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COMPOSITES

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POLYMER BONDED HARD MAGNETIC FOILS FOR MEMS APPLICATIONS

Resin bonded composite magnets were prepared by tape casting using various compositions of polymeric matrix and processing variables. As a magnetic component, MQ-A M30 ribbon powder was used. The magnetic and mechanical properties versus the composite's compositions are presented and discussed. The coercivity does not depend on the amount of MQ powder and its mean value is close to 580 kA/m. The fact that the μ_0H_c does not remarkably change for various specimens means that processing the composites does not cause oxidation of the metallic component, which would lead to degradation of the properties. The remanence changes from 0.43 to 0.65 T and rises with increasing MQ powder content. The mechanical properties depend mainly on the properties of the polymeric matrix. The composite foil containing 64.72% of the magnetic component appears to present the best combination of properties. The composite magnetic films will be used as permanent magnets for applications in Magnetic Micro-Actuators and Systems (MAGMAS).

Keywords: **Nd-Fe-B magnets, polymer bonded hard magnetic foils, hard magnetic composite**

FOLIE MAGNETYCZNE DO ZASTOSOWAŃ W UKŁADACH MEMS

Tematyka niniejszej pracy dotyczy kompozytów magnetycznych na osnowie polimerowej wytworzonych metodą odlewania folii (ang. tape casting) przy zastosowaniu różnych składów i parametrów technologicznych. Dla nadania właściwości magnetycznych wykorzystano sproszkowaną taśmę handlową MQ-A M30. Opisano wpływ udziału proszku MQ na właściwości magnetyczne i mechaniczne badanych folii. Stwierdzono, że koercja nie zależy od zawartości składnika magnetycznego i wynosi średnio 580 kA/m, zatem jest porównywalna z wartością koercji dla samego proszku MQ. Można przyjąć, że wykorzystując tę metodę formowania kompozytu, nie doprowadza się do utleniania składnika magnetycznego. Wraz ze wzrostem zawartości proszku magnetycznego w kompozycie obserwowano zwiększenie remanencji z 0,43 do 0,65 T. Właściwości mechaniczne kompozytu zależą głównie od jego polimerowej osnowy. Najlepsze połączenie właściwości magnetycznych i mechanicznych uzyskano dla folii zawierającej 64,72% proszku MQ. Magnesy wiązane polimerem wytworzone w postaci cienkich folii mogą zostać wykorzystane jako mikroaktuatory lub elementy mikrosilników w technologii MAGMAS (ang. Magnetic Micro-Actuators and Systems).

Słowa kluczowe: **magnesy Nd-Fe-B, folie magnetyczne, kompozyty magnetycznie twarde**

INTRODUCTION

In the last two decades continuous development of hard magnetic alloys containing rare earth metals have been observed. Among them, rapidly solidified, nanocrystalline and nanocomposite alloys have a crucial position, in which the microstructure and phase constitution play an important role. The technologically important phenomenon of remanence and energy product enhancement appears in melt-spun ribbon alloys when the crystallite size is reduced to below 50 nm [1-4]. A further increase in magnetic properties can be achieved by introducing, in the phase constitution, a soft magnetic component in the form of iron or iron borides. Such alloys are called nanocomposites, by analogy to structural composites containing hard and soft (mechanically) components. These alloys take additional advantage of strong magnetic coupling between the hard and soft magnetic phases [5, 6]. Due to their high remanence, nanocrystalline melt-spun alloys are good candidates for resin bonded composite magnets.

The development of miniature magnets enables their application in micro-magnetic systems and actuators - Magnetic Micro-Actuators and Systems (MAGMAS) [7]. Such devices find applications in micromotors, micro generators, optical and medical devices, sensors and others.

Magnets for application in micro-devices are a rather new class of materials and are widely studied. The dimensions of magnetic components having a thickness in the range of a few to hundreds of micrometers require solving problems related to the change of magnetic phenomena in microscale.

