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The influence of the dielectric on the properties of dielectromagnetic soft magnetic composites. Investigations with silica and silica hybrid sol-gel derived model dielectric.

Y. X. Pang, S. N. B. Hodgson
School of Science and Technology, University of Teesside, Middlesbrough, Tees Valley TS1 3BA, UK

J. Koniarek, B. Weglinski
Institute of Electrical Machines, Drives, and Metrology, Wroclaw Technical University, Wyspianskiego, 27, 50, 370, Wroclaw, Poland

Abstract
Dielectromagnetics made from organic-inorganic hybrid silica-coated iron powders were characterised by determination of their physical, mechanical and magnetic properties. The influence of three main factors, dielectric composition, addition level and heat treatment conditions were investigated. Results showed that these factors have significant effects on the performance of the dielectromagnetics. Increase in the organic phase content in these dielectric coatings tends to increase both the electrical resistivity and magnetic permeability of dielectromagnetics, although the strength and density are slightly impaired. Increasing the coating thickness leads to improvements in resistivity and thus reduced eddy current losses, but these are offset by reductions in density, strength and particularly magnetic permeability. A hybrid organic-inorganic coating formulation based on 40mol% MTMS and 60mol% TEOS precursors was found to be the optimum composition investigated. Addition levels between 0.1 and 0.3% were found to offer a good compromise between maximum permeability ($\mu_{\text{max}}>400$) and minimum loss (<typically <8 W/kg) for operation at 50Hz/1T, and the system can be optimised within this range for the desired performance.

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* Corresponding author
1. Introduction

Dielectromagnetics are a member of the family of soft magnetic composite materials (SMC’s) which comprise powdered ferromagnetic powder, normally pure iron with typical average particle size in the range 50 to 350 μm, together with a small volume fraction of a dielectric phase which isolates and binds the powder particles to control eddy current losses and impart mechanical strength to the resultant components [1]. Dielectromagnetics are currently attracting much interest as a cost effective alternative to magnetic sheets or laminates in suitable designs [1-6]. One advantage is the ease with which their properties can be tailored. For instance, they may be formulated to optimise magnetic permeability at the expense of electrical insulation for applications in normal (circa 50Hz) frequency, or with high resistivity at the cost of permeability for use at medium-to-high frequencies.

The properties of dielectromagnetics are affected by a number of factors including the particle size and purity of the ferromagnetic metal powder, the type and amount of the dielectric material, the manufacturing and forming processes used [1, 7-8], with the dielectric material plays a particularly important role, determining to a large extent the density, magnetic permeability, resistivity and eddy current losses, together with the mechanical strength of dielectromagnetic compacts [9]. However, much of the research undertaken to date has been industrially oriented and commercially restricted and there have been few published studies into the relationships underlying these effects. There thus remains a significant need for more fundamental investigations of the factors determining the performance of these materials.

This publication investigates into the effect of the dielectric phase on the properties and behaviour of such dielectromagnetics, using sol-gel derived silica and silica hybrid materials as model dielectrics. In particular, the influence of the coating composition, thickness and process conditions on the key physical and magnetic properties described above was studied to determine the key factors controlling performance of dielectromagnetics. As well as providing a useful model dielectric in which a wide range of physical properties can be readily adjusted, such materials are practically attractive for dielectric applications due to the ease of application, the relatively low cost of the silica precursors, the high electrical resistivity and
thermal stability and the ability to manipulate the chemical and physical properties by incorporation of organic functionality.
2. Experimental Methods

2.1 Powder coating process.

The high purity iron powder (ATOMET 1001HP) obtained from QMP Metal powders GmbH, Germany. The powder has a mean particle size of 96μm. Total level of impurities were <0.21%. This powder was coated by blending with a suitable quantity of a coating sol using a rotational mixer, with the addition levels between 0 and 1 mass %.

