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THE ANISOTROPY OF COERCIVITY AND REMANENCE OF DEFORMED Ni MONOCRYSTALS*

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The anisotropy of coercivity and remanence in {111} plane had been determined for samples deformed in temperature of a range 200—400 K. The influence of dislocations of primary and secondary slip systems on changes of coercivity and remanence was analysed basing on theory of anisotropy induced by dislocation stresses.

1. *Introduction*

The mechanism of demagnetization of deformed Ni monocrystals is reflected in investigations on anisotropic changes of coercivity and remanence. The development of these investigations began with the moment of elaborating the theory of interaction between dislocation stresses and spontaneous magnetization [1, 2]. The action of dislocation stresses on the change of direction of spontaneous magnetization was experimentally registered [3]. Investigations on anisotropic changes of coercivity and remanence had been also carried out [4–6]. The investigations were done on samples which were favourably oriented for one-system glide. The anisotropy of coercivity and the remanence in nickel crystals, which were favourably oriented for a multi-system glide during the deformation process, are the object of this paper.

2. *Methods of the experiment*

Monocrystals for work-hardening investigations were prepared in a form of rods, 12 mm in diameter and 60–80 mm long. All crystals were vacuum annealed for 24 hours at 1200°C. Work-hardening curves have been found by means of the tensile test.

Fig. 1 displays the work-hardening curves at various temperatures. The crystallographic orientation of a sample axis is shown in stereographic projection. This orientation distin-

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guishes three slip systems. The shear stresses exerted in these systems were listed on Table I.

The anisotropic changes of coercivity and remanence were determined on plane $(11\bar{1})$ of the primary slip system. The samples used for investigations were disc-shaped of a diameter 9.3 mm and a height 2.5 mm. They were cut off parallel to the $(11\bar{1})$ plane of the primary slip system. The investigations on anisotropic changes of coercivity were carried out with the help of Foerster's coercimeter while investigations on anisotropic changes of remanence with the help of a rotating magnetometer [7]. The sample had been put into the measuring coil in a way, in which the lines of the magnetizing field were parallel to the surface of the sample. After turning into state of remanent magnetization the sample was pushed into rotary movement. By the value of the voltage amplitude, which is inducting in the measuring coil of the magnetometer, could be determined only a projection of the total remanent magnetization J_R towards the sample surface. The value of J_R was the object of investigations of the anisotropic changes.

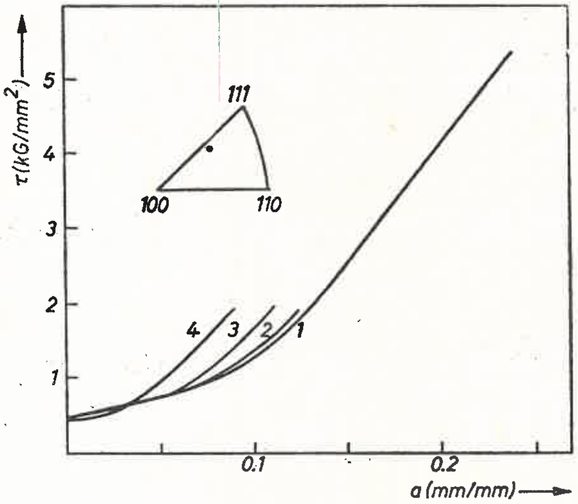

Fig. 1. Work-hardening curves of Ni monocrystals. *1* — more deformed sample at 200 K, *2*, *3*, *4* — less deformed samples at 200 K, 300 K, 400 K, respectively

TABLE I

Shear stresses $\tau = A\sigma$, acting in various slip systems. σ-normal stress acting on the cross section of the sample

Slip system	A
primary (111) [101]	0.46
I secondary $(1\bar{1}1)$ [110]	0.39
II secondary (111) $[10\bar{1}]$	0.36

The installed in the magnetometer referring coil with a ferrite inside, which was mechanically coupled with the sample, made possible to measure the angle α of deflection of the direction $\vec{J}_R$ from the direction of the magnetizing field $\vec{H}$. The characteristics of anisotropic changes $\alpha(\varphi)$ deliver essential informations about the participation of domains magnetized in various directions of the $\langle 111 \rangle$ type in remanent magnetization $\vec{J}_R$. The principle of defining the sign of the angle α, assumed in this work, was presented as an example on Fig. 2.