Several methods of processing such magnets have been developed, all of which have some advantages and disadvantages. Among them, such methods as the electrode positioning of Co-Pt alloys or electroplating of bonded powders, lead to easy production of magnetic films but give low properties in comparison to bulk magnets of the same composition [8]. Other techniques, applied to processing thin films, such as sputtering [9], pulsed laser deposition [10], vacuum-plasma-spraying [11] enable one to obtain good magnetic properties, but the films are too thin for their application in microtechnology (films required for applications in micro-motors and actuators are in the range of 5÷500 μm). The application of thin film technology in mass production is thus not economically viable. A convenient method appears to be the formation of these polymer bonded films containing magnetic powder [12, 13]. In this case, processing foils of appropriate thickness, magnetic and mechanical properties has to be extensively studied.

In this study resin bonded foils for micro-motor applications were produced by foil casting. Their basic magnetic and mechanical properties were evaluated and presented.

EXPERIMENTAL

As a magnetic component of the composites, the commercial powder MQ-A M30 grade was used. The magnetic powder, after additional grinding to mean particle size 20 μm, was mixed with epoxy resin Epidian-5 and hardeners Z-1 or PAC. Additionally a softener, made from a 1:1 mixture of polyethylene glycol and dibutyl phthalate, was applied. Some xylene was also added to improve the casting ability. The foils were made by foil casting using a R. Mistler tape caster device. After casting, the foils were dried at a temperature of 70 °C for 5 or 12 h. From the foils, magnetic composite rings were cut using a laser beam. The compositions of the foils and drying time for the magnetic composite specimens, denoted here as MC-1 to MC-6, are collected in Table 1.

TABLE 1. **Composition of mixtures used for foil casting**
TABELA 1. **Zestawienie składu kompozytów i czasu suszenia**

Sample	Epidian 5 g	Softener g	Hardener g		MQ-A M30 g	Drying time h
MC-1	2.6	3.04	Z-1	0.32	35	5
MC-2	3.0	2.80	Z-1	0.38	35	5
MC-3	3.0	3.02	Z-1	0.36	50	5
MC-4	2.0	2.00	Z-1	0.24	35	5
MC-5	3.2	0.80	Z-1	0.32	33	5
MC-6	2.0	0.60	PAC	1.60	35	12

The magnetic properties were measured at room temperature using a vibrating sample magnetometer, LakeShore VSM7410, in a maximum field of 1600 kA/m.

The mechanical properties were evaluated by measuring the tensile strength versus the strain using MTS. The ram velocity was 1 mm/min. Standard paddle-like specimens were cut from the foils.

The surface of the foils was observed using a ZEISS scanning electron microscope.

RESULTS AND DISCUSSION

Proper films for applications in MEMS should have a thickness below 500 μm and exhibit good magnetic properties and mechanical strength, which enable their application in processing rotors for miniature motors. The basic properties of the foils processed are collected in Table 2.

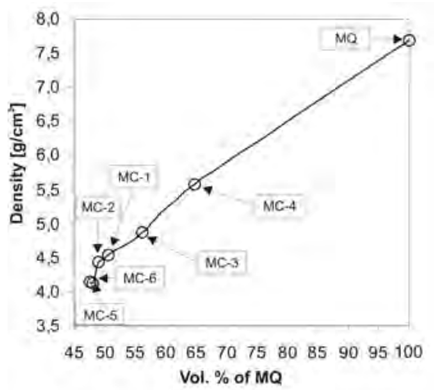

Fig. 1. Density versus MQ powder content for composite magnetic foils

Rys. 1. Zależność gęstości od udziału objętościowego proszku MQ dla badanych folii magnetycznych

TABLE 2. **Basic properties of magnetic composite foils**
TABELA 2. **Podstawowe właściwości badanych kompozytów magnetycznych**

