Magnetic behavior of steel studied by *in-situ* Lorentz microscopy, magnetic force microscopy and micromagnetic simulations

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Background

Many industrially relevant steels are ferromagnetic such as ferritic-pearlitic steel characterized in this study. Ferritic-pearlitic steels are commonly used, for example, in automotive components. Microstructural features of ferromagnetic materials influence their mechanical and micromagnetic properties. Traditionally, the microstructure, for example, cementite (Fe_3C) content, has been studied with destructive methods. To save time and money, destructive methods should be replaced with non-destructive testing (NDT) techniques. One of the potential NDT methods is magnetic Barkhausen noise (MBN) testing. It is used in industry to detect for example localized microstructure and stress variations. MBN testing is based on the motion of magnetic domain walls in ferromagnetic materials exposed to a time-varying external magnetic field. The motion of domain walls is hindered by the microstructural pinning sites such as carbides, grain boundaries, and dislocations. In the varying magnetic field, domain walls stop and finally jump over the pinning features, causing discontinuous and abrupt changes in the magnetization of the workpiece. These changes result in electromagnetic burst-like signal, i.e., Barkhausen noise, measured with an inductive coil. However, the applicability of the Barkhausen noise method is currently limited due to the stochastic nature of the phenomenon itself. Thus, more scientific knowledge is needed. Recently, we mimicked and visualized the Barkhausen noise measurement by *in-situ* Lorentz microscopy. This study gives general information about the behavior of domain walls in ferromagnetic steel. In addition, we have utilized magnetic force microscopy and micromagnetic simulations to deepen our knowledge on the magnetic behavior of steels.

Methods

In this study, we used multi-instrumental and computational approach. Traditional microstructural characterization of ferritic-pearlitic steel was carried out by SEM-EBSD-TKD and (S)TEM-EDS. The magnetic structure of the thin sample was studied by Lorentz microscopy (Fresnel mode), while the bulk sample was studied by magnetic force microscopy (MFM). The dynamics of domain walls were studied by *in-situ* Lorentz microscopy. A varying, external magnetic field was generated by a normal objective lens of TEM, and the images were collected in LOW MAG mode using objective mini lens.

The recorded frames of each sample were jointly post-processed as a single video using video denoising and frame alignment procedures. To measure a single point magnetic flux density generated with different excitation values of the normal objective lens inside the TEM, we used a custom-made holder equipped with a Hall-effect sensor. We also run micromagnetic simulations to verify domain wall dynamics in certain magnitudes of magnetic fields.

Results

Our multi-instrumental characterization, dynamical *in-situ* Lorentz microscopy studies, and micromagnetic simulations with the complex ferritic-pearlitic structure revealed the interaction of different domain walls and pinning sites. Thus, we could visualize and verify hypotheses related to the origin of Barkhausen noise signal. Comparing Lorentz microscopy and MFM results, we indicated that thin and bulk samples studied have similar magnetic structure. So, TEM studies are also relevant from the industrial point of view, although usually bulk samples are used in industrial applications. To measure the magnetic field strength generated by the normal objective lens of TEM in dynamical *in-situ* studies, we built a custom-made Hall-effect sensor holder. It measures the flux density at the same location as the TEM sample. Based on the measurements, the objective lens of our TEM has almost linear response to the magnetic field strength, and when the objective lens is switched off, the magnetic field in the sample area is close to 0 mT.

Based on our studies, the carbides are very strong pinning sites for domain walls. In addition, larger globular and thicker lamellar carbides can have their own magnetic structure. In the increasing magnetic field, domain walls in the ferritic matrix perpendicular to the lamellar cementite carbides begin to move first. Then, the domain walls inside the carbides start to disappear. Finally, domain walls parallel to the lamellar carbides move. However, some of them are very strongly pinned by carbides. When the magnetic field is decreased back to 0 mT, the domain walls appear in the opposite order. We simulated the magnetization dynamics where microstructural information is extracted from the SEM-TKD and (S)TEM results. To explain the domain wall behavior in certain magnitudes of the magnetic field as observed using *in-situ* Lorentz microscopy, we ran dynamical micromagnetic simulations to reproduce the domain wall disappearance in the globular carbide. In general, the simulations supported very well the interpretation of the experimental findings, although the re-appearance of the domain walls with decreasing field could not be reproduced. In the next step, our multi-instrumental and computational approach will be extended by transport of intensity equation (TIE) method and off-axis electron holography. These results will be reported in the near future.

Imaging methods and micromagnetic simulations have their own limitations. Despite using multi-imaging techniques, it is probable that not all magnetic features can be visualized by microscopes and on the other hand, simulations cannot always reproduce all events observed experimentally. However, our combined multi-instrumental and computational approach gives novel knowledge on how iron-based carbides affect magnetic domain wall dynamics in ferromagnetic steel.

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