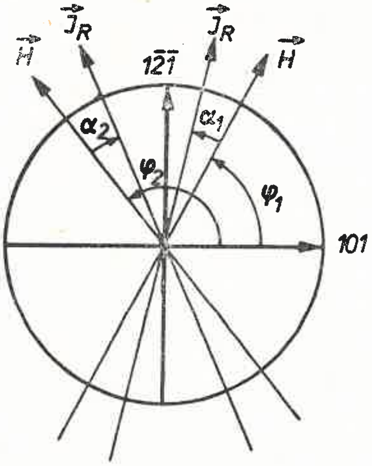

Fig. 2. Conventionally accepted way of defining the sign of the angle α: $\alpha_1 < 0$, $\alpha_2 > 0$

3. *Results and discussion*

No anisotropic changes of coercivity and remanence were stated on the plane $\{111\}$ parallel to the plane of discs cut out from non-deformed crystals. With no regards to the possibility of occurrence of the domain surface structure, weak maximums in directions of $\langle 112 \rangle$ and minimums in directions $\langle 110 \rangle$ can be expected [7]. The investigations on domain structure in the plane $\{111\}$, carried out by Willke [3] for demagnetized samples showed the occurrence of domain surface structure. The image of this structure depended heavily on the direction of the demagnetizing field. The lack of anisotropic changes of the coercity and remanence on the $\{111\}$ plane of discs cut out from non-deformed samples can be linked with the occurrence of the domain surface structure in the state of remanent magnetization.

A distinct anisotropy of $H_c(\varphi)$ and $J_R(\varphi)$ on the plane $(11\bar{1})$ occurred in discs cut out from deformed samples. On Fig. 3 dependence $H_c(\varphi)$ was only presented because the form of dependence course of $J_R(\varphi)$ and $H_c(\varphi)$ was similar for each sample. The increase of mean values $\overline{H_c(\varphi)}$ and $\overline{J_R(\varphi)}$ occured in case of rise in level of deformation as well as in case of rise in temperature, in which the deformation process had been carried out. In both cases this increase can be linked with the increase density of dislocations occurring due to deformation [8, 9]. The courses of anisostropic changes of investigated magnitudes, gained in these investigations, have a character different from those, which Willke [6] had obtained for samples which were favourably oriented for one-system glide in the process of deformation. The characteristic feature of anisotropic changes of $H_c(\varphi)$ and $J_R(\varphi)$

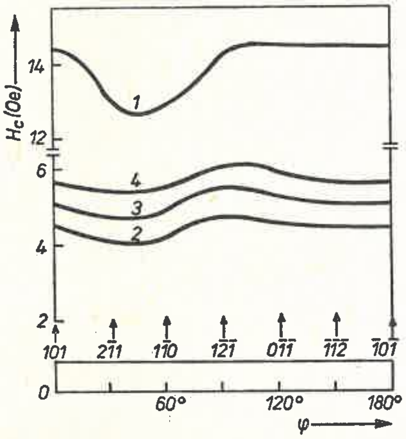

Fig. 3. Anisotropic changes of coercivity on the plane $(11\bar{1})$. 0 — nondeformed sample. Marking of other samples as on Fig. 1

of samples 2, 3, 4, called further samples less deformed, is a maximum in direction $[1\bar{2}\bar{1}]$, a slow decrease of values while approaching the direction $[\bar{1}0\bar{1}]$ and a minimum in the direction near to $[2\bar{1}1]$. On the plane $(11\bar{1})$ of the sample 1, called the sample more deformed, the minimum was kept in the direction near to $[2\bar{1}1]$, but $H_c \approx$ const for $90° \leqslant \varphi \leqslant 180°$.

The analysis of anisotropic changes of investigated magnetic magnitudes is reduced to explanation of the action of the field direction on the demagnetizing process. At room temperature the demagnetizing process in deformed Ni monocrystals occurrs mainly due to movement of interdomain walls [10]. The domains in deformed crystals are separated mainly by 180°-walls [3]. The dislocation structure of crystals determine the direction of the magnetization in domains and the orientation of interdomain walls. The deflection of the magnetization direction in domains from directions $\langle 111 \rangle$ is small even for big density of dislocations [3]. Therefore, the qualification of domains magnetized in directions $\langle 111 \rangle$ will be applied further, however, this expression is inexact.

