JMMMDC 101 (1–3) 1–442 (1991)

ISSN 0304-8853

journal of magnetism and magnetic materials

VOLUME 101, Nos. 1–3
OCTOBER 1991

To be followed by vol. 100

COMPLETE VOLUME

EPS

Recognized by the
European Physical Society

Proceedings of the 4th
EUROPEAN MAGNETIC MATERIALS AND APPLICATIONS CONFERENCE
16–19 April 1991
Dresden, Germany

NORTH-HOLLAND

Journal of Magnetism and Magnetic Materials 101 (1991) 83–85
North-Holland

Study of the incidence of the last annealing on the magnetic characteristics of high silicon (6.0–6.5%) crystalline ribbons directly obtained from the melted state by rapid quenching

I. Ibarrondo [a], J. San Juán [b] and J. González [c]

[a] *Dpto. Fisica Aplicada I, Escuela de Ingeniería Técnica Industrial, 20010 San Sebastian, Spain*
[b] *Dpto. Fisica de la Materia Condensada, Lejona, Spain*
[c] *Dpto. Fisica de Materiales Facultad de Ciencias Quimicas, 20009 San Sebastian, Spain*

The incidence of the last annealing cycle on the grain size, texture, and magnetic characteristics in high silicon crystalline ribbons obtained by rapid quenching is studied. The material was submitted to two types of heat treatment under vacuum and simulating industrial conditions. The first of these was carried out at low temperature (900 °C), the second one at high temperature (1150 °C). In both cases the magnetic characteristics were better than those of the highest grades of conventionally processed magnetic steel sheet. During the last annealing a tertiary recrystallization process was developed. As a consequence, a texture induction, grain growth and improvement of the total losses were obtained.

1. Introduction

Nowadays new procedures for obtaining materials directly from the melted state by rapid quenching allow one to obtain crystalline ribbons and sheets of magnetic materials of a high silicon level (Fe–Si 6.0–6.5%) destined for use, in the short term, as cores of high-performance electric machines.

The present paper concentrates on the study, carried out under conditions simulating industrial processes, of the incidence which the last annealing process applied to the material has on its final magnetic characteristics.

2. Physical background

It is well known that in the case of these materials, and depending on the use for which they are intended, the final magnetic characteristics depend on the grain size and final texture induced in the material, if the silicon level [1,2], work frequency and gauge values are fixed.

These variables are at the same time a function of the parameters of the previous process of solidification and particularly of the last heat treatment [3–5]. This treatment has a great influence on the type of recrystallization, both primary or tertiary [6,7], as a function of the temperature range and the type of atmosphere employed.

The aim of all these procedures is to achieve an optimum grain size and induce a nonoriented cube texture {100} ⟨*ovw*⟩. As a consequence, the losses can be reduced to a minimum, and at the same time, the planar isotropy is preserved.

3. Experimental

Crystalline ribbons (Fe–Si at 5.9%, 0.75 mm × 33 μm) were produced by rapid quenching technique. The parameters of the different stages of the production process (sintering, melting, tapping,...) have been published elsewhere [8].

In accordance with the aim of the present investigation, the material was submitted to two annealing cycles simulating the continous heat treatment which the material undergoes after being produced. Both cycles are schematically represented in fig. 1. The first one (cycle I) is associated with a primary recrystallization process, while the second one (cycle II) with a tertiary recrystallization process. The latter treatment is more expensive and difficult to carry out on an industrial scale.

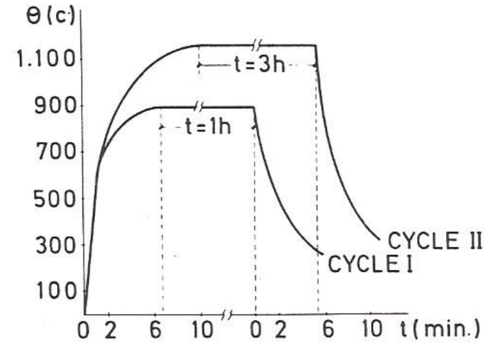

Fig. 1. Annealing cycles supplied to the material. (Atm: vacuum, $P_{\text{heating step}} \approx 5 \times 10^{-5}$ mbar, $P_{\text{soaking step}} = 2 \times 10^{-6}$ mbar.

