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Insulated Iron Powders for Automotive Applications

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ABSTRACT

Insulated iron powders developed for AC or pulsed DC applications may soon find their niche in low frequency automotive applications such as accessory motors and sensors. These materials are produced from a pure iron powder in which the particles are insulated from each other using different dielectrics. Among the interesting attributes of these materials is the possibility to engineer their composition and processing to specifically meet application requirements. For instance, in the case of an iron-resin material system, the iron particle size may be varied as well as the amount of thermoset resin. In certain cases, a lubricant can be added or even totally replace the resin in order to ease the pressing.

This paper discusses the effect of composition and processing technique on the properties of insulated iron materials. The physical, mechanical, and magnetic properties of these materials are presented together with their potential automotive applications.

INTRODUCTION

New motor designs using insulated iron powders provide technical solutions for automotive accessory motors like those used in power seats, antennae, windows, sun roofs, fans, etc. These solutions employ design principles that take advantage of the three dimensional magnetic and thermal properties of insulated iron powders. The result is a smaller motor with higher torque-to-weight ratio, and less copper in the windings (due to the increased fill factor) compared to traditional motor designs which are limited to the use of laminations. The automotive industry has long been aware of the cost savings resulting from near net shape forming and long production runs that powder metal parts allow : minimal waste, smooth surface finish and high efficiencies. The new designs take advantage of all of the cost savings associated with typical powder metal parts.

Insulated iron powders or dielectromagnetics are specifically engineered for soft magnetic applications in alternating magnetic fields where high permeability, high induction and low losses are desired. These materials can be engineered to fill the performance gap between the properties of ferrites and those of laminated steels. Some of the design input variables to be considered in the development of dielectromagnetics are application property requirements, material formulations and processing conditions. These factors, combined with an understanding of the property-application relationship, have lead to the development of the iron-resin systems presented [1,2,3]. A high purity and highly compressible water-atomized iron powder is the ferromagnetic material of choice for these dielectromagnetics. Thermoset resins and lubricating dielectrics are used to electrically insulate the iron particles and to provide adequate strength after curing treatments. Thermoset resins are also less affected by temperature than other dielectrics such as thermoplastics providing durability in service. Finally, the processing of the materials is kept as simple as possible to help reduce costs. The result is a low cost, high performance material directly applicable to powder metal fabrication techniques and automotive motor applications.

Currently, materials are available that cover a broad range of frequencies from low frequency (50-60 Hz) to medium (up to 20 kHz) and to high frequency (up to about 1 MHz). The main differences lie in the particle size of the base iron powder, the quantity of thermoset resin, and in the fabrication process. This paper summarizes the differences between these materials, their properties, and their potential applications.

LOW TO MEDIUM FREQUENCY MATERIALS (50 Hz to 20 kHz)

These materials were specifically developed to compete with steel laminations currently used in low to medium frequency applications (up to 20 kHz). They are composed of high purity water-atomized iron particles mixed with thermoset resins and lubricating dielectrics. The final compositions are tailored to meet the specific application requirements. The quantity of organic compounds is kept as low as possible in order to get the best performance from the ferromagnetic properties of iron. Three typical formulations of composite materials that cover the low to medium frequency range of applications are presented with their characteristics and properties.

MATERIALS CHARACTERISTICS

The first formulation (A) is an iron-resin material, called ATOMET EM-1, that is a relatively high strength material requiring die wall lubrication for the compaction. After pressing, parts are cured at 200°C in air to cross-link the resin and achieve the maximum strength. The second formulation (B) is a lubricated iron-resin material, called FLOMET EM-1, that contains a proprietary lubricant. This formulation can be used when die wall lubrication is not possible and the mechanical strength is less critical. The curing of the pressed parts is made at 160°C. The third formulation (C) is an iron-dielectric material that differs in that the dielectric acts as a lubricant during the compaction as well as an insulator after a low temperature heat treatment (typically 350°C). This material is particularly suitable for pressing complex shapes but, contrary to the two preceding materials, is restricted to AC applications at 50-60 Hz. The characteristics of the three composite materials are described in Table I.

Table I. Characteristics of three typical materials used for low to medium frequency applications.

