INFLUENCE OF THERMAL TREATMENT ON MAGNETIC PROPERTIES OF STEEL SHEET MATERIAL UTILISED IN CABLE ROUTING SYSTEM

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Abstract. *The influence of relax annealing aimed at removal of the residual stresses (so-called stress-relief annealing) on various magnetic parameters, such as the relative magnetic amplitude permeability, coercivity, remanent flux density, etc. is discussed. Samples of steel cable tray material which is a part of commercially available cable routing system were investigated in order to find information about the properties important from the point of view of EMC requirements in extremely demanding industrial environment.*

Keywords

Annealing, carbon steel, electromagnetic compatibility, magnetic properties.

1. Introduction

Various electronic systems functioning in exceptionally demanding industrial environment, especially in situations where the safety of operation is at the first place of importance (such as e.g. power engineering, nuclear power plants, pressure vessels, boilers, pipes, oil and gas transportation, etc.), require reliable protection against spurious electromagnetic fields to avoid malfunctions due to communication breakdowns. The best way, how to provide reliable function of data-logging and control systems is to eliminate the sources of interference, what could be too expensive or even not always achievable. Therefore, all the signal paths for data communication at least have to be shielded as much as possible. This task can be fulfilled by means of carefully chosen shielding materials from the point of view of chemical composition, proper processing technology as well as the geometry of shielding components used for cable trays. The economy of final technical solution has to be kept in mind as well.

2. Experimental Details

2.1. Experimental Set-Up

The block diagram of the equipment for the measurement of magnetisation curves (hysteresis loops, virgin curve, and amplitude curve) of the magnetically closed samples with toroidal shape is shown in Fig. 1. The apparatus consists of a digital function/arbitrary waveform generator (ARB), power operational amplifier (AMP), precise pre-amplifier (optional, not shown in the figure), couple of identical digital multimeters (DMM1, DMM2) and/or digital oscilloscope (not shown in the figure) and personal computer (PC). All the instruments ale connected to the host computer via GPIB (IEEE 488) interface. The main part of the experimental equipment is the driving amplifier designed as power operational amplifier (AMP).

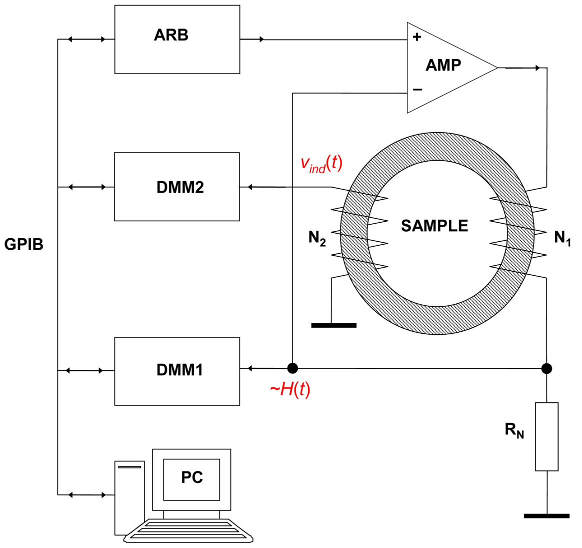


Fig. 1: The block diagram of experimental equipment for automated measurement of the magnetisation curves.

For the measurement of magnetic properties at defined (e.g. sinusoidal) exciting magnetic field waveform $H(t)$, an analogue feedback from the current sensing reference resistor ($\mathrm{R_N}$) is introduced. The voltage across this resistor (directly proportional to the current flowing through the primary winding $\mathrm{N_1}$, thus determining the value of the exciting field intensity) is in the quasi-static and low-frequency mode (0,001 to 200 Hz) measured at defined time instants by DMM1. The voltage $v_{ind}(t)$ induced in the secondary winding $\mathrm{N_2}$ is at the same time instants sampled by DMM2 and numerically integrated. Thus, the instantaneous values of the magnetic flux density $B(t)$ are obtained. In the dynamic mode (above 200 Hz), these voltages are sampled by means of either digitising oscilloscope or data acquisition card.

