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Influence of manufacturing process parameters on magnetic characteristics of high – FeSi crystalline rapidly quenched ribbons

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Parameters of the manufacturing process and final heat treatment of the Fe–5.9% Si crystalline ribbons obtained by rapid quenching are described. The magnetic characteristics (magnetization curves, coercive force and total losses at 50 Hz) as a function of the grain size and induced texture are also studied. The results show that these characteristics are similar to or better than those of the highest grade of conventionally processed magnetic steel sheet.

1. Introduction

Recently, great efforts have been made to obtain crystalline ribbons and sheets of high silicon contents (6.0–6.5%), directly from the melt by rapid quenching and destined for use in the construction of cores of high-performance rotating electric machines [1,2].

It is known that the final magnetic characteristics depend, for specific work frequencies [3,4], gauge values [5] and silicon level [6], on the grain size and texture induced in the material. These variable are, in turn, a function of the parameters of the solidification process [7,8] and most particularly of the last heat treatment; temperature range and the type of atmosphere employed [9–12].

All these procedures are followed with the object of obtaining the optimum grain size and of inducing at the same time, a non-oriented cube texture {100} ⟨ovw⟩ which eliminates the directions ⟨111⟩, hard to magnetize, from the sheet plane, thus minimizing the total losses and preserving the planar isotropy at the same time.

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Considering the economical importance of the subject, the interest in studying the final magnetic characteristics as a function of the manufacturing process becomes evident. All this constitutes the aim of the present paper.

2. Production process

Iron–silicon (Fe–Si at 5.9%, 0.75 mm × 33 μm) crystalline ribbons were produced under conditions simulating those of future industrial manufacturing processes. The main parameters of the production process are:

Sintering: heating step ($t = 20$–30 min, atm.: H_2 (100%)), soaking step ($t = 4$ h, $\Theta = 700$°C, atm.: H_2 (100%)), cooling step up to 80–60°C in argon.

Melting and tapping: melting temperature: 1460°C, tapping temperature: 1410°C, nozzle diameter: 0.3 mm, injection pressure: 0.5 atm (argon), wheel angular velocity: 1800 r.p.m.

Heat treatment: the material was finally annealed at 900°C under vacuum through cycles of high and low heating and cooling rate to simulate continuous annealing (fig. 1(a) cycle I) and batch annealing (fig. 1(b) cycles II and III) respectively.

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3. Results and their analysis

3.1. Material texture and grain size

The average grain size values measured according to the method described in [13] and the material texture determined [14] by X-ray diffraction are given in table 1.

From the results obtained, a primary recrystallization process can be deduced in all cases with a grain size highly appropriate to the minimization of the total losses value as it has been previously reported [15].

In the same way, it is also worth noting the likeness in the textures obtained by the annealing cycles I and II. In both cases the complete elimination of the component {222} ⟨ov′w′⟩ and the decrease in {110} ⟨ov″w″⟩ with respect to the as-quenched state were observed.

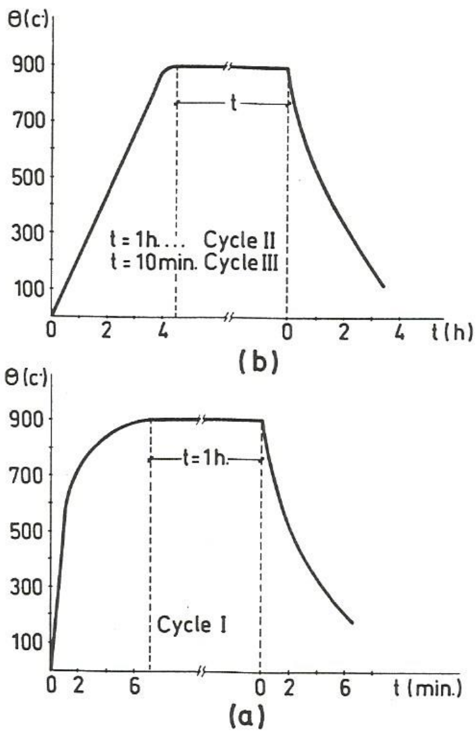

Fig. 1. Annealing cycles applied to the material; (a) cycle I, (b) cycles II and III. (Atm.: vacuum, $P_{\text{heating step}} \approx 5\times10^{-5}$ mbar, $P_{\text{soaking step}} = 2\times10^{-6}$ mbar).