Material	**A**	**B**	**C**
Description	Iron-resin	Lubricated Iron-resin	Iron-dielectric
AD, g/cm³	2.80	3.05	3.00
Hall flow, s/50 g	28	27	28
Compaction	External lubrication	Conventional	
Curing (30 min)	200°C	160°C	350°C
Applications	50-20,000 Hz		50-60 Hz

These free flowing powdered materials have an apparent density between 2.80 g/cm³ and 3.05 g/cm³ and require a low temperature heat treatment after compaction. The mechanical and magnetic properties of such dielectromagnetics are highly dependent on their density, similar to any other powdered metal part. Property-density relationships for these three composite materials are presented and discussed in the following section.

MATERIALS PROPERTIES

The compressibility of the three composite materials, obtained by pressing transverse rupture (TR) bars, is plotted in Figure 1. The materials B and C which contain a lubricant are slightly more compressible than the iron-resin material with a difference in density of about 0.05 g/cm³ at 800 MPa. The stripping and sliding pressures for the ejection of such TR bars (12.7 mm thick) are plotted in Figure 2 as a function of the density.

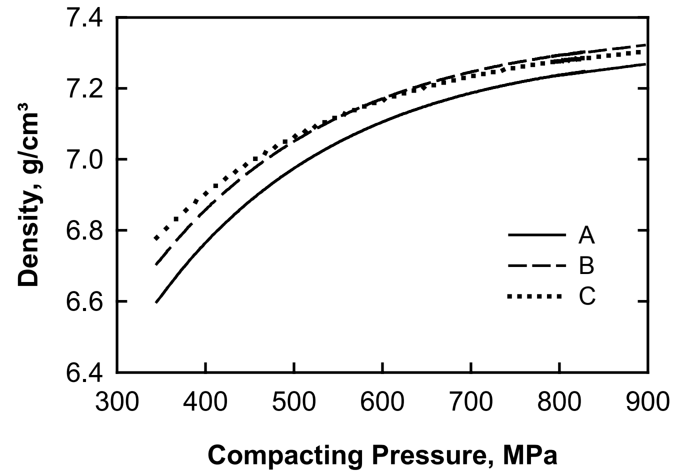

Figure 1. Effect of compacting pressure on the density of TR bars pressed from the three composite materials.

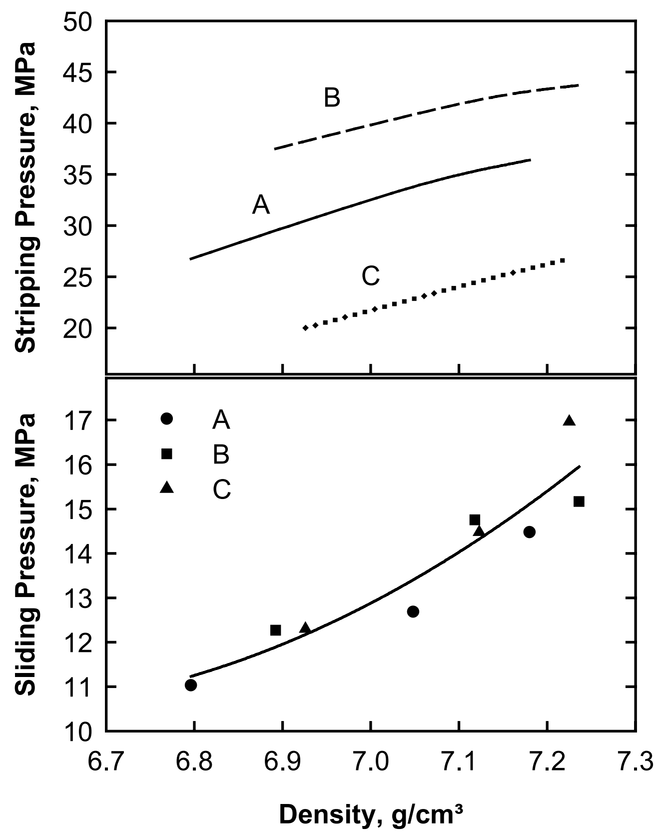

Figure 2. Effect of density on the stripping and sliding ejection pressures of 12.7 mm thick TR bars pressed from the three composite materials.