The SiO$_2$ and hybrid SiO$_2$ sols were prepared from tetraethoxysilane (Si(OCH$_3$)$_4$ or TEOS, Aldrich) or blends of TEOS and methyltrimethoxysilane (SiCH$_3$(OCH$_3$)$_3$ or MTMS, Aldrich) via a primarily aqueous based sol-gel process. Phosphoric acid was dissolved in distilled water to form a 0.078 mol/kg solution. To this, a further addition of 15 vol.% of ethanol was added followed by TEOS or TEOS/MTMS mixtures to produce a total precursor concentration of 2.0 mol/kg. Initially this results in an immiscible two-phase mixture, however stirring the mixture at 60°C results in gradual transition to a clear sol. After heating for 1 hour at the temperature, the synthesised sols were matured by standing at ambient condition overnight before use after which they remained stable for several weeks in a closed container.

A range of coating formulations were prepared ranging from purely inorganic systems using TEOS precursor (denoted M0) to inorganic-organic hybrid coating formulations containing up to 40 mol.% MTMS (and hence 60 mol.% TEOS) precursor denoted M40.

2.2 Beam and toroid preparation

Two types of samples were prepared for characterisation from the variously coated powders. Samples for physical characterisation were prepared in the form of beams with dimension of 5 × 5 × 36mm by uniaxial compaction using a floating die which allows movement of both the top and bottom plungers during compaction. Various compaction pressures in the range 400 to 800MPa were used. The samples for magnetic characterisation comprised toroidal compacts with dimensions in millimetre of 5 (height) × 50 (inner diameter) × 60 (outer diameter). These specimens were also were prepared by uniaxial compaction using a floating die. A compaction
pressure of 700MPa was used for all the toroid samples. To avoid excessive friction during compaction 0.3% of admixed polyolefin lubricant was used in all cases.

Heat treatment of the beams and toroids were carried out in a tube furnace. The default annealing conditions were: temperature 500°C, ramp 10°C/min, duration 30min. and under static air. Other heat treatment conditions were also used in some experiments with these being specified where applicable.

2.3 Measurement of physical and mechanical properties

Density of the compacted beams was measured by gravimetry on the basis of Archimedes’ principle, using distilled water as the medium.

Resistivity of the beams was measured using a four-point method. A 100mA constant current was passed through the beam via end contacts and the voltage drop measured between two further electrodes at a spacing of 26mm.

Flexural strength of the beams was measured using three-point bending with a 26mm span width. Experiments were conducted on a Lloyds Universal Tester under a loading rate of 1.0mm/min.

Five samples were tested for each measurement and the average reported.

2.4 Determination of magnetic performance

Measurement of magnetic parameters was carried out using MAG-TD200 apparatus under alternating fields at frequency 50Hz. The toroidal samples were provided with primary and secondary windings of 240 and 360 turns respectively and a sinusoidal waveform of induction was applied. The equipment, which was specially developed for this purpose, was previously calibrated using test standards and found to provide accurate, reproducible measurements to within an error of ± 0.5%. Losses were determined for a maximum induction value of 1Tesla, at a frequency of 50Hz. The contribution of eddy current and hysteresis losses was determined by extrapolation of a plot of loss per cycle versus frequency.

3. Results and discussion

3.1 Compact density of hybrid-coated iron powders
Figures 1 is concerned with the effect of the dielectromagnetic composition and process conditions on the density of the resultant material. There are a number of evident trends in this behaviour.

The results shown in Figure 1(a), which are for samples compacted under a standardised pressure of 700 MPa, show the effect of increasing additions of the silica hybrid coating containing 20 mol% MTMS (M20) on the density of the dielectromagnetic component and shows an essentially linear trend of decreasing density with increasing dielectric addition level in the 0 – 1 mass% range, varying from approximately 7.25 to 7.00 g/cm$^3$. This is consistent with the addition of an increasing proportion of lower density material. The density in all cases is significantly below the theoretical density value of the solid constituents (assuming law of mixtures) but remains essentially constant at around 90% of theoretical density in each case, indicating that the impact of the coating on the compaction behaviour of the powder is otherwise fairly small.

Figure 1(b) illustrates how the % organic content (expressed as mol. fraction MTMS component) of the dielectric coating formulation influences the density both in the as pressed component and after various annealing heat treatments. In these experiments the dielectric addition level was standardised at 1 mass% and the compaction pressure at 700MPa. Although the effects are rather small and there is some scatter in the data, linear regression of the data does indicate consistent trends, where the density decreases with increasing organic content, which might be anticipated from the lower density of the organic component compared to inorganic silica. The magnitude of this effect can also be seen to reduce as the heat treatment temperature is increased above 500°C, as evidenced by the decreasing slope of the regression lines with increasing temperature in this plot. This can be explained in terms of the effect of removal of the organic phase by pyrolysis at these temperatures, with the relative increase in density implying that this must be accompanied by some shrinkage of the coating.

