Study on the Complex Permeability of NiCuZn Ferrites

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Abstract—The dispersion phenomena of spinel ferrite due to relaxation can be observed at some frequency range, and this is related with the ferrite composition and their initial permeability. In this work, the Cole-Cole plots for NiCuZn ferrites are presented to describe its relaxation process with $\mu'$ versus $\mu''$ spectrum. It is found that the relaxation process with a semi-circle curve of complex permeability is characterized by the magnitude of initial permeability.

I. INTRODUCTION

The low-loss polycrystalline spinel ferrites should be used in a high frequency range for the good performance in applications and classified by the initial permeability. The real part of permeability $\mu'$ decreases with the frequency and the imaginary part $\mu''$ exhibits a broad peak, which is related with the relaxation phenomena.

The characterization of NiCuZn ferrites with frequency dependence of initial permeability gives the way to classify the ferrite composition to applications. In this paper, we are proposing by which the variation of initial permeability and complex permeability of NiCuZn ferrites with addition of Co$_3$O$_4$ may be investigated the loss characteristics of those materials.

II. EXPERIMENT

NiCuZn ferrites were prepared by the conventional ceramic process with each metal oxides as starting materials. The mixture of raw materials were pulverized in a ball-mill for 40 h and calcined at 750°C for 2 h to obtain spinel phase. The calcined powder was formed in a toroidal green body and the toroidal sample was fired at 900°C for 5 h. The initial permeability was calculated from the measured inductances at 100 kHz and the complex permeability at 1~100 MHz using HP 4195A Network Analyzer. The magnetic flux density was measured by B-H Loop Tracer AMH5020. The anisotropy field $H_A$ is calculated from the measured parameters.

III. RESULTS AND DISCUSSION

A. Relaxation Phenomena of the NiCuZn Ferrites

The $\mu'$ decreases with increasing the frequency and the $\mu''$ goes through a broad resonance. The phase difference between the applied field and magnetization of the ferrite occurs due to the damping phenomena. If there is no damping in magnetization process, $\mu''$ is zero for all frequencies, except at the resonance frequency, and then $\mu''$ becomes infinitely large [1-3]. Magnetic relaxations appear as a decrease of $\mu'$ with increasing frequency, while $\mu''$ has a maximum near the relaxation frequency $f_{rx}$.

Fig. 1 is the Cole-Cole plot for the curves of complex permeability of (Ni$_{0.8}$Cu$_0.2$Zn$_{0.8}$O)$_{0.995}$(Fe$_2$O$_3$)$_{0.005}$ (x=0.15~0.25) [4]. The Cole-Cole plots of $\mu'$ versus $\mu''$ shows some semi-circle shaped curves, which means the relaxation dispersion. But there are some differences in the shape of curves comparing to the normalized curve of complex permeability [3]. The NiCuZn ferrites or other spinel ferrites in applications show relaxation phenomena as increasing the frequency owing to the damping in magnetization process. The Cole-Cole plot for x=0.15 shows an small ellipsoidal curve as shown in Fig. 1, which gives the narrower peak of complex permeability than that of other two composition, x=0.2 and x=0.25. This provides another method of representation to identify the relaxation phenomena for various ferrites.

Fig. 2 show the relation between $\mu'$ and $\mu''$ for (Ni$_x$Cu$_0.2$Zn$_{0.8-\gamma}$O)$_{1.015}$(Fe$_2$O$_3$)$_{0.985}$($\gamma=0.15$~
0.25) ferrites. In general, the saturation magnetization increases linearly with the zinc content until all divalent magnetic ions are replaced by zinc ions[3,5]. In other words, for the smaller Ni content, the saturation magnetization decreases due to the exchange interaction. The difference in magnitude of $\mu$ represents the various Cole-Cole plots of $\mu'$ versus $\mu''$ with frequency.

Fig. 3 shows the results for (Ni$_{0.2}$Cu$_{0.2}$Zn$_{0.8}$O)$_{1-w}$(Fe$_2$O$_3$)$_{1+w}$ (w=0-0.02) ferrites. The sintered NiCuZn ferrite of w=0 have a low initial permeability because the composition of Fe$_2$O$_3$ is not so deficient as having the high density after firing at a low temperature[6,7]. But the relation between $\mu'$ and $\mu''$ as a function of frequency which means its relaxation process for these Fe$_2$O$_3$ deficient NiCuZn ferrite seems to be insensitive to the Fe$_2$O$_3$ deficiency(w). It can be seen that the $f_{\text{r}}$ of Fe$_2$O$_3$ deficient NiCuZn ferrite shows a little change for the various w values because the control of each Fe$_2$O$_3$ deficiency(w) is an important factor to improve the sintering properties[6].

