MFM study of domain structure of CoNi microparticles caused by mechanical stress

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Abstract. The domain structure of planar CoNi microparticles with the square shape has been studied under mechanical stress. An array of CoNi particles was formed on the surface of thin polished glass by electron beam evaporation. After studying the initial magnetization distribution, the particles were strained along one side due to bending of the substrate. It is shown that the change in the domain structure of CoNi particles depends on the degree of its tension.

1. Introduction

Recently the magnetoelastic effect (the Villary effect) or the change in the magnetic properties of ferromagnetic materials under mechanical stresses has been studied from the point of view of controlling the magnetization switching of micro- and nanoparticles [1–5]. This effect can significantly reduce the energy required for the magnetization reversal of a single-domain particle. Such particles can be used as a basis of logic elements for processing and storing information [3, 4]. One of the promising methods for studying the magnetic properties of single micro- or nanoparticles is magnetic force microscopy (MFM). It makes it possible to visualize the magnetization distribution in planar micro- and nanostructures with a spatial resolution of up to 20 nm [6].

At the same time, the analysis of MFM images of a microparticle makes it possible to solve the inverse problem - to find the direction and the value of the mechanical stress in the particle. The analysis of magnetic properties of thin planar particles [5, 7, 8] or films [9, 10] deposited on a substrate makes it possible to obtain information about the mechanical stress in the near-surface layer of the substrate. The use of microparticles for stress detection in comparison with the classical methods of measuring tension by strain gauges has a significantly greater spatial resolution. Unlike Romanov's spectroscopy method that have good resolution the microparticles can be used on metal surfaces.

In this work, the possibility of using the Villary effect for detecting the mechanical stress in a planar CoNi microparticle was studied. To this end, the MFM technique and computer simulation were used to study the changes in the domain structure of the CoNi microparticle as a function of the tension. Unlike the previously studied Py microparticles [7, 8], the CoNi particles have a much higher magnetostriction constant. According to our assumptions, this should increase the sensitivity of the magnetization distribution to the mechanical stress. In this work, we estimated the range of the mechanical tension, in which the magnetization distribution of the CoNi particle has a noticeable change, and the dependence of this range on the particle size.
2. Sample preparation and measurement techniques

The studies were carried out on samples being an array of planar CoNi (Co18%, Ni82%) particles formed on the thin glass substrate. Two types of samples were manufactured with particles with size of $25 \times 25 \times 0.03 \, \mu\text{m}^3$ and $7.5 \times 7.5 \times 0.03 \, \mu\text{m}^3$. The particles were formed by electron beam evaporation in ultrahigh vacuum on a “Multiprobe P” (Omicron) device. An array of identical particles was formed by sputtering through a metal grid with identical square holes. During the process the grid was tightly pressed to the surface of the substrate. The lateral dimensions of the glass substrates were $18 \times 3 \, \text{mm}^2$ and the thickness was 0.15 mm. After evaporation of particles, the grid was removed and the sample was annealed at 300 °C for about 15 min under vacuum conditions to remove most of the defects caused by deposition.

A Solver HV (NT MDT) device operating in the MFM mode or in the atomic force microscopy (AFM) mode was used for the study of properties of the CoNi particles. The MFM measurements were carried out in a single-pass method. In this mode, the MFM probe is moved at a constant height above the surface during scanning of the sample and it does not distort the magnetization distribution in CoNi particles. The “Multi75M-G” cantilevers (BudgetSensor) were used in the experiment.

The area filled with CoNi particles with lateral sizes of 25 μm was approximately $6 \times 3 \, \text{mm}^2$ and was shifted with respect to the sample centre. The size of the area was limited by the capabilities of the device for a sample preparation. Therefore, the particle array was shifted with respect to the centre of the substrate in order to study the change in the domain structure in a wide tension range. It will be shown below that the distribution of the mechanical stress generated in the particles was symmetrical around the sample center.

