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INFLUENCE OF SURFACE ROUGHNESS ON NON-DESTRUCTIVE MAGNETIC MEASUREMENTS

G. Vértesy*[1], A. Gasparics [1], I. Uytdenhouwen[2] & R. Chaouadi[2]
[1]Centre for Energy Research, Budapest, Hungary
[2]SCK•CEN Belgian Nuclear Research Centre
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ABSTRACT
Surface roughness affects the magnetic non-destructive testing methods and limits their applicability for testing deeper material regions. This paper presents the results of an experimental study targeting nuclear reactor materials. Samples made of nuclear reactor vessel steel were fabricated with various manufacturing parameters to produce different surface roughness conditions and their describing parameters were determined by a standard measuring device. Magnetic measurements were performed on these samples, series of permeability loops were recorded by the help of a magnetizing yoke attached to the sample surface. Good monotonous correlation was found between the surface roughness parameters and the obtained magnetic characteristics. It is also shown that by applying an adequately chosen nonmagnetic spacer, which is placed between the magnetizing yoke and sample surface, the disturbing influence of the surface roughness can be significantly reduced. This way, even the degradation of samples having different surface conditions can be reliably determined.

Keywords: Nondestructive testing, Magnetic hysteresis, Magnetic adaptive testing, Surface rougness.

INTRODUCTION
Magnetic measurements can be successfully applied for the characterization of structural changes in ferromagnetic materials, because magnetization processes are closely related to their microstructure [1,2]. The magnetic approach is a promising candidate for non-destructive testing, for detection and characterization of any defects or any structural degradation in materials and in products made of ferromagnetic materials. A special way of magnetic measurements, the traditional hysteresis methods, has been applied since long time for non-destructive inspection of materials. A number of techniques have been suggested, developed and currently used in industry, see e.g. [3-5]. They are mostly based on the detection of structural variations via the classical parameters of major hysteresis loops. Several successful measurements were published, which proved practical applicability of magnetic hysteresis methods for the quantitative indication of the embrittlement of steels.

A promising method for the measurement and evaluation of the steel degradation is the method of Magnetic Adaptive Testing (MAT). This method is based on a systematic measurement and evaluation of minor magnetic hysteresis loops[6,7]. This is a *multi-parametric, highly sensitive and robust procedure* of magnetic "structures copy" introduced recently. As an example, in a previous work [8] we measured three series of Charpy samples, made of JRQ,15CH2MFA and 10ChMFT type steels by MAT. The samples were irradiated by E>1 MeV energy fast neutrons with total neutron fluence ranging between 1.58×10^{19}–11.9×10^{19} n/cm^2. Regular correlation was found between the optimally chosen MAT degradation functions and the neutron fluence in all three types of the materials. In another work [9], Charpy samples made of 15Kh2NMFA and of A508 Cl2 type material were thermally treated by a special step cooling procedure, which caused structural modifications in the material. Charpy impact tests were performed and the results were compared with the magnetic parameters. A good, linear correlation was found between the properly chosen MAT degradation function and transition temperature in case of 15Kh2NMFA type material. However, no similar correlation was found in case of A508 Cl2 type material. The most probable reason is, that this thermal treatment was optimized for 15Kh2NMFA type material, and A508 Cl2 type material requires different treatment.

Magnetic measurement of flat samples, which cannot be magnetized (and/or closed magnetically) in any better way than by an attached magnetizing/sensing soft yoke, set into direct contact with the sample surface, suffers often from the fluctuation of quality of the magnetic coupling between the sample and the yoke. This is a well-known problem, in particular with unpolished surfaces, which can be improved by using an as large as possible yoke or by the application of a spacer between the yoke and the sample. However, the dimensions of the applicable yoke are limited due to the sample geometry. In addition, an applied thin nonmagnetic spacer decreases and distorts the measured signal substantially, so that measurement of basic magnetic parameters of the sample material is very difficult in this way, or impossible at all. Nevertheless, spacers are quite applicable for magnetic "structures copy", i.e. for magnetic measurement of relative structural changes of ferromagnetic construction materials, especially if the measurement is carried out by a method analyzing the measured signal (permeability function) like it is done e.g. in the Magnetic Adaptive Testing. The use of spacers was demonstrated in [10]. Samples of gradually increasing brittleness were prepared from ferromagnetic steel in the shape of rectangular prisms. Material for the samples was embrittled by thermal processing. Quality of surfaces of the samples corresponded to their ordinary machining (milling) and grooves from the milling or even scratches were visible on some of them. No polishing of the surfaces was performed, some surfaces were evidently worse than others. The yokes were attached to surfaces of the samples either directly, or over a thin spacer. It was found that the unwanted influence of the rough surface can be reduced by using a nonmagnetic spacer. Of course, the spacers dump and modify the shape of the measured signals, but they substantially reduce the scatter of experimental points accompanied by a slight decrease of the overall degradation functions sensitivity. Spacers, in particular if they are thick, are able to modify the shape of the measured signals qualitatively and to bring about considerable increase of sensitivity, especially in the degradation functions computed from the signal derivatives.

