

ELECTROMAGNETIC NONDESTRUCTIVE EVALUATION OF SURFACE DECARBURIZATION  
ON STEELS : FEASIBILITY AND POSSIBLE APPLICATIONS

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INTRODUCTION

The need of a nondestructive testing of surface decarburization on steels is very high, since, at the present time, only destructive methods (such as optical micrography, hardness tests or chemical analysis) are industrially used to cope with what turns out to be a particularly important problem on grades with high security requirements, due to a resulting lower fatigue strength.

Electromagnetic techniques appear to be suitable to answer the question, since they are surface techniques and show a very high sensitivity to microstructure [1], [2].

The study presented in this communication can be split in several stages, each one corresponding to a profile of carbon concentration (cf. Fig. 1). Stage 1 is a knowledge stage: it consists of observing the response of each technique on a homogeneous sample, in order to obtain reference curves. Stage 2 is a feasibility study performed on specimens with the simplest possible structure gradient, i.e. two distinct layers. Artificial samples displaying a total surface decarburization with no transition with the bulk structure were used for this part of the study. Stage 3 consists of the study of industrial samples and aims to define the possibilities of application in the real testing conditions.

METHODS OF TESTING

Description

Two electromagnetic techniques have been used : Barkhausen noise and incremental permeability.

The principles underlying these techniques are rather well known now and will not be recalled here. A detailed description of them can be found in references [1] and [3]. Both methods have in common the use of an external, low frequency (typically 0.1 Hz) magnetic field.

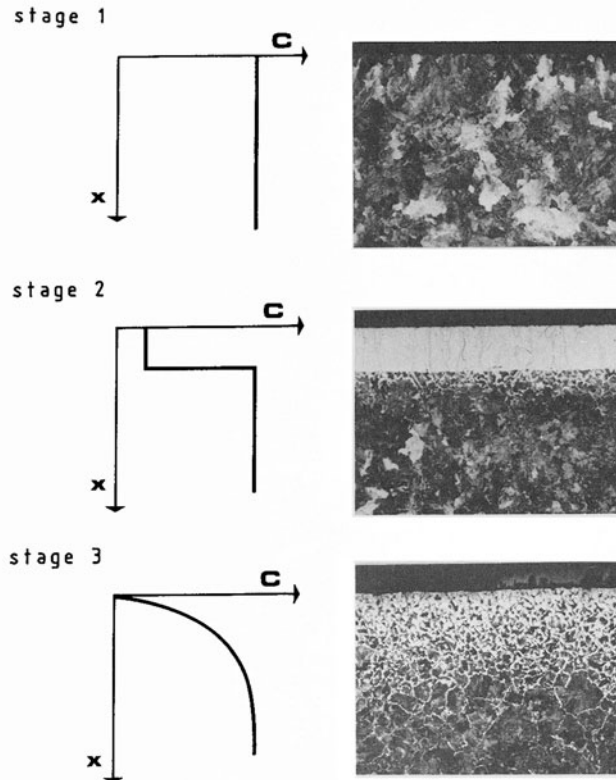


Fig. 1 - Carbon concentration profiles for the different stages of the study.

Figure 2 shows the diagram of both set-ups. It can be seen that the measuring head is the same for each one. This, which can be conceived either for cylindrical or for flat products, ensures three functions (cf. Fig. 3):

- creation of the magnetic field from the power supply through a magnetizing coil and a Fe-Si yoke,
- measurement of the magnetic field with a coil connected to a fluxmeter or a Hall probe connected to a Teslameter,
- measurement of the useful signal through a pick-up coil.

The difference between the two techniques comes from the useful signal. In the case of Barkhausen noise, the pick-up coil has an exclusively receiving function. Once the bearing frequency has been eliminated by a high-pass filter, only the noise remains. This noise is then amplified and rectified and its envelope is taken to provide the useful signal. Barkhausen noise is essentially a wide-band noise, but it can be analysed in well-defined frequency bands through the use of a band-pass filter. All the operations following the measuring head are achieved by the Barkhausen noise equipment built at IRSID. The maximum analysis frequency band is 200 Hz, 300 kHz.

