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Electromagnetic Properties of Soft Ferrites and Development of New Type of Low-Power Loss Ferrite

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Abstract:

A new type of low-power loss ferrite, designated M36, was developed to meet the demand for more efficient power supplies for electronic equipment which are in the midst of transition to personal and portable uses. This paper describes the difference in magnetization mechanism of ferrite cores according to magnetic flux density, variations in physical properties of ferrite cores with the control of ionic configuration according to the nonstoichiometric oxidation degree, and an on-circuit test method that can faithfully simulate the actual service conditions of ferrite cores. The on-circuit test found that M36 is more than 20 % lower in power loss than the best soft ferrites available on the market, which translates into a temperature difference of over 10°C.

1. Introduction

The year 1993 is the quincentenary of the discovery of the New World by Christopher Columbus. He would have been unable to make his navigation and discovery without a magnetic compass. Magnetite (Fe_3O_4), the simplest form of ferrite, is said to be the first material that taught mankind about magnetism. It had already been known as lodestone in China about 3,500 years ago. Lodestone was called magnes lapis, which was the origin of the word "magnet"[1].

Research on ferrite materials was started in the late 19th century, and the term "ferrite" was first used at the beginning of the 20th century. A ferrite produced by sintering and solution treatment and featuring properties close to those of today's ferrites was invented by Kato et al. in 1930, and research data on ferrites were theoretically compiled by J.L. Snoek et al.[2] The theory of ferrimagnetism by L. Neel played a major role in the systematization of ferrite technology. (He was awarded the Nobel Prize for Physics in 1970.)

Simply speaking, ferrite is a crystalline material predominantly composed of magnetic iron oxide. Ferrites can be broadly classified into soft ferrites (soft magnetic materials) and hard ferrites (hard magnetic materials). Soft magnetic materials exhibit magnetism only when they are exposed to a magnetic field, while hard magnetic materials retain magnetism when they are removed from a magnetic field. For example, the magnetic heads of a tape deck are made of magnetically soft material, and the tape is made of magnetically hard material.

This paper focuses on soft ferrites for power transformers that are indispensable devices for electronics technology, describes their electromagnetic properties and the factors governing these properties, and reports on a newly developed low-power loss soft ferrite.

2. Present Situation of Soft Ferrites

The production of soft ferrites rapidly grew with the progress of the electronics industry that started in the 1960s. Particularly noteworthy is the recent rapid increase in the production of soft ferrites (see **Photo 1(c)**) used in transformers for switching regulators (SWRs) (see **Photo 1(b)**). SWRs were developed by the National Aeronautics and Space Administration (NASA) of the United States in the 1950s as small and lightweight power supplies to be mounted on rockets. They are widely used now as power supplies for semiconductor devices in office automation (OA) and other electronic equipment.

Contributing greatly to the size reduction of power supplies

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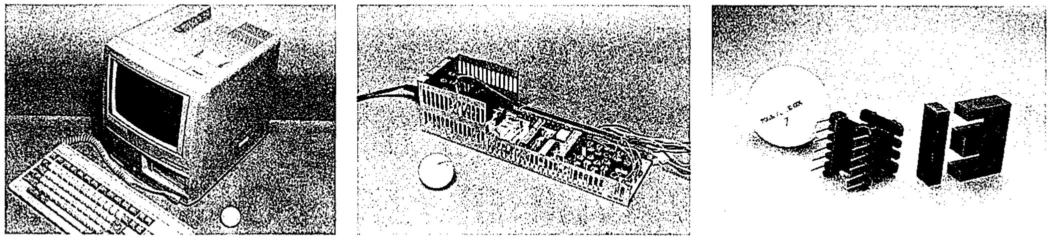

(a) (b) (c)

Photo 1 Soft ferrites used in switching regulators (SWRs)

Switching regulators (b) used in electronic equipment such as personal computers (a) are small-sized and lightweight, for transformers and such in which soft ferrites (c) are used.

is the miniaturization of transformers, which in turn is attributable to the use of power ferrites to simultaneously satisfy the requirements for higher frequency and higher efficiency. An operating frequency of normally 20 kHz, which is higher than 10^3 times the commercial frequencies of 50 to 60 Hz, is obtained, thanks to the high electric resistivity of soft ferrites that is at least 10^7 times greater than that of metals such as silicon steel, as shown in **Table 1**.

2.1 Applications of soft ferrites

Soft ferrites, compared with magnetic metals, have such advantages as high electric resistivity, excellent magnetic properties in the high-frequency region, and superior corrosion resistance, but also such disadvantages as low saturation magnetic flux density, low Curie point, and inferior mechanical properties. Being sintered compacts, however, soft ferrites can be easily fabricated into various complex shapes, by virtue of which they have firmly established themselves as magnetically soft materials.

The application of soft ferrites may be divided into two main fields as shown in **Fig. 1**. One is the field where high permeability and low power loss are required as represented by Mn-Zn and Ni-Zn ferrites with less than 300 MHz, while the other is the microwave region of 300 MHz or higher where magnetic resonance is involved. Mn-Zn ferrites are used in a frequency region of several megahertz or less as transformers for SWRs, flyback transformers and deflection yokes for television, and communicating coils. Ni-Zn ferrites, on the other hand, are used in such applications as rotary transformers at frequencies higher than for Mn-Zn ferrites, and as intermediate-frequency transformers and coils. Recently, soft ferrites have found new use in such applications as developers with electronic copying machines for office use, acceleration cores for synchrotron radiation and free electron lasers where high-current and high-frequency pulses are used, and electromagnetic noise shields.