Figure 1(c) indicates the effect of compaction pressure on the density of resultant dielectromagnetic compacts. Results are presented for the highest (M40) and lowest (M0) organic content coating formulations used in this study. In this case the dielectric addition level was standardised at 0.3 mass% and the default heating condition applied. In all cases, the density of compacted beams rises substantially with increase of compaction pressure, reaching a density of almost 7.3 at a pressure of
800MPa, indicating that all the dielectromagnetic formulations have good compressibility. The two dielectromagnetics showed similar compaction behaviour, but with the M40 coated formulation exhibiting slightly enhanced compactability at pressures up to 600MPa. This can be assigned to the contribution of M40 organic moiety which reduces coating surface energy and friction, facilitating good packing of the coated particles at lower compaction pressures. In addition, the presence of MTMS leads to lower crosslink density imparting increased flexibility [11] which also contributes to the better compressibility. At higher pressures, strain hardening behaviour of the iron powder is likely to dominate the compressibility and there appears to be no benefit from the organic addition. However, this result is potentially significant as commercial processing of these products is likely to be carried out at the lower end of this pressure range. Taken together, the above data suggest that the sol-gel derived coatings do not adversely impact compaction behaviour to a significant effect, and that the incorporation of an organic component in the material may act as a compaction aid at lower compaction pressures.

![Figure 1](image)

**Figure 1** Effects of various factors on densities of dielectromagnetic composite components after heat treatment (a) Effect of dielectric addition level for coating containing 20 mol% MTMS, (b) Effect of organic content and heat treatment for 0.1 & 1 mass% dielectric addition and (c) Effect of compaction pressure on inorganic (M0) and 40 mol% MTMS dielectric coatings (0.3 mass% additions).
3.2 Oxidation

Previous studies into the effects of heat treatment on dielectromagnetic SMC materials [8] have determined that the properties of these materials are substantially affected by the effects of oxidation during heat treatment.

Studies of the mass changes in these materials during heat treatment indicated somewhat different behaviour for the inorganic and organic (MTMS) containing compositions and depending upon the compaction pressure as shown in Figure 2.

Figure 2  Effects of compaction pressure and heat treatment atmosphere (at 500°C) on the mass of dielectromagnetic composites of different composition (M40 and M0 at 0.3 mass% addition level)

Generally the samples heat treated under Argon showed a reduction in mass of approximately 0.3-0.35 mass % irrespective of compaction pressure, with the organic containing compositions showing a slightly larger mass loss than the inorganic (M0) compositions. These mass losses can be attributed to the effects of the volatilisation of residual water, and organic material including the admixed binder. By contrast the samples heat treated in air showed a strong dependence on the compaction pressure with samples subject to lower compaction pressures generally exhibiting larger mass increase. This can be attributed to oxidation of the iron powder. For samples compacted above 600 MPa a small decrease in mass was observed similarly but of reduced extent in comparison to the samples heat treated under argon. This suggests that the increased density achieved with higher compaction pressures inhibits the transport of oxygen within the compacts and thereby the overall extent of oxidation.
3.3 Resistivity of the dielectromagnetics

The effect of the dielectromagnetic composition and process conditions on the electrical resistivity of the resultant material shown in Figures 3(a)-(c) shows some significant and clearly distinguishable effects.

In all cases the resistivity of the material falls significantly during heat treatment from the value achieved in the as pressed components. As shown in Figure 3(a), typically this would amount to approximately 20 fold reduction in resistivity after heating to 450°C, with this fall becoming increasingly significant as the heat treatment temperature is increased.

The effect of incorporating the organic (MTMS) component to the dielectric coating is shown in Figure 3(a) for samples compacted at 700 MPa. It can be seen that increasing the MTMS content results in a significant increase in resistivity both before and after heat treatment. This can be attributed to the increased flexibility or toughness afforded by the organic constituent, allowing the insulating coating to withstand the deformation of the underlying iron powder and remain intact during the compaction process.

