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The Effect of Binder Additions on the Green and Sintered Properties of Mn–Zn Ferrite Ceramics

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Abstract: The suitability of three candidate binders for use in the production of Mn–Zn ferrite has been investigated. A Lab-top spray dryer was used to coat mixed oxide-prepared ferrite powder with binder. The powder obtained from the Lab-top spray dryer was an order of magnitude smaller than commercially prepared powder. Pressed powder compacts prepared from the two types of powder exhibit similar green strengths, and the sintered products exhibit similar magnetic properties and microstructures.

The use of poly(vinyl alcohol), poly(ethylene glycol) or poly(acryl amide) as a binder for Mn–Zn ferrite yielded specimens with measurable flexural green strengths, typically 0·2 MPa for PVA and PAM and 0·15 MPa for PEG (at ~ 1 wt% binder level). After sintering, such specimens exhibited good magnetic properties (initial permeabilities ~2500) and the fired densities were at least 90% theoretical. Specimens prepared with higher binder contents had marginally lower densities and lower initial permeabilities. The solid hydrocarbon residue left after the low temperature burnout of PVA and PAM binder does not cause a measurable degradation of the magnetic properties or affect the microstructures of sintered products.

1 INTRODUCTION

The use of poly(vinyl alcohol) (PVA) as the major constituent in binder formulations for the commercial production of ferrites has been widespread for a number of years.[1] It is well known that PVA is not a 'clean burning' binder,[2] i.e. after heating through the low temperature range to volatilise the binder, a number of solid hydrocarbons remain. These have higher volatilisation temperatures, and two possible scenarios, disadvantageous for ferrite production, may arise: (i) the gaseous hydrocarbons may escape from the partially-sintered compact, causing some internal damage, or (ii) the hydrocarbons may remain trapped within the compact, degrading the sintered properties as an undesirable second phase. Which, if either, of these occurs is not clear.

It is not possible from thermal analysis alone to determine whether a candidate binder is suitable; it must be tested *in situ*. Therefore, a systematic study has been undertaken to investigate the green strength and density, and the microstructures and magnetic properties of sintered Mn–Zn ferrites of composition $Mn_{0.558}Zn_{0.372}Fe_{2.07}O_4$ made using PVA and two other candidate binders, poly(ethylene glycol) (PEG), and poly(acryl amide) (PAM).

In order to model the commercial spray drying route as closely as possible, a 'Lab-top' spray dryer has been used. The properties of commercial-grade powder produced in this way are compared with commercially spray dried powder to justify the use of this route and hence the validity of the results obtained for the three binders investigated.

2 CANDIDATE BINDERS INVESTIGATED

Three binders were investigated.

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(i) Poly(vinyl alcohol) (PVA), the industry-standard binder.
(ii) Poly(ethylene glycol) (PEG). This was considered because it volatilises at low temperature[2] without leaving a residue.

Combining PEG with a similar material, poly(ethylene oxide), was considered but rejected; whilst the combination would have two decomposition temperatures, an advantage for binder burnout (as it would increase the burnoff temperature regime), poly(ethylene glycol) of average molecular weight greater than 600 is solid at room temperature, whilst all poly(ethylene oxides) are liquid at room temperature, which would make the spray dried powder sticky.

(iii) Poly(acryl amide) (PAM) marketed as Versicol. PAM is already used as a binder for tablets and sand moulds, and in metal casting.[3] It is soluble in water over the entire concentration range, and the polymer molecules bond to many solid surfaces and dissolved species, which makes it an ideal candidate as a binder for spray dried material.

3 EXPERIMENTAL

The raw materials used were typical commercial grade Mn–Zn ferrite production materials: Fe_2O_3 (Sidmar Chemicals grade 015, purity 99·4%), ZnO (Durham Chemicals grade N5, purity 99·9%), and MnO (Meclenna/Clemetal grade HP, purity 99·7%). The required amounts of starting powders were weighed to provide 5 kg batches. These were mixed in a Torrance 'IS' attritor mill (containing 1 cm diameter stainless steel balls) with 2 litres of water and 125 cm^3 of dispex. The mixer was operated at 240 revs/min for 1·5 h. The slurry was removed from the mill and dried overnight in an oven at 120°C. The resultant solid was crushed using a pestle and mortar, and sieved through a 2 mm sieve. The powder was weighed into 1·22 kg batches and heated in a calcining oven at 860°C (heating rate 10°C/min; hold at temperature 2 h; natural cooling with the oven).

After calcining, the powder was milled. The powder was added to 1 litre of water and 125 cm^3 of dispex, and mixed in the attritor mill at 240 revs/min for 1·5 h. The powder was then removed from the mill and dried at 120°C overnight. The resultant solid was crushed using a pestle and mortar, and passed through a 35 μm sieve to produce a fine powder. This powder was weighed out into 1 kg batches in preparation for spray drying.

