NOTIZEN

On a New Theory of the Magnetization Curve of Plastically Deformed Nickel Single Crystals

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A new theory of the magnetization process in plastically deformed nickel single crystals of single slip orientation is outlined. It is based on the interaction between the $(\bar{1}01)$-180°-domain walls and the three types of primary edge dislocation dipole and multipole arrangements dominating in stage I, in the transition region and in stage II of the stress-strain curve, respectively, i. e. the $[1\bar{2}1]$-dipole bundles, the rope-like clusters of such bundles extended along $[1\bar{2}1]$, and the $[1\bar{2}1]$-multipole walls, all having $[\bar{1}01]$-Burgers-vectors. In increasing magnetic fields the primary edge dislocation arrangements are shown to be capable to glide to new obstacles under the pressure of the $(\bar{1}01)$-180°-domain walls which will follow them and whose segments at the same time start to vault themselves cylindrically or pillow-shapedly between these dislocation barricades, finally overcoming them at the coercive force by Barkhausen jumps.

In an earlier paper [1] first experimental results had been reported concerning the large decrease of number and size of Barkhausen jumps observed on samples of plastically deformed nickel and on magnetite during simultaneously superposed intensive ultrasonic irradiation. To explain this unexpected effect in terms of domain wall motion, an attempt had been made to modify the usual potential theory of the magnetization curve by introducting a new hypothetical magnetization process which should enable the domain walls also to move to some extent irreversibly *and* continuously but without Barkhausen jumps.

In the meantime, the mentioned problems were subject of a recently published extensive dissertation [2] which contains, in addition to a more detailed description of the experiments and of the apparatus used, also the analysis of the main consequences of these experimental facts with respect to the usual potential theories of the magnetization curve of deformed nickel, showing the strong inconsistency between these theories on the one hand and the experimental results, reported in [1] and [2], and certain other important empirical facts on the other. Last not least this dissertation contains a new consistent quantitative theory of the magnetization curve of plastically deformed nickel single crystals of single slip orientation.

The aim of this note is to summarize in a qualitative manner the main statements of that new theory. Its basic assumptions which could be proved by quoting numerous experimental facts as well as by detailed quantitative estimations are the following ones:

I. Among all 180°-domain walls of possible orientations, and with respect to the standard (001) stereographic projection as proposed by STEEDS [3], in nickel single crystals which are oriented for single slip and to some extent plastically deformed, the $(\bar{1}01)$-180°-domain walls are shown to have lowest energy and highest mobility and are therefore clearly dominating. In addition, among all configurations of primary dislocations existing in such crystals and being able to interact remarkably with these dominating $(\bar{1}01)$-180°-domain walls, only the following three types of primary edge dislocation dipole and multipole arrangements with $[\bar{1}01]$-Burgers-vectors, with $[1\bar{2}1]$-line vectors and with the (111)-plane as primary slip plane are of interest because of their strong predominance in stage I of the stress-strain curve, in its transition region and in its stage II, respectively:

1. Primary edge dislocation dipoles and bundles with average numbers of about 6 dipoles per bundle and with mean dimensions of $0.5 \cdot 10^{-4}$ cm in width, about $8 \cdot 10^{-4}$ cm in length and relative to the $(\bar{1}01)$-planes with mean distances of the same order of magnitude as their own length.

2. Rope-like linear structures of primary edge dislocation dipole bundles, about $100 \cdot 10^{-4}$ cm in length which are clustered together along $[1\bar{2}1]$-directions and partially linked by forest dislocations. The average content of dipoles in these structures is about 17 but their mean width again amounts to $0.5 \cdot 10^{-4}$ cm. Relative to the $(\bar{1}01)$-planes their distances are about one order of magnitude smaller than their length, i. e. about $14 \cdot 10^{-4}$ cm.

3. Multipole walls lying in $(\bar{1}01)$-planes and being composed of primary edge dislocations in multipole configuration as well as larger complexes of such multipole walls, having average numbers of about 4 single walls which are polygonized in $(\bar{1}01)$-planes and especially staggered along $[1\bar{2}1]$-directions. At the end of stage II of the stress-strain curve the mean dimensions of the corresponding multipole walls are: about $2 \cdot 10^{-4}$ cm in length of one single wall along $[1\bar{2}1]$, about $8 \cdot 10^{-4}$ cm in length of the average type of fourfold polygonized walls and about $1 \cdot 10^{-4}$ cm to $2 \cdot 10^{-4}$ cm in height parallel to $(\bar{1}01)$-planes and along [111]-directions. They have an average content of up to 30 dipoles per wall and the mean distances of these polygonized multipole walls relative to the $(\bar{1}01)$-planes amount again to the same order of magnitude as their own maximum linear dimensions i. e. about $8 \cdot 10^{-4}$ cm.