In all the modes further numeric processing of data (integration, Fourier analysis of the signals, noise filtering, etc.) is identical. The operation of the system as a whole is controlled by the software created within commercially available graphical dataflow programming software development environment, that allows simple control of the instruments (adjustment of the parameters of exciting signals, starting of measurement in defined time instants, synchronisation of the instruments, etc.) by means of graphical user interface as well as continuous displaying of the measured quantities and their time-dependencies. From the measured magnetisation curves except basic parameters, such as the coercivity, remanent magnetic flux density and hysteresis loop area, also various secondary parameters (magnetisation loss, amplitude or complex permeability, etc.) can be found.

The measuring system based on the same hardware configuration can also be used to measure the magnetisation curves at defined flux density waveform (sometimes required in industrial practice). This is a very difficult task at low frequencies, since conventional analogue feedback from the secondary winding does not work acceptably because of too low induced voltage. Moreover, since the sample along with both windings behaves like a high-pass filter (in fact it is a transformer), the feedback loop is open for DC signals. As a result, the amplifier output tends to saturate (or even oscillate) in response to random fluctuations of circuit quantities (noise) even without any input signal from the function generator. This could eventually damage the power amplifier. To avoid these complications, either an additional analogue feedback can be introduced to eliminate any DC component at the output of the power amplifier, or various digital feedback principles can be applied. The iterative digital feedback algorithm providing defined sinusoidal magnetic flux density waveform is described in [1]. Further information on hardware and software along with data evaluation procedure "finesses" can be found e.g. in [2], [3].

2.2. Samples and Experimental Conditions

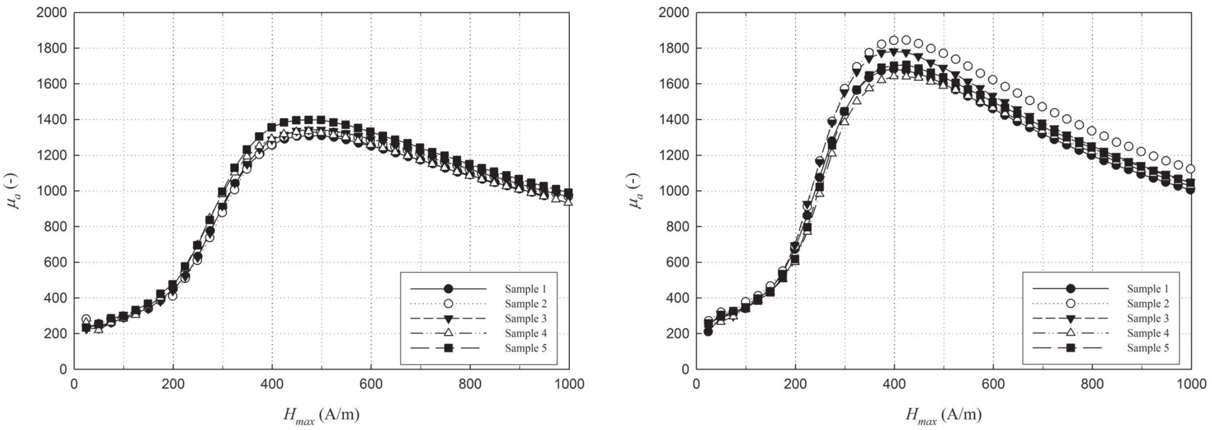
Magnetically closed ring-shaped samples cut out of a steel cable tray material by means of water beam cutting machine were analysed. The dimensions of toroids were measured for each individual sample using a caliper and screw micrometer in several places with the accuracy of $0,05$ mm (average values of all the samples were: inner diameter $d = 25,8$ mm, outer diameter $D = 27,8$ mm and height $h = 1,5$ mm). To maintain sufficient homogeneity of the magnetic field in the sample, the ratio of $d/D \geq 0,9$.

