MAGNETIC PROPERTIES OF VITROVAC/RESIN COMPOSITES

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1. Introduction

Soft magnetic composite materials (SMCs), consisting of ferromagnetic particles and the binder, have certain remarkable advantages over some other types of materials such as steels or amorphous ribbons, e.g. the magnetic and thermal isotropy, low energy losses at medium to higher frequencies and the possibility to create a magnetic circuit in the desired 3D shape [1-3]. The research in the field of preparation and magnetic properties investigations strongly attracts physicists and materials scientists of the world in the last decade [1-4]. The aim of this study was to investigate the influence of different binder content in the SMC based on an amorphous Co-rich material on the complex permeability and power losses frequency dependence.

2. Experimental

For magnetic properties investigations, the SMC samples composed of ferromagnetic powder covered by the phenol-formaldehyde resin (ATM) were prepared. As ferromagnetic base the powder prepared from amorphous VITROVAC ® 6155 U55 F ribbon, provided by VACUUMSCHMELZE GmbH & Co. KG Germany, was used. This amorphous Co-based alloy was chosen due to its excellent soft magnetic properties such as high relative permeability, low coercivity and near-to-zero magnetostriction, having wide utilization in electronics and electrical engineering industry [2,5]. The ribbon approx. 5 mm wide was cut to small pieces of 2 mm length which were milled in the planetary ball mill (RETSCH PM4000) in hardened steel vials and balls. The milling was carried out for 12 h at a ball-to-powder mass ratio of 31:1 and speed of 200 rpm. The obtained powder remained amorphous, as confirmed by X-ray diffractometry (Fig.1).

The powder was sieved with 212 μm sieve to exclude the non-milled large particles for sample preparation. The powder of particles with diameter below 212 μm were mixed with 5, 10 and 20 wt. % of phenol-formaldehyde resin (ATM). Prepared mixtures were compacted under uniaxial pressure of 800 MPa for 15 s. Each pressed sample was after the compaction cured at 165 °C for 60 min. to polymerize the resin. The final ring-shaped samples have outer diameter of about 24 mm, inner diameter of about 18 mm and height of about 3 mm.

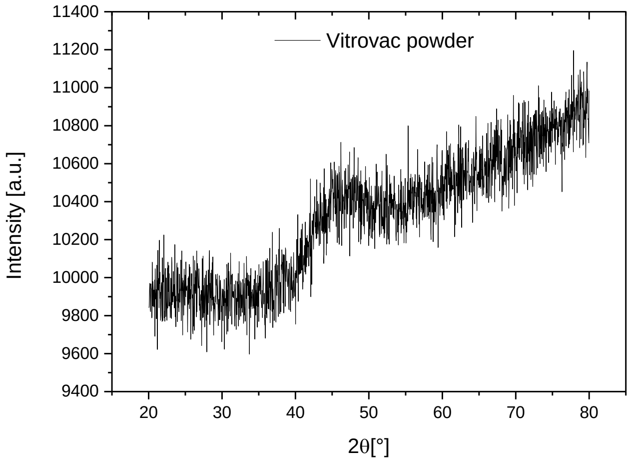

Fig.1: *XRD pattern of the milled VITROVAC®.*

The frequency dependences of complex permeability were measured by the impedance/gain-phase analyzer HP 4194A (connected to PC via HPIB laboratory bus) in the frequency range from 1 kHz to 40 MHz, on ring the shaped samples with one toroidal coil with 15 turns [6,7]. The ac hysteresis loops were recorded by the hysteresisgraph MATS-2010A in the frequency range from 1 kHz to 30 kHz at maximum induction B_m = 0.1 T. The total power losses (in W/kg) were determined from the hysteresis loops. The DC resistivity was measured by Van der Pauw four contact method [8].

Tab. 1 summarizes the parameters of the prepared samples, volume fractions of the constituents and pores, outer diameter *D*, inner diameter *d*, height *h*, mass *m* and specific electrical resistivity *ρ*.