The useful role of the nonmagnetic spacer in magnetic non-destructive testing was demonstrated in the above mentioned work by measuring a series of samples having different degradation levels. In the present work, the direct quantitative influence of the surface roughness on the measured magnetic permeability is studied on one side, and the influence of the spacer on the evaluated MAT descriptors on the other side. Measurements were performed on a series of specimens made of the same material (without any material degradation) having different surface roughness. This work aims to investigate whether a correlation can be found between surface roughness and magnetic behaviour, and further evaluate the role of spacer to reduce the effect of surface roughness.

SAMPLE PREPARATION

Six samples made of 22NiMoCr37 material were fabricated at SCK•CEN. The samples have the standard Charpy sample dimensions (10x10x55 mm^3), but without V-notch. The samples were fabricated with various manufacturing parameters to produce different surface states, one being similar to the machining in controlled area on irradiated samples. Samples have aL-T orientation, engraving was made on one side. Only the top and the bottom of the sample received the different surface states. All other sides were manufactured similar to sample 23. A photograph showing the six investigated samples is shown in Fig. 1. Sample 23 (left side) is the reference one, representing the surface manufacturing conditions with normal parameters. Sample 28 (right side) is different from samples 24-27, the character of the surface roughness is different.It is a consequence of EDM (electrical discharge machining) which puts a layer of brass on the surface and has a small damaged (micro-crack) and heat affected surface.

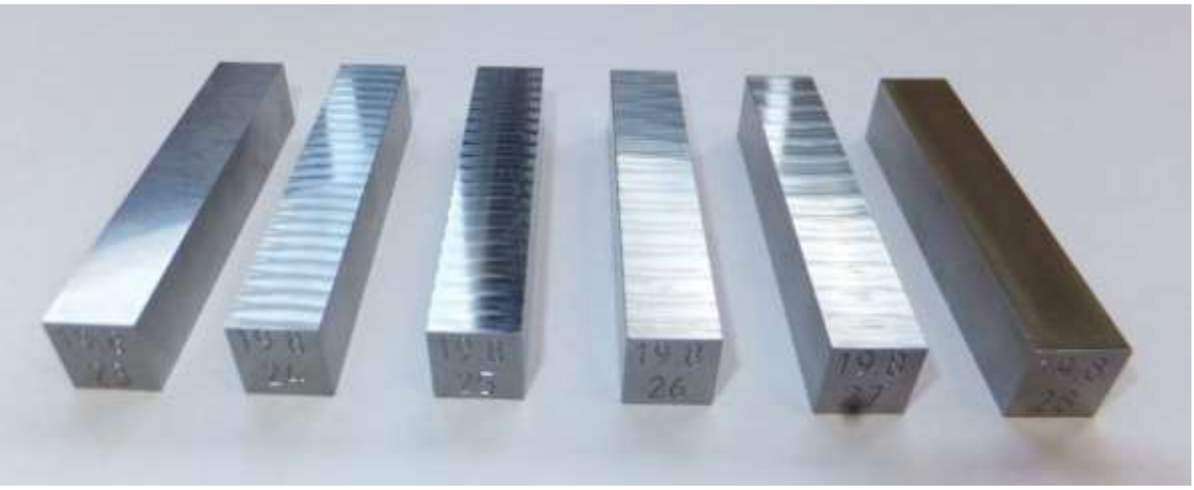

Fig. 1: The investigated samples having different surface roughness conditions

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Surface roughness was measured by an Accretech Handysurf Tokyo Seimistsu E-35B measuring device. Cut-off value was 0.8 mm, evaluation length was 4 mm, and automatic measuring range was applied. The corresponding surface roughness parameters are shown in Table 1., where

$\boldsymbol{R_a} = \frac{1}{L}\int_0^L |\boldsymbol{Z(x)}|\, \boldsymbol{dx}$ is the arithmetical mean deviation for sampling length: ***L***,

and$\boldsymbol{R_z} = \boldsymbol{R_p} + \boldsymbol{R_v}$is themaximum height of profile, where R_p is the maximum peak, R_v is the minimum peak values,

and$\boldsymbol{R_{Sm}} = \frac{1}{m}\sum_{i=1}^{m} \boldsymbol{X_{si}}$is the mean width of the (periodic) profile elements (X_s), where $\sum_{i=1}^{m} \boldsymbol{X_{si}} = \boldsymbol{L}$.

