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COMPOSITES THEORY AND PRACTICE

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# GRADIENT BONDED Nd-Fe-B MAGNETS

**The concept of fabricating disc magnets for application in stepper motors has been presented. The disc magnets are composed of two elements, magnetized in the opposite direction, having a gradient structure. Such a structure produces a effect similar to the one in multi-pole magnetizing, which is difficult to implement, especially for small size magnets. The magnets were processed using Nd-Fe-B powder bonded by an epoxy resin. As a novelty in this concept, one can regard the application of centrifugal casting, directing the magnetic particles to the region of the active part of the magnet i.e. the part interacting with the magnetic core. In the applied solution, an elongated part having axial symmetry and a cross-section equal to that of the thus designed magnet. It was shown that by the application of resin of a carefully chosen viscosity, one can obtain various distributions of powder particles along the radius of the magnet. A more favorable structure of the composite magnet for this particular application was achieved using low viscosity resin, which enabled movement of the entire powder towards the active part and provided a 43% filling ratio. The studies showed that the flake-shaped powder used in the experiment, shows a tendency to form a morphological texture, i.e. the flakes tend to locate themselves perpendicular to the radius of the cast magnet. This method of fabricating disc magnets for stepper motors provides substantial savings, resulting from using a smaller proportion of Nd-Fe-B powder while maintaining a high filling ratio in the active part of the magnet.**

**Keywords:** **graded materials, Nd-Fe-B permanent magnets, bonded magnets**

## WIĄZANE MAGNESY Nd-Fe-B Z GRADIENTEM STRUKTURY

**Przedstawiono koncepcję wytwarzania magnesów tarczowych do silników krokowych jako magnesów złożonych z dwóch, namagnesowanych przeciwnie, elementów o gradiencie struktury. Badana konstrukcja zapewnia taki efekt, jak magnesowanie wielobiegunowe, które jest trudne do przeprowadzenie, zwłaszcza dla magnesów o małych wymiarach. Otrzymano magnesy z proszku Nd-Fe-B wiązanego chemoutwardzalną żywicą epoksydową. Nowatorskim pomysłem było zastosowanie odlewania odśrodkowego, aby cząstki proszku znajdowały się jedynie w obszarze czynnym magnesu, tzn. w części współpracującej z magnetowodem. W zastosowanym procesie uzyskiwano podłużną, osiowosymetryczną kształtkę o takim przekroju, jak założony kształt magnesu. Magnesy otrzymywano, tnąc kształtkę prostopadle do jej osi. Wykazano, że dzięki zastosowaniu żywicy o odpowiednio dobranej gęstości można uzyskać różne rozmieszczenie cząstek proszku wzdłuż promienia magnesu. Korzystniejszą strukturę materiału, do opisanego zastosowania, uzyskano, stosując żywicę o małej lepkości. Pozwoliło to na przemieszczenie całego proszku magnetycznie twardego do części czynnej magnesu i uzyskanie współczynnika wypełnienia 43%. Z przeprowadzonych badań wynika również, że użyty proszek płatkowy posiada tendencję do tworzenia tekstury morfologicznej, tzn. płatki proszku dążą do ułożenia prostopadłego do promienia odlewanego magnesu. Opisana metoda wytwarzania tarczowych magnesów do silników krokowych pozwala na znaczące oszczędności, wynikające z mniejszego średniego udziału proszku Nd-Fe-B, przy zachowaniu wysokiego współczynnika wypełnienia w części czynnej magnesu.**

**Słowa kluczowe:** **materiały gradientowe, magnesy Nd-Fe-B, magnesy wiązane**

## INTRODUCTION

Bonded Nd-Fe-B magnets, i.e. magnets processed by the bonding of highly coercive Nd-Fe-B powder particles by a polymeric binder, have a substantial contribution to the world-wide market of permanent magnets. They find applications mainly in devices converting electrical energy into mechanical and vice verse (motors, generators).