For incremental permeability measurements, the pick-up coil has an emitter/receiver function. (A two-coil system, with separate emission and reception, can be used as well). A sine-shaped, high-frequency current is injected into the coil, the impedance of which is measured by

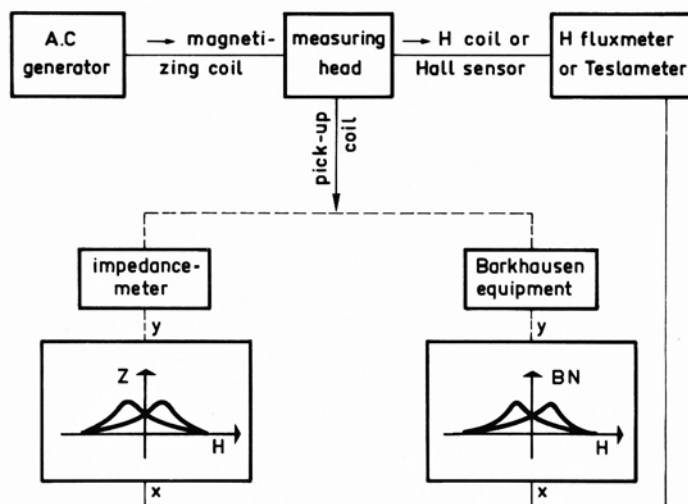


Fig. 2 - Block-diagram of Incremental permeability and Barkhausen noise set-ups

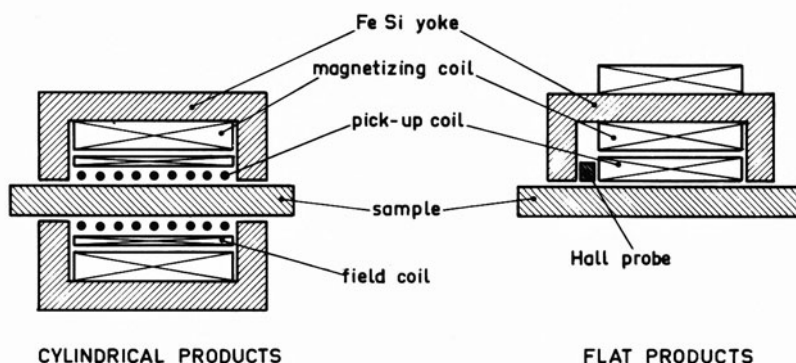


Fig. 3 - Measuring heads

means of a vector-impedance meter or a lock-in amplifier. An incremental permeability test can thus be described as an eddy current measurement performed under an applied magnetic field.

#### Characteristic Curves

Curves obtained from the measurements are of the form  $S = f(H)$  when  $H$  goes through a magnetization cycle ( $H$  being the external magnetic field).  $S$  is the useful signal and is either processed Brakhausen noise  $BN$ , or the impedance  $Z$  of the detecting coil, according to the technique employed.

In both cases, on a homogeneous sample, the curves are identical (cf. Fig. 4). They display one maximum per half-cycle. This maximum is reached for a value of the magnetic field which turns out to be, for carbon steels, very close to the coercive field  $H_c$ , which is tightly correlated to the material mechanical hardness [4], [5], [6]. It already can be seen that a pearlitic sample, being much harder mechanically, will be very easily distinguished from a ferritic sample.

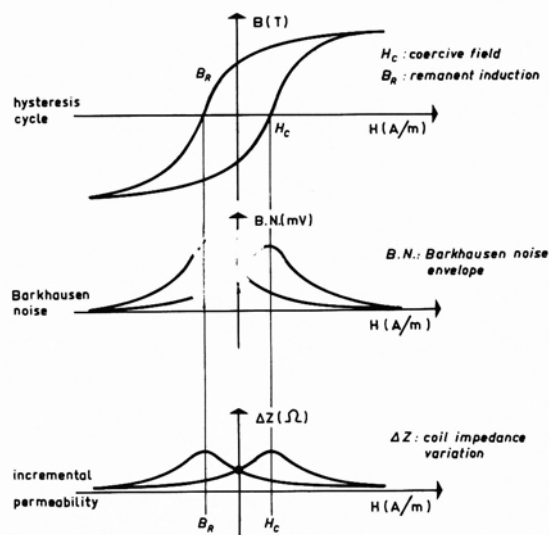


Fig. 4 - Characteristic curves obtained on a homogeneous sample

#### FEASIBILITY STUDY (ARTIFICIAL SAMPLES)

During this stage, corresponding to the second profile in Fig. 1, it has been attempted to solve two problems: first, the detection of the occurrence of a total decarburization, then the evaluation of the decarburized depth.