Tab. 1. *Parameters of the SMC samples.*

Sample	Vitrovac fraction [vol.%]	ATM fraction [vol.%]	pores fraction [vol.%]	*D* [mm]	*d* [mm]	*h* [mm]	*m* [g]	*ρ* [mΩ.m]
5% ATM	58.94	3.10	37.96	24.25	18.02	3.33	3.25	0.23
10% ATM	53.02	5.89	41.08	24.23	17.96	3.73	3.32	0.35
20% ATM	41.85	10.46	47.68	24.24	17.95	3.84	2.76	130

3. Results and discussion

The complex permeability consists of the real and the imaginary part $\mu = \mu' - j\mu''$. The real part of the permeability was calculated from the measured inductance L and the parameters of the sample and the toroidal coil:

$$\mu' = L \frac{2\pi}{\mu_0 N^2 h \ln(\frac{D}{d})} \tag{1}$$

where N is number of turns of the coil, μ_0 is the magnetic constant.

The imaginary part of complex permeability is

$$\mu'' = \frac{2\pi}{R_l \omega \mu_0 N^2 h \ln(\frac{D}{d})} \tag{2}$$

where R_l is serial resistance of the measuring circuit.

The frequency dependences of the real part of complex permeability for all investigated samples (Fig. 2) exhibit near-to-constant behavior at least up to 3.5 MHz. The increase of resin content causes the decrease of the initial permeability as a result of higher inner demagnetizing fields around the ferromagnetic particles surrounded by non-ferromagnetic resin and pores. On the other hand, the permeability is stable up to higher frequencies. High frequency anomalous increase of the real part of permeability above 10 MHz of the 20% ATM sample is caused by undesired increase of stray capacitances and inductances around measurement coil.

The imaginary part of the permeability is shown in Fig. 3. The permeability dispersion is mainly due to domain walls motion. Relaxation frequency, attributed to the peak in the imaginary part, is located beyond the frequency limit of our experimental setup.

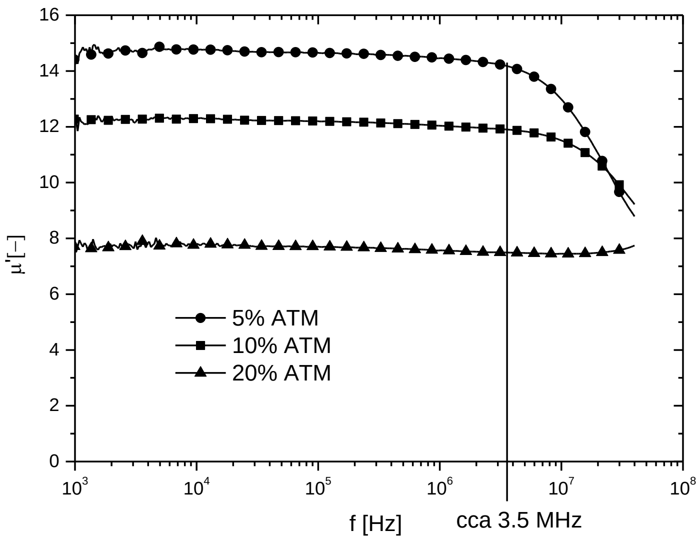

Fig. 2: *The frequency dependence of the real part of complex permeability for VITROVAC® based SMC samples with different ATM content.*