Soft ferrites constitute a market of about 100 billion yen (including magnetic heads and noise shields). Transformers for

Table 1 Typical soft magnetic metals and oxides

Material	Chemical formula	Structure	Saturation magnetic flux density B_s (mT)	Electric resistivity ρ (Ωm)
Iron	Fe	bcc	2150	10×10^{-8}
Silicon steel	Fe-Si	bcc	2000	50×10^{-8}
Mn-Zn ferrite	$Mn_{1-x}Zn_xFe_2O_4$	Spinel (fcc)	400-500	1-10
Ni-Zn ferrite	$Ni_{1-x}Zn_xFe_2O_4$	Spinel (fcc)	300-400	10^4
Y-Fe garnet	$Y_3Fe_5O_{12}$	Garnet (fcc)	175	10^8-10^{10}

SWRs, and flyback transformers and deflection yokes for television account for about 30% of the market. In recent years, the soft ferrite market has rapidly grown with increasing SWR production, registering an annual growth rate of more than 10% from 1989 to 1991. With the absence of materials that are likely to replace such soft ferrites as a high-frequency magnetic material, the market is expected to steadily grow in the future as well.

2.2 Problems with soft ferrites

Among the main development issues of Mn-Zn soft ferrites are: 1) increase in efficiency (decrease in power loss); 2) increase in frequency; and 3) improvement in physical properties such as saturation magnetic flux density and permeability. Although the property requirements vary according to application, the properties 1) and 2) mentioned above are particularly important for power ferrites for the SWRs. When power ferrites are used for coils and transformers, their power loss comes forth as heat and affects the surrounding circuit elements. For this reason, power supply manufacturers and other users strongly call for reduction in the power loss of soft ferrites. In addition the size reduction of SWRs is increasingly called for by decreasing size and weight of

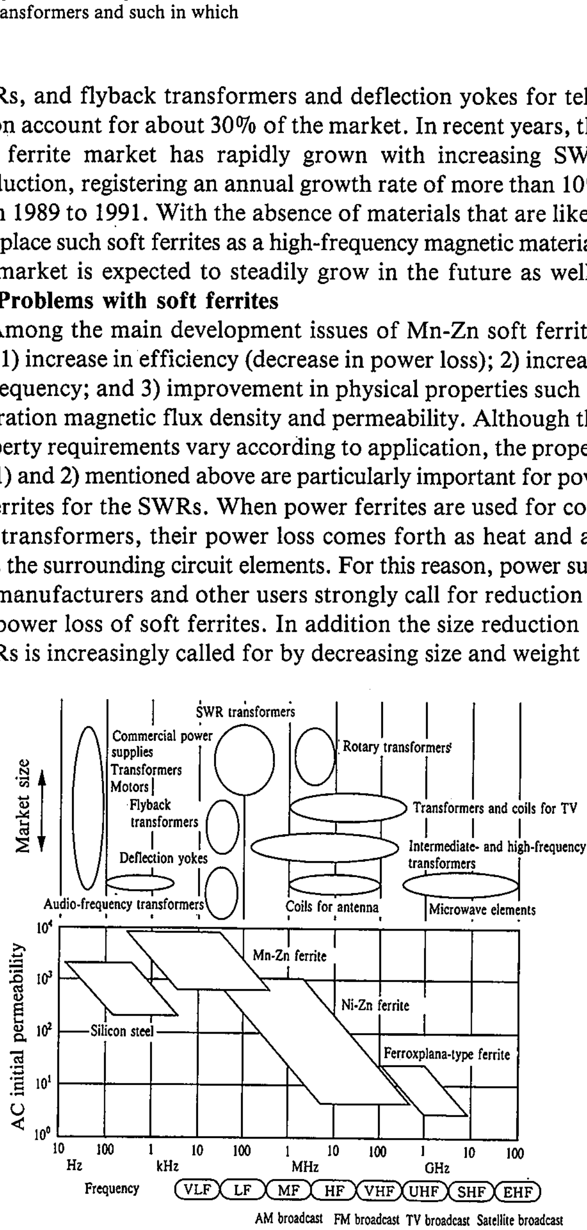

Fig. 1 Applications of soft ferrite and its approximate market size

Soft ferrites have a market of about 100 billion yen p.a., and are for various uses. Soft ferrites have a high electric resistivity and are used at frequencies higher than the ones for silicon steel. Vertical and horizontal dimensions of ovals shown in the upper graph indicate the market size and the frequency band of soft ferrites, respectively.

electronic equipment as seen in laptop and notebook personal computers. This miniaturization can be achieved only by increasing both the efficiency and frequency of switching operations, as shown in **Fig. 2**[3)].

3. New Type of Low-Power Loss Soft Ferrite M36

A new type of low-power loss soft ferrite, called M36, was developed to satisfy both the frequency and efficiency requirements at the same time. The development concepts of M36 were a wide frequency range from 100 kHz, which used to be the main excitation frequency for high-frequency power ferrites in the industry, to 500 kHz; lower power loss than the best soft ferrites available on the market and, in particular, less ferrite core heat generation which produces important marketing value of ferrite cores for users. In the realization of these concepts, new methods were established; namely, 1) optimally controlling the ionic distribution of the ferrite core; 2) optimizing both grain-boundary electrical resistivity and intragranular electrical resistivity for high-frequency service; and 3) establishing a more adequate method for evaluating the amount of heat generation, which becomes the main subject when the soft ferrite is mounted in circuitry. The ionic distribution and grain-boundary electrical resistivity and intragranular electrical resistivity were optimized by applying a non-stoichiometric oxidation degree (γ) as an index.

