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THE INFLUENCE OF TENSION ON THE REMANENT MAGNETIZATION OF Fe—Ni MATERIALS

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The paper presents an experimental investigation of the influence of mechanical tensile stresses in the region of elastic deformation on the magnetization of the remanent magnetic state of the polycrystalline Fe—Ni samples. The obtained results are interpreted on the basis of conclusions resulting from the analysis of energetic conditions in the elastically deformed ferromagnet with a cubic symmetry.

I. INTRODUCTION

Papers [1—5] present a theoretical investigation of the influence of mechanical stresses in the region of elastic deformation on the orientation of the vector of spontaneous magnetization in the ferromagnetic single crystals with a cubic symmetry and an anisotropy of magnetostriction. It can be concluded from the obtained results that the magnetic properties of the multiaxial cubic ferromagnets under the influence of mechanical stresses are determined by some basic factors. These are: 1. The onset of the magnetic texture characterized by the Bloch $\pi/2$ wall displacement. The character of this texture resulting in a $\pi/2$ wall displacement depends upon the signs of the magnetostriction constant λ_{100} (at $K_1 > 0$, where K_1 is the constant of the magnetocrystalline anisotropy) or λ_{111} (at $K_1 < 0$) and that of the stress σ (in the case of the tensile stress $\sigma > 0$). 2. The onset of the magnetic texture caused by the rotation of the easy magnetization axis. The character of this texture, resulting in a rotation of the vectors of the spontaneous magnetization, depends on the signs of λ_{111} (at $K_1 > 0$) or λ_{100} (at $K_1 < 0$) and that of the stress σ . 3. An increase in the gradients of the internal stresses $\partial\sigma_i/\partial n$ under the influence of the external load, which makes the processes of the Bloch wall displacements more difficult.

At lower stresses the factors 1. and 3. play an important role; and depending upon the sign of the appropriate magnetostriction constant and that of the

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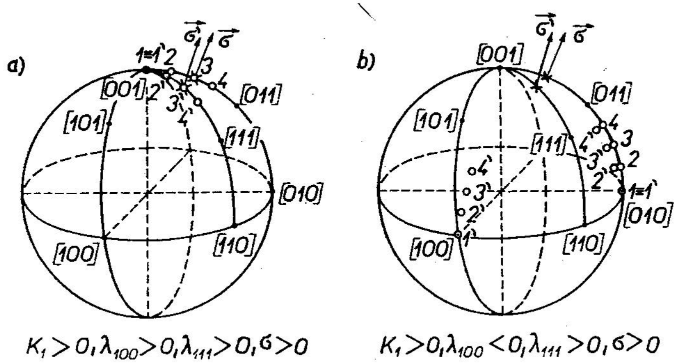
stress these factors can support each other so that for a suitable initial distribution of the domains of the spontaneous magnetization they can eventually lead to changes in the magnetization with the same sign or these factors can act against each other and thus lead to changes in the magnetization with opposite signs. Because the Bloch wall displacements proceed in general (especially at a large value of the energy of magnetocrystalline anisotropy) energetically easier than the rotational processes [6], the factor 2. has a more apparent influence, especially at higher stresses.

Fig. 1 shows two examples of the influence of the influence of the mechanical stress σ on the orientation of the easy magnetization axis in ferromagnetic single crystals having cubic symmetry, with various combinations of the signs of magnetostriction constants λ_{100}, λ_{111} and σ at $K_1 > 0$, as presented by F. N. **Dunajev** in [3]. Circles numbered 1 to 4 or 1' to 4', resp. in the particular figures denote the orientation of the axis of easy magnetization at different values of the applied stress σ or σ', resp. The value of stress increases from the circle denoted with 1 or 1', resp. to circle 4 or 4', resp. For a certain orientation of the stress (see $\vec{\sigma}$ and $\vec{\sigma}'$) inside the spherical triangle [001] — [111] — [011] (the orientation $\vec{\sigma}$ or $\vec{\sigma}'$, resp. is denoted by a cross) the axis of easy magnetization at a relatively small value of the stress σ or σ', resp. is identical with the direction [001] (Fig. 1a). With increasing stress and in dependence upon the value of this stress the axis of easy magnetization starts to rotate from the direction [001] towards $\vec{\sigma}$ or $\vec{\sigma}'$ resp. (circle 2 or 2', resp.). At a certain value of the stress this axis will be identical with the direction $\vec{\sigma}$ or $\vec{\sigma}'$, resp. (circle 3 or 3' resp.) and with the stress increasing still further, the axis of easy magnetization deviates towards the plane perpendicular to the direction of the applied stress. An analogous explanation applied also to Fig. 1b.