To each batch 300 cm^3 of water was added with 15 cm^3 of dispex and the required quantity of binder (PVA, PEG, or PAM). This slurry was mixed in a 1·5 litre plastic container with 5 stainless steel balls (of diameter 1 cm) for 30 min to achieve thorough mixing. Spray drying was performed using a LabPlant, Lab-top spray dryer, model SD-04. This model has a maximum temperature for extended operation of 250°C. A wide range of operating conditions were employed. The feed was pumped to a rotary nozzle atomiser with manual deblocker, and sprayed into a chamber of diameter 11·4 cm and length 45 cm. Coarse powder was collected at the bottom of this chamber in the primary collection jar. Fine powder was carried out in the air-flow through to a secondary chamber where it was deposited in a second collection jar. The waste air and any residual entrapped fine powder were exhausted to the environment.

Particle size analysis of the spray powder was performed using a SediGraph 5000ET Particle Size Analyser, which produced a cumulative mass percent distribution of equivalent spherical diameters for the powder. Direct comparison was made with commercially prepared, bulk spray dried Mn–Zn ferrite powder (SEI Ltd).

The spray dried powders were collected and pressed into toroids or bars using a MB No. 20 air-press. Toroidal specimens were produced having dimensions 23 mm outer diameter, 11 mm inner diameter and 9 mm thickness; flexure strength specimens were produced using a die of cross-section 50 × 6 mm and thickness 2–3 mm. Pressing was achieved using a semi-automatic press, using a pressure of 9·4 MPa.

Specimens were sintered on either a 'line' kiln at 1250°C, or in an experimental tube kiln. The tube kiln had an internal diameter of 10 cm and a constant temperature central region approximately 30 cm long. Air and nitrogen gas flow could be manually adjusted, and a 10 stage heating controller was employed. In all cases, the specimens were placed on alumina bats. Fine alumina powder was sprinkled on the bats to prevent specimens sticking to the supports.

Flexure strengths of 'green' and sintered specimen bars (nominally 50 × 6 × 2–3 mm in size) were determined using an Instron 4301 operating at a crosshead speed of 0·5 mm/min, with the lower supports separated by 35 mm.

Selected specimens were ground and polished down to 1 μm diamond paste and chemically etched in 52% concentrated HF for 15 s. Microstructures were studied by optical microscopy (using an Olympus BH2 microscope) and average grain sizes were determined by the MLI method.[4]

To determine electrical properties, sintered toroids were wound with 30 turns of cotton covered copper wire; a Wayne-Kerr Multibridge model 6425 was used to determine inductance and resistance losses at 10 kHz and room temperature. The primary properties of interest are initial permeability (μ_i) and electrical losses (tan δ).

Thermogravimetric Analysis (TGA) and Differential Thermal Analysis (DTA) of the binders were performed in air, at a heating rate of 5°C/min, using a Seiko SSC/5200 Simultaneous Thermal Analyser.

4 RESULTS AND DISCUSSION

4.1 Comparison of laboratory- and commercially-produced powders

The average particle size of the calcined ferrite powder after drying and crushing was found to be ~4 μm.

In order to produce dry powder with an even coating of binder, it was necessary to operate the spray dryer within the upper part of its available temperature range. A list of the operating conditions used is shown in Table 1. A manual nozzle deblocker was used.

Particle size analysis of the coarse and fine powders produced by the spray dryer are summarised in terms of cumulative mass percent distributions in Table 2.

The flexure strength of bars (50 × 6 × 2 mm) pressed from the coarse and fine powder obtained from the Lab-top spray dryer and commercial powder spray dried in the production facility containing 1·2 wt% PVA are shown in Table 3. The green densities of all bars were approximately 60% of theoretical density.

As an initial trial, toroids were prepared from the three sets of powders. The properties of toroids prepared from the Lab-top spray dried powders (initial permeability ~4800, loss factor ~10 × 10^{-6}, grain size ~9·5 μm) were comparable with commercial ferrite of a similar composition. Microstructures of sintered toroids produced from powder spray dried in the Lab-top and full-scale dryers are shown in Fig. 1.

Subsequently, for the detailed study involving the range of binders, only the fine powder from the Lab-top spray dryer was employed. Although coarse powder is generally preferred for pressing components, the operation of the Lab-top spray dryer meant that loose powder and lumps from the chamber wall tended to collect with the coarse batch, causing it to be less uniform in properties.