Closer inspection of the data in Figure 3(a) also reveals that the magnitude of resistivity decrease with heat treatment temperature comparatively increases as the organic content of the dielectric is increased, particularly above 500°C. This can be attributed to the loss of organic groups from the dielectric. FTIR/DTA Studies carried out on silica hybrid materials reported elsewhere [12-13], indicate that the methyl group in these systems is stable up to approximately 500°C, at which point pyrolysis of the organic group occurs and largely completes by 600°C.

The atmosphere used for heat treatment also significantly influences the temperature dependence of resistivity as illustrated in Figure 3(b). When heat treated in air, resistivity appears to decrease in a linear manner with increasing temperature, whereas it is initially maintained to higher temperatures under argon, but falling more quickly at temperatures of 300°C or above to essentially the same value as achieved under air after heating to 500°C or above.

The temperatures at which these significant effects occur are substantially below the temperatures at which any degradation of the coating would be expected, and rather this reduction in resistivity is believed to occur as a result of other mechanisms
allowing migration of iron atoms driven by thermodynamic criteria. The results suggest that two mechanisms are responsible. At lower temperatures the effects are probably due to the formation of relatively conductive magnetite (conductivity circa 1.25 \( \Omega^{-1} \text{ m}^{-1} \)) providing a conduction path between the iron particles, with such oxides expected to form preferentially in the vicinity of any cracks and pinholes in the coatings. At higher temperatures, the convergence of the behaviour in both oxidising and protective environments suggests an alternative mechanism is responsible. In this case it is believed that direct diffusion of the iron is occurring as the system attempts to reduce its interfacial energy by reducing the iron-SiO\(_2\) interfacial area and through the formation of iron-iron particle contacts, in effect resulting in undesirable incipient sintering of the system. Although this effect could not be observed directly, the corresponding increase of mechanical strength which occurs in these conditions (discussed in the following section) also provides evidence of the formation of bridging between the iron particles. A similar reduction in resistivity during heating has been reported for other fundamentally different dielectromagnetic systems [8] and appears to be primarily an inherent property of the magnetic iron powders rather than the dielectric systems used.

Increasing the dielectric content produces somewhat different effects depending on the dielectric composition as shown in Figure 3(c). In the case of the composition containing a high organic content (40% MTMS), the electrical resistivity increases fairly consistently with increasing dielectric content as might be anticipated. The resistivity with 1 mass% addition is almost double that at 0.5 mass % level. By contrast, for the dielectric coating composition containing a low level of organic (20% MTMS) the resistivity is almost independent of the addition level above 0.5 mass % additions suggesting that an additional mechanism is coming into play limiting the ability of the additional dielectric to provide correspondingly enhanced electrical resistivity. Most probably the degree of flexibility afforded by the organic content for the dielectrics with lower MTMS levels is insufficient to accommodate the deformation during powder compaction at higher coating thickness levels, and coating failure by the formation of cracks begins to occur.

Figure 3(d) shows the effect of compaction pressure on the resistivity of inorganic (M0) and organic containing (M40) compositions. The two systems behave differently. The resistivity of the M0 systems is largely independent of compaction
pressure, indicating the inorganic coating is likely to be extensively cracked and damaged following compaction, irrespective of the compaction pressure in this range. However, the resistivity of the M40 compositions is significantly compaction pressure dependant, showing an almost 50% reduction as the compaction pressure is doubled. This resistivity reduction indicates a gradual degradation in coating integrity as the increased compaction pressure caused by partial redistribution of the dielectric, essentially extruding it away from the points of closest particle contact, leading to an effective decrease in dielectric coating thickness at these critical points.

The results in Figure 3(d) also again confirm the substantial impact of the heat treatment atmosphere on resistivity for the hybrid containing (M40) compositions but also show that this sensitivity to the heat treatment atmosphere reduces with increasing compaction pressure. As with the results shown in Fig. 2 it is likely that the increased density achieved with higher compaction pressure impedes oxygen ingress into the component and reduces the extent of conductive oxide formation. For the inorganic (M0) compositions, the effect of heating atmosphere is virtually absent, probably because the presence of large numbers of cracks and defects caused by the deformation of these rigid coatings masks the effect of oxidation on resistivity.