4. Results and their analysis

Material texture and grain size: the texture of the material determined by X-ray diffraction [9] and the values corresponding to the average grain size [10] are shown in table 1.

The results obtained show that the texture component {200} $\langle ovw \rangle$ is strengthened in the course of the heat treatment.

Moreover, the grain size obtained through cycle I brings the total losses to an optimum [11], whereas that obtained by means of cycle II increases the value of anomalous losses [12].

Magnetic characteristics: the measurements of the magnetic characteristics of the material in its different states were carried out using the experimental device designed previously by the authors [13].

Saturation magnetization and coercive force: the value determined for magnetization at saturation has been of 1.84 T, which is in agreement with values reported earlier [2,3]. With respect to coercive force the values were 198.0 A m^{-1} for the as-quenched sample, and 84.8 and 74.6 A m^{-1} for the samples annealed according to cycles I and II, respectively.

Magnetization curves and total losses: the magnetization curves ($\mu_0 M - H$) and total losses ($\mu_0 M - W$) for the material treated according to the same cycles are shown in figs. 2 and 3. The magnetic characteristics, particularly the total losses, show a remarked improvement when the material is treated according to the cycle II. In this case, the magnetization process (fig. 2) suffers a rather considerable variation and the segment OA′ corresponding to the irreversible movement of domains and associated with the hysteresis losses is lower than the segment OA corresponding to cycle I.

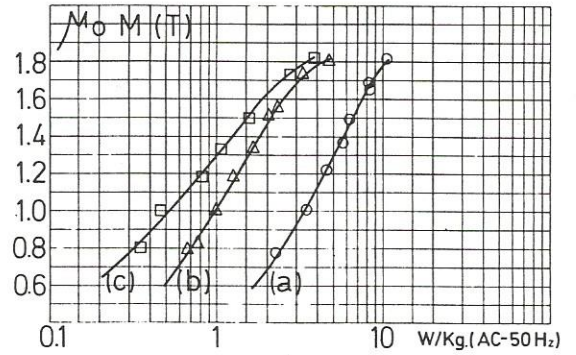

Fig. 3. Total magnetic losses at different inductions: (a) as-quenched; (b) cycle I; (c) cycle II.

In conclusion, with the experimental results obtained in this work, it is possible to say that the material thermically treated under cycles I and II presents magnetic characteristics (coercive field, total losses) which are better than those of the highest grade of conventionally processed magnetic steel sheet, with the exception of the saturation magnetization.

This work has been supported by the University of Basque Country (UPV 057.263-0044/88) and the Excma Diputación Foral de Guipúzcoa (DF 22/1989).

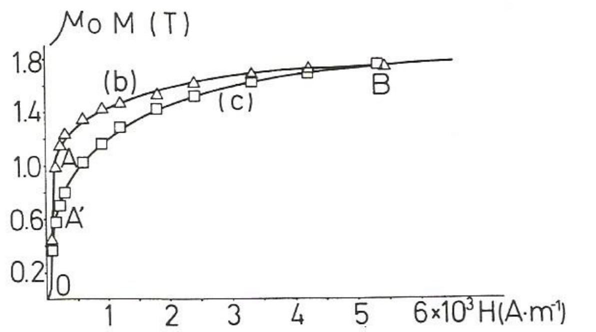

Fig. 2. Magnetization curves: (b) cycle I; (c) cycle II.

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Table 1
Texture and grain size of the material

Sample	Grain size (μm)	I/I_{random}					
		110	200	211	310	222	321
As-quenched	7.2	0.86	2.11	0.65	1.42	0.55	0.42
Cycle I	120	0.16	2.76	0.16	1.96	0.00	0.96
Cycle II	>1100	0.03	3.58	0.00	1.37	0.00	1.04

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TABLE I: Texture and grain size of the material