##### Decarburization occurrence detection

Both techniques have once again a similar behavior : the characteristic curve of the decarburized specimen appears as the superimposition of the curves of each homogeneous layer. This fact is particularly blatant when the comparison is made with the curves obtained on the unaffected pearlitic samples (cf. figure 5). The two-layered specimen curve can thus be described as a two-peak structure including :

- a ferrite peak ( $H \approx 100$  A/m)
- a pearlite peak ( $H \approx 600$  A/m for 0.8 % carbon steel)

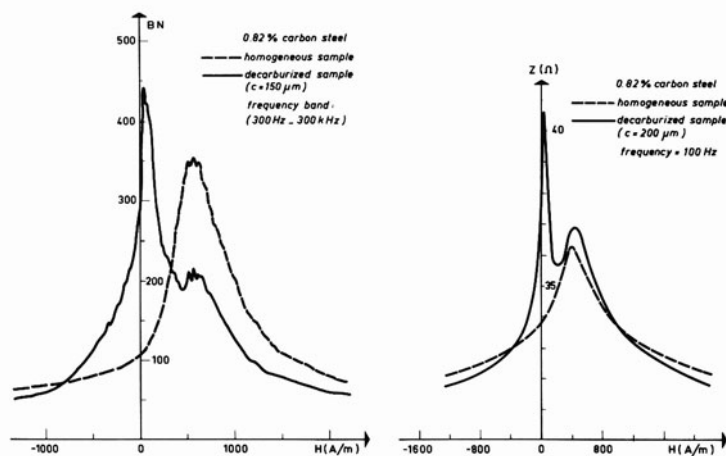


Fig. 5 - Characteristic curves obtained on a two-layered sample

## Decarburized depth evaluation

Both techniques, involving electromagnetic phenomena induced either by an alternating current or directly by the applied magnetic field, display a skin depth effect. The standard depth of penetration, defined as

$$\delta = \frac{1}{\sqrt{\pi} \mu_0} \sqrt{\frac{\rho}{f \mu_r}},$$

is usually a fairly good representation of actual phenomena. It can be seen that  $\delta$  is proportional to  $1/\sqrt{f}$ . Consequently, when the frequency is increased, a smaller and smaller thickness is taken into account. Over a certain frequency  $f_0$ , this thickness will be integrally included in the upper layer and the response of a homogeneous sample will be obtained.

A question still arises: what is frequency to be varied? The answer is quite simple for incremental permeability where measurements are made at a unique, well-defined frequency. On the other hand, Barkhausen noise analysis takes place over a whole range of frequencies. The noise emitted by the most distant points will be very attenuated when it comes to the detector and only its low-frequency components will pass through. On the other hand, for very close subsurface points, most of the noise will be detected. The resulting noise will thus consist of low-frequency components representative of a certain thickness and in high-frequency components only dealing with the nearest points. This shows that the actual penetration depth is fixed by the lowest frequency of the analysis band.

It can be seen in Fig. 6 how the curves evolve with frequency: when it increases, the pearlite peak progressively disappears, and the curve tends towards the "homogeneous ferrite" curve. From this observation, different criteria of determination of  $f_0$  may be selected: in this simple case, we chose the disappearance of the secondary maximum.