Taken together, the above data confirm that that the improved flexibility afforded by the incorporation of an organic component into the dielectric coating composition allows more effective electrical isolation to be achieved. This enhancement is largely maintained even after heat treatment at temperatures up to 550°C, at which point the organic component would be expected to be substantially degraded, providing further confirmatory evidence that the enhancement is primarily a physical rather than a chemical phenomenon, with this being attributed to the coating’s cracking resistance during the compaction process, which is carried out prior to the annealing heat treatment.
Figure 3. Influence of various parameters on dielectromagnetic resistivity
(a) effect of organic content of dielectric (1 mass% dielectric) (b) effect of heat
treatment conditions (0.3 mass% M40 dielectric), (c) influence of dielectric addition
levels for high (M40) and low (M20) organic content dielectrics, and (d) compaction
pressure dependence for the dielectromagnetic composites at 0.3% addition level of
dielectrics without (M0) and with high organic content (M40) heat treated at 500°C
under air and argon atmospheres.

3.4 Mechanical strength of the dielectromagnetic compacts
Figures 4(a) to (c) illustrate the effect of the dielectromagnetic composition and
process conditions on the mechanical properties of the resultant materials. These data
not only provide information on the practical viability of the systems in terms of
mechanical integrity, but also provide useful confirmatory evidence for some of the
phenomena discussed regarding density, oxidation, resistivity and magnetic
properties.

The effect of the organic content of hybrid coatings on the mechanical strength of the
dielectromagnetics is shown in Figure 4(a). Two clearly distinct effects are apparent.
There is a clear trend toward a reduction in mechanical strength as the proportion of organic component (MTMS) is increased and secondly, there is a significant and relatively consistent (approximately 30 MPa) enhancement in strength following heat treatment for all compositions. These effects inversely mirror the effects observed for the electrical resistivity data in Figure 3(a) and strongly suggest a correlation between these phenomena. It can be logically inferred that the formation of oxides and/or incipient metal-metal contacts during heat treatment, which were considered to be responsible for the loss of resistivity, also enhance the mechanical strength of the components.

Although the effects are small and masked by some scatter in the data, closer inspection reveals that the strength enhancement by heat treatment at temperatures of 500°C or above appears less pronounced for the samples with higher levels of organic content. It would be anticipated that two conflicting effects would take place during heat treatment of the organic containing compositions. At temperatures <500°C, the organic phase is essentially stable, and few thermally induced changes would be anticipated. Between 500 and 550°C the organic phase degrades, liberating CO/CO₂ and hydrocarbon by products which generates porosity in the structure which would be expected to degrade the strength, whilst at the same time, particularly at higher temperatures sintering and associated phenomena would be expected to allow the densification of the structure and the formation of additional cross-links in the oxide network which would be expected to enhance the strength. The exact impact of these two largely kinetically controlled phenomena on mechanical strength will be complicatedly related the coating composition and amount, as well and the heating temperature and duration.

Figure 4(b) indicates that the mechanical strength of the dielectromagnetic is largely independent of the addition level of dielectric in the range 0.5 – 1 mass% for M40 dielectric compositions. By contrast, the samples with half this organic content (M20) show a general trend of increasing flexural strength with increasing dielectric content above 0.5%. Once again these results mirror the effects observed for resistivity and suggest these phenomena are correlated. The formation of cracking in the dielectric coating which was proposed to explain the failure to increase electrical resistivity with increasing dielectric content in these samples would also be expected to allow the formation of both increased oxidation and metal-metal contacts which would in turn
result in strength enhancement. It should be noted that in all these samples the mechanism of mechanical failure is generally inherent, with the fracture path being through the dielectric phase.