I a. The dominating $(\bar{1}01)$-180°-domain walls build up a platelike domain configuration and cross the primary slip planes [the (111)-planes] at right angles and along $[1\bar{2}1]$-traces parallel to the line vectors and

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[2] H. MARKERT, Dissertation, Universität München 1970.

[3] J. W. STEEDS, Proc. Roy. Soc. London A **292**, 343 [1966].

to the maximum linear extensions of the three types of dominating primary edge dislocation arrangements defined above.

II. According to the calculations of PFEFFER [4] and to own estimations [2], the maximum interaction forces between the dominating $(\bar{1}01)$-180°-domain walls and the main three primary edge dislocation dipole and multipole arrangements are *repulsive* and have the following orders of magnitude:

1. $$K_{\text{max.}}^{(\text{I})} \approx 1{,}2 \quad [\text{dyn/cm}]$$

in stage I of the stress-strain curve if the dipole bundles have an average content of 6 dipoles.

2. $$K_{\text{max.}}^{(\text{I}-\text{II})} \approx 3{,}5 \quad [\text{dyn/cm}]$$

in the transition region if the linear arrangements of dipole bundles, clustered together along $[1\bar{2}1]$-lines, have an average content of 17.5 single dipoles.

3. $$K_{\text{max.}}^{(\text{II})} \approx 6 \quad [\text{dyn/cm}]$$

at the end of stage II if each $(\bar{1}01)$-multipole wall is assumed to be composed of 30 single dipoles.

III. From PFEFFER's [4] calculations also a somewhat rough estimation follows for the half width $R_{\text{eff.}}$ of the interaction force between the $(\bar{1}01)$-180°-domain walls and the above defined main three primary dipole or multipole arrangements. As could be shown in [2] for all three types of interacting dipole and multipole arrangements, the half width $R_{\text{eff.}}$ has the same order of magnitude: $R_{\text{eff.}} \approx 0.25 \cdot 10^{-4}$ cm. This is a very small amount compared with the mean distance of the dipole bundles from stage I as well as with that of the linear configurations of rope-likely clustered-together bundles dominating in the transition region, or with that of the single and of the polygonized multipole walls. For this reason and with respect to the data summarized in the above point I, two idealizations seem to be allowed:

1. In the transition region of the stress-strain curve and with respect to the $(\bar{1}01)$-180°-domain walls, the long linear configurations of dipole bundles, clustered together along $[1\bar{2}1]$-traces, may be treated as building up relative to the $(\bar{1}01)$-planes a linear lattice of parallel interaction lines.

2. In a corresponding manner the dipole bundles of stage I and also the polygonized multipole walls of stage II may, with respect to the $(\bar{1}01)$-180°-domain walls, be interpreted as constituting two-dimensional lattices of interaction points.

III a. If, by means of applied magnetic fields, the $(\bar{1}01)$-180°-domain walls will be pushed against these linear or two-dimensional lattices of interaction lines or interaction points, they are shown to vault themselves cylindrically or pillow-shapedly between the bordering repulsive interaction lines or interaction points. The amplitudes of the vaulted domain wall segments could be estimated by minimization of the sum of the energies contributed by the applied magnetic field and by the stray fields of the vaulted segments. At magnetic fields comparable with the coercive force, the orders of magnitude for these amplitudes are about half the domain wall width and nearly not dependent on the rate of deformation.

IV. For the following two reasons the maximum repulsive interaction forces are high enough to enable the $(\bar{1}01)$-180°-domain walls to break away the interaction lines and the interaction points from their anchoring and pinning points in the dislocation network and to shift them, damped by cutting processes with crossing forest and secondary dislocations, to new stronger obstacles:

1. In [2] the anchoring forces of the primary edge dislocation dipole bundles, of the $[1\bar{2}1]$-clusters of these bundles and of the multipole walls are shown to be smaller than the respective maximum interaction forces outlined in the above point II.

2. The mechanism of breaking away the primary dipole and multipole arrangements from their anchoring points as well as the mechanisms of cutting with crossing dislocations are *relaxation processes* which will start within their characteristic relaxation times also if the interacting forces are only very small.