Otherwise, the sample material close to the inner cylindrical surface could even be saturated; on the contrary to the outer surface where the field is in principle weaker. All the samples were tested at the same conditions, i.e. the same frequencies, amplitudes and harmonic (sinusoidal) exciting field intensity waveforms $H(t)$.

In regard of the expected origin of the interfering magnetic fields (electric power distribution systems) the frequencies $f = (1, 2, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100)$ Hz were chosen (the lowest frequencies as the reference values for quasi-static mode, maximum of 100 Hz as the second harmonics of the power line frequency). The amplitude of the magnetic field intensity H_{max} was changed in the range from 25 to 1000 $\mathrm{A{\cdot}m^{-1}}$ with the step of 25 $\mathrm{A{\cdot}m^{-1}}$. These values were chosen in relation to the examination of the influence of the Earth's magnetism (the total value of the magnetic field intensity in the region of Central Europe nowadays ranges from about 40–60 $\mathrm{A{\cdot}m^{-1}}$ (50–75 µT), see e.g. [4]) as well as the influence of strong magnetic fields in the vicinity of the conductors generated by high electric currents.

In total, 5 samples were measured in order to perform statistic evaluation of the results. First, the samples were measured as-cut from the material of steel cable tray. Since due to mechanical processing during manufacturing of the tray as well as during cutting-off the samples some residual stresses remained in the samples, the overall magnetic properties are expected to be different from the original material of the cable tray. For this reason, the samples were thermally treated and the magnetic properties were measured again.

Since the exact metallurgical composition of the material was not known, based on the information found in e.g. [5] the sample No. 1 was thermally treated at 400 °C for 3 hours, which is slightly less than the melting point of zinc Zn ($419,58$ °C) used as the anticorrosion coating. The consecutive measurements of the magnetic properties showed that within estimated measuring uncertainty (few tenths to units of %) these practically did not change, see e.g. Fig. 5 and Fig. 6.



(a) as-cut

(b) annealed at 600 °C/3hours

Fig. 2: The dependencies of amplitude permeability μ_a upon maximum magnetic field strength for as-cut (a) and annealed (b) material, samples No. 1–5, frequency $f = 1$ Hz.

Therefore, all the samples (including sample No. 1) were further thermally treated at 600 °C for 3 hours as recommended in [5], [6], for relax annealing, or subcritical annealing to remove the residual stresses (so-called stress-relief annealing). The experiments have shown that various parameters measured at the same conditions exhibit a significant variance. It could be to some extent understood as an evidence of sample material inhomogeneities (such as e.g. various structural defects, crystalline grain boundaries, etc.) associated with inhomogeneous distribution of local internal stresses. An example of such a variance is demonstrated in Fig. 2, where the dependencies of amplitude permeability upon the maximum magnetic field intensity are shown. As can be seen, in case of as-cut samples the internal stresses significantly affect all the magnetic properties. Since the averaged stresses are expected to be more-less comparable, overall properties are likely to be similar as well.