The area of the particles with lateral sizes of 7.5 μm had the circle shape with diameter of about 2.5 mm and was also shifted with respect to the sample centre. The size of the area was limited by the size of the metal grid used for the sample production. In this sample, the tension in the particles was also changed due to the non-uniform bending of the substrate and was symmetrical about the sample center.

The topographic image of the single CoNi particle with size of 25 μm is shown in Figure 1a. A similar image for the CoNi particle with size of 7.5 μm is shown in Figure 2a. The AFM images of the particles obtained in different places of the sample made it possible to confirm that all particles on the sample have the same size and shape. It makes it possible to compare magnetic images from particles obtained in different areas of the sample.

3. Domain structure of CoNi particles

The MFM image characteristic for particles with size of $25 \times 25 \times 0.03 \, \mu\text{m}^3$ without mechanical stress is shown in Figure 1b. In order to determine the magnetization distribution in the particle, the experimental MFM image (Figure 1b) was compared with the result of the computer simulation of its magnetic structure. These calculations were performed using the OOMMF software [11] (Figure 1c). In the computer simulation, the particle was divided into unit cells with the lateral size of 20 nm and size of 30 nm in the out-of-plane direction (equal to the particle height). Then, by changing the direction of the magnetization in each cell, the total magnetic energy of the particle was minimized.

The magnetization distribution obtained by OOMMF was used to simulate the MFM image (Figure 1d). A “Virtual MFM” program [12] was used for calculation of the virtual MFM image and it was compared with the experimental MFM image. The coincidence of the model image and the experimental one made it possible to conclude that this OOMMF calculation corresponds to the real magnetization distribution.

A multidomain structure is typical for the CoNi particles with size of 25 μm in the unstressed state and the domain distribution strongly depends on local defects in each particle. Therefore, it is not possible to obtain the magnetization structure by the OOMMF simulation that exactly corresponds to the experimental MFM image (Figure 1b, d). However, it can be concluded on the basis of the obtained MFM images that the general view of the magnetic structure of the 25 μm particles without the mechanical stress is multidomain.
Figure 1. Topography (a) and MFM (b) images of the CoNi particle with size of 25 μm in the unstressed state. The magnetization distribution in the same particle calculated by OOMMF (c) and its virtual MFM image (d). The scan size of 33×33 μm².

The typical MFM image for particles with size of 7.5×7.5×0.03 μm³ without the mechanical stress is shown in Figure 2b. The OOMMF simulation of magnetisation distribution and the virtual MFM image corresponding to this experimental image are shown in Figure 2c, d, respectively. A four-domain state, in which all domains have approximately the same size and shape, is typical for 7.5 μm particles. Some of the distortions observed in the experimental MFM image are most likely caused by local defects that are not reproduced in the OOMMF simulation.

To produce tension in the particles, the substrate with the particles was elastically bent by fastening in a special holder (Figure 3a). The holder was a flat plate made of the non-magnetic material. A metal wire with a diameter of 0.08 mm was placed on the plate perpendicular to the long axis of the sample. The edges of the sample were tightly pressed by clamps to the surface of the holder. As a consequence, the surface of the substrate was nonuniformly bent. Accordingly, the uniaxial tension was produced in the particles located on the substrate along the long central axis and the direction of its tension was parallel to this axis. The tension in the particles depends on their distance from the sample center, where the wire was placed. A similar approach was used in [5, 9] to produce a gradient of local stresses in the sample under study. The calculations performed in these works confirm that the mechanical stress induced along the long axis of the sample is uniaxial and parallel to this axis.

Figure 2. Topography (a) and MFM (b) images of the CoNi particle with size of 7.5 μm in the unstressed state. The magnetization distribution in the same particle calculated by OOMMF (c) and its virtual MFM image (d). The scan size of 11×11 μm².

