libre $Fe^{+++} \rightleftarrows Fe^{++}$ vers Fe^{+++} (processus a). Toutefois une action complète du calcium nécessite un apport d'oxygène (processus b). Le refroidissement ou le palier de la trempe isotherme doit s'effectuer en atmosphère très légérement oxydante.

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DISCUSSION

E. W. GORTER: Can you explain why in Mn-Zn ferrites practically all of the 0.1% Ca^{++} addition goes into the grain boundaries, whereas in Zn-Ca ferrites we get up to 20% of the Zn replaced by Ca inside the crystal, even after slow cooling?

M. PAULUS: If you add 20% of Ca, its concentration at the boundary is still greater than inside the crystal but the relative difference between boundary and lattice concetration is much smaller, than if you add 0.1% Ca, because the lattice parameter is changed. A detailed paper will appear on this subject.

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Flux Reversal in Square Loop Ferrite Cores*

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The flux reversal mechanisms for Mg-Mn ferrite cores are reviewed and the double pulse experiment is introduced, to select the valid model. On the basis of experimental results, it is shown that the model of domain wall motion is not adequate to explain the flux reversal process for a large range of values of the applied field. However, the model consisting of domain wall motion for low values, incoherent rotation for intermediate values, and coherent rotation of large values of the applied field explains the experimental results adequately.

Using a modification of Haynes's model of domain wall motion, a procedure is outlined to determine β, the Goodenough and Menyuk damping constant. From β it is possible to find α, the modified Landau-Lifshitz damping constant. Using α, the switching constants for domain wall motion and rotation are calculated. A comparison of the experimental and calculated switching constants is given and discussed.

At present there are two hypotheses which describe the flux reversal process in square loop ferrites over a wide range of values of the applied field. The first of these assumes that flux reversal takes place by domain wall motion. The second assumes that the switching process can be divided into three regions of the applied field.[1] For low applied fields, the process is assumed to be domain wall motion; for intermediate applied fields, incoherent rotation; and for high fields, coherent rotation.

Three different models have been postulated to explain flux reversal by domain wall motion. The first model (A) assumes that the number of nucleation centers (n) participating in the reversal process is independent of

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the value of the applied field H_a and that the domain wall velocity $d<r>/dt$ is linearly dependent on H_a.[2] The second (B) assumes that n is independent of H_a but that $d<r>/dt$ increases at a greater than linear rate with respect to H_a (due to demagnetizing effects).[3] The third model (C) assumes that n is a function of the applied field and that $d<r>/dt$ is linearly dependent on H_a and leads to the result[4]

$$n^{1/3}=\frac{(d\Phi/dt)_{\max}}{H_a-H_0} \tag{1}$$

where $(d\Phi/dt)_{\max}$ is the maximum rate of change of flux and H_0 is the threshold field.

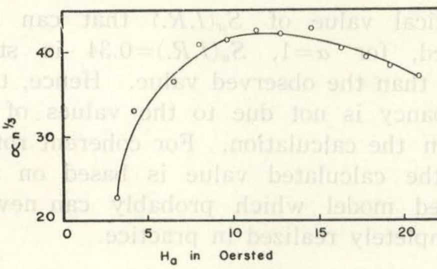

Fig. 1. Experimental $n^{1/3}$ versus H_a.

Using experimental values of $(d\Phi/dt)_{\max}$ versus H_a-H_0 one finds that n increases to a maximum value and then decreases with increasing values of H_a-H_0, as shown in Fig. 1. This result is physically unreasonable and hence (C) does not explain flux reversal over the entire range of values of H_a-H_0, though it may apply for low values of H_a-H_0.

An experiment, the double pulse experiment, provides further evidence to explain the process of flux reversal and will be described here. The two consecutive pulses shown in Fig. 2 will be called here a double pulse. The double pulse experiment consists of applying the double pulse to a previously saturated core in a direction to reverse the magnetization of the core. The time $T_s=$

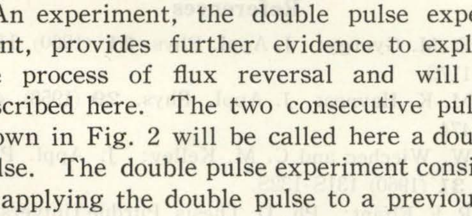

Fig. 2. Double Pulse.

T_1+T_2 is the time required to switch 90% of the total flux in the core. The amplitude H_1 and the time T_1 are adjusted so that a known constant amount of flux (about 25% of the total flux) is always switched by the first pulse. T_s is measured as H_1 is varied, keeping H_2 constant. Then the quantity $T_2=T_s-T_1$ is plotted as a function of H_1.

The predicted T_2 versus H_1 curve for this experiment depends upon the model assumed for the switching mechanism. If the switching mechanism is considered to be entirely domain wall motion, two different cases need to be considered (A and B). For (A), $T_2(H_2-H_0)=S_w{}^A$ where the switching constant $S_w{}^A$ is independent of the applied field. (B) assumes that the instantaneous domain wall velocity is dependent upon the instantaneous value of the applied field. Therefore, one obtains $T_2(H_2-H_0)=S_w{}^B(H_2)$ where $S_w{}^B(H_2)$ is a function of H_2 and independent of H_1.

However, if one considers that the reversal process is composed of three linear mechanisms: domain wall motion, incoherent rotation, and coherent rotation; and if one assumes that once a mechanism starts, it will continue through the entire reversal, one finds that $T_2(H_2-H_0)=S_w$ where S_w takes on three distinct values depending upon H_1.

The results of these predictions and the experimental results are given in Fig. 3.