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	140	0.16	2.76	0.16	1.96	0.00	0.96
cycle II	190	0.16	2.72	0.28	2.63	0.00	0.21
cycle III	120	1.54	2.14	0.14	1.64	0.00	0.53

On the other hand the material annealed under cycle III presents a texture less appropriate that the other ones.

3.2. Magnetic characteristics

The magnetic characteristics were deduced from the hysteresis loop obtained by means of the experimental device described in ref. [16].

Saturation magnetization: the saturation magnetization determined was that of 1.84 T. This value is in agreement with those reported earlier [6,9] for samples of the same chemical composition.

Coercive field: for the as-quenched sample the coercive field value determined was that of 198.0 A m^{-1}, whereas, in the case of the samples annealed according to cycles I, II and III, the values were 84.8, 82.0 and 90.2 A m^{-1} respectively.

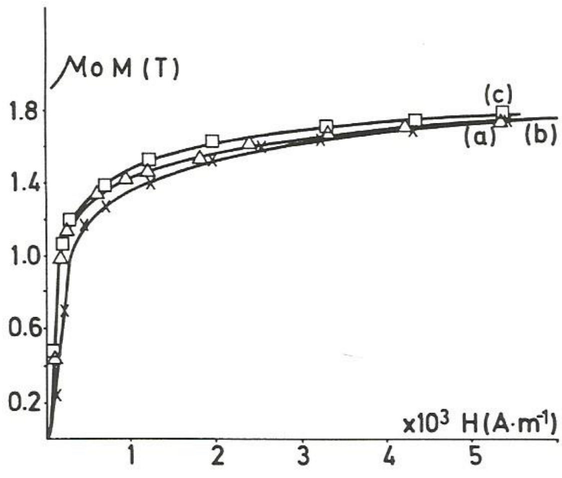

Fig. 2. Magnetization curves (a) as-quenched, (b) cycle I, (c) cycle II.

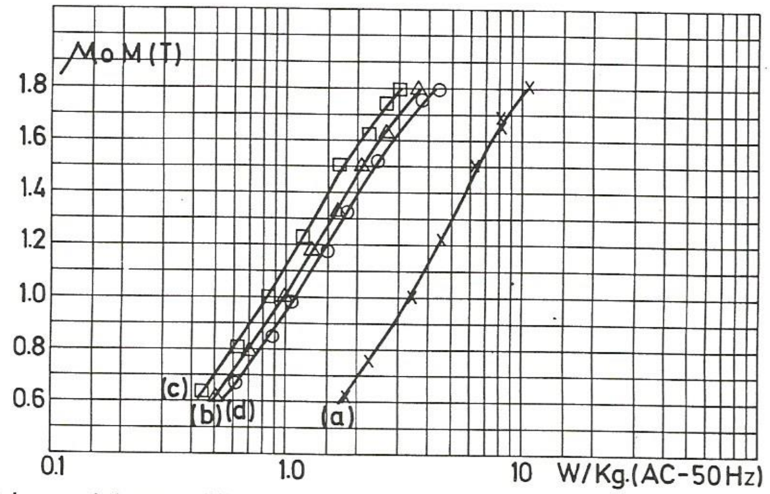

Fig. 3. Total magnetic losses at different inductions (a) as-quenched, (b) cycle I, (c) cycle II, (d) cycle III.

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.

After analyzing these results it can be deduced that the magnetic characteristics of the material which has undergone continuous annealing (cycle I) are only slightly inferior and superior to those obtained by using slow heating and cooling rates, cycles II and III, respectively. The industrial application of these rates is, therefore, of no interest from a technical and economical point of view.

Finally, it can be concluded that the material processed according to the parameter described in this paper presents magnetic characteristics which, with the exception of saturation magnetization, are similar or even superior, to those of the highest grade of magnetic steel sheet manufactured by conventional processes. The heat treatment corresponding to cycle I is easier and more economical to carry out on an industrial scale.