$K_1>0, \lambda_{100}>0, \lambda_{111}>0, \sigma>0$ $K_1>0, \lambda_{100}<0, \lambda_{111}>0, \sigma>0$

Fig. 1. The diagram of the orientation of the axis of easy magnetization in a ferromagnetic single crystal having a cubic symmetry with $K_1 > 0$ for various combinations of the signs of the magnetostriction constants λ_{100}, λ_{111}, that of the anisotropy constant K_1 and that of the stress σ. (According to [3]).

Theoretical considerations given in papers [1—4] are based on a detailed analysis of the expressions for the density of magnetocrystalline and magnetoelastic energy in the ferromagnetic single crystals having a cubic symmetry. As stated in [3], the results of this analysis enable us to form a picture of the influence of mechanical stresses on the orientation of vectors of spontaneous magnetization also in a polycrystalline material and the diagram shown in Fig. 1 is applicable to a polycrystal too.

We must realize that the analysis of the influence of mechanical stresses on the magnetic state of ferromagnets in the above mentioned papers is based on some simplifying and idealizing notions. This is necessary, as this analysis is in general very complicated and has not been carried out yet [7]. The stresses in real single crystal materials and especially in polycrystals are nonhomogeneous and so the conditions are more complex, this beinig mainly due to the presence of internal stresses, due to the anisotropy of elastic constants and due to the local mechanostriction produced by applying the external stress σ.

The object of this paper is to verify qualitatively the conclusions resulting from the outlined theoretical analysis of the influence of mechanical stresses on the magnetic properties of ferromagnets [1—4], using polycrystalline Fe—Ni materials of various compositions and thus different combinations of signs for λ_{100}, λ_{111}, K_1 and σ.

II. SAMPLES AND MEASURING METHOD

The measurements were made on polycrystalline wire samples prepared from Fe—Ni alloys of various compositions. The sample diameter was 1 mm, its length 200 mm. The sample types as well as their magnetostriction constants and the constants of magnetocrystalline anisotropy are listed in Table 1. In order to remove internal strains all samples were annealed in an argon atmosphere at a temperature of 800 °C for 5 hours prior to measurements. The sample cooling rate was ≈ 2 °C/min.

An astatic magnetometer of the Bozorth type [8] was used for measuring the magnetic state of samples. The samples were clamped in special holders to avoid the deformation of the sample ends. The magnetization of the samples was performed in the solenoid of a magnetometer of the length of 500 mm. As shown by the test measurements, the magnetic field along the sample length was sufficiently homogeneous. The remanent magnetic state of the samples was obtained by the usual method, that is by magnetizing in a large enough magnetic field practically to saturation and then decreasing the field intensity down to zero. The used intensity of the magnetic field in the magnetizing solenoid was 4 × 10^4 A/m. It follows from measurements that field is sufficiently large for the remanent magnetization to attain practically its maximum value.

Mechanical loads were applied to the samples by a suitable lever mechanismus.

The remanent magnetic state of the samples was measured by the null method [8]. The sensitivity of the apparatus was 2.67 × 10^{-3} Wb/m^2 for one centimeter of the light mark deviation on the scale.

With respect to the geometrical dimensions of the used samples it was possible to neglect the demagnetizing effect of the free ends on the magnetic measurements.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 2 shows the dependence of the remanent magnetization upon the value of the applied tensile stress σ for the material PY 50. This material, as evident from Table 1, exhibits positive constants of anisotropy and magnetostriction ($K_1 > 0$, $\lambda_{100} > 0$, $\lambda_{111} > 0$). As follows from theoretical considerations, the domain wall displacement caused by the influence of the mechanical tensile stress leads in such a material to an increase in the dimensions of the domains closest to the direction of $\vec{\sigma}$; on the other hand, the gradual increase in the value of the tensile stress leads to the rotation of the axis of easy magnetization (see also the diagram in Fig. 1a) first towards $\vec{\sigma}$; at a certain value of the stress a parallelism between both directions is reached, at a higher stress, on the contrary, the axis of easy magnetization rotates towards the plane perpendicular to the direction of the load. It can be expected therefore that the elementary magnetization processes caused by the gradual increase in the value of the tensile stress will lead to an increase in the remanent magnetization from its initial value up to a certain maximum, after which a decrease of the magnetization is observed. Since an increase in the gradients of internal stresses with an increase in the external tensile stress reterd the processes of the domain wall displacements, the increase in magnetization caused by the onset of the magnetic texture characterized by the displacement of the domain walls will be suppressed. The observed dependence shown in Fig. 2 is a good qualitative confirmation of this concept.

