, and P. Bender, Advanced Science, in press, arXiv 2006.06474 (2020).
16. T. Rojac, A. Benček, G. Drazic, N. Sakamoto, H. Ursic, B. Jancar, G. Tavcar, M. Makarovic, J. Walker, B. Malic, and D. Danjanovic, Nat. Mater. 16, 322 (2017).
17. Y. Todaka, M. Umemoto, J. Yin, Z. Liu, and K. Tsuchiya, Mater. Sci. Eng. A 462, 264 (2007).
18. C.D. Dewhurst, J. Grillo, D. Honecker, M. Bonnau, M. Jacques, C. Amrouni, A. Perillo-Marcone, G. Manzin, and R. Cubitt, J. Appl. Crystallogr. 49, 1 (2016).
19. C.D. Dewhurst, Graphical Reduction and Analysis SANS Program for Matlab (2018), (available at: https://www.ill.eu/support-labs-infrastructure/software-scientific-tools/grasp/).
20. K. Wood, J.P. Mata, C.J. Garvey, C.M. Wu, W.A. Hamilton, P. Abbeywick, D. Bartlett, F. Bartsch, P. Baxter, N. Booth, W. Brown, J. Christoforidis, D. Clowes, T. d’Adam, F. Darman, M. Deura, S. Harrison, N. Hauser, G. Horton, D. Federici, F. Franceschini, P. Hanson, E. Imamovic, P. Imperia, M. Jones, S. Kennedy, S. Kim, T. Lam, W.T. Lee, M. Lesha, D. Mannicke, T. Noakes, S.R. Olsen, J.C. Osborn, D. Penny, M. Perry, S.A. Pullen, R.A. Robinson, J.C. Schulz, N. Xiong, and E.P. Gilbert, J. Appl. Crystallogr. 51, 294 (2018).
21. M. Bersweiler, P. Bender, L.G. Vivas, M. Albino, M. Petrecca, S. Mühlbauer, S. Erokhin, D. Berkov, C. Sangregorio, and A. Michels, Phys. Rev. B 100, 144434 (2019).
22. D. Mettus and A. Michels, J. Appl. Crystallogr. 48, 1437 (2015).
23. A. Michels, Phys. Rev. B 82, 024433 (2010).
24. D. Honecker and A. Michels, Phys. Rev. B 87, 224426 (2013).
25. J. Weissmüller, R.D. McMichael, A. Michels, and R.D. Shull, J. Res. Natl. Inst. Stand. Technol. 104, 261 (1999).
26. J. Weissmüller, A. Michels, J.G. Barker, A. Wiedemann, U. Erb, and R.D. Shull, Phys. Rev. B 63, 214414 (2001).
27. J.P. Bick, D. Honecker, F. Döbrich, K. Suzuki, E.P. Gilbert, H. Frielinghaus, J. Kohlbrecher, J. Cavilano, E.M. Forgan, R. Schweins, P. Lindner, R. Birringer, and A. Michels, Appl. Phys. Lett. 102, 022415 (2013).
28. A. Michels, R.N. Viswanath, J.G. Barker, R. Birringer, and J. Weissmüller, Phys. Rev. Lett. 91, 267204 (2003).
29. A. Vansteenkiste, J. Lelait, M. Dvornik, M. Helsen, F. Garcia-Sanchez, and B. Van Waeyenberge, AIP Adv. 4, 107133 (2014).
30. S. Erokhin, D. Berkov, N. Gorn, and A. Michels, Phys. Rev. B 85, 024410 (2012).
31. S. Erokhin, D. Berkov, and A. Michels, Phys. Rev. B 92, 014427 (2015).
32. A. Michels, D. Mettus, I. Titov, A. Malyeyev, M. Bersweiler, P. Bender, I. Peral, R. Birringer, Y. Quan, P. Haupte, J. Kohlbrecher, D. Honecker, J.R. Fernández, L.F. Barquín, and K.L. Metlov, Phys. Rev. B 99, 014416 (2019).
33. H. Kronmüller and M. Fähnle, Micromagnetism and the Microstructure of Ferromagnetic Solids (Cambridge University Press, Cambridge, 2003).
Figure 1

Figure 1: (a) Magnetic-field dependence of the (over 2π) azimuthally-averaged total (nuclear + magnetic) SANS cross section \(d\Sigma(q, H_0)/d\Omega\) and (b) of the purely magnetic SANS cross section \(d\Sigma_{\text{mag}}(q, H_0)/d\Omega\) (log-log scale). Dashed lines in (b): Extrapolation of \(d\Sigma_{\text{mag}}(q, H_0)/d\Omega \propto 1/q^n\) from \(q_{\text{max}}\) to infinity and of \(d\Sigma_{\text{mag}}(q, H_0)/d\Omega \propto a + bq^2\) from \(q_{\text{min}}\) to \(q = 0\). Inset in (b): Field dependence of the asymptotic power-law exponent \(n\) of the magnetic SANS cross section \(d\Sigma_{\text{mag}}(q, H_0)/d\Omega\) on a semi-logarithmic scale.
Figure 2: Magnetic-field dependence of the normalized magnetic correlation function $C(r, H_0)$. The correlation functions were numerically computed by a direct Fourier transformation [equation (1)] of $d\Sigma_{\text{mag}}(q, H_0)/d\Omega$ shown in figure 1a. Inset: Plot of $C(r, H_0)$ on a semi-logarithmic scale, emphasizing the non-exponential decay of the correlations.
Figure 3: Field dependence of the magnetic correlation length $l_c(H_0)$, determined from the computed $C(r, H_0)$ data shown in figure 2 (log-log scale). Dashed line: Fit of the $l_c(H_0)$ data using equation (3). $\mathcal{L}$ and $H^*$ were treated as free parameters, whereas $A_{ex}$ and $\mu_0M_s$ were fixed to 8.5 pJ/m and 0.6 T, respectively. Note: $A_{ex}$ and $M_s$ values were estimated from magnetic SANS and magnetometry results (data not shown).
Figure 4: Results of the micromagnetic simulations for a spherical defect (magnetic hole) embedded in a uniform Ni matrix. Applied-field values ($H_0$ is parallel to the $z$-direction): (a) 0.05 T and (b) 2 T. Top panel: Projections of the three-dimensional magnetization distribution $\mathbf{M}(\mathbf{r})$ into the $y$-$z$-plane. Bottom panel: Perpendicular magnetization component $M_y$. The black arrows and color bars in (b) indicate the strength and orientation of $M_y$ (arbitrary units). Materials parameters of Ni were used (Ref.\textsuperscript{35}).