For the fabrication of bonded magnets, mostly nanocrystalline powders processed by the continuous casting of a molten alloy onto a rotating metallic roll are used. The ribbons are crushed giving in result flake-shaped powder particles. For some applications, spherical particles produced by liquid atomization are more convenient. Such powders are available commercially and are fabricated with a wide range of properties [1, 2].

One can expect that the market share of bonded magnets will increase in coming years. The current production of sintered Nd-Fe-B magnets achieved such a level that their recycling is becoming a serious problem. The literature reports indicate that the best solution, for recycling Nd-Fe-B magnets, is reprocessing by the HDDR (hydrogenation - disproportionation - desorption - recombination) method, converting sintered magnets into powder which can be used for bonded magnets [3, 4].

Bonded magnets can be fabricated by compacting the mixture of Nd-Fe-B and polymeric thermohardened powders or forming parts by injection molding of the magnetic powder with thermoplastic polymers [5]. Other methods, such as extrusion and calendaring can also be applied [1].

In some papers, the advantages of resin bonding for the fabrication of small magnets for miniature electromechanical devices or MEMS systems are shown. For such applications, other methods such as the cutting of small magnets from ribbons produced by tape casting [2, 6] can also be used.

Processing magnets exhibiting an anisotropy of magnetic properties is also possible. This process requires the application of textured powder which before bonding has to be aligned in an external magnetic field. Such powders can currently be produced using dynamic HDDR [7]. The application of these powders enables the processing of magnets having axial or radial anisotropy [8].

This study is related to the fabrication and characterization of miniature bonded magnets dedicated for stepper motors. Usually, such disc magnets, having an opening in the centre, have to be multi-pole magnetized. This means that the magnetizing must be done at least four times, rotating the magnet by $90^o$. This can be a substantial challenge for very small magnets.

Thus, in this study, the concept of fabricating micromagnets formed of two parts is proposed. Such a structure solves the problem of multi-pole magnetization. Teeth distributed on the circumference of this structure play the role of active parts of the magnet (interact with the magnetic core). In this solution, the magnetic powder should be distributed in the teeth, whereas its presence in other parts of the disc is unnecessary In order to produce such a structure, centrifugal casting was applied, which enabled the formation of gradient bonded magnets. Such materials have not been so far reported in the literature. The practical application of this concept should bring economic benefits.

## EXPERIMENTAL PROCEDURE

For the fabrication of bonded magnets, MQP-16-7 powder provided by Magnequench was used. The powder particles had a flake-like shape, with a thickness of about 30 μm and other dimensions up to 200 μm. As a binder two chemihardened epoxy resins having various viscosities were applied. These resins were respectively: Epidian 5 produced by Organika-Sarzyna S.A. and AKA-resin from AKASEL. Selected properties of both resins are collected in Table 1.

TABLE 1. **Properties of applied epoxy resins**
TABELA 1. **Właściwości zastosowanych żywic epoksydowych**

| Resin | Hardener | Density [g/cm$^3$] | Viscosity [mPa s] |
|---|---|---|---|
| Epidian 5 | Z-1 | 1.17 | 20000÷30000 |
| AKA-resin | AKA-Cure Slow | 1.14 | 500÷700 |

The proportions of the magnetic powders in the Epidian 5 resin and AKA-resin were 20 and 30 vol.%, respectively. The mixtures of powder and resin were cast into silicon moulds having steel cores and a diameter of 1 mm. The mould was rotated with a frequency of 30 Hz (1800 rev/min) for the time required for cross-linking. The cast material in the form of magnets is shown in Figure 1 a, having a diameter of 8 mm and length 20 mm. After removing from the mould, the material was cut with a diamond blade for magnets having a thickness of 1.3 mm. For the study of gravitational sedimentation, the rod was cut into sections of 5 mm long and their density was assessed by the Archimedes method.