Table 1. Operating conditions for Lab-top spray dryer

Nozzle diameter (mm)	Inlet T (°C)	Outlet T (°C)	Pump setting (%)	Blower setting (%)
2·0	240	130	35	70

Table 2. Particle size distributions of coarse and fine powder from the Lab-top spray dryer

Powder	90% particle size (μm)	50% particle size (μm)	10% particle size (μm)
Coarse	5·8	1·8	0·58
Fine	4·2	1·8	0·53

A typical particle size analysis of fine powder produced using the optimum settings of the Lab-top spray dryer is shown in Fig. 2, with a typical analysis for powder from the commercial spray dryer for comparison. A SEM micrograph of typical laboratory spray dried powder is shown in Fig. 3.

The Lab-top spray dryer is significantly smaller than the industrial type used to spray dry ferrite powder—the latter have main chambers up to 11 m in length. The large chamber results in a significantly longer residence time in the hot airflow. Industrial spray dryers also operate at significantly higher air input temperature—400°C is common,[5] whilst the Lab-top spray dryer has a maximum inlet temperature for extended operation of 250°C. The higher temperature allows a faster slurry feed rate, and the longer residence time in the airflow allows the growth of larger spray dried particles. As a result of its smaller dimensions, the Lab-Top spray dryer is a slow method of spray drying ferrite powder (it can take up to an hour to collect 200 g of fine powder) and, due to this and the reduced size, it is not practical to produce large amounts of ferrite powder in one run. Depending upon operating conditions there is also the risk that some powder will be lost as chamber wall deposits.

The powder produced in the Lab-top spray dryer is smaller by an order of magnitude than that produced commercially (Fig. 2). The smaller size of the laboratory powder means that it has poor flow characteristics compared to the larger, commercially-produced material.

In spite of the disadvantages outlined above, the results obtained using ferrite powder spray dried in the laboratory were very good. The values

Table 3. Flexure strength of 'green ferrite' bars pressed from powder from the Lab-top spray dryer and the production spray dryer

Powder	No. specimens	Modulus of rupture (MPa)	σ_{n-1}
Coarse (Lab-top)	12	0·226	0·034
Fine (Lab-top)	13	0·208	0·027
Commercial	15	0·228	0·027