The pressures required to start the ejection of the bars vary from one mix to the other but are, in all cases, as low or even lower than those typically obtained with conventional P/M mixes, e.g., 30 to 40 MPa at a density of about 7.0 g/cm³. The pressures required to slide the bars out of the die are very similar for the three mixes and increase with the density or compacting pressure.

The mechanical strength of these materials after their respective curing treatment is illustrated in Figure 3 as a function of the density. The highest values, up to 125 MPa, are obtained with material A that contains no lubricant. Material B exhibits the lowest values which are almost independent of the density (about 55 MPa). The strength of material C is very density dependent and values as high as 110 MPa at densities above 7.20 g/cm³ can be reached. For this latter material, it is also possible to resin impregnate the low density parts (below 7.0 g/cm³) in order to increase their strength to values of about 100 MPa [3].

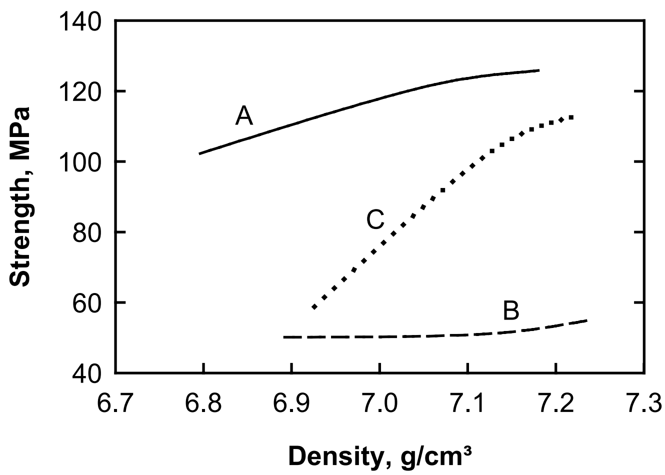

Figure 3. Effect of density on the mechanical strength of TR bars for the three materials cured 30 min in air : material A at 200°C, B at 160°C and C at 350°C.

In these composite materials, electrical insulation between the iron particles is required in order to minimize eddy currents [4]. It is possible to evaluate the degree of insulation in these composite materials by measuring the bulk electrical resistivity, i.e., the one that results from the combination of the conducting phase (iron) and the insulating phase (dielectric) [5]. The bulk electrical resistivity of the three materials, as determined on TR bars using a four-point contact direct-current measurement method, is given in Figure 4 as a function of the density. The resin-containing materials A and B are much more resistive than material C : 400 to 1000 μΩ-m for the formers versus 100 μΩ-m for the latter, which is also less density dependent. Materials A and B are thus adequate for applications at frequencies up to a few kHz while material C is suitable for applications at low frequencies (50 to 60 Hz).

The effect of density on the magnetic induction and maximum permeability is presented in Figure 5. Magnetic properties were measured at an applied field of 120 A/cm (150 Oe) on toroids 5.26 cm OD by 4.34 cm ID by 0.635 cm thick. The induction is proportional to the density and not greatly affected by the mix formulation. However, while the maximum permeability increases with density it is also affected by composition and processing. This is exhibited in material C which has approximately 15% higher permeability at a given density than materials A and B. This is partly attributable to a certain extent of stress relief that occurs during the 350°C heat treatment. Indeed, hysteresis losses are relatively high in these materials and a low temperature heat treatment has a beneficial effect on their magnetic properties [6,7,8]. Here, even at a temperature as low as 350°C, the coercive force in material C is reduced by about 15% : 375 A/m versus 415 A/m for materials A and B.

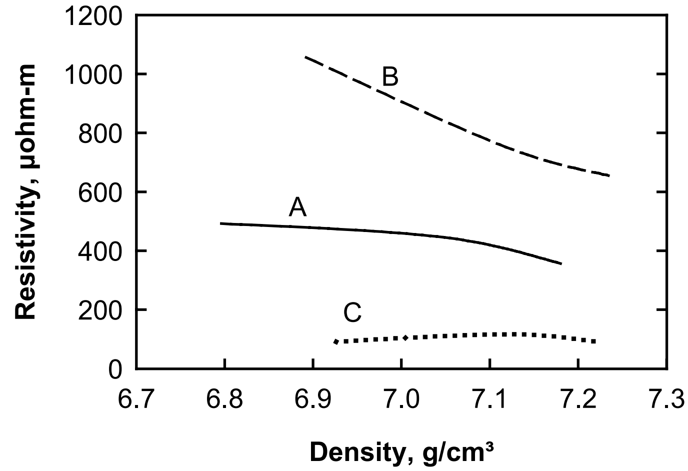

Figure 4. Effect of density on the bulk resistivity of the three materials as determined on TR bars cured 30 min in air : material A at 200°C, B at 160°C and C at 350°C.