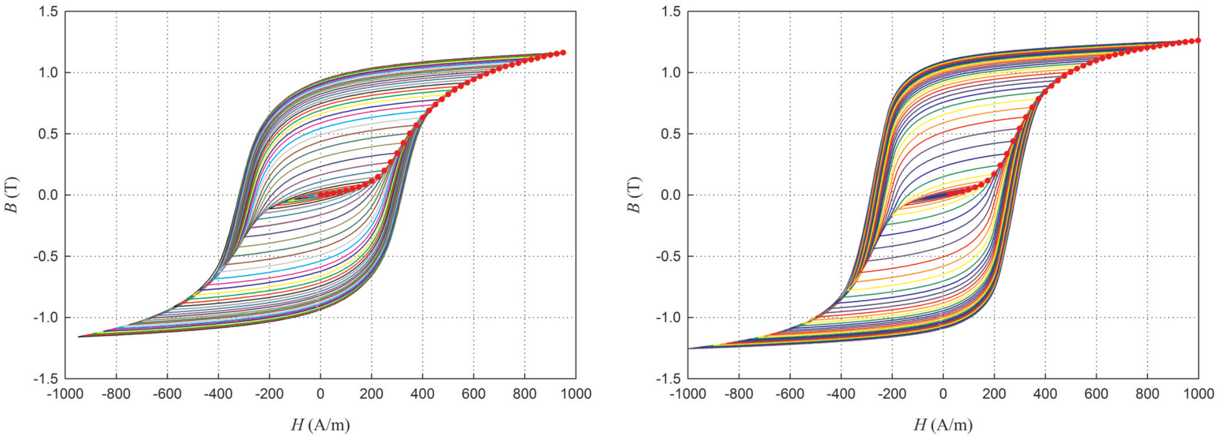
As a result, the differences among the samples are smaller (the absolute difference between the highest and the lowest value of the amplitude permeability at the same applied field is about 100). On the other hand, after removal of internal stresses by thermal treatment the influence of structural inhomogeneities increases, resulting in the increase of the total difference to more than 200 (relative change of 100 %). Note that the relative change of maximum permeability (from about 1300 to 1700 in case of sample No. 1) is about 30 %. This can be explained by changes in the magnetisation processes, especially domain wall motions dominant in weak fields strongly depend on the domain wall pinning on the structural irregularities.

The rotational processes are influenced by both the internal stresses and crystalline structure as well. Similar behaviour was observed for all the parameters evaluated from the experimental data (regardless of the sample); nevertheless the same final conclusions can be stated for all the samples. Therefore, only the results for the sample No. 1 are shown further in this paper.

3. Results and Discussion

3.1. Magnetisation Curves, Coercivity, Remanence

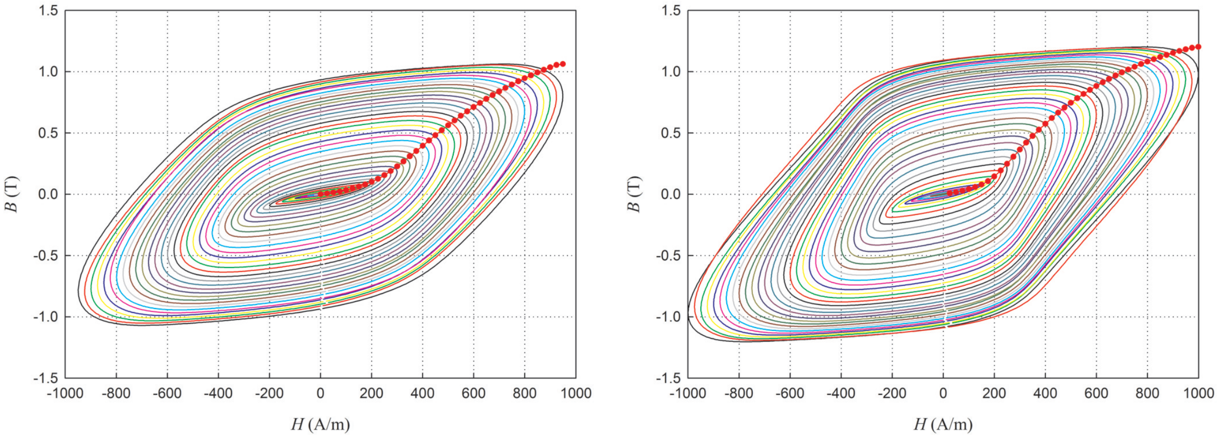
The examples of typical measured quasi-static ($f = 1$ Hz) and dynamic ($f = 100$ Hz) magnetisation curves of the sample No. 1 prior to and after thermal treatment at 600 °C for 3 hours are shown in Fig. 3 and Fig. 4, respectively. The curve drawn in red with closed circles represents so-called amplitude curve, which is the dependence of the maximum flux density value B_{max} upon the maximum exciting field value H_{max} (i.e. connecting the peaks of quasi-static hysteresis loops). From the measured magnetisation curves the influence of thermal treatment is clearly visible. It is manifested by a slight increase of the value of B_{max} for given H_{max} as well as the shape - the hysteresis loops became more rectangular and narrow. This is more evident from Fig. 5, where the coercive field H_c (coercive field is the value of magnetic field corresponding to zero magnetic flux density B) as well as the remanent magnetic flux density B_r are plotted against maximum exciting field value H_{max}. One can see that after annealing at 600 °C for 3 hours the coercivity value increased if the applied field amplitude is less than about 300 A·m^{-1} comparing to its as-cut value, meanwhile for $H_{max} > 300$ A·m^{-1} annealing decreases the coercivity (see Fig. 5–(a)).