The magnetic properties of the samples were measured using a VSM magnetometer (Lake Shore). The morphology was analyzed in a redial Micro-XCT-400 X-ray micro-tomograph. These observations enabled evaluation of the local filling ratio, which is defined as Nd-Fe-B powder volume to the volume of the composite. For the studies with the application of quantitative metallography, images of microsections observed with an optical ZEISS microscope were used. The analysis was performed with the use of the Micrometer program [9].


Fig. 1. Centrifugally cast bonded magnet ingot
Rys. 1. Odlana odśrodkowo kształtka Nd-Fe-B

## RESULTS

A sketch of the disc magnet is show in Figure 2. The setting-up of two such magnets, magnetized in opposite directions, enables one to produce a rotor having the same properties as a multi-pole magnetized one. The authors undertook the effort to produce a magnet having a gradient structure and required magnetic properties. It was assumed that it would be a bonded magnet produced by the centrifugal casting of a mixture of Nd-Fe-B powder with chemihardened resin. In an optimal solution, the magnetic powder should be located only in the teeth. The middle part of the magnet does not have to possess magnetic properties.

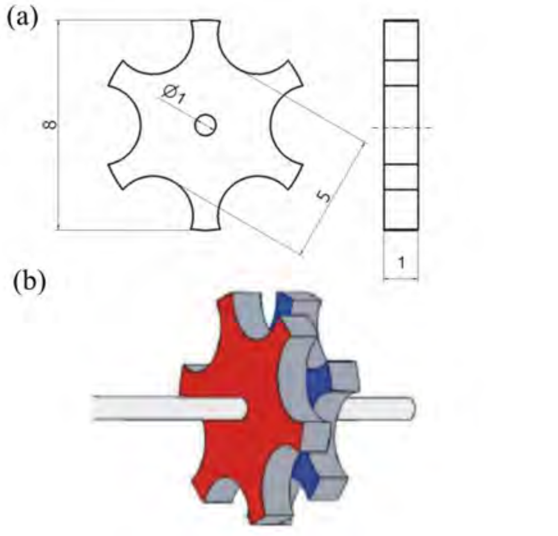


Fig. 2. Disc stepper motor magnet (a) and concept of rotor composed of two discs (b)

Rys. 2. Magnes silnika krokowego tarczowego (a) oraz koncepcja budowy wirnika złożonego z dwóch tarcz (b)

In the course of casting, the particle is subjected to centrifugal force. Simultaneous movement of the particle is retarded by the resistance of liquid, which is proportional to the viscosity (Stokes force). Gravitational force also acts on the particles, which contributes to sedimentation. Buoyancyacts in the opposite direction. Mathematical models which describe the movement of the particles in rotating liquid, as well as software which enables the simulation of particles distribution in the centrifugally cast composite are available [10]. However, for obvious reasons they contain many simplifications regarding the real systems.

In Figure 3 a and b, the microstructures of centrifugally cast magnets containing both resins are presented. The image shows the area from the verge of the tooth until the orifice in the middle of the magnet.

The filling ratio was evaluated by quantitative metallography dividing the shown areas into rectangles having an width equal to the tooth width (1000 μm) and height 350 μm. The results, shown in Figure 3c, are average values calculated from three areas (three teeth). The values of the filling ratio obtained by the above mentioned way are rather low, however, changes in these values well characterize the gradient structure of the material. These results show that the differences in the proportion of powder content versus distance from the verge of the tooth depends on the resin type. For Epidian 5 (high viscosity resin), the filling ratio changes gradually - for the distance equal to ¼ of the magnet radius, the ratio is equal to 60% of the maximum value, whereas in the position of ½ of the radius, the filling ratio amounts to 18%. For AKA-resin (low viscosity resin) for the same positions, the respective values of the ratio are 93 and 3%. In the latter case, almost all the powder moved towards the teeth. From the practical point of view, the application of low viscosity resin is more convenient. However, further studies should be performed in order to asses the optimal degree of filling of the magnet with magnetic powder in the light of motor parameters. Such studies will be carried out for a prototype motor, and the filing parameter will be controlled by an appropriate choice of mean filling ratio.