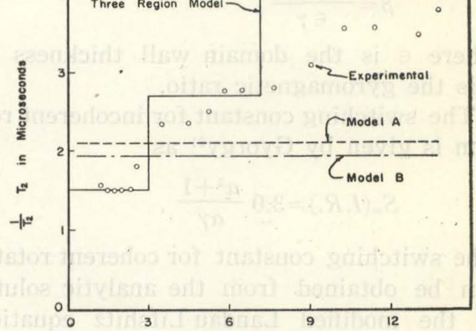

Fig. 3. Double Pulse Experiment.

The switching constants used in the three regions were determined from the experimental switching curve. It is seen from this figure that neither (A) nor (B) is adequate to explain the double pulse experiment, but that the three linear mechanisms model explains the double pulse experiment quite well.

Table I.
Switching Constant in Oersted μ seconds

	S_W(D)	S_W(I.R.)	S_W(C.R.)
Experimental	0.42	0.25	0.16
Calculated	0.43	0.44	0.08

One concludes that domain wall motion models of flux reversal are not adequate by themselves to explain the reversal mechanism over a wide range of values of the applied field.

For the low field region, (A) is modified to take into account the finite initial size of the nucleation centers which is required to account for the observed non-zero velues of $d\Phi/dt|_{t=0}$ and $d/dt(d\Phi/dt)|_{t=0}$. For a nucleation site of circular cross section with radius r_0 one finds[4] that

$$S_w(D) = -\frac{r_0\beta}{2(qV_0)^{1/3}}\{(qV_0)^{1/3} + \ln[-0.90 + e^{-qV_0}]^{\frac{1}{3}}\} \tag{2}$$

where qV_0 is the normalized total volume of the nucleation centers at $t=0$ and β is the domain wall motion damping constant.[5] This is an approximate expression which holds for small values of qV_0. It was shown[4] that β is related to α, the modified Landau-Lifshitz damping constant, through the expression

$$\beta = \frac{6.0\alpha M_s}{\epsilon\gamma} \tag{3}$$

where ϵ is the domain wall thickness and γ is the gyromagnetic ratio.

The switching constant for incoherent rotation is given by Gyorgy[6] as

$$S_w(I.R.) = 3.0\,\frac{\alpha^2+1}{\alpha\gamma}\,. \tag{4}$$

The switching constant for coherent rotation can be obtained from the analytic solution of the modified Landau-Lifshitz equation[7] and is found to be

$$S_w(C.R.) = 3.0\frac{\alpha}{\gamma}\,. \tag{5}$$

It is possible to find β from Haynes's model[2] with the modification of finite starting domains by substituting the experimental values of $d\Phi/dt|_{t=0}$ and $(d\Phi/dt)_{\max}$ into the analytic expression for $d\Phi/dt$.[4] For the material studied here (Mg-Mn) $\beta=0.63$ ergs /cm^3 cm/sec and the corresponding $\alpha=0.48$.

From these values of α and β the switching constants can be calculated. The calculated values and experimental values of S_w are given in Table I.

The transition from domain wall motion to rotation is a gradual one Hence, for intermediate values of applied field, the reversal process consists of a combination of wall motion and rotation, accounting for the discrepancy between calculated and observed values of S_w. The minimum theoretical value of $S_w(I.R.)$ that can be obtained, for $\alpha=1$, $S_w(I.R.)=0.34$ is still larger than the observed value. Hence, the discrepancy is not due to the values of α used in the calculation. For coherent rotation, the calculated value is based on an idealized model which probably can never be completely realized in practice.

Conclusion

Experimental evidence and the result of calculations have been presented which establish the model, consisting of domain wall motion at low fields, and rotation at high fields, as the most plausible.

A method for experimentally determining α, and from α the switching constants, is indicated.

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DISCUSSION

L. F. BATES: I take it that a very simple domain wall motion is envisaged; I am used to domain walls which strike obstacle and branch out in many directions.

F. J. FRIEDLAENDER: A relatively simple domain wall model is used here as in previous work, since calculations are not possible otherwise. It is hoped that the effect of obstacles etc. is accounted for by the H_0 term to some extent.

F. B. HUMPHRAY: What is the magnitude of H_2? Did you calculate S_w in Table I for this particular experiment or was it an S_w calculated in the usual way?

F. J. FRIEDLAENDER: The value of H_2-H_0 was 0.48 oersted.

S_w was calculated in each case from the value of α, which was obtained from β as indicated in the paper. β was obtained from measurements at low fields ("domain wall region"). For details, reference (4) is to referred.

K. HOSELITZ: Does the proposed model apply only to major or also to minor hysteresis loops?

F. J. FRIEDLAENDER: I suppose that Dr. Hoselitz would like to know that would happen, for instance, if an interval is allowed to occur between the two parts of the double pulse. In this latter case the model does not apply—in fact, what occurs depends on length of the interval, and we have no satisfactory model so far to explain the observed results. However, as long as flux reversal proceeds continuously from saturation, we suggest that our model applies.

A. A. HIRSCH: By applying an external field we introduce a momentum in the sample. This momentum will put in motion a number of nucleation centers and this phenomenon represents the switching mechanism. I do not see the reason why this number of centers will remain constant for different values of the applied magnetic field. The switching machanism is a dynamical process and we can find a field for which the probability for this mechanism is maximum.

F. J. FRIEDLAENDER: Please refer to reference (1) for further discussion of your question. As stated in the paper, model (C) may apply for low values of the applied field.

A. A. HIRSCH: The wall velocity depends on the driving force which acts on the wall. This force depends generally on the change in magnetization.

F. J. FRIEDLAENDER: In the region in which flux reversal takes place by means of domain wall motion, 180°—walls probably account for most of the flux reversal process, for the square loop ferrites considered here. Hence the change in magnetization is constant and equals to $2M_s$.