Sample	MQ content wt.%	MQ content vol.%	Density g/cm³	Foil thickness μm	H_c kA/m	J_r T	BH max kJ/m³
MQ-A	100.00	100.00	7.690	-	586	0.90	101.4
MC-1	85.41	50.49	4.546	329	583	0.51	38.7
MC-2	84.99	49.05	4.438	357	583	0.50	39.2
MC-3	88.68	56.24	4.877	399	574	0.56	49.3
MC-4	89.19	64.72	5.580	179	572	0.65	62.4
MC-5	88.42	47.65	4.144	540	577	0.43	30.9
MC-6	89.29	47.95	4.130	382	587	0.45	32.1

The density of the foils is proportional to the volume fraction of the metallic component (Fig. 1). In our case, the maximum fraction of the MQ powder was 64.72 vol%. The density varies from 4.13 g/cm^3 up to 5.58 g/cm^3. Obviously the greater the magnetic powder fraction, the better the magnetic properties. However, proper content of the epoxy resin is necessary to provide an appropriate mechanical strength.

The foil thickness varied from 179 to 540 μm and was controlled by the processing variables. This means that this parameter was controlled within the required range.

The magnetic properties strongly depend on the fraction of the magnetic powder. The demagnetization curves are shown in Figure 2. The remanence (J_r), coercivity ($\mu_0 H_c$) and maximum energy product (BH)max are presented in Figure 3.

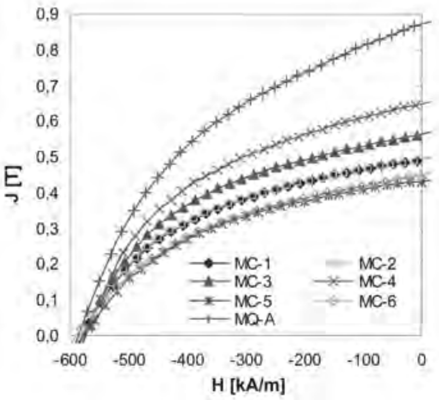

Fig. 2. Demagnetization curves for composite magnetic foils

Rys. 2. Krzywe odmagnesowania dla badanych folii magnetycznych i proszku wyjściowego MQ

The coercivity does not depend on the amount of the MQ powder and its mean value is close to 580 kA/m. The fact that the $\mu_0 H_c$ does not remarkably change for various specimens means that processing the composites does not cause oxidation of the metallic component, which would lead to degradation of the properties.

The remanence changes from 0.43 to 0.65 T and rises with increasing MQ powder content. For the greatest volume fraction applied, of 64.72 vol.%, the J_r reaches a value of 0.65 T (MC-4). For a constant value of coercivity, the maximum energy product follows the remanence dependence (Fig. 3). Thus, again the highest (BH)max of 622.4 kJ/m^3 was obtained for the 64.72 vol.% of MQ powder.

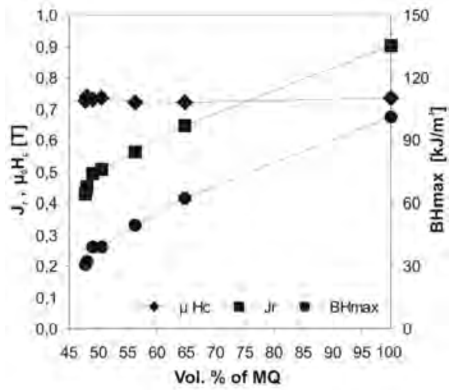

Fig. 3. Remanence (J_r), coercivity ($\mu_0 H_c$) and maximum energy product (BH)max versus MQ powder content for magnetic composite foils

Rys. 3. Zależność remanencji (J_r), koercji ($\mu_0 H_c$) i maksymalnej energii magnetycznej (BH)max od udziału objętościowego proszku MQ dla badanych folii magnetycznych

The lower surface of the foils, which had contact with the substrate, was smooth, whereas the upper surface was more or less rough, depending on the composition of the precursor mixture. The magnified morphologies of the rough surfaces are shown in Figure 4. The surface roughness was comparable. A slightly less rough surface was obtained for specimens MC-1 and MC-2 due to the greater amount of xylene addition.