(a) as-cut

(b) annealed at 600 °C/3hours

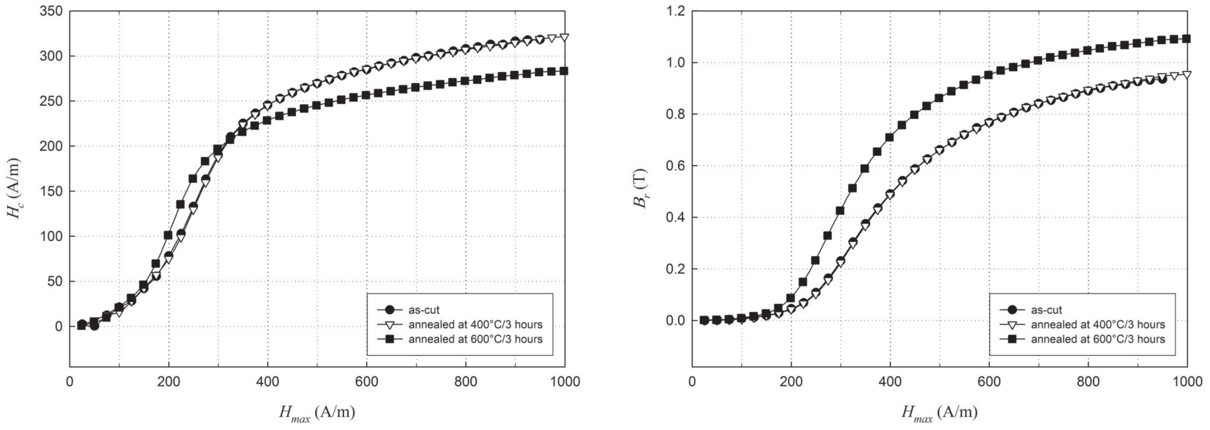
Fig. 3: Quasi-static ($f = 1$ Hz) magnetisation curves of the sample No. 1 prior to (a) and after (b) thermal treatment.



(a) as-cut

(b) annealed at 600 °C/3hours

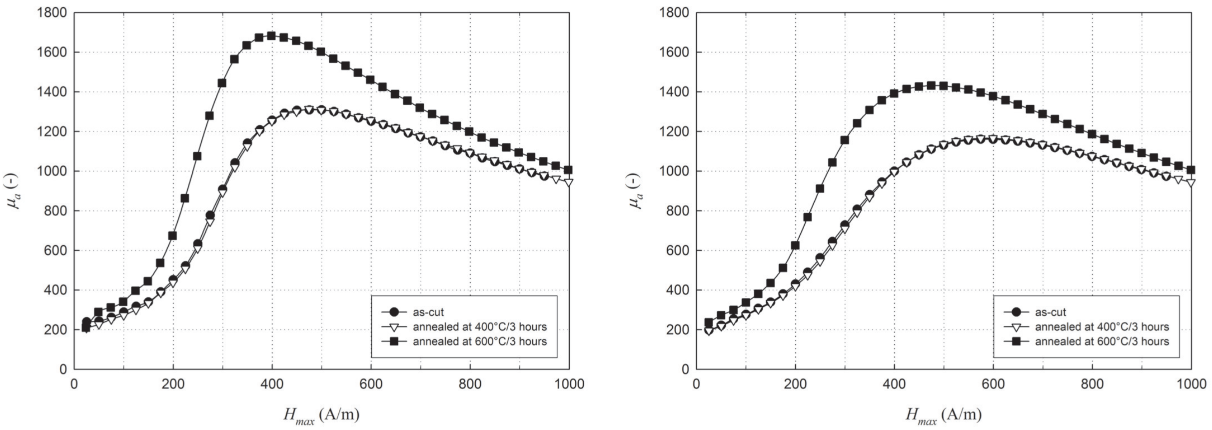
Fig. 4: Dynamic ($f = 100$ Hz) magnetisation curves of the sample No. 1 prior to (a) and after (b) thermal treatment.