Table 1.Surface roughness parameters of the investigated samples

Sample No.		**23**	**24**	**25**	**26**	**27**	**28**
RPM	[t/min]	1000	500	600	500	600	
Feed	[mm/min]	75	1200	1700	2000	2500	
Lateral offset	[mm]	0,1	0,1	0,1	0,2	0,25	
R_a	[µm]	0,13	0,49	0,33	0,73	0,61	3,65
R_z	[µm]	0,83	2,33	1,59	3,9	3,3	19,56
R_{sm}	[µm]	77,6	129,1	244,3	382,2	195,3	127,3

Parameters R_a and R_z are dependent on each other, as can be seen in Fig. 2. So the magnetic parameters can be considered only as a function of $R_a$in the following figures. The character of the correlation between magnetic parameters and R_z is the same, only the numerical values are different.

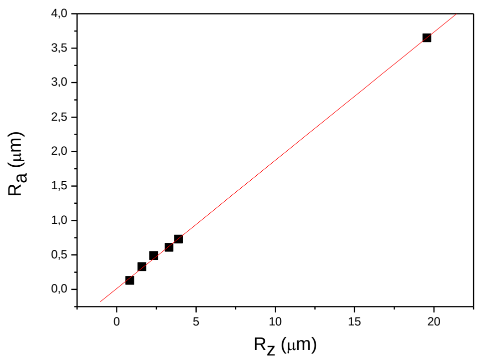

Fig. 2: Surface roughness parameter R_a as a function of R_z

MAGNETIC MEASUREMENTS

Magnetic adaptive testing measurements were performed on the above mentioned samples. In the experiment – by applying a magnetizing yoke put on the surface of the sample which magnetizes the specimen – the differential magnetic permeability is measured and then evaluated. The size of the sample determines the size of the magnetizing yoke, which is a C-shaped laminated Fe-Si transformer core. In our measurements, the cross-section of the yoke was 10mm x 5mm, the total outside length was 18 mm, and the height of the yoke was 22mm. Magnetization was made by a magnetizing current, led into the 100 turns magnetizing coil, wound on the bow of the yoke. Voltage output signal was detected by a 50 turns pick-up coil, wound the yoke leg. A triangular waveform magnetizing current was applied. The slope of the current (time variation) was fixed and its amplitude was increased step by step. The output signal is proportional to the differential permeability if the magnetizing current increases linearly with time. In our measurements, shown below, the slope of magnetizing current was 0.1250 A/s in all cases.

The measured permeability loops are presented in Fig. 3 for all investigated 22NiMoCr37 steel samples. The sets of minor loops with step-by-step increasing amplitude are clearly visible. These measurements were made from the top side of the samples. Comparing the measurements performed on top and bottom sides, it is seen that there is a slight difference in the maximal value of permeability depending on the measured side but the difference is not significant. It reflects the uncertainty of manufacturing grooves rather than the error of the magnetic measurement. In the following evaluation both results (measured on the top and on the bottom sides of the same sample) will be considered. (This is the reason, why two different points appear at each R_a and R_{sm} values.)

First, it is evident from the measured permeability loops that a significant influence of the surface roughness can be detected. The maximum value of permeability loops decreases dramatically withsamples having a rougher surface (see Fig.4). This fact itself is not surprising and was expected. In the next sections, the correlation is analyzed and it is investigated if the influence from the surface roughness can be reduced by applying a nonmagnetic spacer.