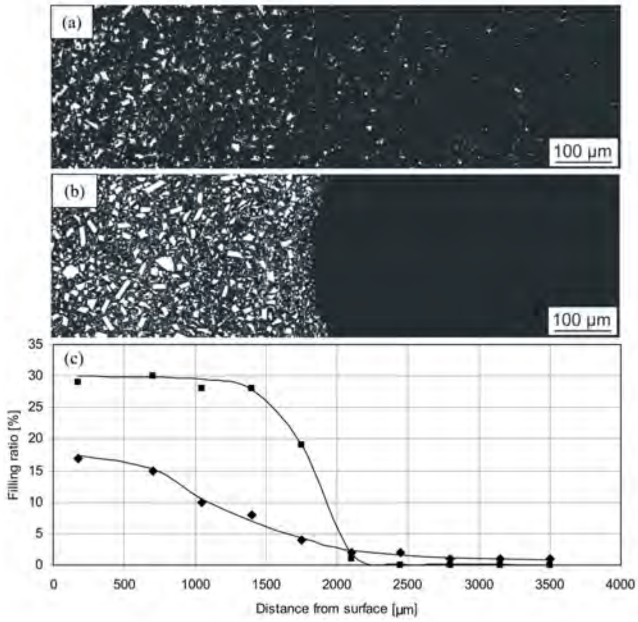


Fig. 3. Microstructure of bonded magnets: a) Epidian 5, b) AKA-resin and c) changes of filling ratio.

Rys. 3. Mikrostruktura magnesów a) z żywicą Epidian 5, b) z żywicą AKA oraz c) zmiany współczynnika wypełnienia od krawędzi zęba do otworu

The filling ratios in the teeth area were also evaluated using X-ray tomography. For the composite containing Epidian 5, in the upper part of the tooth magnetic powder amounted to 37 vol.%, whereas in the specimen with AKA-resin, the respective content was 43 vol.%. The differences between the values obtained from x-ray tomography and metallography apparently result from the non-random distribution of powder particles. In the process of studies of forming flake-shape powders by injection moulding, it was found that the flakes distribute themselves with the large surface perpendicular to the direction of material flow in the mould [2]. A similar tendency may also occur in the course of centrifugal casting of the composites with flake-shaped powders. In Figure 4, the 3D image of a part of the tooth for the magnet cast with AKA-resin is shown. One can observe a tendency for the location of the flakes to be perpendicular to the radius of the magnet. On the cross-section perpendicular to the tooth axis (disc radius) and parallel to the axis of the magnet, a relatively large amount of flat surfaces of the particles is visible. This observation supports the abovementioned hypothesis, however, further studies on the orientation of flake-shaped particles distribution in centrifugal casting are required.