Generally there are following reasons for the occurrence of anisotropy of the investigated magnitudes;

— the nucleation probability of domains magnetized in directions of the $\langle 111 \rangle$ type during the demagnetizing process is various for domains magnetized in different directions,

— during the demagnetizing process the retarding of interdomain walls movement depends on their orientation towards the direction of dislocation lines and on the type of dislocation occurring in the area of walls shifting.

The presence of dislocations in crystals in linked with the occurrence of free energy, which is a result of magnetoelastic interaction between dislocations and the spontaneous magnetization. This interaction has been investigated in works [1, 2]. An analytic form of anisotropic changes of the free energy on the plane ($11\bar{1}$), stemming from different types of dislocations in deformed nickel monocrystals, has been received in works [7, 11]. The course of changes for some types of dislocations was shown on figures 4 and 5. Taking

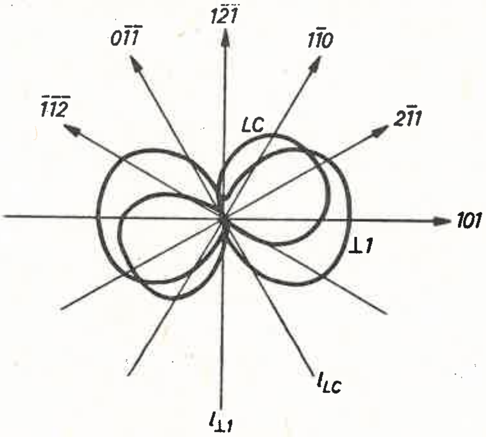

Fig. 4. Changes of free energy, inducted by stresses stemming from edge dislocations ($\perp_1$; $\vec{l} \parallel [\bar{1}21]$, $\vec{b} = \frac{a}{2}$ [101]) and LC dislocations ($\vec{l} \parallel$ [011], $\vec{b} = \frac{a}{2}$ [$01\bar{1}$]) for different directions of magnetization in the plane ($11\bar{1}$)

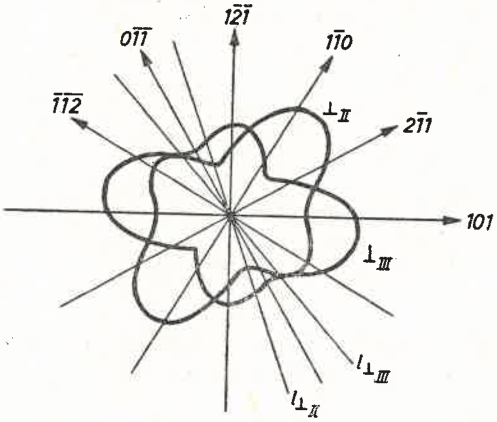

Fig. 5. Changes of free energy inducted by stresses stemming from edge dislocations ($\perp_2$; $\vec{l} \parallel [\bar{1}12]$ $\vec{b} = \frac{a}{2}$ [110]) and edge dislocations ($\perp_3$, $\vec{l} \parallel [1\bar{2}1]$, $b = \frac{a}{2}$ [$10\bar{1}$]) for different directions of magnetization in the plane ($11\bar{1}$)

into account the real dislocation structure it is possible to determine the value of the total free energy of domains magnetized in various directions of the ⟨111⟩ type and thus to assess the probability of their occurrence during the demagnetizing process. The results of investigations of dislocation structure, carried out using methods of electron and X-ray diffraction, were shown in work [8]. The investigations had shown that in less deformed samples the edge dislocations $[\bar{1}21]$ with Burgers vector of $\frac{a}{2}[101]$ prevailed. The density of edge dislocations $\left(\vec{l}\,\|[\bar{1}12], \vec{b} = \frac{a}{2}[110]\right)$, belonging to the secondary slip system, as well as the Lomer Cottrell's (LC) dislocations density $\left(\vec{l}\,\|[011], \vec{b} = \frac{a}{2}[01\bar{1}]\right)$ grew with the increase of deformation temperature. An increase density of LC dislocations and edge dislocations of the secondary slip system were stated in the dislocation net of the more deformed sample.

