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**MAGNETOELASTIC EFFECTS IN NICKEL SINGLE CRYSTALS STUDIED BY
ULTRASONIC ATTENUATION AND VELOCITY**

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Abstract.- Sound attenuation and velocity in nickel single crystals have been studied as function of frequency (10 to 250 MHz), temperature, strength and direction of external magnetic field along $\langle 111 \rangle$, $\langle 110 \rangle$ and $\langle 100 \rangle$, for the three pure wave modes propagating along $\langle 100 \rangle$. The observed effects are found to be specific for each combination of sound mode and field direction, and especially interesting for the field along $\langle 100 \rangle$ which is the hard magnetization direction in Ni. The measured frequency, field, and temperature effects on sound attenuation and velocity can be rationalized in terms of field induced changes of the domain structure.

I - INTRODUCTION

Earlier studies of magnetoelastic damping in nickel single crystals refer to effects of frequency /1-8/, magnetic field /1,3,5-13/ and temperature /8,9,11,13-15/. The frequency dependence (mainly studied between 10-100 MHz) has been explained by micro-eddy currents generated by ultrasound set up by magnetoelastically induced changes of magnetization /1,4,5,7,10,13/. The effect of field strength and direction seems more controversial; the pronounced attenuation peaks observed for some combinations of wave mode and field direction have been attributed to the ferroacoustic resonance /8,9,11,12/, magnetoelastic coupling /5,7/ and to internal stress effects /10/. The decrease in attenuation in zero field with decreasing temperature has been explained by the change in spontaneous magnetization due to the strongly increasing anisotropy energy /16/. The frequency /17-19/, magnetic field /2,18/ and temperature /16/ dependences of wave velocity have also been explained by magnetoelastically induced oscillations of domain walls or magnetic moments inside domains. The present work intends to contribute to the understanding of the magnetoelastic effects in nickel single crystals by combining measurements of field, frequency and temperature dependence of sound attenuation and velocity on a high purity Ni single crystal.

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II - EXPERIMENTAL

Specimen #A (diameter $\phi=14$ mm) was cut from a $\langle 110 \rangle$ oriented high purity nickel single crystal prepared by the Kristall-Labor of the IFF of the KFA Jülich. The specimen was carefully lapped to a planparallelity and flatness of the endsurfaces within 10^{-4} cm/cm and to an accuracy of crystallographic orientation $\langle 110 \rangle$ within 0.3° . After the first part of measurements a smaller specimen #B ($\phi=6$ mm) was trepanated by spark-erosion from sample #A for measurements in a small magnet which was put together with the sample inside a He⁴ cryostat. The attenuation measurements (10-250 MHz) were made by the standard pulse echo technique using a MATEC 6000 system. The pure wave modes with propagation vector $q \parallel [110]$ were used, i.e. the longitudinal wave L, the slow transverse wave T1 (polarization vector $e \parallel [001]$) and the fast transverse wave T2 ($e \parallel [110]$). The sound velocity was measured by the pulse-overlap method. The magnetic field was applied perpendicular to the wave propagation direction $[110]$ and parallel to $[001]$, $[110]$ or $[111]$ which are the hard, medium and easy magnetization direction in Ni. The field direction was accurate within 0.5° (#A) or 2° (#B). The magnetic induction was changed very slowly with a rate of about 15 G/s (#A) or 38 G/s (#B). The measurements of field dependence at different temperatures were performed during cooling with 1 K/min. The field dependence of attenuation was measured after full commutation (magnetization and demagnetization of the specimen repeated with inversion of magnetizing current). The measurements in zero field were carried out after AC demagnetization.

III - RESULTS

The frequency dependence: The logarithmic decrement δ for the longitudinal L and transverse T1 waves (for T2 the attenuation was too high to be measured at $f > 30$ MHz) in demagnetized specimen #A as function of frequency is shown in Fig. 1. Here $\delta = 0.115(\alpha(0, f) - \alpha(B_s, f)) / f$ (MHz); B_s is the induction leading to suppression of magnetoelastic damping.

Figure 1: Frequency dependence of magnetoelastic contribution to logarithmic decrement in demagnetized nickel (specimen #A).

Magnetic field dependence of attenuation: For $H \parallel [111]$ or $[110]$ the attenuation decreased monotonously with increasing fields. In decreasing field slightly lower $\alpha(B)$ values were observed, both reminding on the smooth behaviour of magnetization as function of field ("magnetic hysteresis loop"). However, for $B \parallel [001]$ the wave L (Fig. 2) became strongly attenuated around 4.5 kG, i.e. on approach to magnetic saturation (~ 6.5 kG). The same behaviour was observed for T2. The wave T1 shows less pronounced effect in this B-range (Fig. 3). As seen in Figs. 2 and 3, the attenuation during demagnetization is always higher except for the highest B-values in contrast to $\alpha(B)$ behaviour observed for the other field directions. The attenuation peaks are accompanied by corresponding changes in wave velocity (Fig. 4). The peak position B_p as well as the induction B_s at which $\Delta\alpha = 0$ are independent of frequency.

Fig. 2: Magnetoelastic attenuation of the longitudinal wave as function of magnetic field along [001] (specimen #A).

Fig. 3: Magnetoelastic attenuation of the transverse wave T1 as function of magnetic field along [001] (specimen #A).

Fig. 4: Comparison of magnetic field dependence of wave velocity (open circles for increasing field and closed circles for decreasing field) and attenuation (solid lines) for longitudinal wave (specimen #B). v_s = velocity at magnetoelastic saturation (induction B_s).