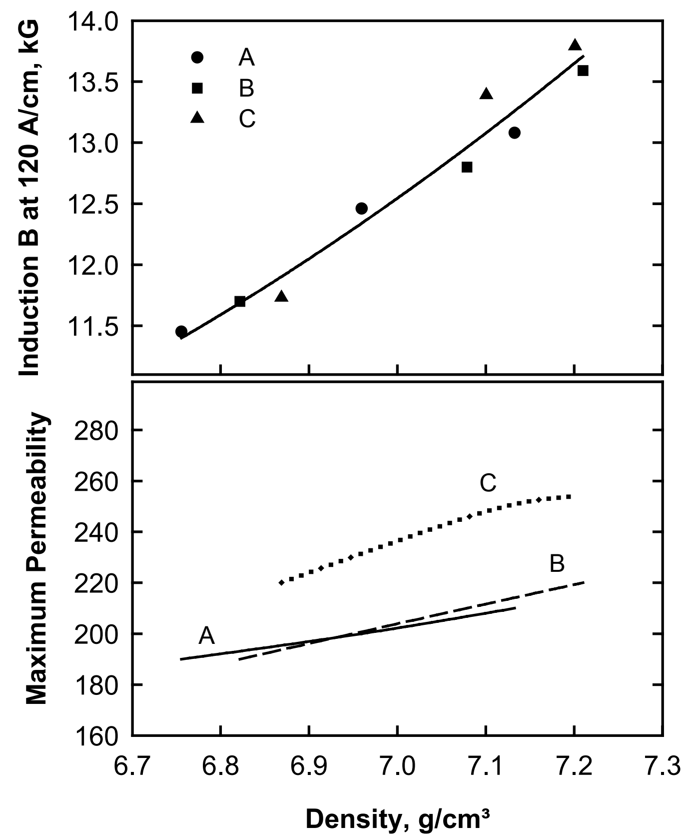

Figure 5. Effect of density on the magnetic induction and maximum permeability (120 A/cm applied field).

The effect of the density on the AC losses at 1 Tesla measured at 60 Hz and 400 Hz for the three materials is presented in Figure 6. The AC losses decrease with an increase in density for all materials. This can be attributed to a decrease in the hysteresis loss. Indeed, with powdered materials, as the density increases magnetization becomes easier because of the resulting higher magnetic induction, higher permeability and lower coercive force. This improvement in DC characteristics with an increase in density translates into a decrease of the hysteresis portion of the core loss. Losses are the same for materials A and B and approximately 12% lower for material C. Again, this is due to the 350°C heat treatment that slightly reduced the hysteresis loss in this material. For these materials at densities above 7.0 g/cm³, losses are about 10 W/kg at 60 Hz and 70 W/kg at 400 Hz. The fact that the AC losses are proportional to the frequency and not to the square of the frequency, is a good indication that the insulation is efficient and eddy currents remain low, even in material C which has a lower resistivity. However, for these composite materials it is known that the induction of eddy currents not only depends on the frequency and extent of insulation or resistivity but also on specimen geometry (in low resistivity materials, the induction of eddy currents increases with an increase of the part cross section) [5]. Thus depending on the part dimension, field induction and frequency, it may be found that material C is too conductive for the application.

