Shedding light on the coercivity mechanism in Nd-Fe-B sintered magnets through high-field magnetic domain observations

Nd-Fe-B sintered magnets are being used everywhere in modern life because they are the best permanent magnets we currently have. However, from an industrial perspective the next-generation of green-energy applications such as electric vehicles and wind turbines will require higher-performance permanent magnets than those currently available. In order to make technological progress, understanding their coercivity mechanism and its relationship with the microstructure is vitally important. Elucidating the coercivity mechanism requires detailed knowledge of where reversed magnetic domains are nucleated and how they propagate.

Some recent studies have implied that the fractured and polished surfaces of Nd-Fe-B permanent magnets reflect the interior and exterior magnetic states, respectively, because the coercivity of the fractured surface is very similar to the bulk, while the coercivity of the polished surface is drastically reduced. This degradation is thought to occur because the polishing process introduces numerous defects that facilitate the nucleation of additional reversed magnetic domains which, essentially, mask the true magnetic domain distribution. Contrary to the polished surface, the magnetic $Nd_2Fe_{14}B$ grains are not directly exposed; they are covered by a thin-film-like grain boundary phase due to the dominant grain boundary fracturing. Although magnetic domains in the polished surface of these materials have been investigated extensively, observations of the fractured surface have proven to be particularly challenging because of the technical difficulties in imaging the rough surface under magnetic fields large enough to saturate the magnet.

For the purpose of imaging element-specific magnetic distributions under high magnetic fields, a scanning soft X-ray absorption microscope has been developed at SPring-8 **BL25SU** [1] under the ESICMM (Elements Strategy Initiative Center for Magnetic Materials) project. Figure 1 shows a photograph of the scanning soft X-ray microscope apparatus. Circularly polarized soft X-ray photons, which are generated by twin helical undulators, are focused using a Fresnel zone plate to a beam size of about 100 nm at the sample surface. The scanning X-ray microscope utilizes total electron yield (TEY) detection of absorbed circularly polarized soft X-rays in order to observe magnetic domains through the X-ray magnetic circular dichroism effect. The TEY method is advantageous because it allows us to observe magnetic domains in the surface of non-transmittable samples. Crucially, this new instrument has a focal depth of ±5 μm from

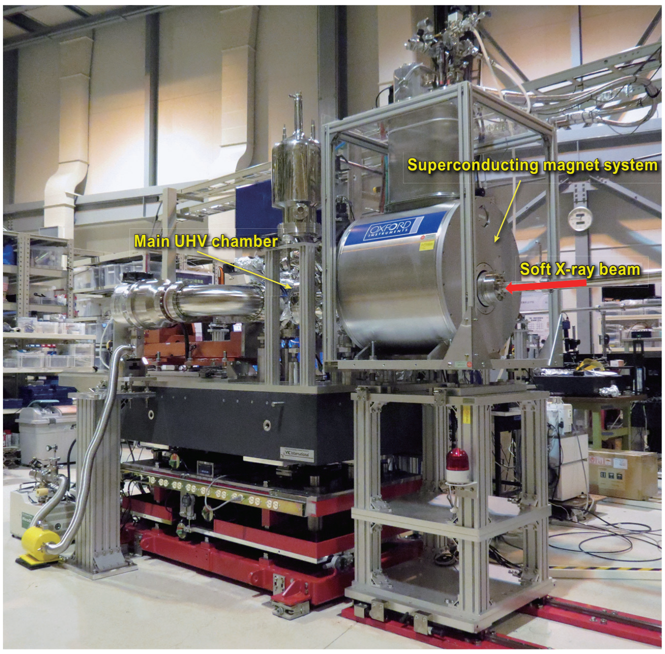

Fig. 1. Photograph of the scanning soft X-ray absorption microscope apparatus equipped with an 8 T superconducting magnet. This apparatus is installed at the b-branch of BL25SU. (UHV = ultra-high vacuum)

the focal point and is equipped with a superconducting magnet that can generate a maximum field of 8 T, thereby significantly advancing the previous limit of 0.5 T and permitting the observation of magnetic domains in the fractured surfaces of granular materials.

To unmask the interior magnetic domain structure of Nd-Fe-B sintered magnets that represents the bulk, the soft X-ray absorption microscope was employed to track the reversal of individual grains in the polished and fractured surfaces [2]. As the applied field is varied, significant differences in the reversal behavior of the polished and fractured surfaces were observed and intergranular correlations could be identified. Figures 2(a) and 2(b) show the magnetic domain images recorded in the polished and fractured surfaces, respectively, of a Nd-Fe-B sintered magnet near their respective coercive fields. In the polished surface, large regions are covered by a maze-like domain pattern and, as the applied magnetic field is varied, the domain walls can easily move because of the fine balance between the external field and the magnetostatic stray field at the surface. The maze-like multiple-domain structure in the polished surface reflects the reduced magnetic anisotropy, as evidenced by the narrow domain widths, and this is clearly a consequence of the surface damage. In contrast, the demagnetization process of the fractured surface occurs grain-by-grain where most of the grains completely reverse their magnetization without exhibiting the maze-like domain pattern and the domain walls are able to travel through multiple whole grains for small changes in applied field.

The scanning soft X-ray absorption microscope that we have developed provides a new opportunity for element-specific magnetic domain imaging and spectroscopy under much higher applied magnetic fields than those previously available. This instrument has provided a comprehensive, state-of-the-art experimental description and comparison of the magnetic domains in both the interior and exterior regions of a Nd-Fe-B sintered magnet. Furthermore, we anticipate that the advanced capabilities of this measurement system will be particularly advantageous for observing magnetic domain structures formed from other kinds of first-order phase transitions and possible metamagnetic transitions induced by strong magnetic fields. Finally, improving the spatial resolution to less than 50 nm and increasing the applied magnetic field are possibilities for future technical developments.

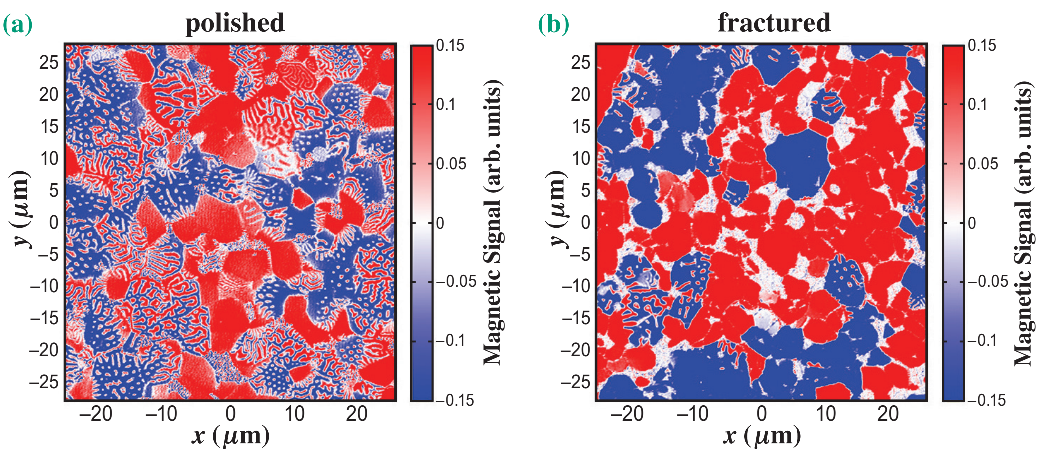

Fig. 2. Magnetic domain images of **(a)** the polished surface and **(b)** the fractured surface of a Nd-Fe-B sintered magnet close to their respective coercive fields.

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