As a result, as shown in **Fig. 3**, M36 marked a power loss of $350\ kW/m^3$ at the excitation frequency of 100 kHz, operating magnetic flux density of 200 mT and temperature of 80°C, which is at least 20% lower than that of the best soft ferrite available on the market. Even at the high frequency of 500 kHz, M36 registers a power loss of $150\ kW/m^3$ at the operating magnetic flux density of 50 mT and temperature of 80°C. Thus, M36 provides excellent properties over a wider switching frequency range compared with the conventional soft ferrites. Further, in the evaluation of heat generation in the as-mounted condition, M36 exhibits superior heat generation characteristics surpassing those of the best soft ferrites available on the market, as shown in **Fig. 4**. Particularly at the excitation frequency of 500 kHz, M36 achieves a heat generation difference of more than 10°C.

When translated into a corresponding SWR internal temperature difference, this heat generation difference represents a service life about twice as long as that of electrolytic capacitors having low heat resistance. M36 is expected to enable SWRs to attain higher reliability and reduce its size. It can be mass produced in various core shapes of commercial value on an integrated production line.

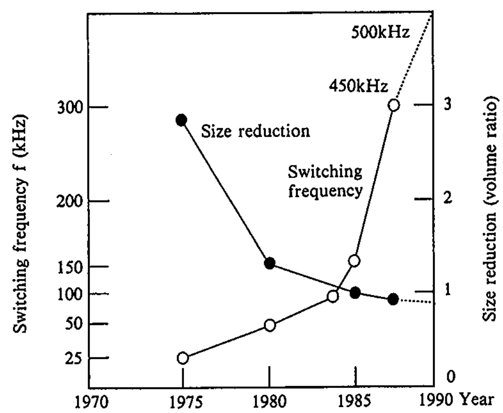

Fig. 2 Down-sizing of switching regulator and switching frequency[3)]
Increase in efficiency (decrease in power loss) and increase in frequency of soft ferrites are indispensable for reducing the size of switching regulators.

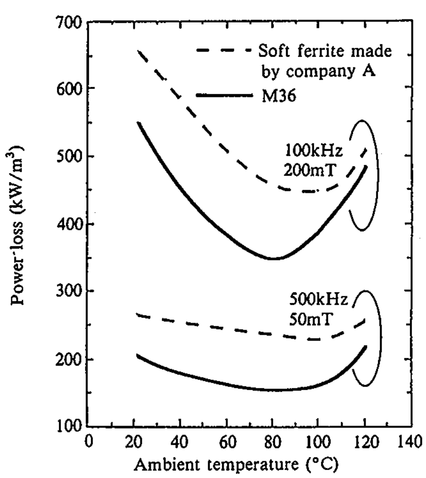

Fig. 3 Comparison in power loss of new soft ferrite M36 with best soft ferrite available on market

4. Research on Electromagnetic Properties of Soft Ferrites

The new low-power loss soft ferrite M36 was manufactured according to the above-mentioned development concepts and on the basis of various research results, namely, analysis of magnetization mechanism of the ferrite core with respect to excitation frequency, introduction of optimum ionic distribution control in the ferrite core and evaluation of heat generation in the ferrite core, taking into account the actual service conditions. These research results are described in detail below.

4.1 Magnetization mechanism of ferrites

One of the focuses in developing the new low-power loss soft ferrite M36 was to clarify the effects of excitation conditions such as frequency and morphological structure such as grain size on magnetic properties such as power loss. Research on the magnetization mechanism was essential in linking these factors.

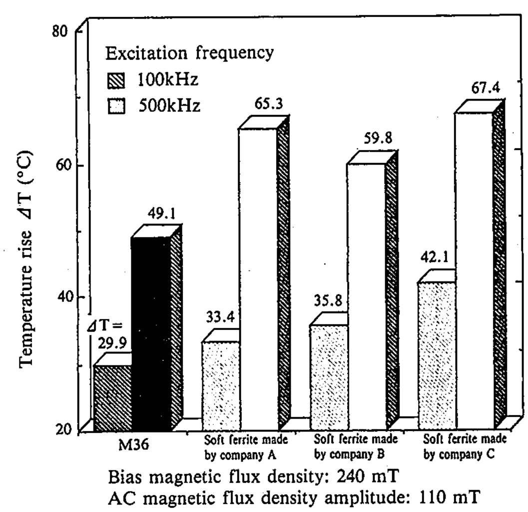

Fig. 4 Evaluation of heat generation of new soft ferrite M36 as mounted on equipment, as compared with best soft ferrites available on market
M36 exhibits excellent heat generation characteristics over a wide frequency range from 100 to 500 kHz. Particularly at the frequency of 500 kHz, its temperature difference of heat generation from commercial soft ferrites is more than 10°C.

Magnetization is a phenomenon that the direction of magnetic moments in a material is changed by the external magnetic field. The magnetic moments in the case of Mn-Zn ferrite are assumed by the 3d shell electron spin magnetic moments of Mn and Fe ions. These magnetic moments are oriented in the parallel and antiparallel directions by superexchange interaction through oxygen ions. Since the parallel and antiparallel magnetic moments are not equal in number, the ferrite is magnetized as bulk, which is called ferrimagnetism.

As shown in **Fig. 5**, a hysteresis loop is drawn when the changes in the external magnetic field H are plotted along the horizontal axis against the resultant changes in the magnetic flux density B along the vertical axis. Generally speaking, magnetic materials may be magnetized by two mechanisms: magnetization rotation and magnetic domain movement. Magnetic materials assume a magnetic domain structure to lower their magnetostatic energy, resulting in forming domain walls at the boundaries between domains. The domain wall movement increases the magnetization in the direction of the magnetic field i.e., the magnetic domain movement. Magnetization rotation is such a magnetization mechanism that magnetization within the domains is rotated when the domain walls cannot move for some reason or when the magnetic field is strong enough to cause the domain walls to disappear.