(a) $H_c = f(H_{max})$

(b) $B_r = f(H_{max})$

Fig. 5: The dependencies of coercivity H_c (a) and remanence B_r (b) upon maximum magnetic field intensity H_{max} at $f = 1$ Hz for as-cut and annealed material, sample No. 1.



(a) $f = 1$ Hz (b) $f = 50$ Hz

Fig. 6: The dependencies of amplitude permeability μ_a upon maximum magnetic field intensity for as-cut and annealed material, sample No. 1.

On the other hand, the remanent flux density Br increased after annealing (along with saturation flux density) over a whole range of applied fields, Fig. 5–(b). As can be seen, annealing at 400 °C does not have any noteworthy influence. The changes of magnetic properties after relax annealing can be attributed to the inverse magnetostrictive (magnetoelastic) effect, also known as Villari effect, characterised by changes in the magnetisation (magnetic polarisation) of a material when a mechanical stress is applied [7]. Another reason for such a significant change in the resulting properties can be related to changes in the crystalline structure, such as the recrystallisation and/or grain growth processes. However, this assumption has to be confirmed by direct observation of the structure changes in the samples before and after the annealing. Nevertheless, a hint approving this assumption can be found e.g. in [5], where it is mentioned that annealing cold-worked mild steel in the temperature range 550–600 °C will result in complete recrystallisation of ferrite, although the cold-worked pearlite will be largely unaffected.

3.2. Amplitude Permeability

Relative amplitude permeability μ_a is calculated from the measured amplitude curves for various values of the maximum magnetic field intensity according to:

$$\mu_a = \frac{1}{\mu_0} \cdot \frac{B_{max}}{H_{max}}, \qquad (1)$$

where $\mu_0 = 4\pi \cdot 10^{-7}\text{H} \cdot \text{m}^{-1}$ is the vacuum permeability.

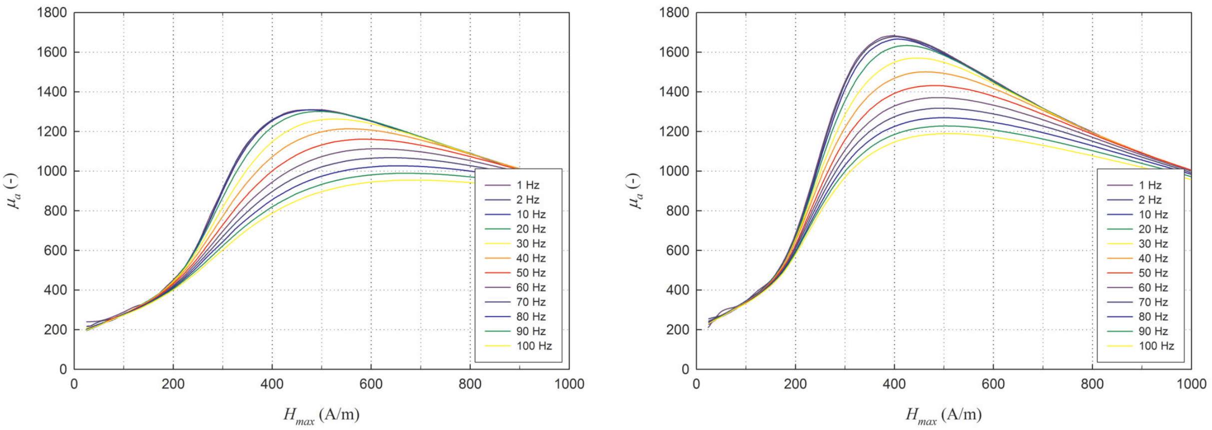
In Fig. 6 the dependencies of the amplitude permeability μ_a upon the maximum magnetic field intensity of the sample No. 1 for the frequencies 1 Hz and 50 Hz prior to and after the thermal treatment at 400 and 600 °C for 3 hours are shown. From the figure it is obvious that the thermal treatment at 400 °C almost does not influence the magnetic properties even if in both cases a thin film of iron oxide appeared on the sample surface (i.e. indication of the corrosion process emerged). From Fig. 5 expressly results the fact that the subcritical annealing at 600 °C for 3 hours substantially increases the values of the permeability in medium magnetic fields (above 200 $\text{A} \cdot \text{m}^{-1}$).