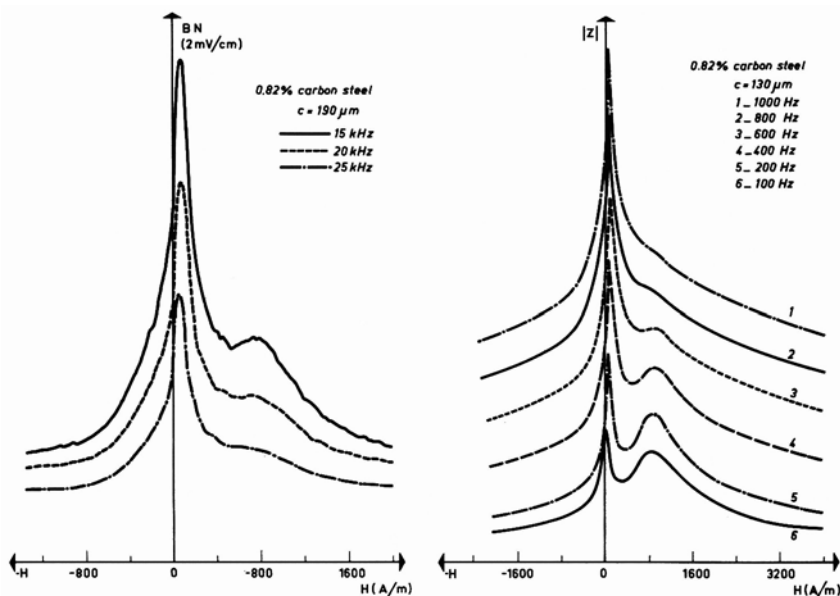


Fig. 6 - Evolution of the characteristic curves with the test frequency

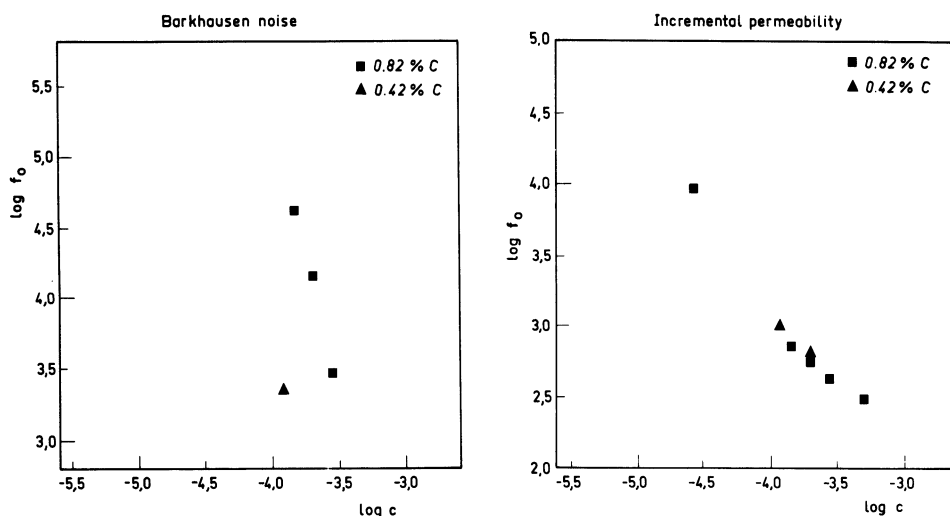


Fig. 7 - Relationship between  $f_0$  and the upper layer thickness. The scale is logarithmic.

In Fig. 7,  $f_0$  is represented vs.  $c$ , thickness of the upper layer, for specimens representing 2 bulk carbon concentrations (0.82% and 0.42%), and depths varying from 30  $\mu\text{m}$  to 500  $\mu\text{m}$ . Incremental permeability shows a good correlation, independently from the grade. With Barkhausen noise, some points are missing, due to the impossibility to determine  $f_0$ . For the higher (resp. lower) thicknesses,  $f_0$  would be under (resp. over) the limits of the maximal frequency band. This technique appears thus to be more depth-sensitive, but on smaller ranges of values. Due to the small number of points available, it is difficult to tell how good the correlation is, but the result seems to be grade-dependent.

#### APPLICATION TO INDUSTRIAL SAMPLES

The main characteristic of industrial samples is a progressive profile of decarburization (cf. Fig. 1). These profiles may be very diverse and so are the curves  $S = f(H)$ . A trend remains constant, though: all curves tend towards the "homogeneous ferrite" curve for very high frequencies (for samples totally decarburized in surface). Two conclusions may be drawn from these observations [3]

- Every single application will require a specific treatment
- The main problem will arise from the choice of the criterion of determination of  $f_0$ .

It should be noted that the presence of scale on the sample surface does not seem to affect the measurements very much.

In order to foresee a possible industrial application, we studied the case of plates used for the manufacture of springs. Four different grades were tested that way.

In contrast to the previous stages of the study, the two techniques show a different behavior. With Barkhausen noise (cf. Fig. 8), the ferrite and pearlite peaks remain distinct, the ferrite peak being always the more intense. This last fact is not surprising, since the near-surface ferritic zone emits Barkhausen noise in the whole analysis frequency band, while, for deeper zones, only low-frequency components manage to reach the detector. A raise in frequency results in a behavior analogous to the one of the artificial samples used in stage 2. Hence,

the same criterion can be chosen to determine  $f_0$ , namely the disappearance of the secondary maximum.