In order to achieve the coincidence of the virtual MFM images with experimental ones (i.e., to determine the magnetization distribution in the particle) during the OOMMF calculations, the effective anisotropy coefficient (K_{eff}) was varied. In the case under consideration, the effective anisotropy coefficient of a particle depends on the crystalline anisotropy coefficient and on the of magnetoelastic anisotropy coefficient. The CoNi particles had the crystalline anisotropy coefficient close to zero due to their composition and the polycrystalline structure due to their preparation technique. Therefore, the anisotropy coefficient of the particle is determined only by the magnetoelastic anisotropy coefficient.
The variation of $K_{\text{eff}}$ is often used by other authors in order to determine the magnetization distribution in microparticles under the mechanical stress. For example, such technique was used in [5] to determine the magnetization distribution in nickel particles.

**Figure 3.** Scheme of the production of stressed particles (a): 1 – flat sample holder; 2 – substrate; 3 – particles; 4 – metal wire for the substrate bending; 5 – clamp for fixing the sample. MFM images (up) of a CoNi particle with size of 25 μm in the stressed state and the corresponding magnetization distribution (down) calculated by OOMMF: four-domain state under tension of about 15 MPa (b), four-domain state under tension of about 25 MPa (c), seven-domain state under tension of about 25 MPa (d). The scan size of 33×33 μm².

To determine the effect of the mechanical tension on the magnetic structure of particles, the sample surface was scanned by MFM with a fixed step along the long axis of the sample. It was established that the 25 μm particles transfer into the four-domain state when the tension exceeds 10 MPa (Figure 3b). In this case, the domains with the direction of the magnetization perpendicular to the tension direction have a larger size and a characteristic bridge is formed between them. Such magnetization redistribution is typical for a material with a negative magnetostriction coefficient. The length of the bridge is proportional to the ratio between the areas of the domains with the direction of the magnetization parallel and perpendicular to the axis of tension and can be used to compare the tension in the particles.

With increasing mechanical tension in the particle up to 20 MPa, two main domains remain with the direction of the magnetization perpendicular to the tension direction and two very small areas at the particle edges where the magnetization is reversed (Figure 3c). In this case, it is impossible to determine the mechanical tension on the basis of the length of the bridge between domains. At the same tension, a seven-domain state was also observed on some particles. In this case, there are three main domains with the direction of the magnetization perpendicular to the direction of tension and four small areas on the particle edges where the magnetization is reversed (Figure 3d). Thus, it was
established that the magnetization of 25 μm particles is very sensitive to the mechanical stress and can be used to detect the tension in a very narrow range.

The mechanical tension of higher than 10 MPa in 7 μm particles leads to the increase in the size of the domains with the direction of the magnetization perpendicular to the tension direction (Figure 4a). The length of the bridge changes more slowly with increasing tension than that in 25 μm particles (Figure 4b). Moreover, the magnetization distribution in the 7 μm particle (in comparison with the 25 μm particle) is much more resistant to the influence from the MFM probe due to the anisotropy of the shape. The seven-domain state was observed in some of 7 μm particles at the tension above 20 MPa (Figure 4c).

As shown by the OOMMF calculations, a decrease of the particle size leads to an increase of the density of its magnetic energy due to an increase of the contribution of the shape anisotropy. Accordingly, a large energy is also required to change the magnetic structure of the particle. This leads to an increase of the stress value required to change the magnetic structure of this particle and to an extension of the stress range in which this change occurs. At the same time, an increase of the magnetostriction coefficient leads to a decrease of the stress value required to change the magnetic structure. This leads to a decrease of the stress range to which the particle is sensitive and to shift of this range towards lower values. Therefore, the change in the domain structure of 7 μm particles occurs in a wider tension range (of about 50 MPa) and, these particles are promising for the usage as mechanical stress detectors for the near-surface layer, where they are located.

4. Conclusions
By using the MFM technique, it was shown that the magnetic structure of CoNi particles changes under the mechanical tension. The changes in the magnetic structure of particles with 25 μm size were observed in a narrow tension range (of 10-20 MPa). Such particles can be used only as a detector indicating the presence or absence of the mechanical stress. The CoNi particles with size of 7 μm changed their magnetic structure over the entire tension range (up to 50 MPa). These particles can be used as mechanical stress detectors, which make it possible to determine the mechanical stress from the analysis of their magnetic structure.
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