The edge dislocations of the primary slip system prefer the direction $[1\bar{2}\bar{1}]$ as most favourable from the energetistic point of view (Fig. 4). The secondary edge dislocations as well as the LC dislocations (Fig. 5 and 4) prefer this direction too, though less distinctly. In connection with this it became possible to distinguish the domains $[1\bar{1}\bar{1}]$ with a tendency of turning the easy direction towards direction $[1\bar{2}\bar{1}]$. The distinguishing of domains $[1\bar{1}\bar{1}]$ admits the possibility of missing the deflection of magnetization direction $\vec{J}_R$ from the direction of the magnetizing field $\vec{H}$ (Fig. 6), $\alpha([1\bar{2}\bar{1}]) = 0$, when $\vec{H}\,\|[1\bar{2}\bar{1}]$. Bloch's walls, which seperate the domains, are not very mobile with regard to a strong retarding of their movement by primary edge dislocations and an enough strong retarding by secondary edge dislocations $[\bar{1}12]$. In this situation the maximum occurring in direction $[1\bar{2}1]$ is justified. The domains $[\bar{1}\bar{1}\bar{1}]$ and $[1\bar{1}1]$ should most intensively influence the value of remanence measured respectively in directions $[\bar{1}\bar{1}\bar{2}]$ and $[2\bar{1}1]$. With regard to the value of free energy no type of domains among domains $[\bar{1}\bar{1}\bar{1}]$ and $[1\bar{1}1]$ is privileged taking into account the primary and secondary edge dislocations. However, because $J_R([\bar{1}\bar{1}\bar{2}]) >$

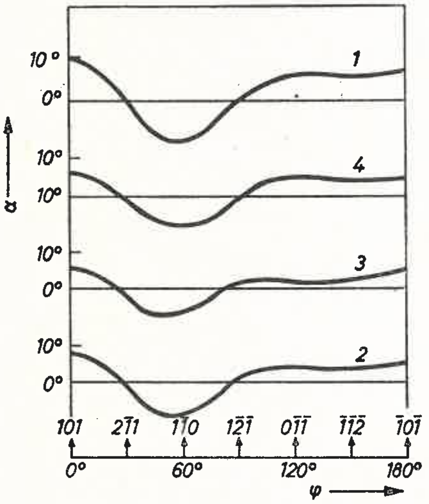

Fig. 6. Anisotropic changes of the angle α on the plane $(11\bar{1})$. Marking of samples as on Fig. 1. The meaning of the sign of the angle α as on Fig. 2

$> J_R([2\bar{1}1])$, it can be inferred that the domains magnetized in direction $[\bar{1}\bar{1}\bar{1}]$ are more favourable. It is possible to privilege the domains $[\bar{1}\bar{1}\bar{1}]$ in relation to domains $[1\bar{1}1]$ taking into account the LC dislocations (Fig. 5). A further reason pointing at privileging the domains $[\bar{1}\bar{1}\bar{1}]$ is the fact that $\alpha(\varphi) > 0$ for $\varphi < 30°$. It amounts to a participation of domains [111] in the magnetization J_R measured in direction $[2\bar{1}1]$. The very low value of coercivity for $\varphi = 30°—40°$ can be put down to great mobility of walls which seperate the domains $[1\bar{1}1]$ and in the case of remanence, additionaly, to vectorial summing of magnetization of all three types of domains: $[1\bar{1}1]$, $[1\bar{1}\bar{1}]$, [111].

The increase of deformation level deepened the differentiation of domains unfavourably for domains $[1\bar{1}1]$, what revealed in form of a clear minimum J_R for $\varphi \approx 40°$. Therefore, one can draw the conclusion that the third of possible slip systems, i.e. the system (111) $[10\bar{1}]$, did not become active because otherwise the edge dislocations $\left(\vec{l}\,||\,[1\bar{2}1],\ \vec{b} = \frac{a}{2}[10\bar{1}]\right)$ would have favourably influenced the relative lowering of domain energy $[1\bar{1}1]$. It can be inferred from the calculated dependence $\alpha(\varphi)$ that as in case of samples less deformed the domains $[1\bar{1}\bar{1}]$ in contribute their share to the magnetization J_R, irrespective of the direction of the magnetizing field. The inferred highest increase energy of domains $[1\bar{1}1]$ in the sample more deformed can be also linked with a big increase density of LC dislocations. The LC barriers with dislocation lines parallel to the direction [011] do not impede the mobility of walls which separate the domains $[1\bar{1}1]$ — what gives a coercivity minimum for $\varphi \approx 40°$ — and at the same time increase the coercivity value for $\varphi \approx 120°$.

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