The tensile strength and maximum strain to failure depend on the composition of the composites (Fig. 5). The specimens studied had visible differences in their mechanical properties. The MC-5 foil, which contained the lowest amount of softener (0.8 g), was very brittle and it was impossible to perform the tensile test on it.

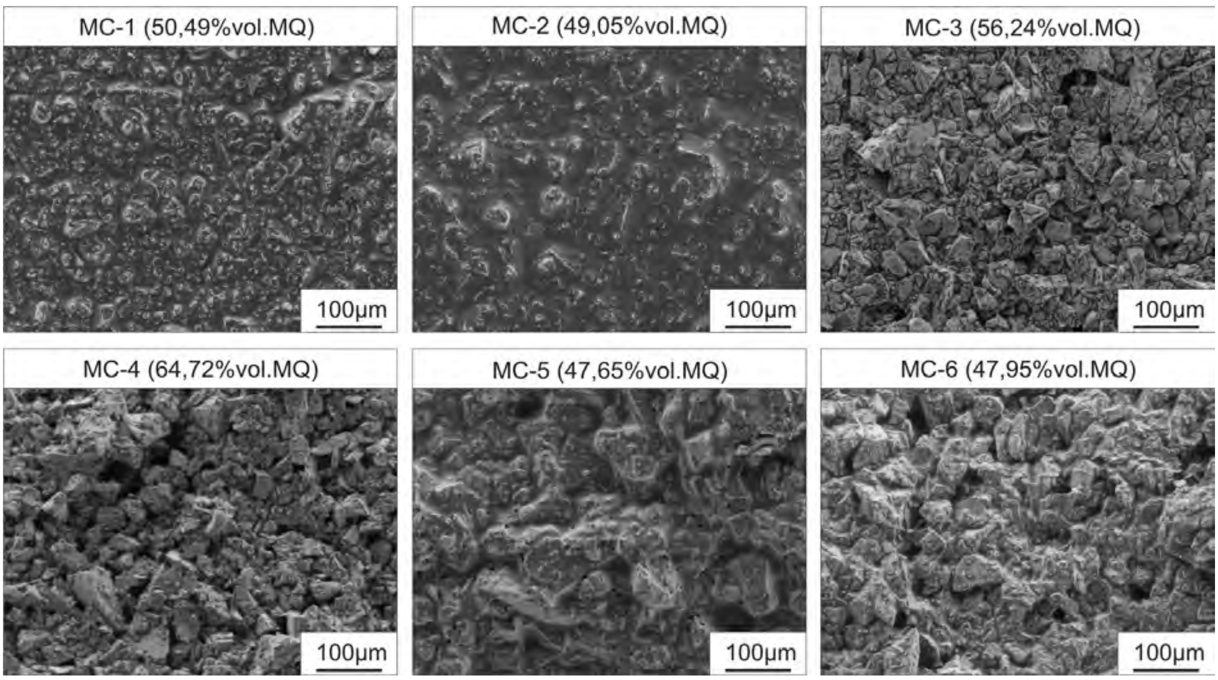

Fig. 4. Morphology of rough surfaces of composite magnetic foils

Rys. 4. Morfologia powierzchni swobodnej folii magnetycznych

The maximum strain for failure depends on the volume fraction of MQ powder. The MC-1 and MC-2 foils, which contained about 50 vol.% of the metallic component, show a maximum strain between 2.8 and 3.3%. The MC-3 and MC-4 foils exhibited visibly smaller strain due to a greater MQ content. All the above mentioned foils contained the same components and showed similar tensile strength between 3.2 and 5.5 MPa. This illustrates/demonstrates that this parameter depends mainly on the properties of the polymeric matrix. A substantially higher both tensile strength and tensile strain was exhibited by the MC-6 foil and this we attribute to both the smaller amount of MQ powder and the clearly advantageous effect of the PAC application as a hardener. Considering the currently obtained foils, the MC-4 foil exhibits practically useful parameters, concerning both the magnetic and mechanical properties.