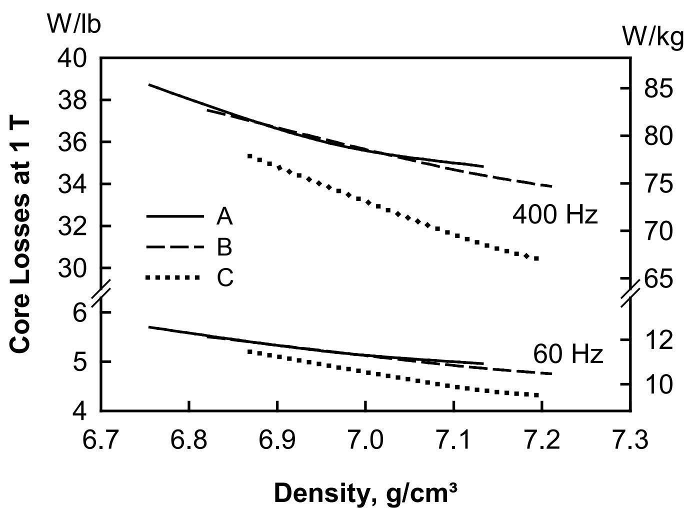

Figure 6. Effect of density on total core losses at 1 Tesla measured at 60 Hz and 400 Hz.

POTENTIAL AUTOMOTIVE APPLICATIONS

These new composite materials are just starting to penetrate applications previously dominated by steel laminations. They are intended for use in AC applications at low-to-medium frequencies and even if they can replace existing laminated parts without modification (drop-in), much better results are obtained by redesigning the parts to take advantage of their isotropic properties. These materials show stable properties in applications subjected to temperature variations such as in under-the-hood and indoor automotive applications [9,10]. They have been proven to be cost effective and reliable in automotive ignition coil applications. They can be used in small motors, especially DC brush and brushless motors, alternators and generators, speed sensors and relays. Topologies impractical with steel laminations may now be suitable with these materials. Some examples of their utilisation are in permanent magnet brush and brushless motors [11,12]. By using concentrated windings in the design [13], a topology adapted to these isotropic materials and P/M shaping techniques, both the copper winding volume and weight of the armature were reduced with identical performances.

HIGH FREQUENCY MATERIALS (UP TO 1 MHZ)

Material and property requirements differ for high frequency AC magnetic applications. For instance, core loss and initial permeability are the most important properties to consider when selecting materials for high frequency applications. As frequency increases, the relative importance of eddy current losses compared to hysteresis losses increases and most of the improvement in total core loss at high frequencies comes from improvements in eddy current shielding. The relationship between material characteristics and eddy current losses (P_e) is given by the following equation :

$$P_e = \frac{K_e B^2 f^2 d}{\rho}$$

where K_e is a constant depending on geometrical factors, B the magnetic induction, f the frequency, d the smallest dimension in the plane of the eddy current circuits and ρ is the electrical resistivity. In a classical approach, the electrical resistivity ρ is that of the single conducting phase (0.1 μΩ-m for iron). However, in dielectromagnetics it is common to consider a bulk resistivity because eddy currents are not always strictly confined to particles and can circulate in agglomerates of contacting particles and even in the whole sample depending on the degree of insulation [5]. Also, in dielectromagnetics, d, the diameter of the insulated domains perpendicular to the eddy current paths, is difficult to determine, but can be modified by varying the particle size of the iron particles and the degree of insulation between them. This material approach was applied to the development of an iron-resin material system for high frequency applications [2].

The material system is composed of a fine high purity and high compressibility water-atomized iron powder wet mixed with a thermoset resin powder. The process consists of dissolving the resin in an adequate quantity of solvent, spraying the solution onto the iron particles, mixing and drying. As in the low frequency materials, the composition of the high frequency composite material can be engineered to meet specific property requirements. For instance, the fineness of the iron powder and the quantity of resin can be varied. The effect of varying these parameters on the initial permeability measured at 0.5 mT and the total losses calculated at 1 mT are given in Figure 7 and 8 respectively. The two graphs also show the typical performance of a low-to-medium frequency material for comparison purposes. The reference composite material contains an iron with a particle size typical of a water-atomized powder (< 250 μm) admixed with 0.8% resin. The two high frequency materials contain the same base iron powder but screened differently. One is screened to remove the particles larger than 75 μm and the other to remove the particles larger than 45 μm. Both are wet mixed with three levels of resin. Their typical bulk resistivity ranges from 1000 to 3000 μΩ-m.

