Magnetostatic Critical Point Phenomena of Single Crystalline Ni

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The magnetostatic critical point phenomena of a single crystalline Ni (fcc) were first investigated using a computer controlled vibrating sample magnetometer in the uniformly applied bipolar fields from 0 to ± 8 kOe. The magnetization M was measured along both of the easy axis [111] and hard axis [100]. A clear kink point locus was observed for the whole critical region in the extremely low fields measurement and the spontaneous magnetization and the critical point were directly obtained without data reduction for both easy and hard axes. The critical indices for the easy axis and hard axis were obtained to be $\beta=0.385 \pm 0.002$ and 0.426 ± 0.003 , $\gamma=1.302 \pm 0.003$ and 1.19 ± 0.01 , and $\delta=4.27 \pm 0.01$ and 3.80 ± 0.01 , respectively. The effect of the magnetocrystalline anisotropy on the critical indices is first found to be significantly large and not negligible in Ni. It was clearly shown that the Griffith's inequality is valid and the scaling law for the critical indices fails, and that all of the measured data for easy axis support the existence of the equation of states $\Psi(H, M)$ but does not for the low field data at hard axis.

Key words: magnetostatic critical point phenomena, critical indices, magnetization, Ni single crystal, magnetocrystalline anisotropy

1. Introduction

The magnetostatic critical point phenomena are theoretically well defined for the spins in zero-magnetic field. Thus the experimental work in zero-field takes an indispensable role to check the validity of the theoretical model. In most cases of the previous experimental works, the extrapolation to the zero field were engaged to estimate the zero-field values, the critical temperature T_c , the spontaneous magnetization $M_0(T)$ and the initial susceptibility $\chi_0(T)$. We pointed out in our recent work¹⁾ that the critical indices obtained on the Arrott plot using extrapolation of the high field data are reduced to the predicted result of the molecular field theory.

One of present authors (K.M) first succeeded to obtain the zero-field magnetization on the kink-point locus from the magnetization measurements in the extremely low applied fields using a vibrating sample magnetometer (VSM).^{2,3)} It was shown that the magnetically homogeneous single crystalline YIG shows the clear critical phenomena, and the magnetic inhomogeneity and anisotropy are expected to influence seriously on the

experimental results. At present, the effect of the magnetocrystalline anisotropy on the critical point phenomena is not quantitatively understood yet, and the frequently referred data on polycrystalline Ni by Kouvel et al⁴⁾ are needed to re-evaluate the application limit.

In this paper, we first report the whole view of magnetostatic critical point phenomena of a single crystalline Ni, and discuss about the effect of the magnetocrystalline anisotropy.

2. Sample and experimental procedure

A single crystalline Ni sphere sample ($OD=3.751 \pm 0.005$ mm) with a polished surface was obtained from a Ni single crystal ingot (99.9% in purity) grown by a Bridgmann method using an aluminum crucible. The sphere sample was annealed in vacuum at 1273K for 2 hours before the measurement.

The magnetization was measured along an easy axis [111] and also along a hard axis [100] using a computer controlled vibrating sample magnetometer. A Chromel-Almelth thermocouple was directly contacted with the sample surface to measure the sample temperature. The size of blank magnetization for the sample holder and the thermocouple was less than one part of 10^{-4} compared with that for the Ni sample. The experimental procedure and the data handling method were followed our recent work.⁵⁾

3. Results and discussion

The magnetization curves along the easy and hard axis of Ni single crystal were measured at 300K. The magnetocrystalline anisotropy energy between them is estimated to be 2.5×10^4 erg/cm³ which shows a reasonable agreement with the previously reported value 5×10^4 erg/cm³.

The constant field magnetizations along the easy axis and hard axis were measured in detail from $H_a=0$ Oe to ± 8 kOe at the temperatures between 621.15 to 641.15 K. Figure 1 shows the measured results along the easy axis, where the sharp kink points are clearly observed as a locus on the curves. The kink point directly corresponds to the zero-field spontaneous magnetization $M_0(T)$. The constant field magnetization along the hard axis also showed similar curves and the clear kink points were also observed. The Curie temperature was estimated to be $T_c^K=630.50 \pm 0.05$ K from the kink point locus.

The magnetization isotherm, $M^2(H_{eff}T)$ vs $H_{eff}/M(H_{eff}T)$ plot, for the measured data M along the easy axis is shown in Fig.2. The effective field H_{eff} was given by $H_{eff} = H_a - 4\pi nM$, and the demagnetization factor n was obtained to be 0.332 from the magnetization measurement along the easy axis at 600K. Analogous type of the magnetization isotherm pattern was also obtained for the hard axis. The temperature dependence of the zero-field magnetization $M_0(T)$ and the zero-field inverse susceptibility $\chi_0^{-1}(T)$ were directly read on the $M^2(H_{eff}T)$ and $H_{eff}/M(H_{eff}T)$ axes, respectively, and are shown in Fig.3.