To analyze the dependence of the magnetization mechanism on the excitation magnetic flux density and frequency, the frequency dependence of the maximum magnetic flux density under a constant external magnetic field ($B_{max} < B_s$) was investigated for three materials of different grain sizes. The results are shown in **Fig. 6**[4]. The frequency dependence of B_{max} is affected by eddy current. With the increase of frequency, the magnetic field increases to cancel the external magnetic field owing to eddy current, and thus B_{max} decreases with increasing frequency. The curves of frequency dependence of B_{max} calculated by a simple model that assumes a uniform eddy current in the sample approximately agree with measured values. The calculated curves are denoted by solid lines in **Fig. 6**.

To examine the magnetization mechanism of soft ferrite in more detail, the following three magnetic flux density regions must be considered:

- Low-magnetic flux density region (0 to 0.1 B_s): B_{max} monotonously increases [in the applied magnetic field of 20 A/m in **Fig. 6(a)**].
- Medium-magnetic flux density region (0.1 to 0.8 B_s): B_{max} peaks near 100 kHz and then decreases [in the applied magnetic field of 70 A/m in **Fig. 6(b)**].
- High-magnetic flux density region (> 0.8 B_s): B_{max} has no peak and decreases from the vicinity of 100 kHz [in the applied magnetic field of 700 A/m in **Fig. 6(b)**].

In this way, the three regions have different magnetization mechanisms, presumably corresponding to domain wall movement, nonuniform magnetization rotation, and uniform magnetization rotation, respectively[5]. The characteristics of each B_{max} curve depend on the grain size (see **Fig. 6**). When the magnetization mechanism illustrated in **Fig. 7** is considered and a uniform magnetization rotation model[4,6] is applied in the high-magnetic flux density region, the calculated results well represent the characteristics of the measured results (see the solid curves in **Fig. 6(b)**).

The magnetization mechanisms in the low- and medium-magnetic flux density regions are discussed below according to

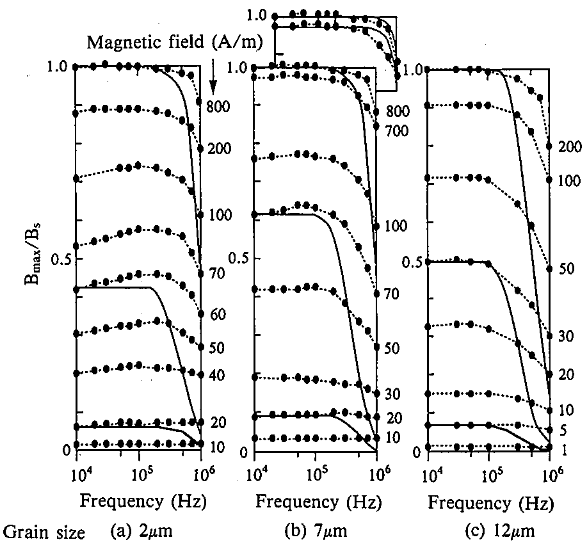

Fig. 6 Frequency dependence of maximum magnetic flux density

Frequency dependence of the maximum magnetic flux density as normalized by saturation magnetic flux density is shown. Solid circles (•) are measured values and are connected by dotted lines. Solid lines denote values calculated according to a uniform eddy current model. Solid lines inserted in Fig. 6(b) denote values calculated according to magnetization rotation model.

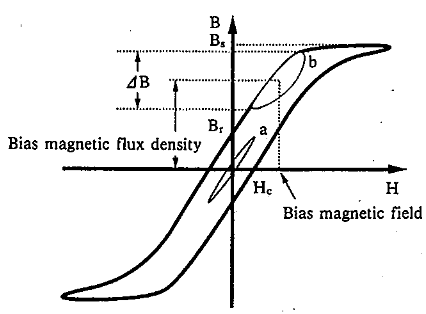

Fig. 5 Hysteresis loop

Figure shows magnetization curves of ferrite when it is magnetized. B_s, B_r, ΔB, and H_c are saturation magnetic flux density, residual magnetic flux density, change of magnetic flux density, and coercive force, respectively. Areas enclosed by loops a and b show power losses. The power loss of an actual power supply draws minor loop b, but according to the conventional JIS evaluation method, the evalution is based on minor loop a.

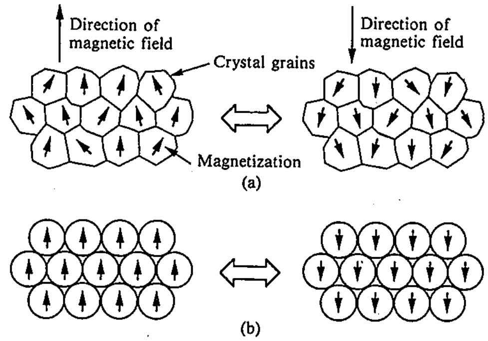

Fig. 7 Magnetization rotation model

(a) In a high-magnetic flux density region, domain walls are considered to disappear and each grain to form a single domain. (b) Variation between grains is averaged and represented by saturated spherical single domain model.

pulse response characteristics. Let the change with time in the magnetic flux density B be as given by

$$\frac{dB}{dt}=K^*\frac{H}{t_r} \quad \cdots\cdots(1)$$

where t is the time. The relation between the coefficient K* and the time of rise t_r of the pulse magnetic field H was experimentally determined. When a magnetic moment of the material was rivaled, K* was considered to be constant even when t_r was shortened. When no bias magnetic field (see **Fig. 5**) is applied to the single-crystal and coarse-grain size (12 μm) samples, K* decreases with shortening t_r, and the magnetization cannot follow the change of magnetic field fast enough, as shown in **Fig. 8**. When bias magnetization is applied, the magnetization response improves, and the declining tendency of K* decreases or disappears.