With incremental permeability (cf. Fig. 9), the progressive aspect of the decarburization profile is translated on the curves and the two peaks are not necessarily distinct. When the frequency is raised, the absolute maximum goes from the "pearlite" position to the "ferrite" position. This transition did not appear to us, however, as a valuable criterion to determine  $f_0$ , since it is subject to change from one sample to another. Sometimes inside the same grade, one can find a two-peak pattern as well as a flat feature including both of them. Furthermore, it does not take into account the shift towards homogeneous ferrite, since the pearlite peak remains present as a "bump". When the frequency is raised further, this bump disappears: this corresponds to a displacement of the inflexion point, i.e. the derivative minimum (cf. Fig. 10). This transition occurs at a rather well-defined frequency that can be chosen as  $f_0$ .

$f_0$  has then been plotted vs.  $P_{max}$ , maximum depth of decarburization on the sample width, measured by optical micrography (cf. fig. 11).

The Barkhausen noise curve has been obtained for 2 relatively similar grades. For the left two grades, the secondary maximum is already absent with the maximal band [200 Hz, 300 kHz] : one faces the same grade dependence as on artificial samples. For the available points, the correlation is good and the curve is rather steep. For the larger depth (350  $\mu m$ ),  $f_0$  is smaller than 200 Hz, since the secondary maximum has already disappeared with the totality of the frequency band.

In incremental permeability, the correlation is valid for all grades. Every encountered depth (from 90  $\mu m$  to 650  $\mu m$ ) yields a point. On the other hand, the resolution is not so fine as in Barkhausen noise.

Each technique has thus a behavior which is similar to the one observed on artificial samples (cf. stage 2), though the criteria of choice of  $f_0$  may be different.

Limitations on the depths detectable by each method can be evaluated by extrapolating the curves, considering the frequency limitations of the devices. In Barkhausen noise, the high band frequency being

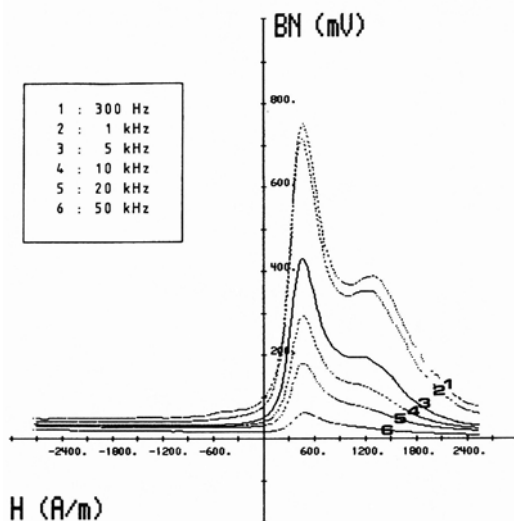


Fig. 8 - Industrial sample : Evolution of Barkhausen noise curves with test frequency

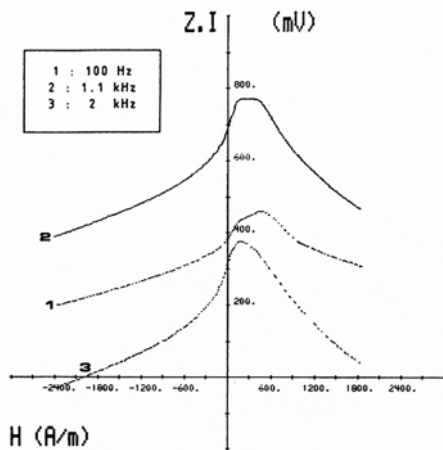


Fig. 9 - Industrial sample: Evolution of incremental permeability curves with test frequency.

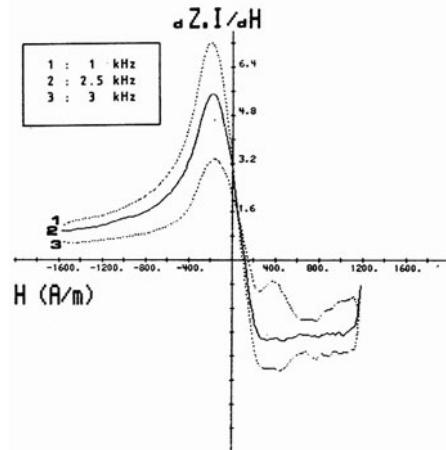


Fig. 10 - Industrial sample: Evolution of the derivative of incremental permeability curves with test frequency.

fixed to 300 kHz, the maximal low band frequency can be considered to be 50 kHz (over this value, the noise amplitude is too small to be analysed). The minimal low band frequency is, as already seen, 200 Hz. This yields a range of depths going from  $70\text{ }\mu\text{m}$  to  $300\text{ }\mu\text{m}$ . In incremental permeability, the instruments limits are roughly 50 Hz and 30 kHz, which corresponds to depths between  $80\text{ }\mu\text{m}$  and  $1.25\text{ mm}$ .