The Curie temperature T_c^z , defined as an infinitive divergent point of $\chi_0(T)$, was assumed to be 630.46 ± 0.02 K from the T^* vs T plot⁶⁾ where $T^* = \chi_0^{-1}(T)/(\partial\chi_0^{-1}(T)/\partial T)$. This value is confirmed to be the same as T_c^K within the experimental error. Thus the critical temperature was obtained to be $T_c = 630.46$ K. The critical indices were determined by the same way for the easy axis and the hard axis, and were obtained to be $\beta = 0.385 \pm 0.002$ and 0.426 ± 0.003 for $\epsilon = 1 \times 10^{-3} - 2 \times 10^{-2}$, $\gamma = 1.302 \pm 0.003$ and 1.19 ± 0.01 for $\epsilon = 3 \times 10^{-4} - 2 \times 10^{-2}$, and $\delta = 4.27 \pm 0.01$ and 3.80 ± 0.01 , defined as $M_0(T) = \epsilon^\beta$, $\chi_0^{-1} = \epsilon^\gamma$ for $\epsilon = T - T_c/T_c$, and $M_0(H_{eff}T_c) = H_{eff}^{1/\delta}$, respectively.

Fig.1 The temperature dependence of the constant field magnetization along the easy axis at near the critical temperature.

Fig.2 Data of Fig.1 plotted as isotherms as $M^2(H_{eff}T)$ vs $H_{eff}/M(H_{eff}T)$.

Fig.3 The temperature dependence of the zero-field spontaneous magnetization M_0 and the zero-field inverse susceptibility χ_0^{-1} for the easy axis.

Table 1 Critical indices of Ni.

Experimenters	Ref.	β	γ	δ	comments
Present work	-	0.385 ± 0.002	1.302 ± 0.003	4.27 ± 0.01	easy axis
Present work	-	0.426 ± 0.003	1.19 ± 0.01	3.80 ± 0.01	hard axis
Tanaka, Miyatani	5)	0.389 ± 0.005	1.270 ± 0.005	4.19 ± 0.05	polycrystalline
Kouvel, Comly	4)	0.378 ± 0.004	1.34 ± 0.01	4.58 ± 0.1	polycrystalline
Arrott, Noakes	7)	0.3864	1.31 ± 0.01	4.39 ± 0.02	single crystal*

* The measured direction was not specified.

Fig.4 $H_{eff}/M\epsilon'$ vs $M\epsilon^b$ plot of M for the easy axis data for using $T_c=630.46K$ in the temperature range from 621.15 to 641.15K.

These critical indices are listed in Table 1 with those of the previously reported values. The values for the easy axis show a relatively good agreement with those reported for the single crystalline Ni which measured in applied field $H_a=500$ Oe to 800 Oe by Arrott and Noakes⁷⁾, while show an apparent mismatch with Kouvel's data.⁴⁾ In the case for the hard axis, β becomes larger by about 10%, γ and δ smaller by 9% and 11%, respectively. It is first shown that the critical indices have the different values between the easy axis and the hard axis. The effect of the magnetocrystalline anisotropy on the critical indices for the hard axis is thus found to be significantly large and not negligible even in Ni which has a relatively small magnetocrystalline anisotropy in ferromagnetic metals. The critical indices obtained from the polycrystalline sample are thus affected by the magnetocrystalline anisotropy. The previously reported values of the critical indices on polycrystalline Ni are scattered approximately

between the values for the easy axis and for the hard axis as listed in Table 1.

We checked the validity of the scaling law and the existence of the universal critical equation of state $\Psi(M,H)$ for second-order phase transition using the data. The value of $\beta(\delta-1)$ is 1.26 for easy axis and 1.19 for hard axis. Thus the Griffith's inequality,⁸⁾ $\gamma \geq \beta(\delta-1)$, is valid and the scaling law, $\gamma = \beta(\delta-1)$ fails for both easy and hard axis data. The all of the magnetization data for the easy axis are plotted in the form of $H_{eff}/(M(T)\epsilon')$ vs $M(T)/\epsilon^b$ in Fig.4. The magnetization below and above T_c clearly fall on the two separate curves, respectively. Contrarily, only the high field data gave the same function $\Psi(M,H)$ for the hard axis data, and the low field data measured at less than 200 Oe shifted to the low magnetization side from the $\Psi(M,H)$, because the magnetocrystalline anisotropy reduced the magnetization near the kink-point at the low magnetic field. These facts suggest the existence of the universal critical equation of state $\Psi(M,H)$ except for the low field data of the hard axis. The form of the function $\Psi(M,H)$ shows a similar function as that for Fe.⁹⁾

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