Starting from the basic ideas and definitions outlined above, the main phases of the magnetization processes, taking place along the initial magnetization curve of plastically deformed nickel single crystals of single slip orientation, may, according to the mentioned new theory of the magnetization curve [2], be summarized qualitatively by the following points:

1. At the origin of the initial magnetization curve, the $(\bar{1}01)$-180°-domain walls try to push away the primary interaction lines (the $[1\bar{2}1]$-clusters of dipole bundles) or, in stages I and II auf the stress-strain curve, the interaction points (the dipole bundles or the multipole walls) to the periphery of their interaction zone of half width $R_{\text{eff.}}$. That means: they try to lower their own potential or to "dig themselves in" between the primary dislocation arrangements.

2. In the Rayleigh-region of the initial magnetization curve, the applied magnetic field again pushes the $(\bar{1}01)$-180°-domain walls forward against the interaction lines or interaction points, thereby causing the latter – which on their part will be followed by the domain walls – to move away to new obstacles by means of glide mechanisms which are strongly irreversible mainly because of being damped by the cutting processes mentioned in the above point IV. In this way the $(\bar{1}01)$-180°-domain walls shift the $[1\bar{2}1]$-interaction lines or interaction points foreward, pile them up and start to vault themselves cylindrically or pillow-shapedly between them.

3. At a certain critical starting field – the coercive force H_c – the most suitable dimensioned one of the cylindrical or pilow-shaped domain wall segments may overcome one of its bordering interaction lines or interaction points, say the line with number i. Then it will, together with its neighbouring segment, build up one new segment which, by carrying out the first Barkhausen jump, will vault itself again, but now between the bordering lines $(i+1)$ and $(i-1)$. Therefore the resulting force of the applied magnetic field, acting on

[4] K.-H. PFEFFER, Phys. Stat. Sol. **20**, 395 [1967]; **21**, 837 [1967].

this new segment, also increases and enables it again to overcome its new bordering interaction lines (or interaction points), carrying out a new Barkhausen jump and so on. This so called "catastrophic process" is assumed to be the main mechanism of discontinuous domain wall motion. Obviously it is the origin of the experimentally known cascades of coupled and to more or less extent superposed elementary Barkhausen jumps.

4. Each $(\bar{1}01)$-180°-domain wall is defined by 90°-closure domains, the shape and size of which only may be changed (from equilibrium position) if the energy of their increasing stray fields and magnetostrictive deformations will be supplied. The discontinuous motion of a $(\bar{1}01)$-180°-domain wall, being started at the wall's critical field, stops again when the surplus of the external field force which becomes free during the "catastrophic process" of the vaulted domain wall segments, is compensated by the opposing forces resulting from the increasing stray fields of the closure domains of the discontinuously moving domain wall and from the primary interaction lines or interaction points piled up by it.

5. From the mean distances over which the $(\bar{1}01)$-180°-domain walls move discontinuously by "catastrophic process" and from the time intervals between their starts and stops, surprisingly good estimations of maximum pulse sizes (if all elementary jumps are assumed strongly to superimpose themselves) and time constants of the Barkhausen jumps are possible. But there is still another process, leading also to large resulting Barkhausen jumps: because of the local varying density of the primary $[1\bar{2}1]$-interaction lines and interaction points there exist regions of smaller and of higher density than the mean one. If, in the first case and in external fields $H \geqq H_c$, a $(\bar{1}01)$-180°-domain wall passes through such a region of smaller interaction density, a new "catastrophic process" will be started on it against the same opposing forces as known from the above point 4.; and it will stop again only under the equilibrium conditions also pointed out above. A quite similar situation occurs when the domain wall leaves a region of higher than the mean interaction density. In both cases large cascades of more or less superimposed elementary Barkhausen jumps will be observed.

As has been shown in detail in [2], the above theory leads to surprisingly good *quantitative* estimations of the deformation dependence of the coercivity and of the initial susceptibility of nickel single crystals oriented for single slip as well as to orders of magnitude for the sizes and the time constants of the Barkhausen jumps which agree at all rates of deformation with the experimental data. Furthermore this theory makes possible to understand completely the Jordan type magnetic aftereffect, the Rayleigh hysteresis, effects based on magneto-mechanical coupling processes as those reviewed by BLANK [5] and by CULLITY and ALLEN [6], and last not least it gives a satisfying explanation of all experiments concerning the influence of ultrasonic irradiation on magnetic processes.

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[6] B. D. CULLITY and C. W. ALLEN, Acta Met. **13**, 933 [1965].