The deterioration of response is attributable to domain wall damping, while the improvement of response, when the bias magnetic field is applied, can be explained by the disappearance of domain walls and the predominance of magnetization rotation. For the fine-grain size (2 μm) samples, on the other hand, the decrease of K* is not observed, irrespective of whether or not the bias magnetic field is present (see **Fig. 8**), and the magnetization rotation dominates as the grain size becomes finer. This agrees with the magnetic domain structure measured by the neutron technique[7].

4.2 Nonstoichiometric oxidation degree and electromagnetic properties of ferrite

Low-power loss ferrites must be low in the absolute value of power loss and good in the temperature characteristics of the power loss. To meet these two requirements at the same time, the absolute values of the magnetocrystalline anisotropy constant and the magnetostriction constant must be minimized, and their respective temperature chacteristics must be optimized. The magnetocrystalline anisotropy indicates a characteristic by which magnetization is oriented easily in a given crystalline direction by the interaction between the orbital angular momentum and the electron spin angular momentum. Magnetostriction is a phenomenon of crystal lattice deformation by magnetization, and is dependent on the crystalline orientation. These physical constants are largely influenced by the site in the crystal lattice of metal ions contained in the ferrite.

As shown in **Fig. 9**, the Mn-Zn ferrite [MFe_2O_4(M:Mn, Zn)] assumes a crystal structure, called the spinel structure, where metal ions are situated to fill apertures between oxygen ions closely packed in the face centered cubic[8]. There are two types of ion coordination. Cations, metal ions, are coordinated by four anions, oxygen ions, to make tetrahedral coordination (A sites), and by eight anions, oxygen ions, to make octahedral coordination (B sites). Ions of even the same species differ in their contribution to the magnetic properties according to their sites. In other words, cations having magnetic moments such as Fe^{3+}, Fe^{2+}, Mn^{3+} and Mn^{2+} exist in the crystal lattice as shown in **Table 2** and **Fig. 10**. These cations, however, differ in conductivity to the physical constants, depending on their locations. Of the cations, the effect of Fe^{2+} is so great as to be comparable to that of host ions[9].

To reduce the power loss of ferrites, therefore, the ionic configuration in the crystal lattice must be optimized. In particular, controlling the Fe^{2+} content corresponding to the ferrite composition of is a key to improving the magnetic characteristics of ferrite. Ferrite developments, however, have been of a trial-and-

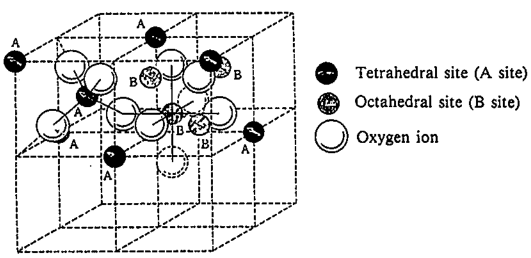

Fig. 9 Spinel structure[8]
Arrows on metal ions indicate the spinning direction.

Table 2 Contribution of iron ions to magnetocrystalline anisotropy constant K_1 and magnetostriction constant λ[9]

Ion	$\frac{dK_1}{dx}$ at 0 K*1)	Magnetostriction (λ_{111})*2)	G_{44}	F_{44}
$Fe^{3+}_{A\,site}$	+0.03 cm^{-1}	Small effect	} −0.8	—
$Fe^{3+}_{B\,site}$	−0.05 cm^{-1}	Small effect		
$Fe^{2+}_{B\,site}$	+1 cm^{-1}	Large effect	540	−145

*1) x is defined by $M_xFe_{2-x}O_4$
*2) λ_{111} = a(b·G_{44} + c·F_{44})
where G_{44} and F_{44} are magnetoelastic constants; and a, b and c are constants related to elastic constant, internal magnetic field, magnetic moment, respectively.

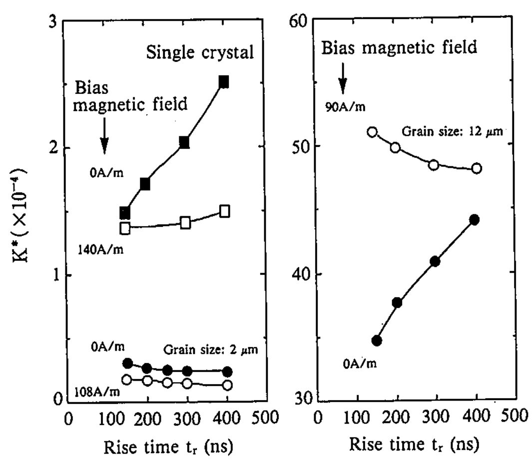

Fig. 8 Response characteristics of magnetization against pulse excitation

In the absence of bias magnetic field (0 A/m) to single-crystal and coarse-grain size (12 μm) samples, coefficient K* that indicates response of magnetization decreases with shortening t_r. Application of the bias magnetic field eliminates K* decreasing tendency. In the case of fine-grain size (2 μm), coefficient K* do not show decreasing, irrespective of whether the bias magnetic field is present or not.

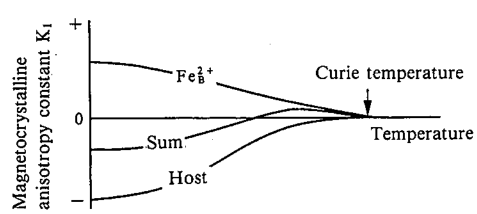

Fig. 10 Temperature dependence of magnetocrystalline anisotropy constant[9]

Host ions: Contribution of ions other than Fe^{2+}_B
Sum: Including contribution of Fe^{2+}_B to host ions

error nature, and few approaches have been made from an ionic configuration point of view. This is because the relationship between the power loss and the magnetocrystalline anisotropy constant or the magnetostriction constant has not been investigated so systematically as to consider cation apertures in the ferrite. The authors developed the low-power loss ferrite M36 according to indexes for the ionic distribution that take into account cation apertures in the ferrite.