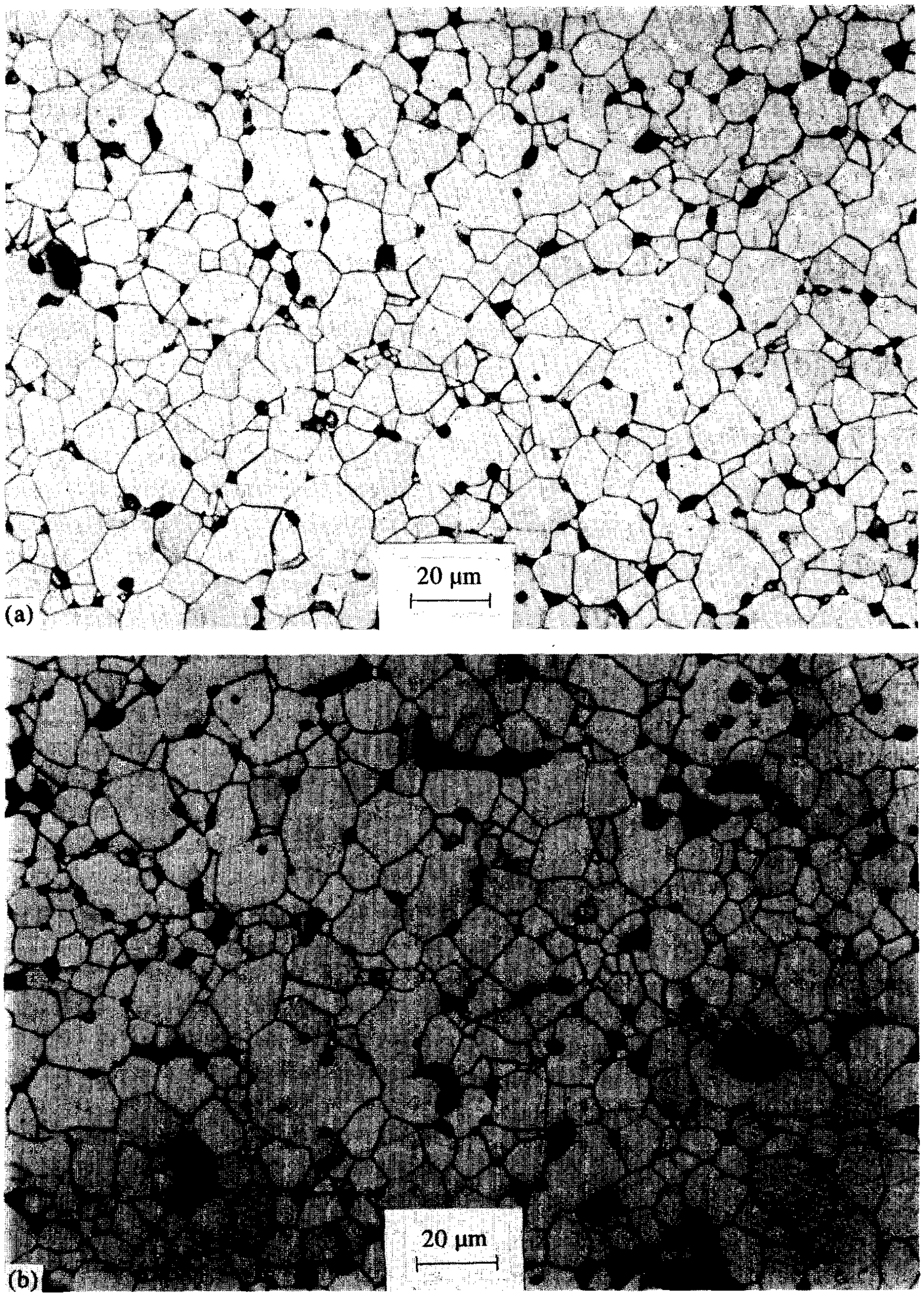

Fig. 1. (a) Microstructure of Mn–Zn ferrite toroids prepared from fine laboratory spray dried power. (b) Microstructure of ferrite toroid prepared from conventionally-produced powder.

of green flexure strength of 0·226 and 0·208 MPa were in excellent agreement with the green strength of powder spray dried commercially (0.228 MPa). This, along with optical evidence, confirmed that the powder produced in the laboratory is similar in nature to that produced commercially (having similar binder content and particle shape) but with smaller particles. Furthermore, it suggests that strengths of the specimens in the green state, determined using material produced in the laboratory, can be applied, as being representative of the larger commercially-produced powder, with confidence.

The green densities of the specimens produced from laboratory powder were comparable with densities of specimens produced with commercial powder (≈60% TD). This infers that the pressing characteristics of the laboratory powder are acceptable.

The powder produced in the laboratory could be sintered to yield specimens with magnetic properties similar to those of specimens produced by the commercial route. Magnetic losses and initial permeabilities of the laboratory-prepared specimens were comparable with those of commercially-produced material. The microstructures of

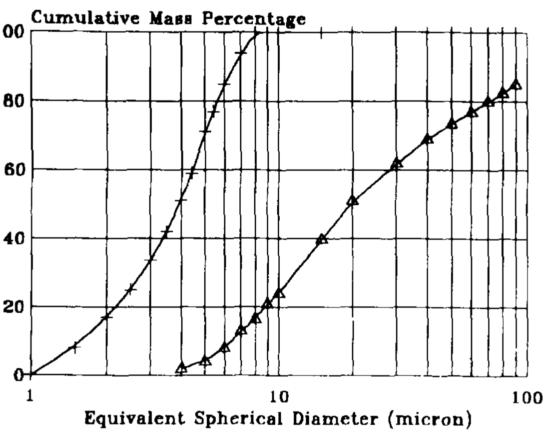

Fig. 2. Particle size analysis traces for laboratory-spray dried (+) and commercially-spray dried (Δ) powders.

specimens produced by the two spray drying routes were also similar, with similar grain sizes.

It can be concluded from these experiments that the Lab-top spray dryer, whilst producing powder of different average particle size under a different temperature regime, can be used to produce good quality spray dried ferrite powder; when pressed, the powder yields specimens with similar green state properties to specimens produced via the commercial route; on sintering, the laboratory-prepared powder yields specimens with similar magnetic and microstructural properties to specimens produced via the commercial route.

4.2 Binders and their behaviour

Differential Thermal Analysis (DTA) and Thermogravimetric Analysis (TG) were performed on the PVA, PEG and PAM materials used as binders. The results are illustrated in Figs 4–6. After heating to 500°C, a black tar-like residue remained in the crucible for PVA and PAM specimens; no residue was found after heating PEG to 500°C.

For PVA, an endotherm was found at ~100°C, with strong exotherms at 300°C and 400–500°C. Weight loss started at low temperature but was strongest at the first exotherm.

For PEG, the endotherm was found at 60°C, with strong exotherms at ~350°C and 430°C. Weight loss commenced at 230°C and was virtually complete by 350°C.

For PAM the endotherm was at 115°C, with a strong exotherm at 320°C, at which point the weight loss was most rapid.

The primary slurry for spray drying comprised 1 kg ferrite powder, 300 cm^3 water, 15 cm^3 dispex and the required quantity of binder. For PVA, 30–90 cm^3 of a PVA solution (prepared from 2 kg solid PVA added to 10 litres of water) was used. The PVA content was equivalent to 0·6–1·8 wt%. The inlet temperature set was 240°C, and the outlet temperature was found to be 120–130°C. The quantities of PEG used were 1·0–2·5 wt% (10—25 g). The PEG was obtained as a waxy solid; it dissolved in water on stirring. For spray drying, an inlet temperature of 240°C was used, which produced an outlet temperature of 126–133°C. For PAM, 30–60 cm^3 of a solution containing 16 wt% polymer was spray dried. The PAM content was equivalent to 0·48–0·96 wt%. The fine powder was collected and pressed into bars for three-point bend testing. The results of the mechanical tests are shown in Table 4. Data for specimens bound with PVA are displayed graphically in Fig. 7. For all binders, there was a general increase in flexure strength with binder content.