Acknowledgements

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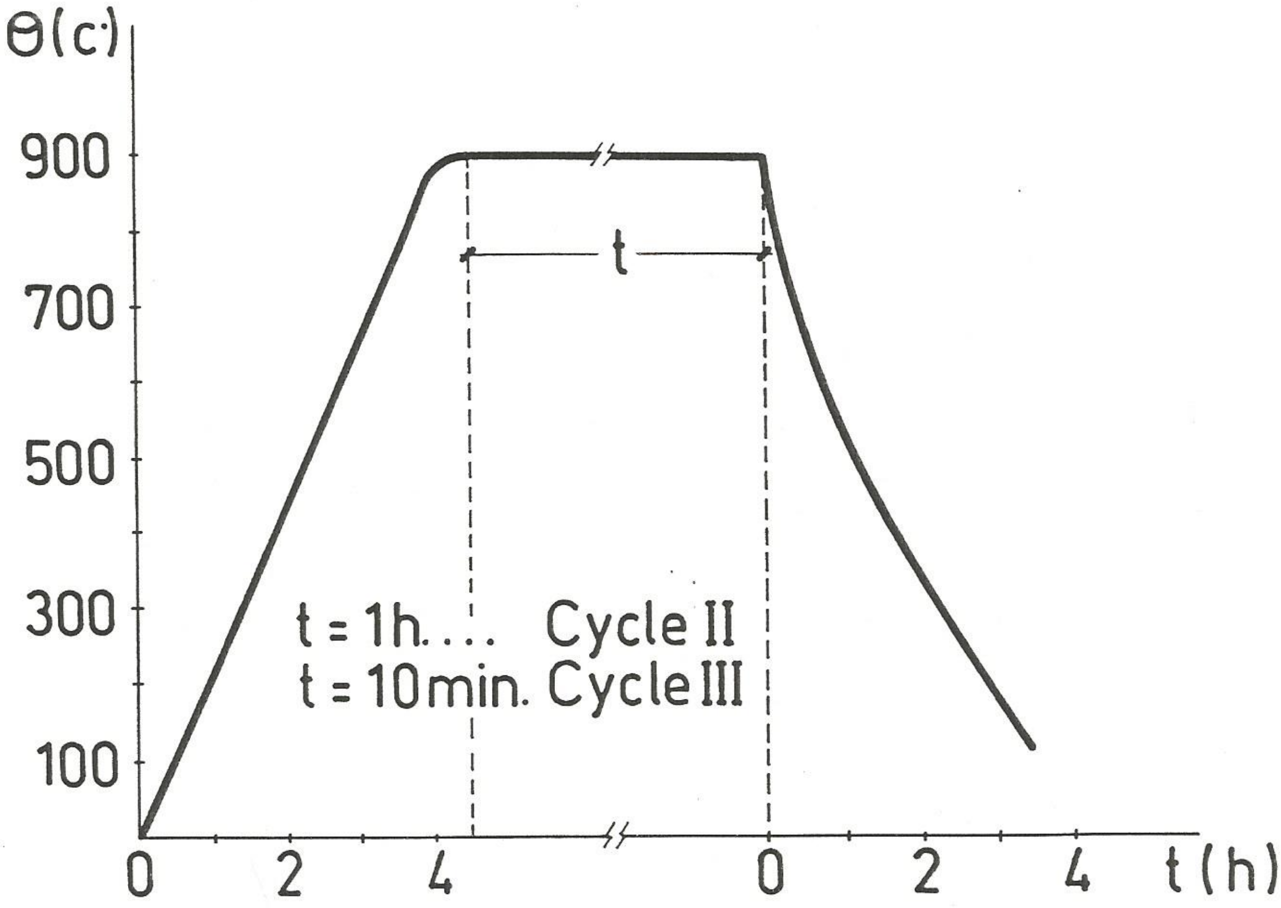