The relaxation time $\tau$ and anisotropy field $H_A$ are expressed as follows[3,5]:

$$\tau = \frac{1}{2\pi f_{\text{r}}}$$

$$\mu' - 1 = \frac{2}{4\pi} \left( \frac{M_s}{H_A} \right)$$

where $M_s$ is the saturation magnetization, $f_{\text{r}}$ is the relaxation frequency of $f\mu''_{\text{max}}$.

As shown in Fig. 4, it is found that the relaxation time is nearly proportional to the initial permeability. This means that the magnitude of initial permeability is crucial to classify the relaxation process in application of NiCuZn ferrites at high frequencies. The relation between relaxation time and anisotropy field is shown in Fig. 4 as a description for frequency dependence of NiCuZn ferrites. Since the initial permeability becomes smaller, at the same time the coercive force also becomes larger[3], so that the anisotropy field increases as decreasing the initial permeability. As $H_A$ increases, the peak width of $\mu''$ curve becomes narrower, and one can find the frequency of maximum $\mu''$ at higher frequencies.

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B. Effect of Composition of NiCuZn Ferrites on the Variation of Complex Permeability

The peak width of imaginary part of permeability presents a dispersion of magnetic relaxation with frequency. Fig. 5 shows the variation of complex permeability of \((\text{Ni},\text{Cu},\text{Zn})_0.8\text{O}_1\cdot w(\text{Fe}_2\text{O}_3)_{1+w}\) ferrites. The peak of imaginary permeability becomes narrower with increasing of Ni content, which is due to the jump of magnetostriction constant. Fig. 5 shows another features from these results that the relaxation frequency \(f_{\text{r}}(\mu''_{\text{max}})\) is shift to higher frequency range with increasing of Ni content in NiCuZn ferrites.

The complex permeabilities of \((\text{Ni},\text{Cu},\text{Zn})_0.8\text{O}_1\cdot w(\text{Fe}_2\text{O}_3)_{1+w}\) ferrites with addition of \text{Co}_3\text{O}_4 (in wt.%) are shown in Fig. 6. It is shown that the \(f_{\text{r}}\) of cobalt-contained NiCuZn ferrites becomes higher than that of some cobalt-free ferrites. The substitution of cobalt ions in NiCuZn ferrites leads to an increase of \(f_{\text{r}}\). This improvement is attributed to domain wall stabilization and reduces the high-frequency losses, which is related with the increasing of magnetic induced anisotropy by substitution of cobalt ions[5,8]. The relation between \(\mu'\) and \(\mu''\) for variable frequencies in above results represents the variation of relaxation process as increasing the cobalt content.

IV. Conclusion

The Cole-Cole plots of complex permeability determined in the NiCuZn ferrites can effectively explains the magnetic relaxation process which is related with the anisotropy field. The resulting frequency dependence of complex permeability for various NiCuZn ferrites can be classified with initial permeability. The complex permeability for NiCuZn ferrites can be presented as a form of a semi-circle, so called the Cole-Cole plot. The relaxation time \(\tau\) is calculated from magnetic relaxation frequency \(f_{\text{r}}\), where \(\mu''\) is maximum. The primary emphasis of these Cole-Cole plots will be on the identification for frequency dependence of complex permeability with the relations between anisotropy field \(H_A\) and relaxation time \(\tau\), initial permeability \(\mu_1\) and \(H_A\). The results gives a better insight into understanding of the different characteristics of NiCuZn ferrites for the high-frequency in applications.

A brief description can be given in another characterization for the complex permeability of

\[\text{NiCuZn ferrites} + \text{ addition of \text{Co}_3\text{O}_4}\]

and with addition of \text{Co}_3\text{O}_4. It is shown that the NiCuZn ferrites with \(y \geq 0.6\) have a relatively small peak width of the imaginary part of permeability \(\mu''\). The resonance frequency is most sensitively dependent on the variation of Ni content. The \(\mu''\) value decreased with increasing of \text{Fe}_3\text{O}_3 deficiency, but the resonance frequency(\(f_{\mu''_{\text{max}}}\)) was almost insensitive to \text{Fe}_3\text{O}_3 deficiency. The addition of \text{Co}_3\text{O}_4 makes the \(f_{\mu''_{\text{max}}}\) increase and initial permeability decrease. It can be concluded that the Ni content in the NiCuZn ferrite is a dominant factor for the total loss of these spinel ferrites.

Reference