The densities of ferrite specimens in the green

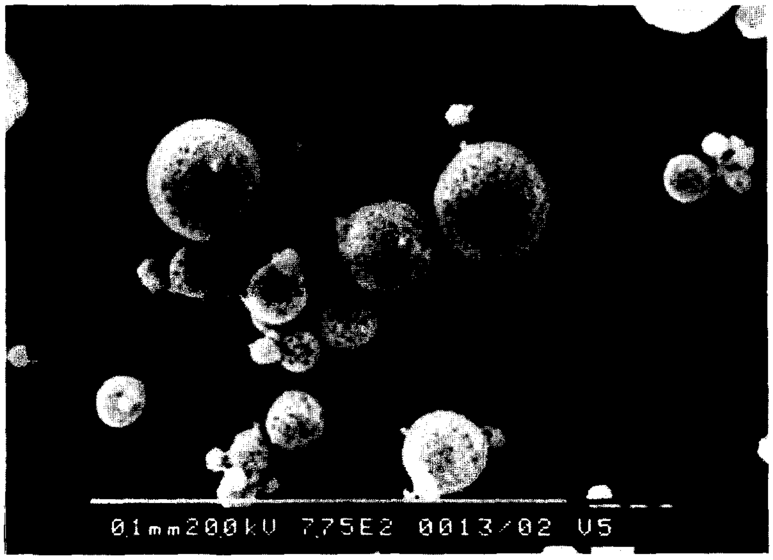

Fig. 3. SEM micrograph of spray dried powder produced by the Lab-top spray dryer.

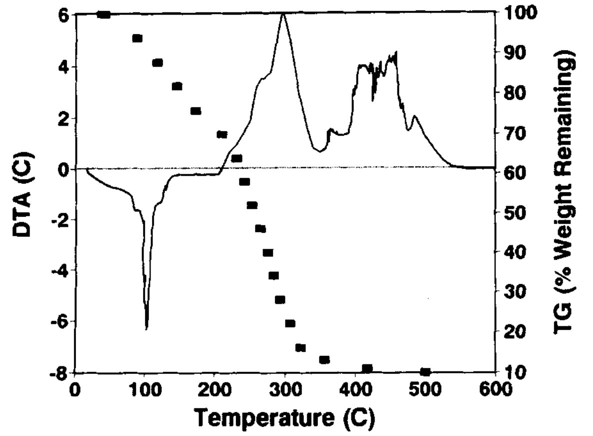

Fig. 4. Differential thermal analysis (solid line) and thermogravimetric analysis (■) of PVA in water (performed in air with a ramp rate of 5°C/min).

state were determined by weighing and dimensional analysis. For PVA it was found that the green state density varied from 55·1% theoretical density (TD) for the specimens containing 0·6% PVA to 51·9% TD for the specimens containing 1·8% PVA. For specimens containing PEG, the densities varied from 55·2 to 53·8% TD, with the lowest densities occurring in the specimens with the highest binder content. For specimens containing PAM, green state densities were found to vary from 54·2% TD (specimens containing 0·48% PAM) to 52·5% TD (specimens containing 0·72% PAM).

For PEG-coated powders, green specimens having different binder contents were sintered in the tube kiln; a heating rate of 50°C/h was used up to 500°C, and 80°C/h up to 1320°C (with a 0·7 h lag up to the peak temperature). Sintering was performed in air. Over the first 300°C of the cooling part of the sintering cycle the atmosphere was changed to pure nitrogen according to a logarithmic relationship. The strengths of sintered specimens are shown in Table 5. There appears to be a slight increase in the flexure strength with initial binder content, but the trend is not significant.

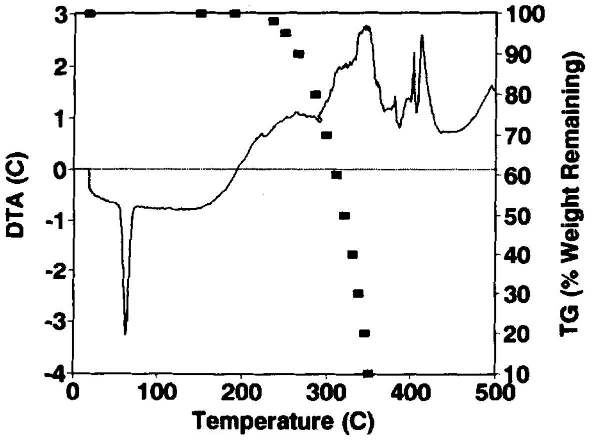

Fig. 5. Differential thermal analysis (solid line) and thermogravimetric analysis (■) of PEG (performed in air with a ramp rate of 5°C/min).