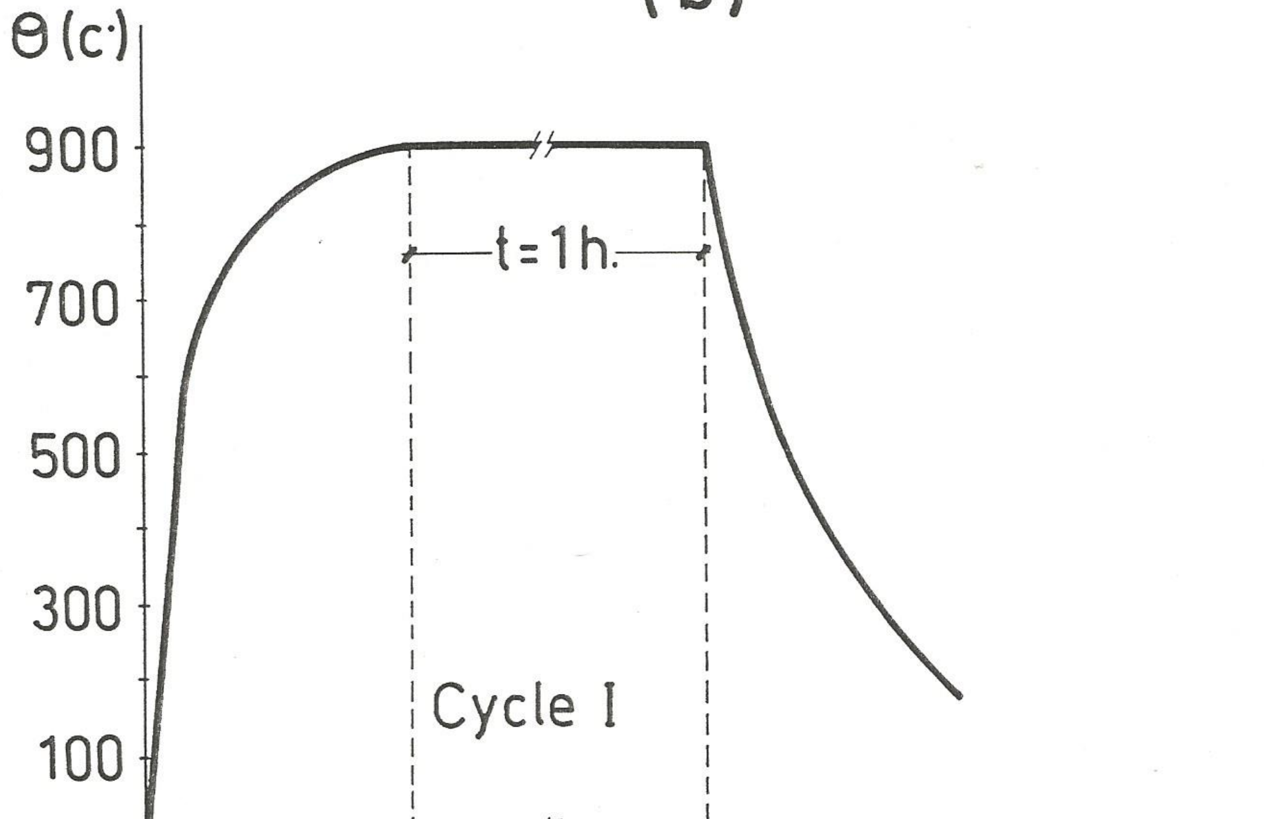
TABLE I : Texture and grain size of the material