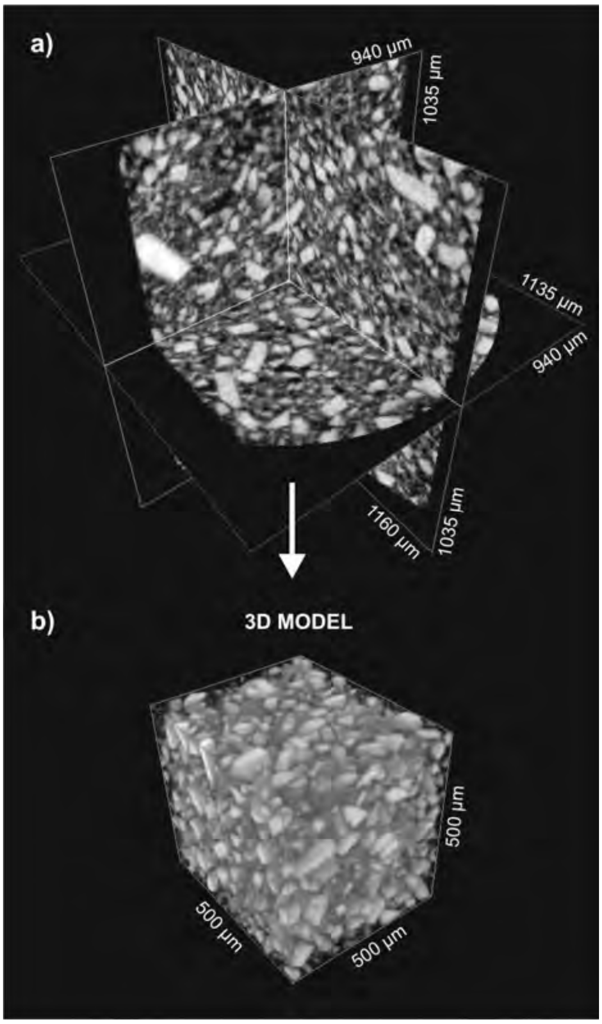


Fig. 4. Three perpendicular cross-sections of tooth (a) and 3D image of tooth cast with AKA-resin (b)

Rys. 4. Przekrój trzema prostopadłymi płaszczyznami fragmentu „zęba" magnesu odlewanego z żywicą AKA (a) oraz jego obraz 3D (b)

Gravitational sedimentation of the powder progresses in the course of casting until the viscosity of the resin is high enough and leads to an increase in the filling ratio in the bottom part of the ingot. As a result, the magnets cut from the bottom part would contain more magnetic powder, which would lead to higher remanence (in expense compared to the magnets cut from the upper part). Assessment of how essential this fact is for the magnets performance was undertaken. In order to do this, changes in the density along the length of the ingot were measured (Figs. 5 and 6). For both the cases, a higher density in the bottom part of the ingot is visible. The differences between the bottom and upper part of the ingot strongly depend on the resin viscosity. For the AKA-resin, the difference at the bottom and upper relative density equals 6.25%. For Epidian 5 this difference does not exceed 2%. One can conclude that gravitational sedimentation does not cause a serious problem for centrifugal casting. Sedimentation can further be limited by applying a higher rotation speed.

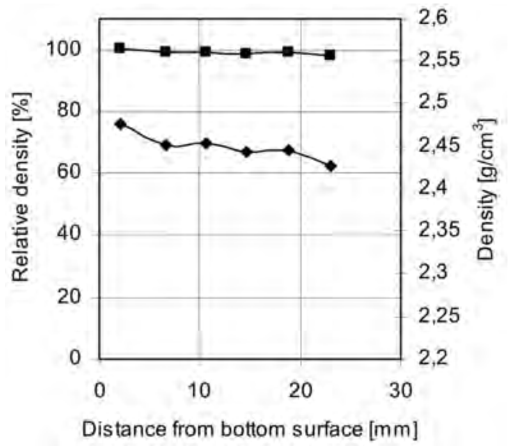


Fig. 5. Density changes caused by gravitational sedimentation versus distance from bottom surface. Epidian 5: ♦ - density, ■ - relative density

Rys. 5. Zmiana gęstości odlanej kształtki na jej długości wywołana sedymentacją grawitacyjną proszku w żywicy Epidian 5: ♦ - gęstość rzeczywista, ■ - gęstość względna

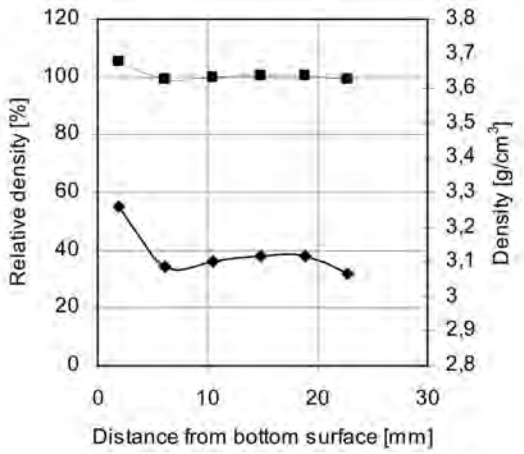


Fig. 6. Density changes caused by gravitational sedimentation versus distance from bottom surface. AKA-resin: ♦ - density, ■ - relative density