Temperature dependence: The effect of temperature on attenuation of specimen #B in different fields is shown in Fig. 5. With decreasing temperature the attenuation peak also decreases and its position B_p shifts towards higher induction values, and B_s , the induction needed for ultrasonic saturation, increases considerably. As Fig. 6 shows, the temperature dependence of the peak height $\Delta\delta_p$ comes out to be very close to the temperature dependence of $1/K_1$ where K_1 is the magnetoelastic anisotropy constant /15/. Furthermore, as Fig. 7 shows $\Delta\delta_p$ is proportional to $1/B_p$, i.e. the peak induction.

Fig. 5: Magnetoelastic attenuation of the longitudinal wave as function of magnetic induction in specimen #B measured at different temperatures.

Fig. 6: Temperature dependence of the attenuation peak height in Fig. 5 (open circles) and of the anisotropy constant K_1 (closed circles) /15/.

Fig. 7: Peak height $\Delta\delta_p$ in Fig. 5 as function of peak position B_p .

IV - DISCUSSION

It is generally assumed [1,20-23] that an ultrasonic wave in the present frequency range induces by magnetoelastic coupling two relaxation processes: oscillation of domain walls and periodic rotation of magnetization vectors inside the domains. The relaxation frequency of the former process does not exceed 1 MHz [20,21]. For sound wavelengths λ comparable or larger than the domain size D the rotation of magnetization is coherent, with a relaxation frequency between 0.1 and 10 MHz [20,21]. Thus both relaxation processes are likely to cause the observed $\alpha(f)$ behaviour at low frequencies (Fig. 1, wave L). For $D > \lambda$ or high frequencies the incoherent rotation of magnetization in the domains takes place with a correspondingly high relaxation frequency. We assume that this process gives rise to the increase in $\alpha(f)$ behaviour for the wave L at high frequencies (Fig. 1). The more complicated $\alpha(f)$ behaviour for the wave T1 reflects magnetoelastic coupling to walls and domains considerably different from those "seen" by the wave L.

In the course of magnetization, at low fields first energetically unfavourable 180° domain walls, then at slightly increased fields 71° and 109° walls move out of the sample, i.e. growth of domains with most favourable field energy but still with magnetization along the $\langle 111 \rangle$ easy magnetization directions takes place. In a single crystal it is the direction of the external magnetic field with respect to sample orientation which determines the sequence of magnetization processes (if influences of internal strain and sample shape are neglectable). In still increasing fields finally the magnetization is rotated out of $\langle 111 \rangle$ towards the external field direction. We believe that fields of sufficient strength for complete rotation into the field direction have not been applied during the present experiments. Since the magnetoelastic attenuation is caused by magnetostrictively induced oscillation of domain walls and magnetization (both damped by induced micro-eddy currents), the disappearance of domain walls results in the generally observed decrease in the attenuation. However, for special field directions, in the present case for $H \parallel [001]$, the attenuation increases with field up to the sharp maximum at the induction B_p , at which the rotation of magnetization towards the external H direction just commences. Since B_p is observed to be independent of frequency, the peak cannot be associated with ferroacoustic resonance.

The presently observed $\alpha(B)$ -peak (Figs. 2-5) can be rationalized if we assume that with increasing field the four domain magnetization directions $[111]$, $[\bar{1}\bar{1}1]$, $[\bar{1}1\bar{1}]$ and $[1\bar{1}\bar{1}]$ with components along and symmetric about the $[001]$ field direction remain populated and that correspondingly two different 109° and four different 71° Bloch walls exist. The wave L along $[110]$ only couples to the $[111]$ and $[\bar{1}\bar{1}1]$ magnetizations which leads to the conclusion that the 71° walls are responsible for the $\alpha(B)$ -peak. The step decrease of α at $B > B_p$ is attributed to immobilization of these walls as the magnetization is forced towards $[001]$. Dietz [7] has shown earlier that for the present combination of wave mode and field direction (as well as for other combinations not presently studied) the magnetoelastic coupling considerably increases with increasing external field in the course of the magnetization.

The observed change in wave velocity with field (Fig. 4) represents a magnetoelastic modulus defect (ΔE -effect) which also reflects the changes in magnetization, e.g. domain wall motion. The fact that the observed velocity behaviour exactly corresponds to the $\alpha(B)$ behaviour additionally confirms our conclusion that the $\alpha(B)$ -peaks are caused by domain wall motion.

Furthermore, the temperature dependence of attenuation in unmagnetized and magnetized nickel can be explained in terms of domain wall effects. The magnetoelastic damping by domain wall movement is approximately inversely proportional to the 1st order magnetocrystalline anisotropy constant K_1 which considerably increases with decreasing temperature [15]. This explains the decrease in peak height with decreasing temperature as well as $\alpha(T)$ at zero field (Figs. 5 and 6). The shift of the attenuation peak towards higher induction values (Figs. 5 and 7) points to a loss of wall mobility with decreasing T , i.e. increasing K_1 , in accordance e.g. with other results [9-11], e.g. the wellknown decrease of the permeability of Ni.

V - CONCLUSIONS

The present results can be explained by phenomena described by the domain wall damping theory. The frequency dependence of attenuation in unmagnetized nickel originates from the oscillation of domain walls and from the rotation of magnetization vectors, in part incoherent at higher frequency, all damped by micro-eddy currents. The field dependence of attenuation and velocity in a magnetic field along the hard magnetization direction shows a pronounced damping peak and modulus defect that for special combinations of wave mode and field direction is caused by strong magnetoelastic coupling to the wall configuration occurring during rearrangement of the domain structure in the course of magnetization. The temperature dependence of damping in unmagnetized and magnetized Ni as well as the influence of temperature on the height of the damping peak and the induction at which the peak is observed are explained by the temperature dependence of the anisotropy constant K_1 via its influence on domain structure and wall mobility.

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