SAMPLE	GRAIN SIZE (μm)	I / I_{random} 110	200	211	310	222	321
A.Q.	7.2	0.86	2.11	0.65	1.42	0.55	0.42
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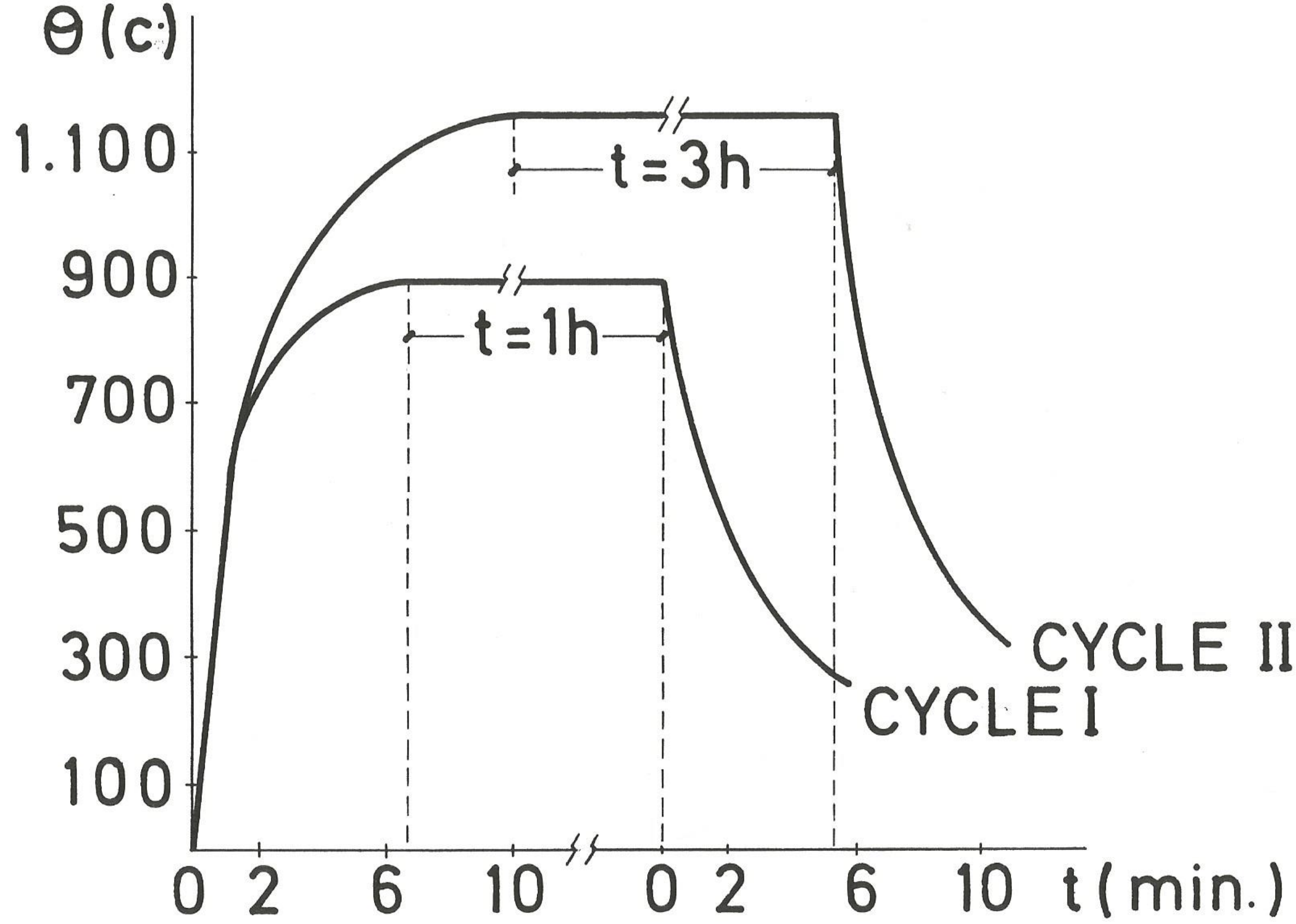
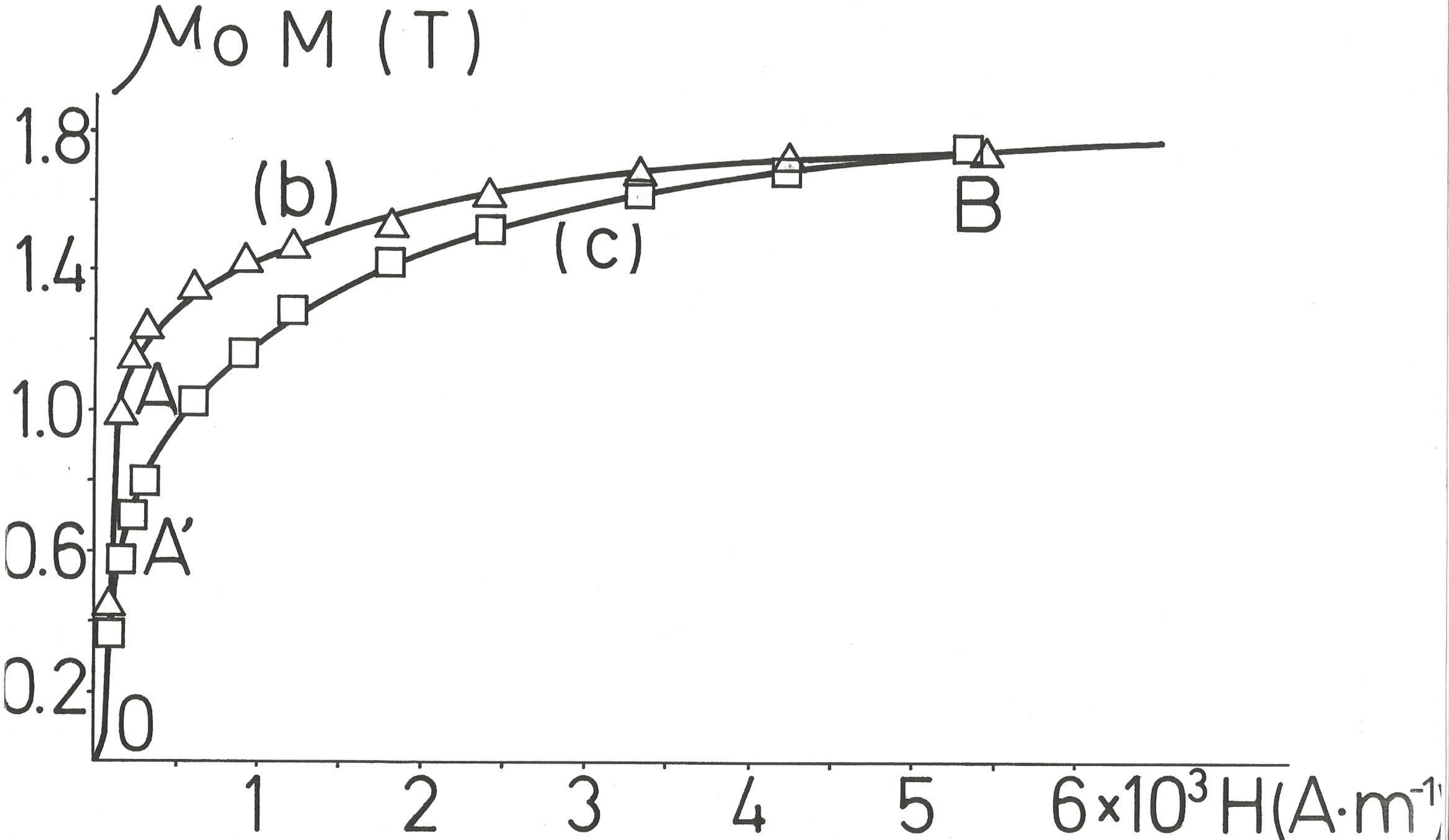