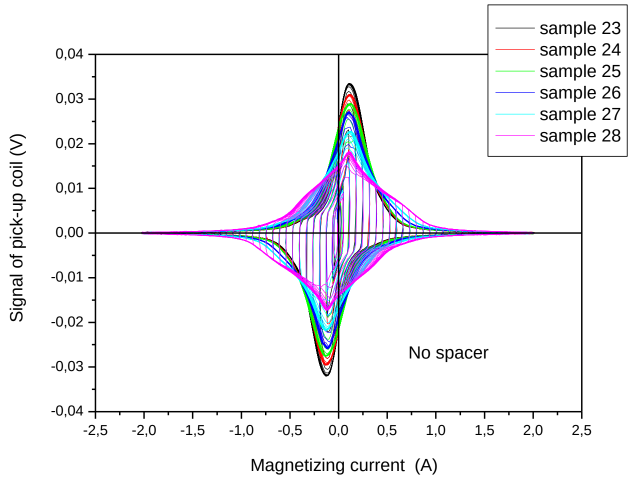

Fig. 3: Series of permeability loops measured on the top sides of the samples.

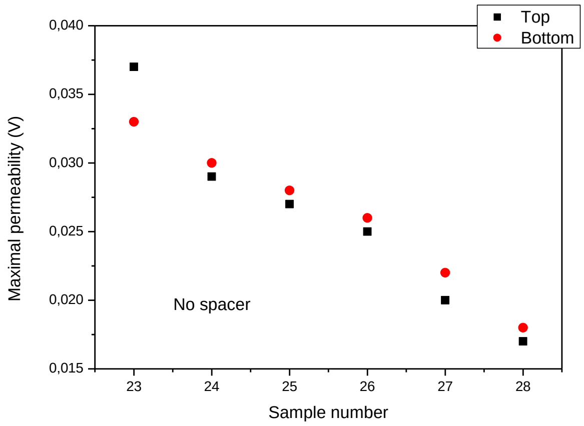

Fig 4: Maximal permeability values of the investigated samples, as can be determined from the top of permeability loops of Fig. 3. The difference between top and bottom sides are demonstrated.

CORRELATION BETWEEN SURFACE ROUGHNESS AND MAGNETIC PARAMETERS

Permeability matrices were evaluated from the series of measured minor hysteresis loops, and each element of the matrices was normalized by the corresponding element of the reference sample 23. Alarge data pool was generated and the optimal matrix elements, which characterize the best modification of magnetic behaviour, were selected. Details of magnetic adaptive testing evaluation is described in detail in [7]. In Fig. 5, the optimally-chosen normalized elements of permeability matrix are given as a function of R_a. A very similar correlation was found for R_z as well, but it is not shown here, as explained above. Optimally chosen MAT descriptor means that this parameter gives the best correlation between magnetic characteristics and the roughness parameter. In this case the optimally chosen MAT descriptor is the (F100A1150) parameter, where the magnetizing field, *F*, is 100 mA and the minor loop amplitude, *A*, is 1150 mA.

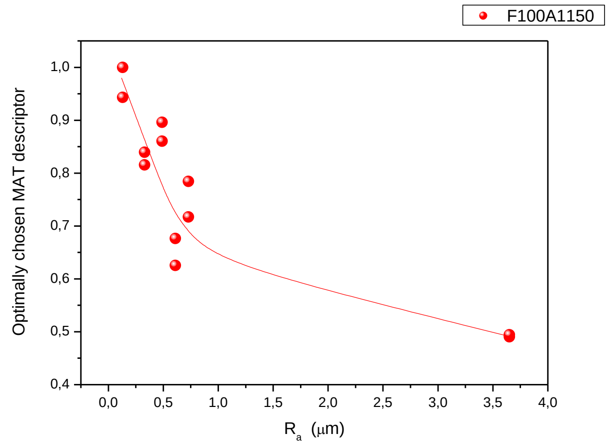

Fig. 5: The optimally chosen MAT descriptor for characterizing the correlation with R_a surface roughness parameter

This parameter is taken from the area where the permeability has the maximal value. It is corresponding to the peak values of Fig. 3. It can beseen that the magnetic parameters change by more than 50%,compared with the reference sample. Adirect quantitative correlation between the magnetic behaviour and the surface roughness was obtained. Our purpose was to investigate the influence of surface roughness on the magnetic parameters, but in the light of our result – considering the unambiguous monotonous correlation between these quantities – it would be also possible to derivethe surface roughness from magnetic parameters and to substitute the measurements of R_a and R_z. The solid line in Fig. 3 can be considered as a calibration curve, and if the measurement is made later on a sample with unknown surface condition, R_a and $R_z$can be estimated from the magnetic measurements if experimentsare made on samples with the same material, geometry and properties.
As described for e.g. in [7], MAT is a multiparametric method: a lot of descriptors are evaluated from the measured loops. For finding a correlation between MAT parameters and the other surface roughness parameter, R_{sm}, other MAT descriptors should be chosen. Fig. 6 represents such a case where again a monotonous calibration curve between MAT descriptors and R_{sm} was found. In this case, the optimally-chosen MAT descriptor is characterized by (F400,A700) values. Here, the sensitivity is less. About 25% modification of magnetic parameters is observed in the full range of R_{sm} and the scatter of the measured points is also larger. At higher values of R_{sm}, the curve which characterizes the correlation seems to reach saturation. If we want to make a correlation between surface roughness and magnetic behaviour, R_a or R_z parameters are recommended.