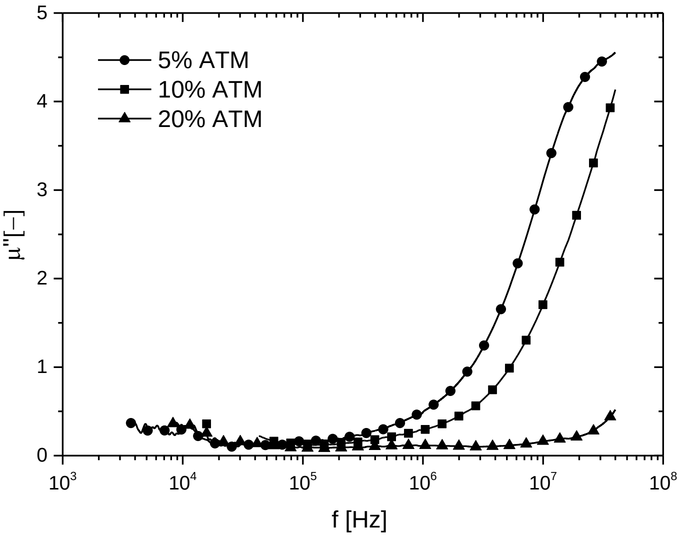

Fig. 3: *The frequency dependence of the imaginary part of complex permeability for VITROVAC® based SMC samples with different ATM content.*

The total power losses P_t [W/kg] measured in the frequency range from 1 kHz to 30 kHz of prepared samples are in Fig. 4. It has been found that the higher amount of resin has a positive effect on total power losses in a whole investigated frequency range.

Generally, the total power losses P_t [W/kg] of SMC can be separated to four parts [9]

$$P_t = P_{dc} + P_c^{inter} + P_c^{intra} + P_e. \tag{3}$$

Hysteresis losses (P_{dc}) can be experimentally determined from dc hysteresis loop or from extrapolation to $f \to 0$ Hz of total losses frequency dependence. Parameters of hysteresis losses are depending on the material properties. are frequency independent. P_{dc}/f [J/kg] is frequency independent.

Inter particle eddy current losses (P_c^{inter}) are caused by eddy currents flowing between the particles in the cross-section area oriented transversally to the magnetic flux. In SMC where ferromagnetic particles are well isolated P_c^{inter} can be neglected [9].

Intra particle eddy current losses (P_c^{intra}) are always present because ac magnetic flux flow through electrically conductive material and eddy currents flowing inside ferromagnetic particles causing power dissipation are invoked.

Excess losses (P_e) also named as anomalous losses are caused by domain wall branching and bowing as it is described in Bertotti's statistical theory [10].

The inter particle eddy current losses P_c^{inter} can be neglected in the investigated samples, because the specific resistivity is high enough (Tab. 1). Therefore classical eddy current losses are present due to eddy currents circulating only inside the particles.

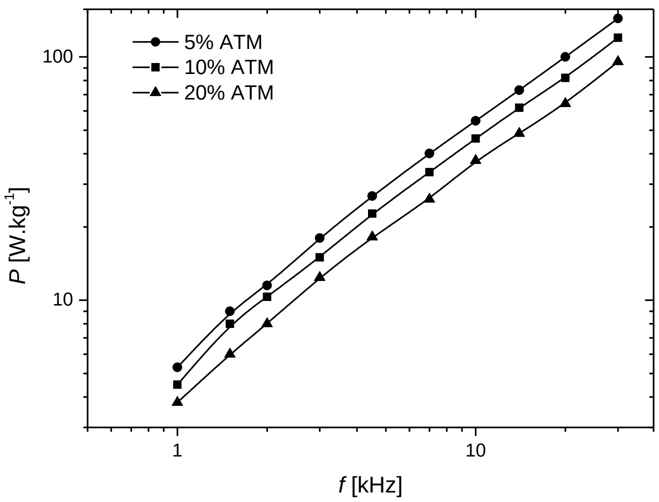

Fig. 4: *Frequency dependence of total power losses.*

4. Conclusion

This work presents the results of magnetic characterization of soft magnetic composite materials based on the amorphous alloy commercially available under the trademark VITROVAC® mixed with phenol-formaldehyde resin ATM in three different ratios. The real part of initial complex permeability exhibits a constant behavior up to 3.5 MHz. The absolute value of the real part permeability decreases with increasing of resin fraction in composite, due to the larger non-ferromagnetic distances between particles. On the other hand, the larger amount of resin results in the lower total power losses in investigated frequency range probably as a consequence of the decrease of inter particle eddy currents.

5. Acknowledgement

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