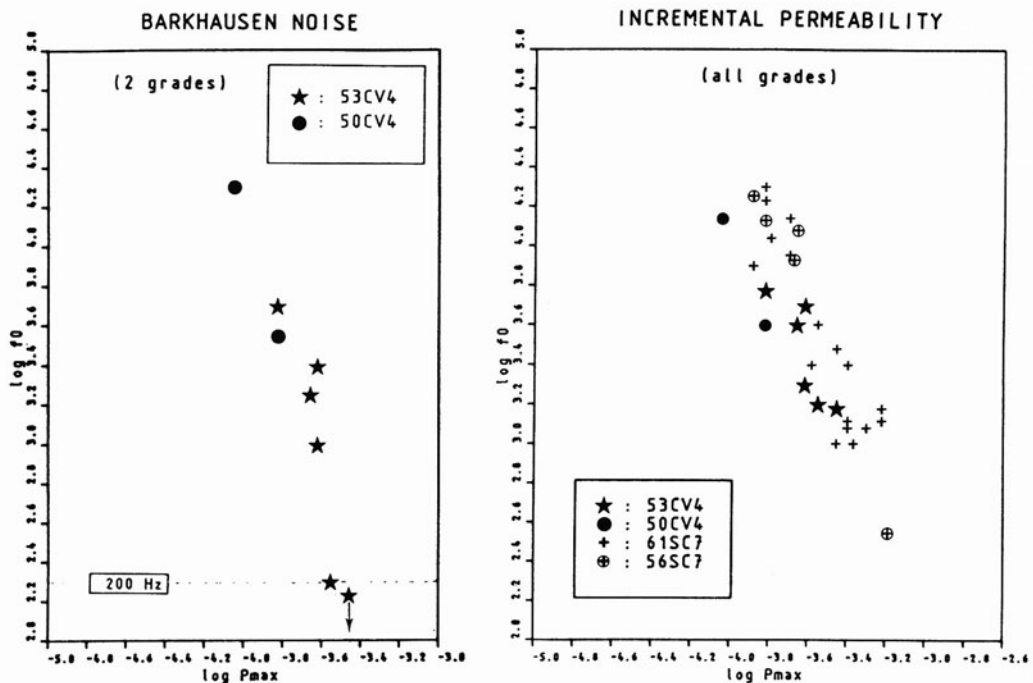


Fig. 11 - Relationship between  $f_0$  and the decarburized depth



## CONCLUSION

The Barkhausen noise and incremental permeability non-destructive techniques allow, thanks to the application of an external low-frequency magnetic field, detection of surface decarburization on steels. Due to the skin depth effect, it is possible to evaluate the decarburized thickness by varying the analysis frequency.

Tests performed on industrial spring plates specimens confirm the trends observed on artificial two-layered samples : Barkhausen noise allows a fine evaluation of the decarburized depth, but on a rather restricted range of values and with a strong dependence on the grade, while incremental permeability gives a rougher estimation but on a wider range (80  $\mu\text{m}$  to 1.25 mm), and independently of the grade.

## REFERENCES

1. S. Segalini, M. Mayos, M. Putignani, "Utilisation de methodes magnetiques pour le controle de la microstructure des aciers" (in French), M. E. S. Revue de Metallurgie, 10 (1985), 569.
2. S. Tiitto, "On the influence of microstructure on magnetization transitions in steel", in: Acta Polytechnica Scandinavica, Appl. Physics Series, 119, Helsinki (1977).
3. M. Mayos, M. Putignani, S. Segalini, "Nondestructive testing of Surface decarburization on steels", RE 1203 IRSID, (1985). Submitted for publication in "Materials Evaluation".
4. W. Theiner, B. Reimringer, P. Deimel, D. Kuppler, D. Schroeder-Obst, "Nondestructive analysis of the structure of pressure-vessel steels by micromagnetic techniques" in: Fracture behavior and NDT, Stuttgart, 251 (1982).
5. K. Goebbels, W. Theiner, "Zerstörungsfreie Analyse der Gefüge und Spannungszustände in metallischen Werkstoffen" (in German), Material-prüfung, (March 1985), 64.
6. S. Segalini, M. Mayos, M. Putignani, "Heat treatment evaluation by means of magnetic methods", Soft Magnetic Materials 7, (1985).