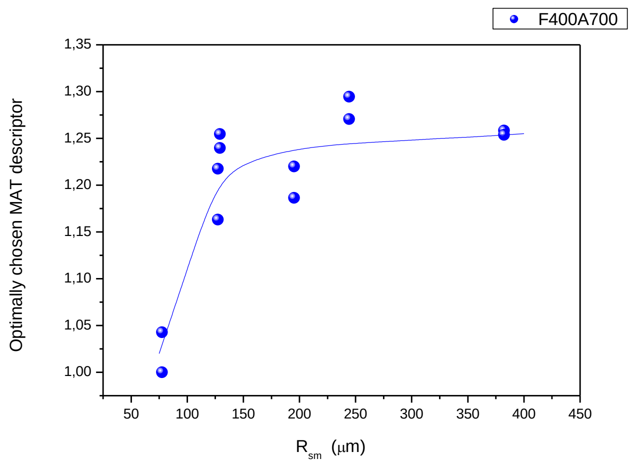

Fig. 6: The optimally chosen MAT descriptor for characterizing the correlation with the R_{sm} surface roughness parameter

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INFLUENCE OF NONMAGNETIC SPACER

The above described measurements were repeated after placing a nonmagnetic spacer between the sole of the magnetizing yoke and the sample surface. Two spacers with different thicknesses, 40 µm and 70 µm respectively, were applied. Spacers were made of a thin plastic foil.The influence of the spacer on the permeability loops measured on the reference sample can be seen in Fig.7.

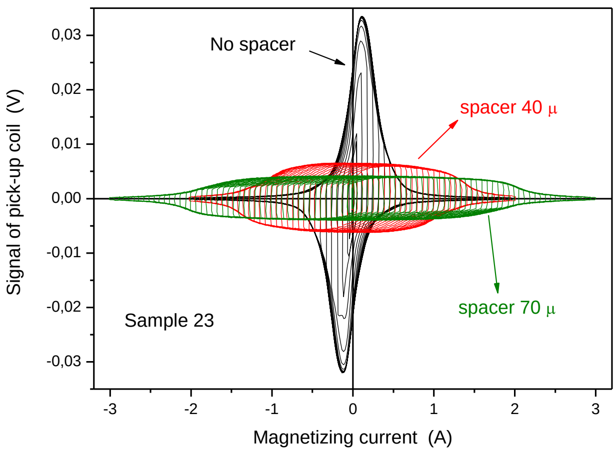

Fig. 7: Series of permeability loops measured on the top side of the reference sample for the no spacer case and for applying two spacers having different thicknesses, 40 µm and 70 µm, respectively

It can be seen very well that the introduction of a spacer decreases dramatically the measured permeability loops. This is totally in accordance with our expectations and with the previous results. Nevertheless, even in case of the 70 µm thick spacer, the permeability loops can be well recorded and MAT evaluation can be carried out without difficulties. In Fig 8, magnified permeability loops of all measured samples are shown for the two cases where spacers with various thicknesses were applied. The permeability loops can be well measured.

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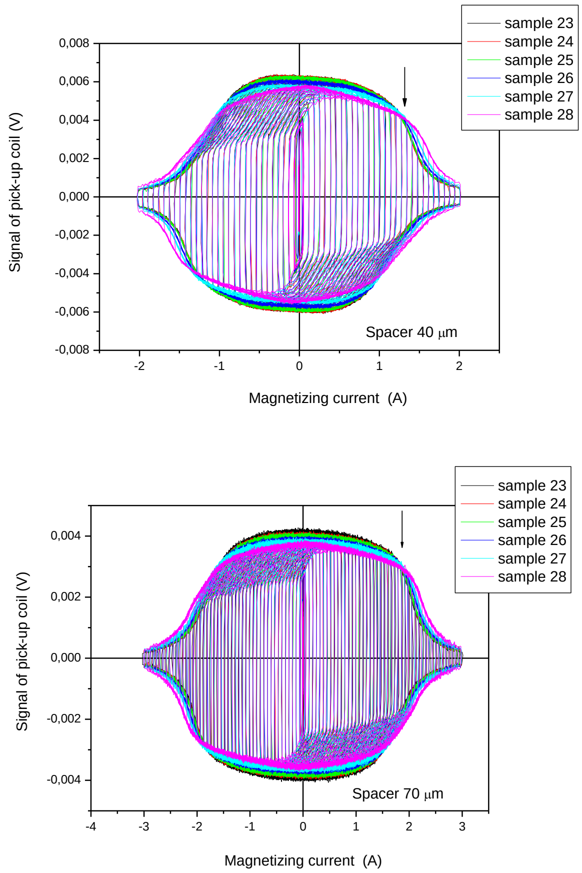