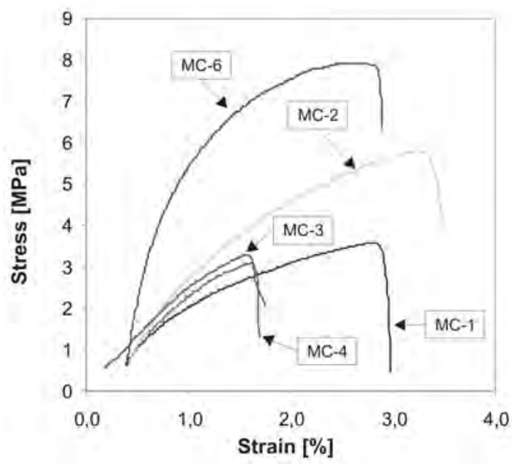

Fig. 5. Stress strain curves for composite magnetic foils

Rys. 5. Krzywe naprężenie - wydłużenie dla badanych kompozytów

From the magnetic composite foils, small discs were cut using a laser beam (Fig. 6). The discs are 4 and 5.6 mm in diameter and have a thickness of 179 μm. The rings were subjected to four and eight pole magnetization and will be applied as permanent magnet rotors in miniature electric motors.

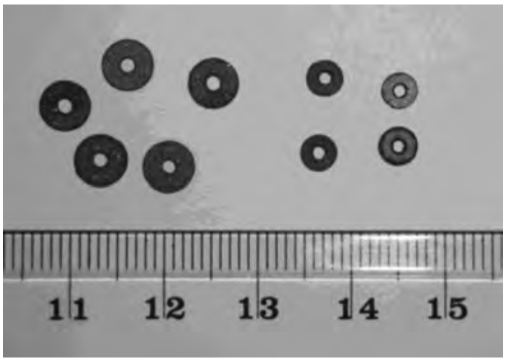

Fig. 6. Composite magnetic discs rotors for miniature electric motors

Rys. 6. Dyski wycięte z folii magnetycznej przeznaczone do zastosowania w miniaturowych silnikach elektrycznych

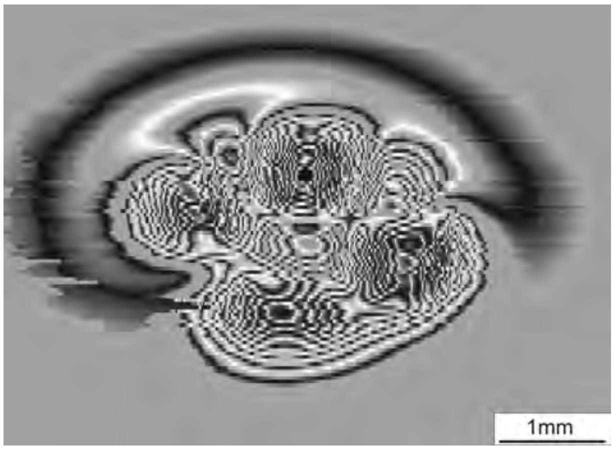

Fig. 7. Magnetic field distribution map in four pole magnetized composite disc

Rys. 7. Mapa rozmieszczenia pola magnetycznego w ośmiobiegunowo namagnestowanym dysku

In Figure 7, the mapping of the composite magnetic disc in the eighth pole magnetized composite disc is shown. The darker and lighter areas represent magnetic orientation perpendicular to the disc surface and oriented in opposite directions.

CONCLUSIONS

From the studies performed, one can conclude that the application of the foil casting procedure results in the formation of composite magnetic foils having usable magnetic and mechanical properties.

It is possible to multipole magnetize the discs cut from the foil and produce rotor magnets for application in miniature DC motors.

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