Figure 4(c) shows that the pressure dependence of flexural strength is quite different for heat treatment under Argon and Air. The strength shows a linear increase with increasing compaction pressure when samples are annealed in protective atmosphere, which is consistent with an increase in density as the compaction pressure is increased (Fig. 1(c)) and most probably the formation of an increasing number of strong metal to metal contact points. However, the composition of the dielectric coating also plays a significant effect. The dielectromagnetics containing M40 show less dependence of flexural strength on compaction pressure compared with those incorporating completely inorganic (M0) dielectric. On the other hand, heating in air leads to the opposite trend of flexural strength as a function of compaction pressure. These results show a trend toward decreasing strength with increasing compaction pressure, with the inorganic dielectric coating system again being more sensitive to compaction pressure. These are consistent with the profiles of resistivity versus compaction pressure (Fig. 3(d)), not only again suggesting that similar mechanisms underlie this – whereby the enhanced density achieved at higher compaction pressures inhibits the transport of oxygen into the sample and reduces the enhancement effect of oxidation on the bulk mechanical properties, but also providing a further evidence that the incorporation of organic moiety provides a more flexible coating which remains intact during compaction and impedes the formation of metal to metal contacts.

By comparison of these mechanical data obtained in argon and air, it can be concluded that formation of iron oxides during heat treatment at elevated temperature (as shown in Figure 2) plays a dominant role in the development of mechanical strength heated in air. There are two complementary phenomena which would be expected to contribute to such an effect. Firstly the adhesion and wetting of the dielectric coating on the iron powder is likely to be significantly influence by the heat treatment atmosphere. Studies of glass to metal seals have shown that strong chemical bond is formed at the coating-metal interface only when the coatings is saturated with an oxide of the substrate metal [14], and secondly as evidenced by the electrical resistivity measurements (Figures 3(b) & (d)), heat treatment in oxidising
conditions appears to result in the formation of iron oxide bridges between metal particles, which might be anticipated to result in increased strength.

![Graph showing flexural strength vs. temperature](image)

**Figure 4.** Influence of dielectric composition, addition levels, compaction pressure and heat treatment conditions on the flexural strength of the dielectromagnetic composites (a) change as a function of organic content of dielectric at 1 mass% addition and 700 MPa compaction, (b) relationship to dielectric addition levels for high and low organic content organic-inorganic dielectrics before and after heat treatment and (c) variation with compaction pressure and annealing atmosphere of dielectromagnetic components (0.3 mass % dielectric additions and 500°C heat treatment temperature).

### 3.5 Magnetic properties

The effect of the dielectric coating composition on the magnetic permeability ($\mu$) and induction ($B$) of dielectromagnetic toroid samples are shown in Figure 5 as a function of applied magnetic field intensity ($H$). All of the formulations display similar trends in magnetic permeability and induction towards magnetic field strength, with the maximums of permeability at about 900 A·m$^{-1}$. However, the magnitude of the values, in particular the maximum magnetic permeability ($\mu_{max}$) are significantly different among the various compositions, with the maximum permeability achieved with the M40 containing formulation ($\mu_{max}$=422) being improved by approximately 25% in comparison with the M0 coating (344) at the same addition level. This is a very
significant enhancement. Whilst these values are somewhat lower than the $\mu_{\text{max}}$ values achieved in some other dielectromagnetic soft magnetic composites [10], this is largely a function of the particle size distribution of the 1001HP iron powder used in these investigations. In fact the $\mu_{\text{max}}$ values are close to the value of ($\mu_{\text{max}}$ =550) obtained for uncoated HP1001 powder (which is not suitable for practical application due to very high magnetic losses) under similar test conditions, and which can be considered to represent the theoretical upper limit of $\mu_{\text{max}}$ for this system. As such this represents excellent performance.

The improvement in permeability with increasing organic content is rather more surprising since this effect is in opposition to the trend of decreasing density (normally a critical determinant of permeability) in these materials. It is believed that this is another consequence of the increased flexibility of the dielectric coatings, which allows the coating to exhibit some limited mobility during the compaction process, in particular moving from peaks to troughs on the surface of the irregular iron powder particles (see Figure 7), so that reduces the coating thickness at points of the closest approach of iron powder particles and, hence, the impediment to magnetic flux. Such an effect seems in consistence with the reduction in resistivity noted for M40 containing systems as the compaction pressure was increased (Figure 3(d)), which was attributed to a similar mechanism. It should be noted however, that the decrease in resistivity is not on a corresponding scale, indicating that any such effect is limited in extent and that the coating must remain continuous and intact throughout this process. Most probably magnetic permeability exhibits significantly more sensitivity to the distribution of the dielectric coating than resistivity, explaining the apparent discrepancy between the responses of these parameters to changes in dielectric composition.