Fig. 8: Series of permeability loops measured on the top side of all samples afterapplying two spacers having different thicknesses (40 µm and 70 µm, respectively).

There is an interesting feature of these permeability loops. In a certain range of magnetizing current, the measured permeability seems to be independent on the used sample. This range is around 1250 mA if 40 µm thick spacer is applied, and about 1850 mA in the case of 70 µm thick spacer. These areas are indicated by arrows in Fig. 8. In other words, the permeability in this range does not depend on the surface roughness.Thiscan be even better seen if the MAT descriptors are considered, as done in Fig. 9. The properly chosen MAT descriptors do not depend on the surface roughness. It is valid for both thicknesses: if 40 µm thick spacer is applied, the dependence is very limited, and if 70 µm thick spacer is applied the fitting line is totally horizontal.

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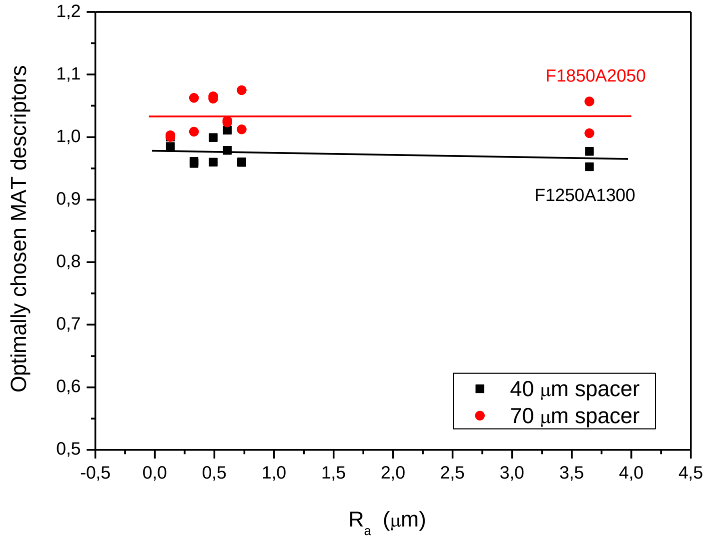

Fig. 9: MAT descriptors taken from the area of magnetizing current (indicated by arrows in Fig. 8) for the two different spacers

Considering that all measured samples are made of the same material, this MAT descriptor magnetically characterizes the material regardless ofthe surface roughness. It means that if aseries of samples,having different degradation factors but also different surface conditions,are investigated, the modification in the magnetic parameters due to degradation alonecan be derived by using a spacer. This will garantee successful nondestructive testing of series of samples exhibiting different degradation levels even if the surface conditions are different for the various investigated samples.

In our geometry, the application of 70 μm thick spacer seemsadequate and no thicker spacer is required. Application of such a spacer is technically very easy. Evidently, the optimal thickness of the spacer depends on the geometry of the sample and on the magnetizing yoke.

CONCLUSIONS

The influence of the surface roughness on the magnetic behaviour was studied on a series of ferromagnetic samples magnetized and measured by a magnetizing yoke attached on the sample surface. The surface roughness was characterized quantitatively by suitable parameters. Good, monotonous correlation was found between the roughness parameters and the magnetic descriptors.

It was found that by applying a nonmagnetic spacer between the magnetizing yoke and sample surface, a range of magnetizing field still exists where the magnetic parameters did not depend on the surface condition. This finding makes it possible to conduct reliable and effective non-destructive testing of different samples having different surface conditions.
The magnetic adaptive testing method was used in the present work but this result can be useful for any other magnetic measurement method where magnetic hysteresis is measured by magnetizing the sample by an attached yoke.

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