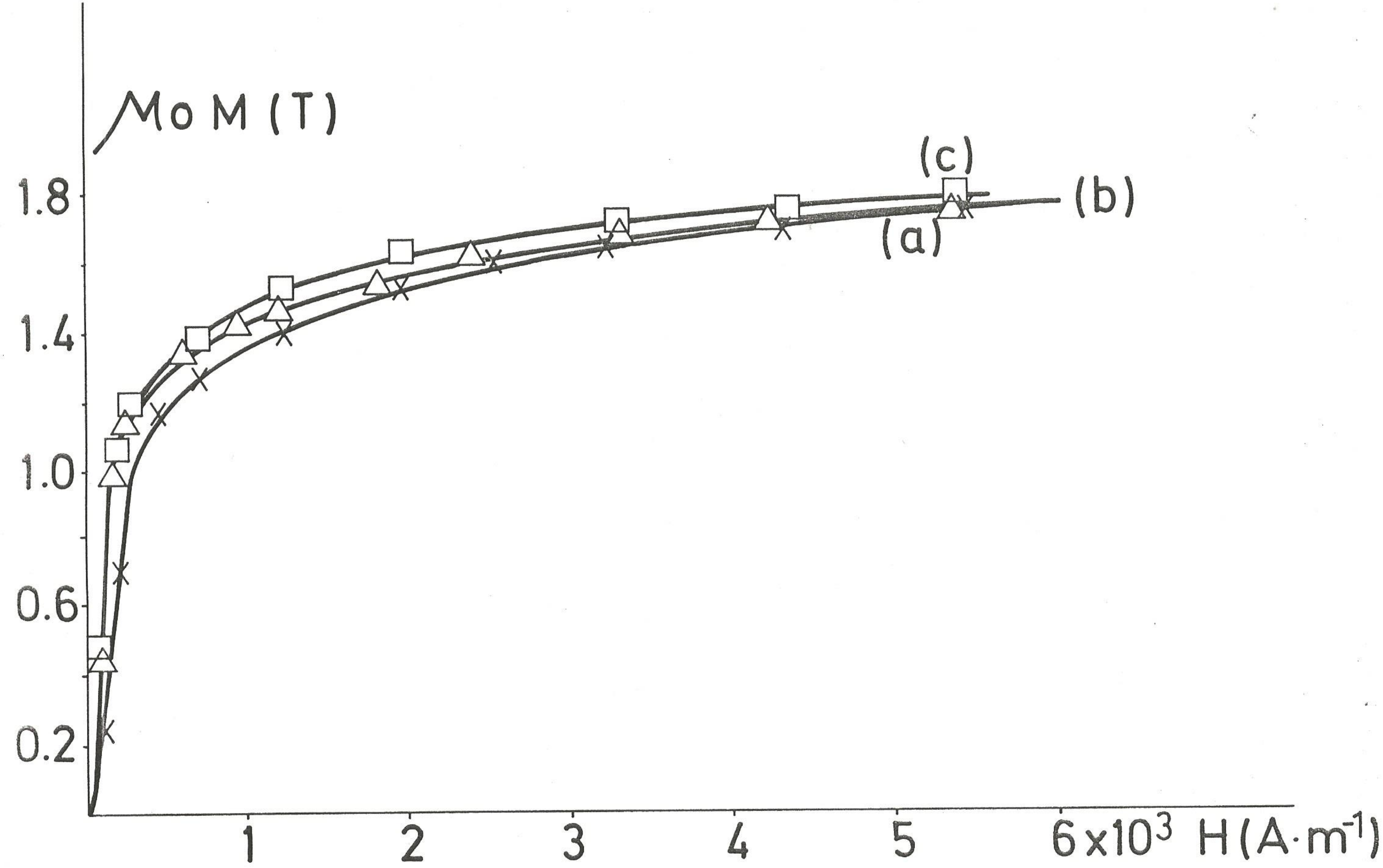
SAMPLE	GRAIN SIZE(μm)	I / Irandom					
		110	200	211	310	222	321
A . Q .	7.2	0.86	2.11	0.65	1.42	0.55	0.42
CYCLE I	140	0.16	2.76	0.16	1.96	0.00	0.96
CYCLE II	190	0.16	2.72	0.28	2.63	0.00	0.21
CYCLE III	120	1.54	2.14	0.14	1.64	0.00	0.53


