Domain structure of CoNi microparticles under mechanical stress

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Abstract. In this work, the results of the study of the domain structure of planar CoNi microparticles are presented. The microparticles represented squares with a side of 7 μm and height of 0.03 μm. It was shown that in the non-stressed state the particles had the regular four-domain state. The mechanical stress (compression) of the particles led to a change in domain size, which depended on the degree of compression, the angle between the direction of magnetization, and the side of the mechanical stress. Under the mechanical stress, the change in the coercive force and the residual magnetization of the particles was observed.

1. Introduction
The magnetic properties of a solid may change under mechanical stress. This effect is called “the magnetoelastic effect” (or the Villary-effect). Recently, this phenomenon has been studied in connection with the possibility of its application for the magnetization reversal of microparticles. The mechanical stress can significantly reduce the energy required to magnetization reversal of a single-domain or multidomain microparticle [1-5]. Straintronics is separated as special area of magnetoelastic effect that studies this phenomenon for micro and nano-objects [3].

The materials with crystalline anisotropy being close to zero and high magnetostriction coefficient (usually the alloys of ferromagnetic metals) are interesting for studying the magnetic properties under mechanical stress. The effect of crystalline anisotropy on the magnetic properties can be reduced almost to zero in polycrystalline materials. This is due to the random orientation of the crystallographic planes in each grain of a polycrystal.

In this paper, the effect of mechanical stresses on the magnetic structure of CoNi microparticles was studied. The magnetic force microscopy and microscopy based on magneto-optical Kerr effect (MOKE) were used for this study. The composition of alloy (Co18%, Ni82%) was chosen in order to get a sufficiently large value of the magnetostriction coefficient and to exclude the influence of crystalline anisotropy on the magnetic properties. Therefore, the anisotropy of the studied microparticles was induced by mechanical stress and shape.

2. Sample preparation
The planar CoNi microparticles of size 7.5×7.5×0.03 μm³ has been studied. An array of these microparticles was formed on the thin glass substrate. The lateral size of substrate was 18×3 mm² and the thickness was 0.15 mm. The microparticles were fabricated by electron beam evaporation technique using the ultrahigh vacuum setup “Multiprobe P” (Omicron). The deposition on the substrate was performed through the metal grid tightly pressed to the surface. The uniformly spaced square holes of
the grid were located on the substrate in the way that one of the sides of the resulting particle was parallel to the axis of compression of the particle and the long axis of the substrate. The area with the particles had a diameter about 2.5 mm. The size of this area was limited by the grid.

Before deposition, some part of the substrates was elastically bent by placing into a special holder. After deposition, the sample was removed from the holder, this caused substrate straightening and the compression of particles on the surface. A similar technique was used to induce stresses in thin films [6,7] and particles [5]. Due to uniform bending of the substrate, the particles were also compressed uniformly throughout the sample. This made it possible to study samples by MOKE, when a signal is collected from a certain array of particles and it is important that all the particles under study had the same physical properties. In our case, the size of region under study was $10^{-2}$ mm$^2$.

The P47-Pro and Solver HV setups (NT–MDT) in magnetic force microscope (MFM) mode and atomic force microscope (AFM) mode were used. Both setups allow making MFM-measurements of the samples in an external magnetic field directed in the sample plane. For research purposes, the commercial Multi75M-G cantilevers (BudgetSensor) were used. The MFM-measurements were performed by single-pass technique, when the probe moved during scanning at a constant height above the sample surface. In this case, the influence of magnetic field of MFM probe on the magnetization distribution in microparticles is significantly reduced. This allows one to determine more precisely the value of external magnetic field corresponding to a change in the particle magnetic structure.

3. Magneto-optical Kerr effect (MOKE)

The setup using the Kerr-effect based on modified LEFT-3M-1 ellipsometer was used to register hysteresis loops. The setup allows measuring the dependence of the polarization rotation of the light reflected from the sample surface on the external magnetic field. In addition, it is possible to make in-plane rotation (with resolution of $4.5^\circ$) of the sample and measure in different sample points with spatial resolution about 0.1 mm. The initial sample orientation was approximately parallel to the long axis of the substrate and one of the sides of the square particle. The initial orientation of the sample was close to the direction of compression under mechanical stress. Each hysteresis loop is the result of averaging of 200 measurements. The hysteresis loops in the direction of easy axis and hard axis are presented in Figure 1a and Figure 1b, respectively. The angular dependences of the relative remnant magnetization (Fig. 1c) of the particles were calculated by analysis of the recorded hysteresis loops.

It is seen at the angular dependences that in the absence of mechanical stresses the microparticles have two easy axes (EA) oriented along the square diagonals and two hard axes (HA) of magnetization oriented along the sides of the square. The corrective force along EA is about 14 Oe and 21 Oe along HA. The anisotropy field is about 60 Oe along EA and HA. The compression of the particles leads to the formation of the one EA in the direction of compression and one HA rotated 90 degrees relative to EA. The coercive force along EA increased to 24 Oe, the anisotropy filed decreased to 40 Oe. Anisotropy field along HA is above 85 Oe and coercive force is 6.7 Oe.