It should be noted that an analogous dependence for the given kind of polycrystalline material was theoretically predicted by F. N. Dunajev in [2], but the considerations presented in his paper were not generalized for an arbitrary orientation of the stress in a crystal. A polycrystalline material with a crystalographic texture was considered, in which the planes {100} and {110} were parallel to the direction of the applied stress. In paper [3], however, the theoretical consideration related to the influence of mechanical stresses on the orientation of magnetization in ferromagnetic single crystals were generalized also for a polycrystalline material without a crystalographic texture.

The influence of the second constant of anisotropy K_2 on the observed dependence should also be mentioned, since this constant has quite a high value for PY 50, namely $K_2 = -180 \times 10^2$ J/m^3 [9]. It follows from [3] that

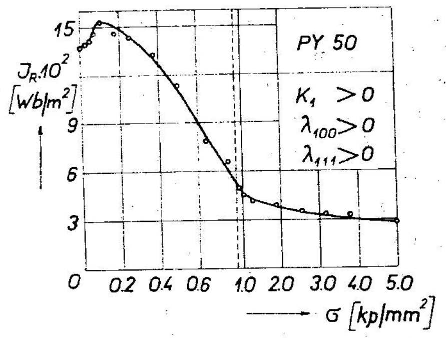


Fig. 2. The dependence of the remanent magnetization upon the appoied tensile stress in the region of the elastic deformation for the material PY 50.

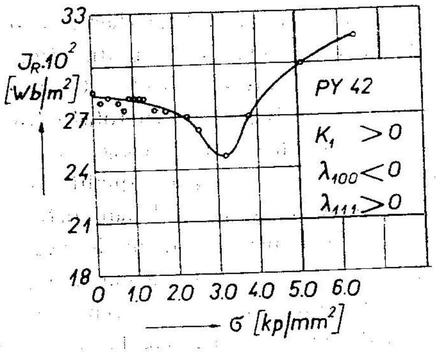


Fig. 3. The dependence of the remanent magnetization upon the applied tensile stress in the region of the elastic deformation for the material PY 42.

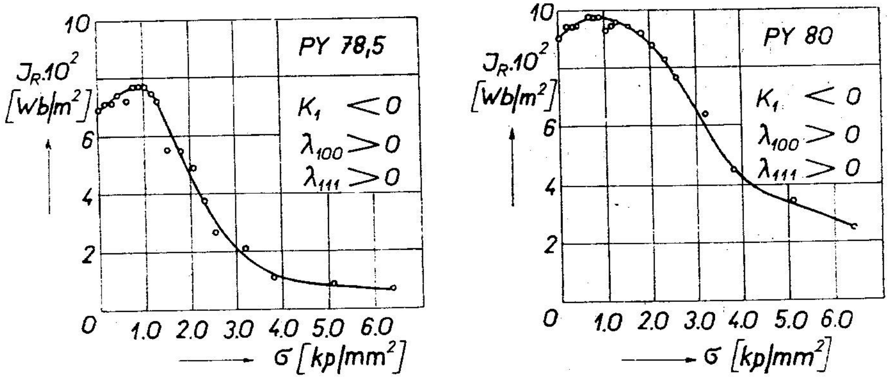


Fig. 4. The dependence of the remanent magnetization upon the applied tensile stress in the region of the elastic deformation for the materials PY 78.5 and PY 80.

this constant has no influence on the character of the described magnetization processes caused by the application of a mechanical stress. As it follows from this paper, in such a case the value of the stress σ, at which a parallelism is reached, depends on the orientation of the stress $\vec{\sigma}$ in the crystal. It cannot be expected therefore that a complete uniaxial state develops in the polycrystalline material under the influence of a mechanical stress, since different crystals align themselves at different values of σ.

Fig. 3 shows the observed dependence of the remanent magnetization upon the value of the applied tensile stress σ for the PY 42 sample. As it can be seen from Table 1, this sample exhibitis the constants $K_1 > 0$, $\lambda_{100} < 0$ and $\lambda_{111} > 0$. The displacement of domain walls induced by the influence of mechanical tensile stresses lead therefore to an increase in the dimensions of those domains magnetized in the directions of easy magnetization, which deviated most from the direction of $\vec{\sigma}$. On the orther hand, since $\lambda_{111} > 0$, the vectors of magnetization tend to rotate towards $\vec{\sigma}$ with a gradual increase of the tensile stress (see also the diagram in Fig. 1b). As seen from Fig. 3, the observed dependence is in a good qualitative agreement with the concept based on the theoretical analysis. It supports the fact that at lower values of the tensile stress the displacements of domain walls have a predominant influence on the changes in magnetization and with the gradual increase in the value of the tensile stress the processes of rotation of the axis of easy magnetization towards the applied stress become more and more effective. Since the value of the ratio $|\lambda_{111}/\lambda_{100}|$ is quite large for this material ($|\lambda_{111}/\lambda_{100}| \approx 5.45$), the processes of rotation play here an important role. It should be obvious that — like in other materials — with a gradual increase in the tensile stress there increases here also the influence of the increasing gradients of internal stresses. This factor, as already mentioned earlier, always retards the processes of the displacement of domain walls.