θ(c°)
900
700
500
300
100
t
t = 1h. . . . Cycle II
t = 10min. Cycle III
0
2
4
0
2
4
t (h)

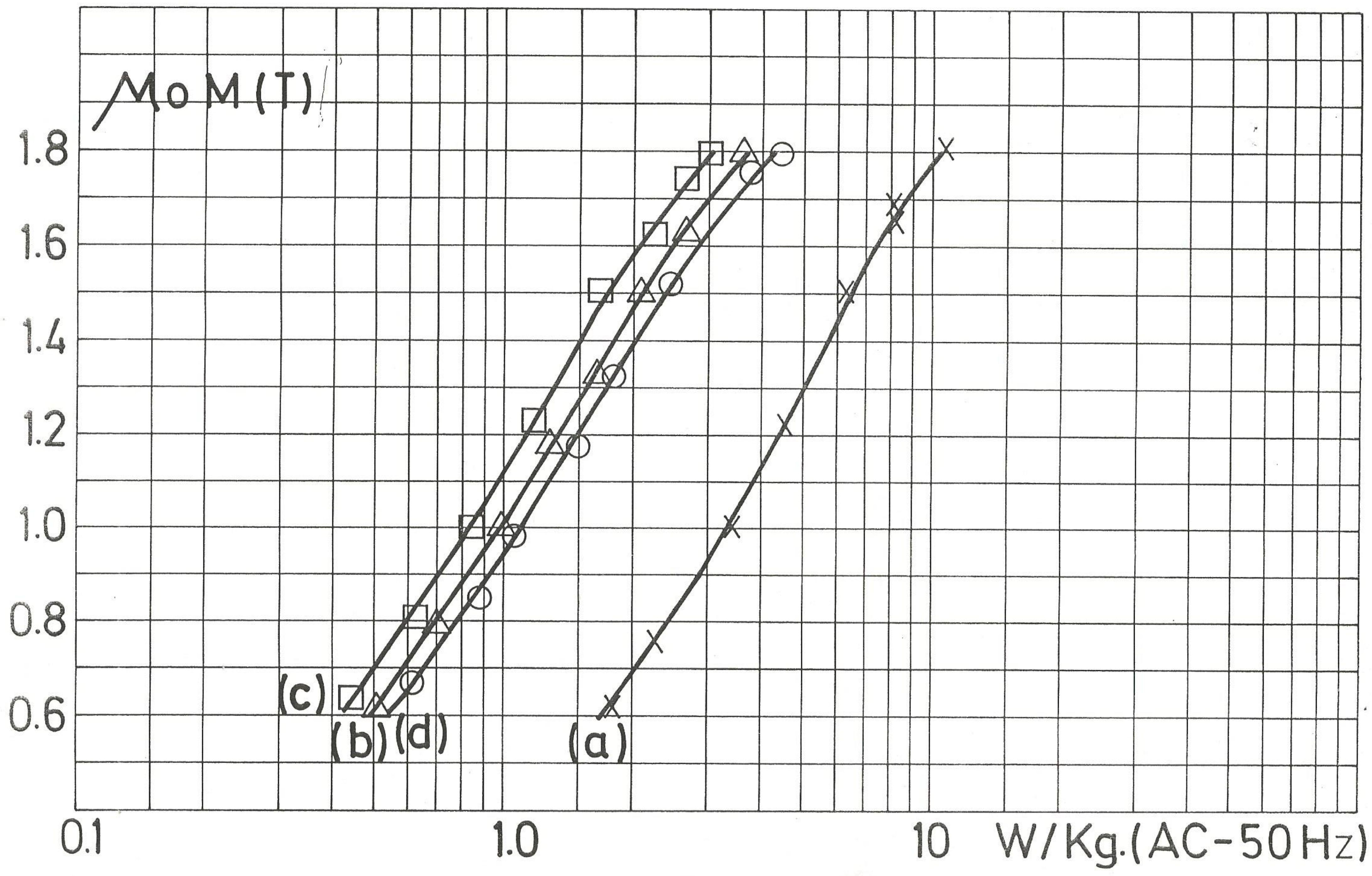
(b)


θ(c°)
900
700
500
300
100
t = 1h.
Cycle I
0
2
6
0
2
6
t (min.)

(a)



μoM (T)
1.8
1.4
1.0
0.6
0.2
(c)
(b)
(a)
1
2
3
4
5
6x10³ H(A·m⁻¹)



MoM (T)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
(c)
(b)
(d)
(a)
0.1
1.0
10
W/Kg.(AC-50Hz)

CAPTIONS

Fig. 1 Annealing cycles applied to the material; (a) Cycle I, (b) Cycles II and III. (Atm.: vacuum, $P_{heating\ step} \approx 5.\ 10^{-5}$ mbars, $P_{soaking\ step} = 2.\ 10^{-6}$ mbars)

Fig. 2 Magnetization curves (a) As - quenched, (b) Cycle I, (c) Cycle II

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