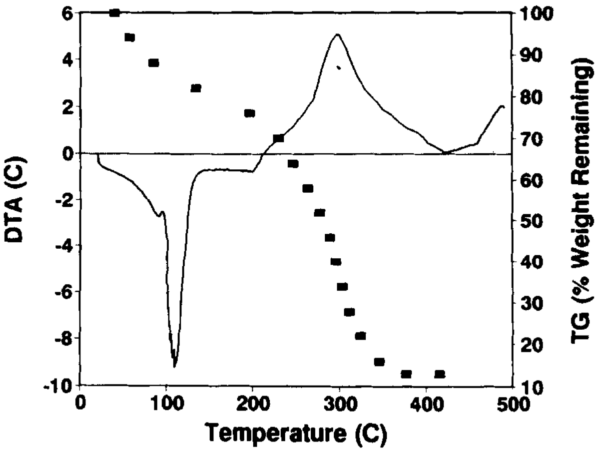

Fig. 6. Differential thermal analysis (solid line) and thermogravimetric analysis (■) of PAM in water (performed in air with a ramp rate of 5°C/min).

These flexure strengths of ferrite prepared with PEG binder cannot be compared directly with the flexure strengths of sintered ferrite specimens prepared with PVA binder, as the use of a different furnace produces specimens with different properties; however, the strengths of all these sintered specimens are of comparable magnitude.

Specimens containing PVA and PAM were sintered at the same time on the line kiln at 1250°C for 2 h; the results are shown in Table 6. As specimens containing PEG binder were sintered in the experimental kiln at 1320°C for 2 h, and ferrites are extremely process-sensitive, these results cannot be strictly compared with each other. The properties of the toroids prepared from powders containing PVA and PAM binder are shown in Table 7.

PVA is one of the standard binders used in industry at the present time. The PVA commonly used is not pure, but contains 78% PVA and 22% poly(vinyl acetate), a by-product of the production routes.[5] Madorsky[2] found that the degrada-

Table 4. Flexure strength of 'green ferrite' as a function of binder content

Binder	Wt% binder	No. specimens	Modulus of rupture (MPa)	σ_{n-1}
PVA	0·6	11	0·185	0·028
	1·0	11	0·211	0·024
	1·2	10	0·211	0·021
	1·5	11	0·281	0·030
	1·8	3	0·264	—
PEG	1	12	0·146	0·020
	1·3	13	0·109	0·016
	1·6	13	0·146	0·011
	1·8	17	0·182	0·019
	2	14	0·196	0·025
	2·5	11	0·228	0·027
PAM	0·48	9	0·132	0·021
	0·72	9	0·174	0·020
	0·96	4	0·201	0·048

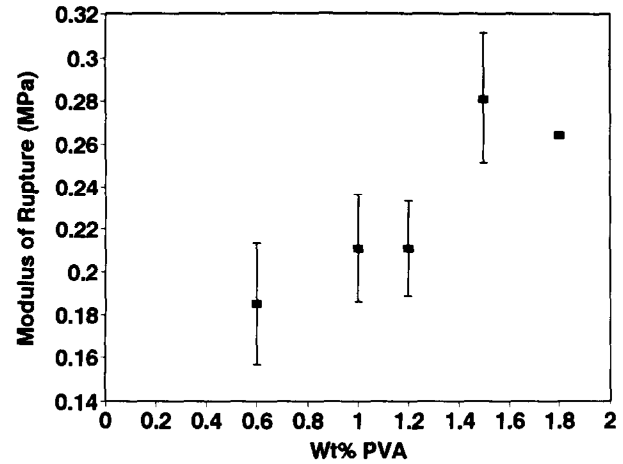

Fig. 7. Flexure strength of Mn–Zn ferrite in the green state (prepared with PVA) as a function of binder content.

tion products of PVA and poly(vinyl acetate) included a number of hydrocarbon compounds that were solid at 500°C, and that after carbonisation at 900°C included CH_4, C_2H_6, CO and CO_2. This was confirmed by the presence of a black tar-like substance in the crucible after DTA. The presence of these solid hydrocarbons at temperatures at which reactions leading to ferrite formation are starting is a source of concern, as there remains the possibility that some of these hydrocarbons may become trapped in the specimens and act as impurities, degrading the magnetic properties. One possibility is to use purer PVA; most of the hydrocarbon residue is the product of poly(vinyl acetate) degradation. However, the purer the PVA, the less soluble it is in water, up to the point where 98% pure PVA is insoluble in water.[6] As a result of these uncertainties, the present study was undertaken.