Fig. 4 shows the dependences of the remanent magnetization on the value of the applied tensile stress σ as observed on the PY 78.5 and the PY 80 samples. These samples are characterized by the constants $K_1 < 0$, $\lambda_{100} > 0$, $\lambda_{111} > 0$. Therefore the processes of the domain wall displacements under the influence of the tensile stress lead to an increase in the dimensions of those domains of spontaneous magnetization, which are closest to the direction of $\vec{\sigma}$. This is because the term of magnetoelastic energy, which includes the constant λ_{111}, intensifies the minimum of the function of magnetocrystalline energy in the direction {111} closest to $\vec{\sigma}$ only if σ and λ_{111} have the same sign, and this requirement is satisfied by the given samples. On the other hand if follows from the theoretical consideration [3] that at $K_1 < 0$ and $0 < \lambda_{111}/\lambda_{100} < 1$ — with an increase of the applied tensile stress in the polycrystalline sample — the rotation of the vectors of the spontaneous magnetization towards $\vec{\sigma}$ takes place at lower values of the stress, then at certain value of $\vec{\sigma}$ an alignment is reached and at higher stresses the vectors of magnetization deviate from the direction of $\vec{\sigma}$. An increase of the gradients of internal stresses with an increase of the values of external tensile stresses has — as in all preceding cases — a retarding effect on the changes of magnetization. It follows trom the above that for materials of the described type an initial rise, a certain maximum and then a decrease of the curve $J_R(\sigma)$ can be expected. As seen from Fig. 4, this dependence is qualitatively well confirmed by the given samples.

When a quantitative comparison between the experimental results obtained in this work and the expected theoretical values resulting from the analysis of F. N. Dunajev is made, it should be stated that the theoretical conclusions are not in agreement with the experimental results. It follows from the theoretical analysis [3], that for example for materials of the PY 50 type the parallelism between $\vec{\sigma}$ and $\vec{J}_S$ should be reached at $\sigma = 2K_1/3(\lambda_{111} - \lambda_{100})$. By putting the values $K_1 = 33 \times 10^2$ J/m³, $\lambda_{100} = 10 \times 10^{-6}$ and $\lambda_{111} = 31 \times 10^{-6}$ valid for PY 50 (see Table 1) into this expression, we have $\sigma \doteq 10$ kp/mm². By comparing this result with the experimentally observed dependence shown in Fig. 2 we can see that the difference between the observed value and the theoretically calculated one is about two orders of magnitude.

It follows from the above that to apply F. N. Dunajev's theory to real polycrystalline ferromagnetic materials it would be necessary to add some Duna- more terms to it, thus enabling a closer approach to the real situation. jev himself states in [3] that his theoretical analysis is based on some simplifying concepts and the conditions in the real single crystal and polycrystalline materials are much more complicated. It should be also noted that the indi-

Table 1

Sample type	$K_1 \times 10^{-2}$ [J/m³]			$\lambda_{100} \times 10^6$		$\lambda_{111} \times 10^6$	
PY 42	10 [6]	10 [9]		−5.5 [9]		30 [9]	
PY 50	5.8 [9]	33 [9]	7 [6]	10 [9]		31 [9]	
PY 78.5	−5 [9]	−21 [6]		12 [9]	11.1 [6]	3.5 [6]	
PY 80	−7.6 [9]	−13.5 [6]		9.5 [9]	8 [6]	1.8 [9]	1.0 [6]

vidual authors give different values for the constants appearing in the theoretical analysis so that a quantitative comparison between the observed values and those expected from the theory is even more complicated.

IV. CONCLUSION

The influence of the mechanical tensile stresses in the region of the elastic deformation on the remanent magnetic state of selected polycrystalline Fe—Ni materials with various combinations of the signs of the constants K_1, λ_{100} and λ_{111} was studied in this work. Experimentally observed results were compared with the conclusions resulting from the analysis of energetic conditions in an elastically deformed ferromagnet having a cubic symmetry. Even if the theoretical considerations presented in [1—4] are based on some simplifying assumptions that are hardly encountered in a real material, there is a good qualitative agreement between the conclusions of the theoretical analysis and the experimentally obtained results of this work.

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