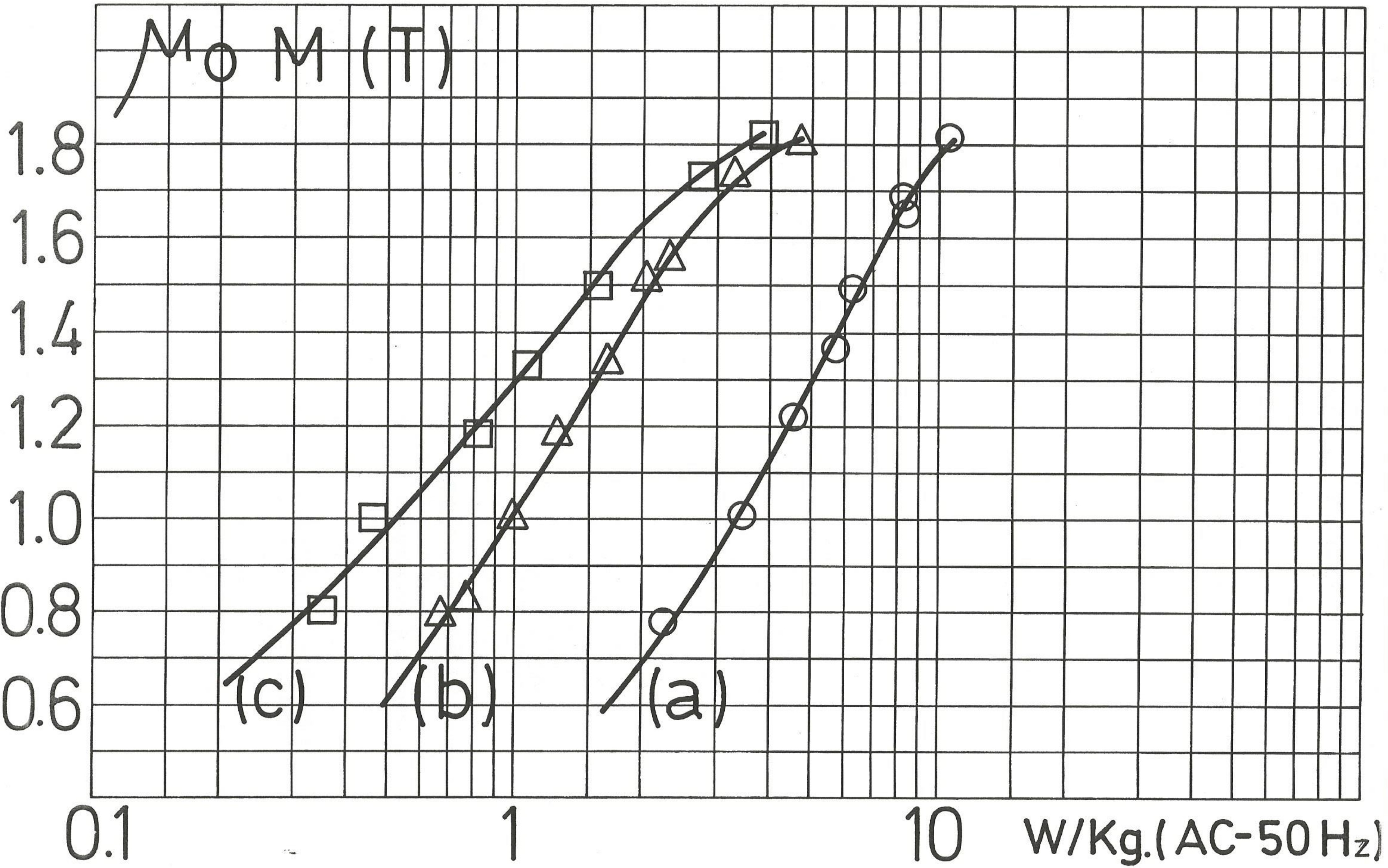
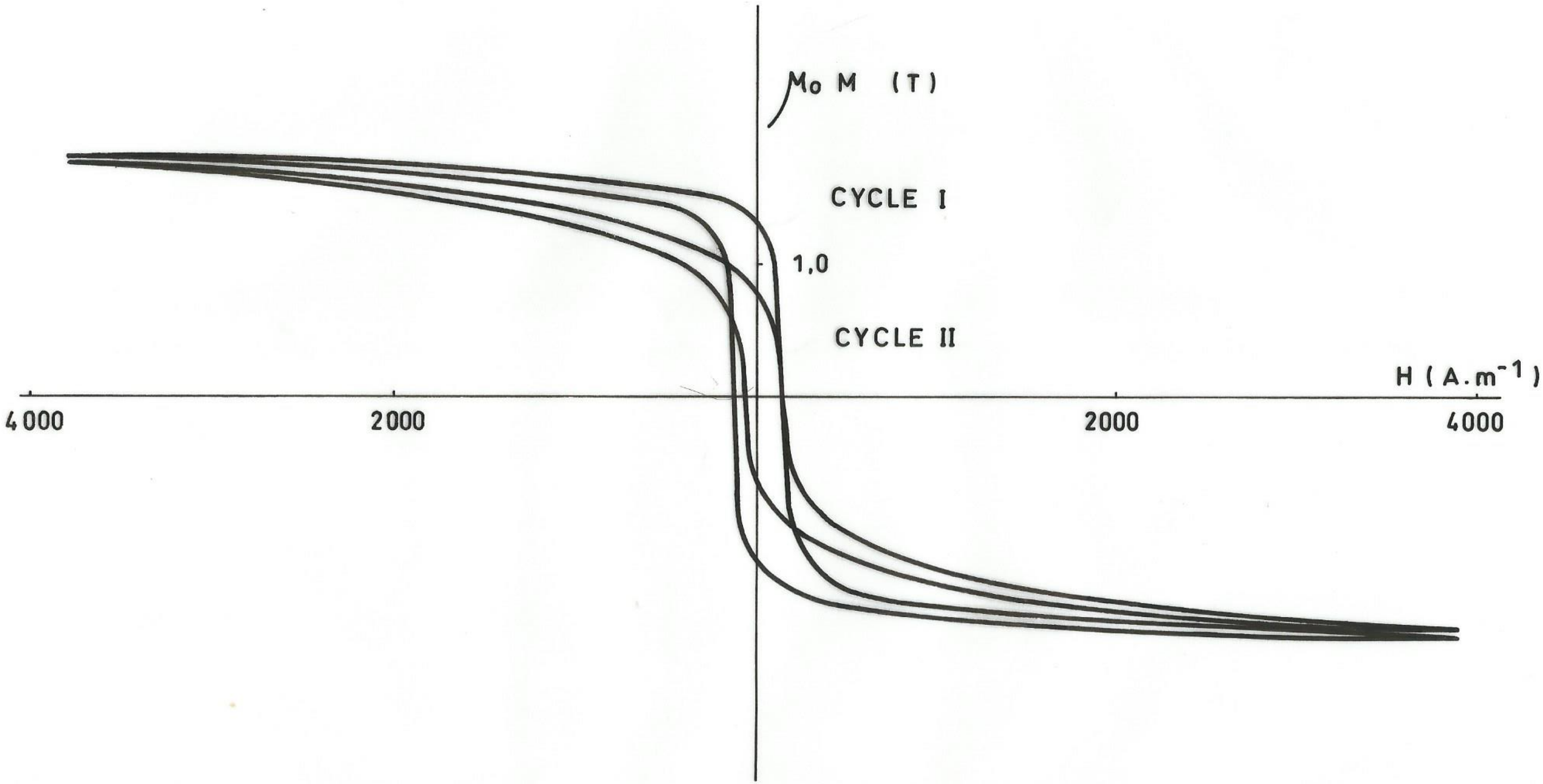

θ (c)
1.100
900
700
500
300
100
0 2 6 10 0 2 6 10 t (min.)
t = 3h
t = 1h
CYCLE II
CYCLE I


μo M (T)
1.8
1.4
1.0
0.6
0.2
0
1
2
3
4
5
6×10³ H(A·m⁻¹)
(b)
(c)
A
A'
B



$\mu_0 M$ (T)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
(c)
(b)
(a)
0.1
1
10
W/Kg.(AC-50 Hz)



μo M (T)
CYCLE I
1,0
CYCLE II
H (A.m⁻¹)
4000
2000
2000
4000

CAPTIONS

Fig. 1. Annealing cycles supplied to the material. (Atm :vacuum, $P_{heating\ step} \approx 5.10^{-5}$ mbars, $P_{soaking\ step} = 2.10^{-6}$ mbars)

Fig. 2. Magnetization curves ; (b) Cycle I , (c) Cycle II.

Fig.3. Total magnetic losses at different inductions. (a) As-quenched, (b) Cycle I, (c) Cycle II .