In Fig. 7 one can see the dependencies of the amplitude permeability μ_a upon the maximum magnetic field intensity of all the samples at various frequencies prior to (a) and after the thermal treatment (b) at 600 °C for 3 hours. Significant frequency dependence of the amplitude permeability at given maximum exciting field value $H_{max} > 200$ $\text{A} \cdot \text{m}^{-1}$ can be seen as well.

4. Conclusion

Experimentally obtained facts reported in this paper can be interpreted as follows:

- In a given range of exciting fields (25 to 1000 $\text{A} \cdot \text{m}^{-1}$) the amplitude permeability of measured samples μ_a was not less than about 200, based on the trend of the measured dependencies one can expect, that the value of so-called initial amplitude permeability μ_i (μ_a extrapolated to zero exciting field $H_{max} = 0$ $\text{A} \cdot \text{m}^{-1}$) will not be significantly lower. Moreover, this limit value appears to be practically almost independent of the frequency as well as the heat treatment procedures.
- Positive influence of thermal treatment at 600 °C for 3 hours, which is clearly evident, is most likely



(a) as-cut

(b) annealed at 600 °C/3hours

Fig. 7: The dependencies of amplitude permeability μ_a upon maximum magnetic field intensity at various frequencies for as-cut and annealed material, sample No. 1.

associated with removal of mechanical stresses caused by shaping processes during manufacturing of the cable tray itself as well as by cutting of the samples to be measured. Mechanical stress removal could probably be accompanied with the recrystallisation (or crystalline grain growth) of sample material. However, this conclusion needs to be verified by the comparison of the crystalline structure before and after thermal treatment. Note that also heavy mechanical loads due to the weight of cables can influence the shielding properties.

On the basis of knowledge obtained we can declare that in case when even higher values of permeability are required, the thermal treatment within the temperature range specified in corresponding metallurgical literature for subcritical or stress-relief annealing depending on the actual composition of the material used can be suggested as the additional technology step inserted between final mechanical shaping and zinc coating of the cable trays. To avoid accelerated oxidation, it is highly recommended to carrying out the thermal treatment in the protective reductive atmosphere (such as e.g. nitrogen N_2).

As a final conclusion, one can state that even without further thermal treatment the material tested is usable in a variety of applications, where in a wide range of magnetic field intensities the value of amplitude permeability greater than 200 is required. In the region of extremely high fields, where the materials tend to saturate, the amplitude permeability significantly decreases (it is an attribute of all such materials). For this reason it is recommended to place the objects that have to be protected against strong spurious magnetic fields (data and low-level signal cables) into a covered cable tray as far as possible from the sources of interfering fields (e.g. power cables, electric power distribution systems, etc.). Detailed recommendations for the construction of the cable trays and the installation of various classes of cables from the point of view of EMC requirements can be found in [8], [9].

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