Rys. 6. Zmiana gęstości odlanej kształtki na jej długości wywołana sedymentacją grawitacyjną proszku w żywicy AKA: ♦ - gęstość rzeczywista, ■ - gęstość względna

The ensity of the material in the area of the teeth was determined on the basis of experimentally determined filling ratios. These values were further used for evaluation of the magnetic properties of active parts - teeth - for both bonded magnets. In the case of the magnet cast with resin having a low viscosity, the results of the measurements were very reproducible. For the magnets with Epidian 5, the remanence and

 

$(BH)_{max}$ values obtained for particular teeth were somewhat different, reflecting the different filling ratios. The magnetic properties of the magnetic powder and final composite magnets are collected in Table 2. The respective hysteresis loops are shown in Figure 7. The achieved values enable us to conclude that the magnets are suitable for application in stepper motors. The applied method of centrifugal casting opens the possibility to optimize the structure of the magnets. On the current stage of research, one can also conclude that an increase in the rotational speed of the mould and reduction of the resin viscosity, for example by the addition of solvents, should further improve the magnetic properties.

TABLE 2. **Magnetic properties of MQP powder and bonded (teeth area)**
TABELA 2. **Właściwości magnetyczne wyjściowego proszku Nd-Fe-B oraz otrzymanych magnesów wiązanych (w obszarze „zęba")**

| Property | Powder MQP 16-7 (data from suplier) | Bonded magnet Epidian 5 | Bonded magnet AKA-resin |
|---|---|---|---|
| Coercivity [kA/m] | 525÷605 | 583 | 583 |
| Remanence [T] | 0.94÷0.98 | 0.223÷0.316 | 0.393 |
| Energy $(BH)_{max}$ [kJ/m$^3$] | 114÷130 | 8.56÷16.72 | 25.2 |

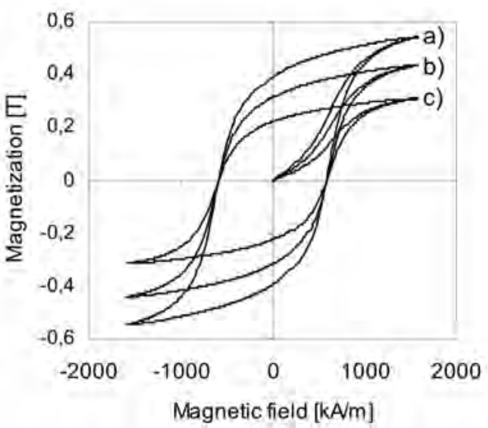


Fig. 7. Hysteresis loops measured for active parts of teeth, for magnet cast with AKA-resin (a) and magnets having extreme properties cast with Epidian 5 (b and c)

Rys. 7. Pętle histerezy części czynnej „zębów" magnesu odlewanego z żywicą AKA (a) oraz magnesów o skrajnych właściwościach odlewanych z żywicą Epidian 5 (b i c)

## SUMMARY

The obtained results showed the possibility of fabricating gradient bonded magnets and controlling their microstructure, in the centrifugal casting process of magnetic powder-epoxy resin mixtures. In this way, ring magnets in which the powder is distributed in the active part only, i.e. interacting with the magnetic core, can be formed. Such magnets can contain less magnetic powder and for this reason have a competitive price to bonded magnets with a constant filling ratio. This method allows also for the use of powders obtained from the recycling of sintered Nd-Fe-B magnets. In the active part of the magnet, the filling ratio was 43%, which is close to the one obtained for flake-shape powder bonded magnets fabricated by injection moulding [2]. The results of this study enable initiation of research on a stepper motor with gradient structure magnets.

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