From the results for specimens prepared using PVA it can be seen that using as little as 0.6wt% PVA can still produce specimens with measurable strength. Figure 7 shows the expected trend of increasing flexural strength of green state specimens with increasing binder content. The final datum in this figure (corresponding to specimens containing 1·8 wt% PVA) is less reliable as it was based upon only three specimens. The flexural strengths of green state specimens (Table 4) compare well with those of specimens prepared from commercial powder (modulus of rupture 0·175–0·228 MPa for specimens with binder content ≈1·2 wt%[7]). The green state densities of the specimens prepared using powder containing PVA decreased from 2·845 g cm^{-3} (55·1% TD) for specimens containing 0·6 wt% PVA to 2·724 g cm^{-3} (52·7% TD) for specimens containing 1·5 wt% PVA to 2·689 g cm^{-3} (51·9% TD) for specimens containing 1·8 wt% PVA. This small decrease is expected as the binder has a lower density than the powder. Thus, increasing the amount of binder will decrease the overall green-state density.

Table 5. Flexure strength of sintered Mn–Zn ferrite as a function of PEG binder content

Wt%	No. specimens	Modulus of rupture (MPa)	σ_{n-1}	m
1·0	10	7·84	2·01	4·11
1·3	10	8·12	2·54	3·41
1·6	10	8·59	1·84	4·78
1·8	9	8·97	1·43	6·60
2·0	10	8·93	2·28	3·45

The magnetic properties of sintered specimens prepared using powder containing PVA (Table 6) show an initial decrease in initial permeability with increasing binder content. The uncertainties in magnetic properties for each set of specimens with different binder contents do span the change in initial permeability between sets of data; however, there is a definite downward trend. The presence of PVA residue in the specimens with larger initial binder contents might account for this; however, this is not the only possible explanation. The densities of the sintered specimens decreased slightly as the initial binder content increased; this may be expected—after binder burnoff, the specimens with higher initial binder content will have higher porosity, and if sintered under the same conditions, may retain higher porosity in the final product. The slightly lower densities may account for the slightly lower permeabilities (lower density means higher porosity, which means more pinning centres for domains, hence smaller domains and lower permeabilities).

Table 6. Magnetic properties of sintered Mn–Zn ferrite toroids prepared with powder containing PVA and PAM binders

Binder	Wt% binder	No. specimens	Initial permeability (μ_i) (σ_{n-1})	tan δ/μ_i ($\times 10^{-6}$) (σ_{n-1})	Density (σ_{n-1}) (% TD)
PVA	0·6	6	2707 (45)	4·531 (0·224)	91·3 (1·5)
	1·2	6	2627 (53)	4·900 (0·554)	90·5 (0·3)
	1·8	6	2502 (63)	4·701 (0·300)	90·4 (0·3)
PAM	0·48	6	2725 (15·0)	4·48 (0·65)	91·1 (0·2)
	0·96	6	2666 (31)	4·80 (0·37)	90·3 (0·5)

Table 7. Magnetic properties of sintered Mn—Zn ferrite toroids prepared with powder containing PEG binder

Wt% binder	No. specimens	Initial permeability (μ_i)	tan δ/μ_i ($\times 10^{-6}$)	Density (σ_{n-1}) (% TD)
1·0	5	2379 (±115)	5·63 (±1·3)	91·5 (0·3)
1·3	4	1649 (±12)	4·73 (±0·7)	90·2 (0·4)
1·6	4	1597 (±33)	5·31 (±1·8)	90·0 (0·2)
2·0	4	1941 (±120)	4·79 (±1·1)	90·1 (0·3)

From the combined data for the magnetic properties of specimens prepared from powder containing PVA it is not possible to ascertain whether or not a hydrocarbon char affects the final magnetic (and presumably mechanical) properties.

PEG has the potential advantage over PVA of not leaving a char at 500°C, but volatilising completely by about 360°C.[2] DTA and TG analyses of PEG in this study (Fig. 5) confirm that only one reaction was experienced, at approximately 320°C, and that weight loss was complete at approximately 360°C. This clean burn-off makes PEG a very interesting alternative to PVA as a binder.

As expected, the green state strength of the ferrite bars prepared using powder containing PEG (Table 4) increased with increasing binder content; however, a binder content of approximately 2·2 wt% was required to achieve the green strength of ferrite powder containing 1·0 wt% PVA. Specimens prepared using powder containing 1·0 wt% PVA and 2·2 wt% PEG would have approximately the same green state densities. This trend is carried through to the sintering stage, as a comparison of densities in Table 8 shows. From these results it can be seen that the specimens prepared from powder containing PEG exhibit values of permeability, loss, and density all within one standard deviation of the results for specimens prepared using powder containing PVA. It may be implied that, given PEG is a clean-burning binder, the fact that specimens prepared from powder containing different quantities of PEG show very similar magnetic and physical properties to specimens prepared from powder containing different quantities of PVA suggests that the residue left by PVA successfully escapes from the specimens without causing serious damage.