**Figure 1.** Hysteresis loops obtained by the MOKE for non-stressed (solid lines) and stressed (dashed lines) CoNi particles with the direction of the external magnetic field along: (a) easy and (b) hard axes. (c) The angular dependences of the normalized remnant magnetization.
Figure 2. MFM images (up) and corresponding distribution of the magnetization (down) (a) for unstressed CoNi particle in four-domain state, for compressed particle: (b) in four-domain state and (c) in seven-domain state.

Thus, based on the analysis of hysteresis loops, it can be concluded that particle compression leads to an increase in the coercive force in about 1.7 times and decrease in anisotropy field on 30% along the compression axis. This fact indicates a significant change in the magnetic properties of particles under the mechanical stress.

4. Magnetic properties of CoNi particles studied by MFM

MFM-image of a CoNi particle without mechanical stress is shown in Figure 2a. According to the MFM-image, the particle is in a four-domain state with equal domain size. The direction of magnetization in each domain is parallel to the nearest square side. In order to establish the magnetization distribution in a particle, the following steps were performed. First, the magnetization distribution in the particle was calculated by means of the Object Oriented Micro Magnetic Framework (OOMMF) [8] using the sizes and shape of the particle obtained by AFM (Fig. 3a). Second, a virtual MFM-image was calculated on the base of the magnetization distribution by the algorithm described in [9] and if the experimental MFM-image coincided with the virtual one, it was concluded that the calculated magnetization distribution was correct.

If the uniaxial mechanical compression was applied to the microparticles, the sizes of two domains with magnetization direction parallel to the compression axis were increased (Fig. 2b). A characteristic domain wall in the shape of a bridge is formed between these two domains. The length of the bridge depends on the magnitude of the mechanical stress in the particle. In addition to the four-domain state, some particles were in a seven-domain state (Fig. 2c). The energy of the magnetic subsystem in the seven-domain state is higher than that in the four-domain state according to the OOMMF calculations; therefore, it is energetically unfavourable. It can be assumed that the seven-domain state of a microparticle is attributed to the presence of local defects, which is not taken into account in the OOMMF calculation.

MFM studies of the magnetization reversal in CoNi particles were carried out in an external magnetic field ranged from +160 Oe to -160 Oe applied with the step of 5 Oe in-plane along two directions (EA and HA). A uniform magnetization with the direction parallel to the magnetic field was observed for the particles without mechanical stresses along HA in the range from +160 Oe to +60 Oe. This distribution is displayed as black and white stripes at the opposite ends of the MFM-image (Fig. 3b). In the field range from +55 Oe to -55 Oe, the microparticles were in the multidomain state (Fig. 3c,d) and the magnetic contrast at the edges of the particles switched when the direction (sign) of the external magnetic field changed. The breaks on these images are related to the influence of the magnetic field of MFM probe. It is impossible to eliminate this effect, because the magnitude of MFM-probe field is
Figure 3. (a) AFM image and (b-e) MFM images of two unstressed CoNi particles in external magnetic field: (b) +70 Oe, (c) +20 Oe, (d) -20 Oe, (e) -70 Oe. Magnetic field is directed along the long side of the scan. Scan size 21×12 μm².

For particles under uniaxial mechanical stress, the magnetic field was also applied in two directions: parallel (EA) and perpendicular (HA) to the axis of stress, which coincided with one of the sides of the particle. In this case, the MFM images of the particles were similar to the images obtained for uncompressed particles with the field parallel to the particle side (Fig. 3). Only the values of external magnetic fields, at which magnetization transform occurred, were changed. In a magnetic field directed along the compression axis (i.e. along EA), the particles retained uniform magnetization in the range from +160 Oe to +10 Oe. A multi-domain structure was observed in the fields from +5 Oe to -30 Oe. In the fields from -35 Oe to -160 Oe, the particles became uniformly magnetized in the opposite direction.

The MFM data allow making analysis of the changes in the anisotropy field of a particle under mechanical compression in the selected direction. Here, the anisotropy field means the value of the external magnetic field, at which the particle becomes uniformly magnetized in the direction of this field. In the direction of compression (along one of particle sides), an EA is formed and the anisotropy field decreases from 60 Oe to 35 Oe. Along the other side of the particle and perpendicular to EA, the HA is formed and the anisotropy field increases from 60 Oe to 95 Oe. A significant change in the particle anisotropy field under the mechanical stress is due to the high value of the magnetostriction coefficient of CoNi alloy (-25×10⁻⁶), and the directions of EA and HA are caused by its negative sign. The values of the anisotropy field obtained by MFM measurements are in good agreement with the data obtained by MOKE (anisotropy field decreases from 60 Oe to 40 Oe along EA and increases from 60 Oe to more than 85 Oe along HA when mechanical stressed).

5. Conclusion
According to the experimental data, in the absence of mechanical stress, CoNi particles have a four-domain structure with domains of the equal size. Each particle has two axes of easy magnetization (parallel to the diagonals of the particle) and two axes of hard magnetization (parallel to the side of the
due to the shape anisotropy. The mechanical compression of the particles leads to a change in their domain structure. The two axes are formed: one easy axis is parallel to the direction of compression of the particle, and one hard axis is perpendicular to the direction of compression of the particle. The coercive force of the compressed particle along the EA increases about 1.7 times, and the anisotropy field decreases about 2 times. Thus, using materials with high magnetostriction coefficient for producing particles allows varying their magnetic properties over a wide range by applying mechanical stress.

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