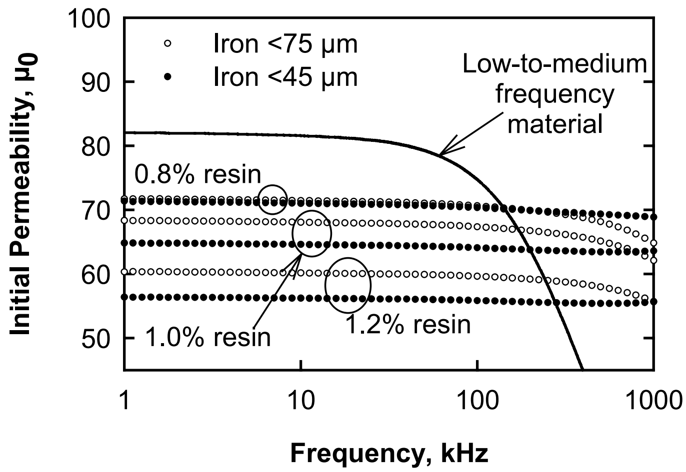

Figure 7. Effect of iron particle size and resin content on the initial permeability at 0.5 mT of high frequency materials and a low-to-medium frequency material.

In Figure 7, the level and stability of initial permeability with respect to frequency gives a good indication of the domain of applications of these materials. The reference low frequency material has a high initial permeability with a value of 82 which is constant up to about 50 kHz and then decreases rapidly. Conversely, the high frequency materials permeability is lower but remains constant as the frequency is increased to hundreds of kHz. This results in a lower permeability at low frequency but a higher permeability (than the low frequency material) at the intended high frequency. A finer iron powder generally yields a lower permeability that is more stable with respect to frequency. A higher resin level decreases the density of the material and consequently the initial permeability.

The domain of applications for these two types of materials is also evidenced in Figure 8 where the total losses for the low frequency material are almost one order of magnitude higher than those of the high frequency materials. The inset also shows that losses decrease with a decrease in the iron particle size and an increase of the resin content. Typically, there is a decrease of about 30% in losses by decreasing the iron particle size from 75 μm maximum diameter down to 45 μm maximum diameter.

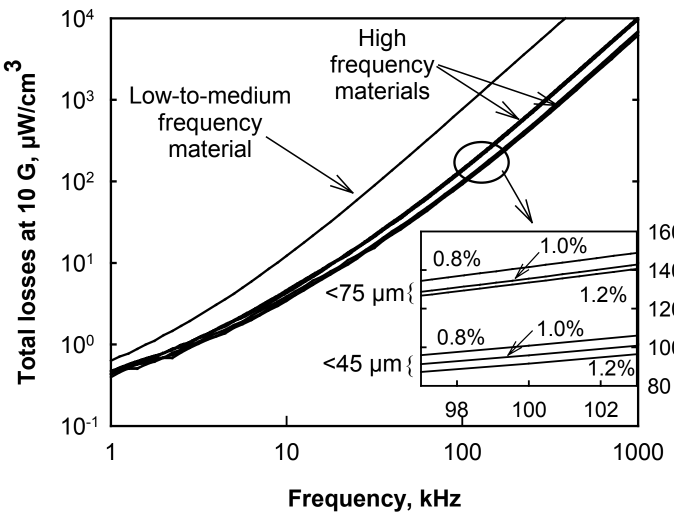

Figure 8. Total losses at 1 mT for high frequency materials compared with a low-to-medium frequency material. The inset at 100 kHz shows the effect of the iron particle size and resin content.

These materials are suitable for applications such as high frequency inductors, ballasts, magnetic fluids, transformer cores, etc.

CONCLUSION

It is now possible with ferromagnetic material systems combined with new electrical machine design principles to break new ground in the area of automotive magnetic applications. Depending on the application, the material system can be engineered to meet the specific requirements or processing constraints. For instance, parts with very similar magnetic properties (induction, permeability, core loss at low to medium frequencies) can be obtained from different formulations of composite materials. They are all composed of a high purity iron powder which contains a unique resin binder and/or proprietary lubricant. They differ in the processing at the press (external versus internal lubrication) and at the curing step. They differ also in the level of mechanical strength they can yield. Furthermore, by modifying the manufacturing process and decreasing the iron particle size in order to increase the electrical resistivity, high frequency materials can be used to produce parts with low core loss at frequencies up to 1 MHz.

In the future, motor designers using these new materials, will provide the automotive community with lower cost and more efficient accessory motors as well as other electrical devices. The use of such dielectromagnetics offers new opportunities to reduce cost, reduce the number of parts per component and increase design flexibility [12].

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