The effect of dielectric loading on magnetic permeability and induction are shown in Figure 6 for the M40 containing compositions over the range 0.05 to 0.3 mass%. As with the previous results, the most significant differences seen are for the maximum magnetic permeability, albeit with the differences between the highest (430) and lowest (382) $\mu_{\text{max}}$ values being rather smaller in this case at around 10%. These results show a clear trend toward increased magnetic permeability and induction with decreasing dielectric content. As anticipated, the presence of a non-magnetic material between the magnetic powder acts similarly to an air gap in a magnetic circuit, as a
partial barrier to magnetic flux. The large numbers of such phases between each magnetic powder particle cumulatively generate a large magnetic reluctance and low permeability. Indeed this is a basic limitation of all dielectromagnetic soft magnetic composites [1, 15-16] that must be circumvented through appropriate design [2,5-6].

Fig. 5 Influence of dielectric coating composition (expressed as mol % MTMS content) on (a) magnetic permeability and (b) induction for 0.1 mass% dielectric addition and 700 MPa compaction.
Figure 6. Influence of M40 addition level (mass %) on the (a) magnetic permeability and (b) induction.

Figure 7 SEM micrographs of (left) HP1001 powder as received and (right) after coating with 0.3 mass% M40 dielectric.

The power losses of the variously dielectromagnetic formulations are shown in Figure 8(a) and (b) as a function of the organic contents of the dielectric coating formulation.
and the dielectric addition level respectively. The results indicate that the power losses are relatively insensitive to these parameters over the range of compositions and additions investigated here. In all cases the losses are respectable, with total losses being of the order of 7-9 watts per kg at 1T and 50Hz. However some trends can be identified. The principal effect associated with increasing the organic content of the dielectric coatings is a trend toward decreasing hysteresis loss, with the total loss also being correspondingly reduced. This would again be consistent with the improved flexibility of the higher organic coating formulations, aiding the compaction process and reducing the extent to which high localised contact stresses are generated within the powder, with corresponding work and magnetic hardening effects. Increasing the addition level of the hybrid, with the organic content held constant, produces little effect on the hysteresis loss, but produces a reduction in eddy current loss and a corresponding reduction in total losses. This is consistent with the improvement in resistivity shown in Figure 3(c), with the improved electrical isolation of the powder particles being more effective in controlling eddy currents in the material.

![Figure 8. Influence of (a) dielectric coating composition at 0.1 mass% loading and (b) addition level of M40 dielectric on the eddy current, hysteresis and total losses of dielectromagnetic toroids at 50Hz and 1T.](image)

4. Conclusions

The sol-gel organic-inorganic hybrid silica as dielectrics dielectromagnetics described in this work provide useful fundamental understanding of the factors
determining the performance of soft magnetic composites, as well as exhibiting promising properties for practical applications. The organic component of the coatings produces a number of beneficial effects stemming from the enhanced flexibility and toughness. In particular, electrical resistivity, magnetic permeability, eddy current, hysteresis and total losses are improved as the proportion of organic component is increased. The organic containing dielectric coatings are essentially thermally stable up to 500°C. Although the organic group starts to pyrolyse above this temperature, the coatings remain in situ and continue to provide some electrical insulation.

For a standardised coating addition of 0.1 mass %, as the MTMS content of the coating formulation is increased from 0% (M0) to 40 mol% (M40), the resistivity and $\mu_{\text{max}}$ increase from 2.5 to 6.2\(\mu\Omega\)-m and 344 to 422, respectively, while density and flexural strength decrease from 7.20 to 7.16g/cm\(^3\) and 37.6 to 32.0MPa. For a standardised organic content (40 mol % MTMS), increasing the addition level from 0.05 to 0.3 mass\%, results in increases in resistivity and flexural strength from 5.7 to 15.7\(\mu\Omega\)-m and 31.7 to 37.8MPa respectively, whilst $\mu_{\text{max}}$ and density decrease from 425 to 383 and 7.2 to 7.15g/cm\(^3\) respectively.

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