When the apertures and atomic valence are taken into account, the chemical formula of ferrite is given by the following equation, using the nonstoichiometric oxidation degree γ:

$$(Zn^{2+}_{\alpha_1} Mn^{2+}_{\alpha_2} Fe^{3+}_{\alpha_3})\ [Mn^{3+}_{\beta_1} Fe^{2+}_{\beta_2} Fe^{3+}_{\beta_3}]O_{4+\gamma} \quad \cdots\cdots(2)$$

where α_i and β_i (i = 1 through 3) are values that depend on the composition and the nonstoichiometric oxidation degree γ. If the composition and γ are determined, the site and the amount of ions in the spinel lattice can be determined, respectively. The amount of oxygen deviates by γ from the stoichiometric composition, and the volume of cation aperture is expressed by the nonstoichiometric oxidation degree γ, which can be obtained by specifying the composition and oxygen partial pressure in the sintering atmosphere[10]. Concerning the change in Fe^{2+} content in the case of varying composition and oxygen partial pressure in the sintering atmosphere, the values calculated from γ agree fairly well with the values of chemical analysis[11], as shown in **Fig. 11**. This means that the nonstoichiometric oxidation degree γ is an appropriate index for the configuration of Fe^{2+} and other ions in the spinel lattice.

With regards the temperature characteristics of power loss, a temperature (T_m) at which the power loss becomes minimum is a particularly important thermal property. The minimum-power loss temperature T_m is related to the magnetocrystalline anisotropy constant, the magnetostriction constant and, consequently, the initial permeability. It corresponds to the temperature of secondary maximum of permeability T_s, the temperature lower than the Curie temperature (T_c) at which the material loses magnetism and at which permeability becomes maximum. The behavior of T_s has been examined in detail and is known to heavily depend on the Fe^{2+} content[12]. Accordingly, investigating the positional relationship between the minimum-power loss temperature T_m and the temperature of secondary maximum of permeability T_s is important in knowing the mechanism that governs the temperature characteristics of power loss.

When T_m and T_s are both normalized by the Curie temperature T_c ($T_{rm} = T_m/T_c$ and $T_{rs} = T_s/T_c$) and arranged by the calculated Fe^{2+} content, they monotonously decrease with

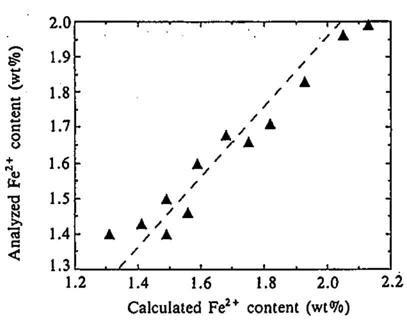

Fig. 11 Analyzed versus calculated Fe^{2+} values

Dotted line indicates the case in which analyzed and calculated values are in agreement.

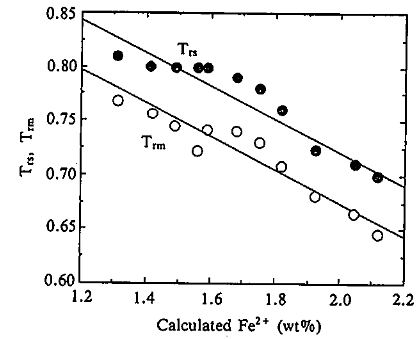

Fig. 12 T_{rs} and T_{rm} versus calculated Fe^{2+} content

T_{rs} is secondary peak temperature T_r normalized by Curie temperature T_c, and T_{rm} is minimum-power loss temperature T_m normalized by Curie temperature T_c. Solid lines are primary regression lines for T_{rs} and T_{rm}.

increasing Fe^{2+} content, as shown in **Fig. 12**. The phenomenon of decreasing T_s with increasing Fe^{2+} content is in accord with the past reports[12]. The rate of change in the minimum-power loss temperature T_m with the change of Fe^{2+} content (slope of the primary regression line) is approximately the same as that of the temperature of secondary maximum permeability T_s. This indicates that the temperatures T_m and T_s have the same governing factors. It is thus obvious that, like the temperature of secondary maximum permeability T_s, the minimum-power loss temperature T_m is dependent on the Fe^{2+} content and is controllable by the nonstoichiometric oxidation degree γ. The minimum-power loss temperature T_m has an almost constant deviation from the temperature of secondary maximum permeability T_s. This is because the temperature dependence of the power loss is the summation of the temperature dependence of permeability and electrical resistivity[11].

Additions of trace elements are also made to improve the magnetic properties of ferrites. Some additives, however, can change the ionic valence balance of ferrite and the temperature dependence of the power loss. The temperature dependence of the power loss changed through the introduction of additives could be compensated for by adjusting the production conditions, but it has been difficult to systematically optimize the adjustment.

When TiO_2 is added, the presence of Ti^{4+} in the spinel lattice increases the Fe^{2+} content. The minimum-power loss temperature T_m, therefore, decreases with increasing TiO_2 addition[11]. If the change of Fe^{2+} content with the TiO_2 addition makes the same contribution to T_m as the change in the Fe^{2+} content with the change of γ by adjusting the composition or the oxygen partial pressure in the sintering atmosphere, the effects of the composition, the oxygen partial pressure during sintering and the additives on the temperature dependence of the power loss can be referenced by the nonstoichiometric oxidation degree γ on an integrated basis. Study was made on the change in the minimum-power loss temperature T_m with the change in the Fe^{2+} content in both cases of variable γ with constant TiO_2 addition and vice versa. As shown in **Fig. 13**, both cases were found to be equivalent.