Table 7 shows that the magnetic properties of toroids prepared from powder containing PEG do degrade slightly with increasing PEG binder content. This may be a function of the slightly lower densities of specimens with higher binder content. To achieve the higher densities, the sintering schedule may require optimisation, though care must be taken not to degrade the magnetic properties through ‘over-sintering’ (giving the specimen excess time at high temperature, promoting grain growth and increasing losses). Alternatively, the use of low levels of PEG binder (1·0 wt%) should improve the results. However, this leads to lower strength in the green state (Table 4) and the sintered state (Table 5).

This work on the binding properties of PEG clearly refutes the statement of Rambaldini *et al.*[8] that ‘PEG hasn’t any kind of binder’s properties’. Whilst PEG has previously been used as a plasticiser, to soften PVA,[9] the present study shows that PEG is as good a binder (in terms of providing green strength and not degrading magnetic and mechanical properties of sintered specimens) as PVA. However, approximately twice as much PEG is required to impart the same green strength as that currently achieved by PVA in use commercially. It is therefore not clear that PEG is necessarily a better binder than PVA.

PAM was found, after thermal analysis, to leave a small residue at 500°C. This places it in the same category as PVA, as not being a clean-burning binder.

The green state strengths of specimens prepared from powder bound with PAM show that, once again, the green strength increased with increasing binder content. The green state strength of specimens containing 0·96 wt% PAM is very close to

Table 8. Properties of toroids prepared from powder containing 2·2 wt% PEG or 1·2 wt% PVA binder

WT% binder	No. specimens	Initial permeability (μ_i) (σ_{n-1})	tan δ/μ_i ($\times 10^{-6}$) (σ_{n-1})	Density (%TD)	MLI grain size (μm)
2·2% PEG	10	2622·9 (83·1)	3·79 (0·40)	92·1 (±0·1)	7·07
1·2% PVA	14	2642·1 (121·1)	4·11 (0·57)	91·5 (±0·1)	8·08

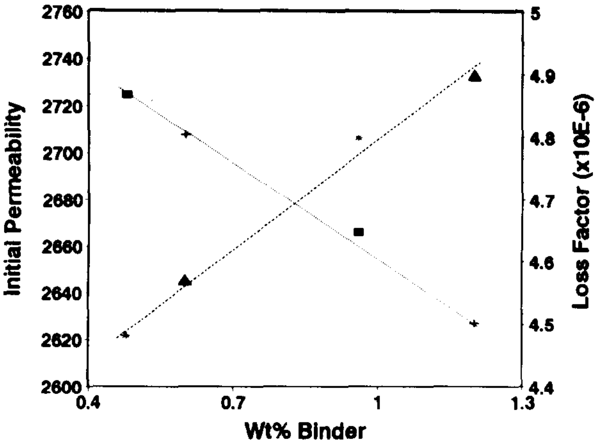

Fig. 8. Initial permeability (μ_i) and loss factor (tan δ) as a function of binder content for specimens prepared from powder containing PAM and PVA as binders: ■ initial permeability (PAM), + initial permeability (PVA), * loss factor (PAM), ▲ loss factor (PVA).

the green state strength of specimens containing 1·0 wt% PVA (Table 4). The green state densities of specimens containing PAM were slightly lower than those of specimens containing PVA; however, this slight difference was not observed in the densities of the sintered specimens of the two toroid types, which were within a few tenths of one percent TD of each other.

The magnetic properties of toroids prepared from powder containing PAM and PVA are directly comparable, as they were sintered at the same time. The initial binder contents of the sintered specimens were different, but allow a direct comparison: 0·48 wt% and 0·96 wt% for specimens bound with PAM and 0·6 wt% and 1·2 wt% for specimens bound with PVA. Figure 8 shows the initial permeability and loss factors plotted as a function of binder content. A comparison of the magnetic properties shows that there is virtually no difference between the magnetic properties of the two sets of materials.

5 CONCLUSIONS

An overall comparison of the binders shows that PVA, PEG and PAM all exhibit good binding properties. The use of PVA, PEG and PAM yielded sintered ferrite specimens with very similar magnetic properties. This suggests that the clean burning nature of PEG is not so much of an advantage as might first be considered. Indeed, PEG may seem the least favourable of the three binders on the grounds that to achieve a green state strength comparable with that of a specimen produced from powder containing either PVA or PAM requires twice as much binder, making it the more expensive option. Further work on the properties of material containing greater amounts of PAM as binder would be useful, to examine if the green strength could be further improved, and how the magnetic properties of specimens with increasing binder content degrade.

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