It was confirmed that the nonstoichiometric oxidation degree γ is an index whereby the effects of the ferrite composition, the oxygen partial pressure in the sintering atmosphere and the addition elements can be referenced on an integrated basis, which has made it possible to systematically develop the new low-power loss ferrite M36.

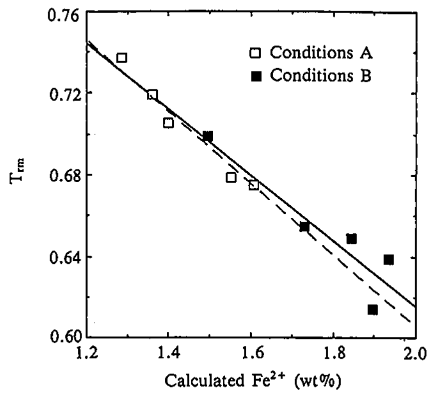

Fig. 13 Calcurated T_{rm} versus Fe^{2+} content when TiO_2 was added

T_{rm} is minimum-power loss temperature T_m normalized by Curie temperature T_c. Condition A: Samples were sintered with constant TiO_2 addition and varying γ. Conditions B : Samples were sintered with varying TiO_2 addition and constant γ. Solid line and broken line are primary regression lines for conditions A and B, respectively.

4.3 New method of evaluating the power loss of ferrite by bias excitation

Methods of measuring the power loss of ferrites are specified by JIS and the like[13,14]. That is, the ferrite core is excited by voltage and current of a sinusoidal waveform as shown in **Fig. 14(a)**, and the resultant power loss of the ferrite core is measured[15,16]. On the other hand, most of the ferrite cores used in actual SWR transformers and choke coils are excited by rectangular waveformed voltage and triangular waveformed current, as shown in **Fig. 14(b)**.

SWR manufacturers have been pointing out discrepancy between the JIS power loss measurement of ferrite cores and the actual heat generation of ferrite cores when used on-circuit in the SWR. This has prevented measured core loss data from being effectively utilized in designing SWR. A difference in the excitation waveform was generally blamed for the data discrepancy, but it has not been clearly analyzed[17,18]. A more realistic method of evaluating the power loss of ferrites was called for.

A system was developed for faithfully simulating the excitation conditions of a power ferrite as mounted on the SWR and evaluating the power loss of the ferrite in terms of a heat generation as shown in **Fig. 15**, in order to practically evaluate the power loss of the ferrite and use its result in evaluating the new low-power loss ferrite M36. This system consists of a circuit configuration simulating the smoothing circuit of the SWR, reproduces the excitation conditions by the same rectangular waveformed voltage and triangular waveformed current as those for the actual SWR, and evaluates the power loss in terms of the temperature rise ΔT of the heated core with respect to the ambient temperature.

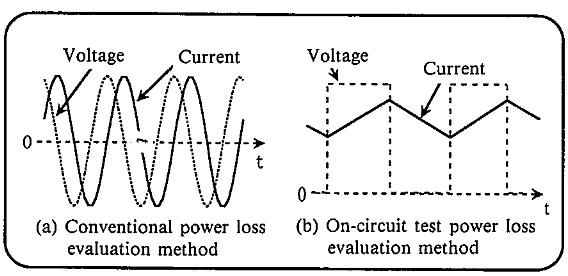

Fig. 14 Comparison of excitation voltage and excitation current waveforms according to the conventional power loss evaluation method and on-circuit test power loss evaluation method

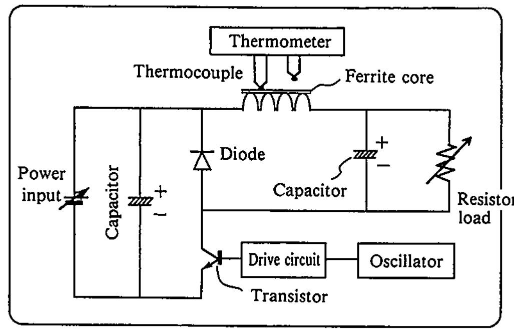

Fig. 15 Circuit diagram of apparatus with choke-coil type ferrite coil mounted on SWR for evaluating power loss

SWR excitation is simulated, and temperature rise of ferrite core due to power loss is measured.

Using the system, changes in the power loss of ferrite were measured by varying the output current while keeping the excitation voltage and excitation current amplitude constant. The output current is equal to the dc bias component of the triangular waveformed excitation current. As shown in **Fig. 16**, the temperature rise ΔT of the ferrite core increases with increasing bias current, although the excitation amplitude does not vary. The temperature rise ΔT estimated from the power loss evaluated by the conventional method (indicated by the arrow at the lower left of the left-hand side figure in **Fig. 16**) is almost the same as the power loss extrapolated to the zero value of the bias current. The fact that the SWR excitation current accompanies the bias current is considered responsible for the difference arising between the power loss evaluated by the conventional method and the actual heat generation.

The increase in the power loss of the ferrite core with the bias current is taken as a change in the power loss of the ferrite core dependent on the position of the minor loop (ML) on the B-H plane. The minor loop under the conventional method is centered at the origin, while, when the ferrite core is excited by the bias current (bias magnetic field), the center of the minor loop shifts from its original point, as shown in **Fig. 5**. The power loss of the ferrite core corresponds to the area of the minor loop, and it increases with the bias magnetic field strength. When the bias magnetic field is 300 mT as indicated by the line connecting the solid squares in **Fig. 17**, the area of the minor loop becomes about four times larger than when the bias magnetic field strength is

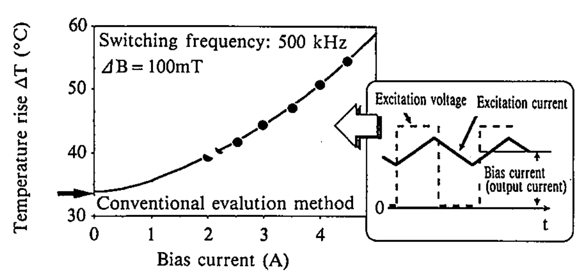

Fig. 16 Bias current dependence of temperature rise of ferrite core

Even with a constant excitation amplitude (excitation current amplitude in right-hand side figure), temperature of the ferrite core rises with increasing bias current. The power loss of ferrite core as evaluated by the conventional method shows the same value as the heat generated in the ferrite core when the bias current is zero.

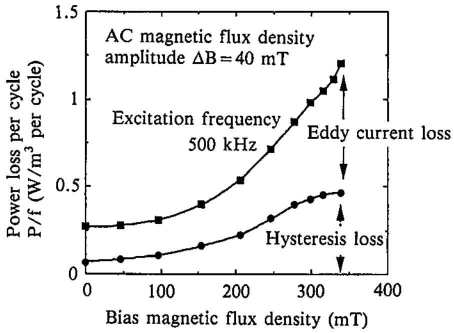

Fig. 17 Power loss versus bias magnetic flux density

Hysteresis loss and eddy current loss, both of which are components of power loss, increase with increasing bias magnetic field strength.

zero. When the power loss was divided into hysteresis loss and eddy current loss as indicated by the line connecting the solid circles in **Fig. 17**, the effects of power losses in both were evident.

The mechanism whereby the power loss of the soft ferrite increases in the presence of a bias magnetic field may be explained as follows. In regard to the increase of hysteresis loss by the bias excitation, as illustrated in **Fig. 18**, individual grains in the soft ferrite have different coercive forces H_c and thereby bring about domain wall distributions. When the ferrite is exposed to a magnetic field, domain walls with relatively low H_c start shifting. When the ferrite is exposed to a bias magnetic field, domain walls with coercive force lower than the critical H_c disappear, and the remaining domain walls having grains of higher H_c participate in the magnetization, resulting in increasing the hysteresis loss of the soft ferrite in a bias magnetic field. The mechanism whereby the eddy current loss of the soft ferrite is increased by the bias

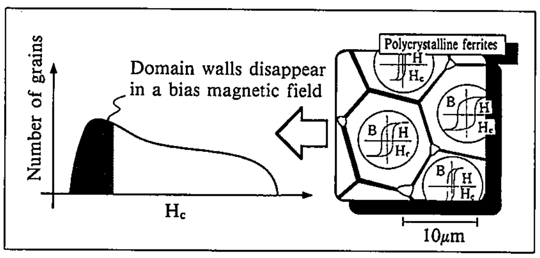

Fig. 18 Mechanism of increase in hysteresis loss due to bias excitation

Individual grains in the ferrite core have different coercive forces H_c (right-hand side figure) and exhibit domain wall distributions peculiar to a material (left-hand side figure). Under bias excitation, domain walls with coercive force under the critical level disappear, and remaining domain walls participate in magnetization, thereby increasing the power loss of ferrite core.

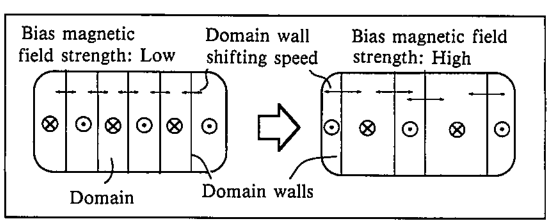

Fig. 19 Mechanism of increase in eddy current loss due to bias excitation

Eddy current loss is proportional to the square of domain wall shifting speed. Since the number of domain walls decreases in a bias magnetic field, domain walls shift faster to satisfy the magnetization with same magnetic flux density amplitude, resulting in increasing the eddy current loss.

excitation is as illustrated in **Fig. 19**. The soft ferrite decreases in the number of domain walls in the bias magnetic field as discussed above, although this depends on the shifting speed of domain walls. The domain walls shift at a higher speed in order to magnetize with the same magnetic flux density amplitude, resulting in increasing the eddy current loss of the ferrite.

The dependence of the increase of power loss of soft ferrites on a bias magnetic field varies for different materials. When the bias value rises above a certain level, a ferrite with initially a low power loss at zero bias value may rise even to exceed the power loss value of another ferrite with initially a larger power loss. Thus problems with the on-circuit use of soft ferrites cannot be solved even if they exhibit excellent properties when the bias value is zero. Instead, they must exhibit excellent properties even under bias excitation applied. When measured by the new method discussed here, M36 is superior by 10°C in terms of heat generation to the best soft ferrites available on the market.

5. Conclusions

The new low-power loss ferrite M36 was developed to meet the requirements for higher efficiency of power supplies in electronic equipment which are amid rapid transition toward personal and portable use. In the development, the ferrite magnetization mechanism was clarified, the ionic distribution in the ferrite core was optimized according to the nonstoichiometric oxidation degree γ, and production technology was established to accomplish such optimum ionic distribution. A new power loss evaluation method was developed that can faithfully simulate the actual service conditions of power ferrites.

It is fully possible that power ferrites will be further improved in properties through continuing efforts for the clarification of basic mechanism behind grain-boundary electric conduction, for instance.

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