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Injection Moulding of Highly Filled Soft Magnetic Compounds for the Production of Complex Electric/Electronic (Micro-) Parts

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Summary: Electric/electronic devices become increasingly more complex and are used in highly integrated assembly groups. Soft magnets generally show only "moderate" magnetic properties; however, they exhibit a comparably high permeability which allows the material for being used in conjunction with hard magnets as a "magnetic conductor". Thus, the magnetic flux density of such parts can be improved leading to a better accuracy and functionality of switches, valves or pumps. In particular for micro applications the use of plastics-bonded soft magnets in combination with hard magnets integrated in one injection moulded part provides new opportunities for electric/electronic devices. The Institute of Plastics Processing (IKV) at the RWTH Aachen further develops in cooperation with Siemens, Oechsler, and Arburg soft magnetic compounds focusing on micro applications. The magnetic properties of plastics-bonded soft magnets are significantly reduced compared to pressed or sintered materials. Compounds filled with spherically shaped fillers as iron-silicon show better flow and processing properties compared to irregular- or flaky-shaped fillers. Due to the specific flow conditions the magnetic properties are not homogeneous throughout the part. At the end of the flow path the filler content is considerably increased leading to higher soft magnetic properties. This can be well correlated by means of microscopic analyses.

Keywords: compounding; ferroelectricity; fillers; injection molding; injection moulding; magnetic polymers; morphology

Introduction

Many technical developments, as in the automotive or electronic industry, are not possible without the innovative use of innovative plastics. The development of technical parts requires more and more highly integrative solutions. Thus, plastics and metal fillers are combined in order to benefit from the positive properties of both materials. By the use of magnetic fillers (metals or ferrites) plastics compounds can be equipped with magnetic properties.

Ferromagnetic fillers can be divided into hard and soft magnetic materials. The difference can be explained by the different hysteresis behaviour. A demagnetized test specimen is exposed to a magnetic field strength H and the magnetic flux density B of the materials is measured depending on the frequency.[1] From the hysteresis loop important magnetic properties can be read off (cp. Figure 1 left).

Important values for soft magnet materials are:

- coercivity H_C is the opposing magnetic field which has to be applied to demagnetize the part
- relative permeability μ_r and polarization J, which describe the increase of the magnetic field by the material
- hysteresis loss, characterized by the enclosed area of the hysteresis loop

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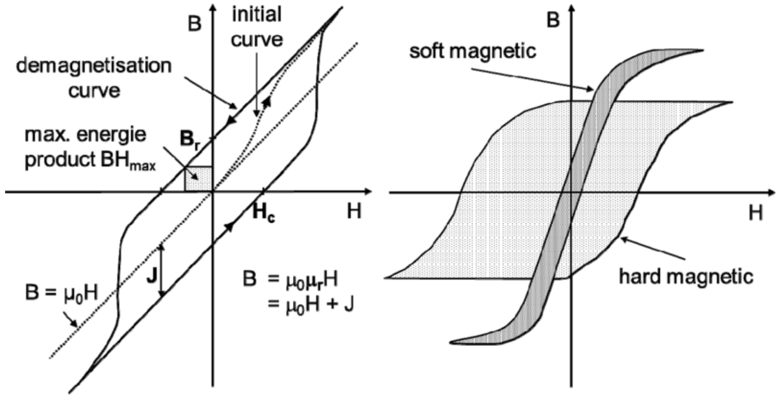

Figure 1.
Hysteresis loops of ferromagnetic materials and comparison between hard and soft magnets.

– and the magnetic remanence B_r, which describes the residual magnetic flux density after stopping the magnetic field.

The basic difference between hard and soft magnetic materials is shown in Figure 1 on the right by schematic curve courses of soft and hard magnets. Hard magnets exhibit high values of coercivity ($H_C > 10^4$ A/m), magnetic remanence ($B_R =$ 400–1500) and max. energy product BH_{max}. This results in a wide hysteresis curve and high magnetic losses during reversal of magnetisation. Thus, hard magnetic materials are generally used as permanent magnets. In contrast, soft magnetic materials show "moderate" magnetic properties. However, they exhibit low values of coercivity between $10^{-1} - 10^3$ A/m and narrow hysteresis loops. Thus, soft magnetic materials are advantageous if the magnetic polarity is changed frequently, as in sensors or relays.[2] In many cases soft magnets offer a high relative permeability μ_r, already at low magnetic field strengths. That is why soft magnets can be used in combination with hard magnets as a "magnetic conductor" in order to increase the local magnetic flux density.

Hard and soft magnetic powders are conventionally used in a compression and sinter process. However, the freedom of scope is considerably restricted.[3] Due to increasing requirements regarding miniaturisation and complexity the easier production of plastics-bonded magnets with a high geometrical design freedom is desirable. In recent years, plastics-bonded magnets are already used in varied fields of application;[3] however, almost only hard magnetic fillers, as ferrites and rare earths elements, are applied.[3] Since the magnetic properties are exponentially depending on the filler content, a high filling degree is required. But only plastics compounds with a maximum filler content of 60 vol.-% can be further processed by conventional injection moulding process. Plastics-bonded hard magnets additionally provide the opportunity of being directly magnetized in an injection mould using integrated magnetic coils. Hitherto, soft magnets plastics compounds are not similarly developed and thus not used for numerous industrial applications. Only some applications of soft magnetic plastics compounds are known for magnetic detectable systems, for example, as a conveyor band in the food industry. In that case a low filler content of approx. 5–10 vol.-% is sufficient. Figure 2 shows some applications of magnetic plastics compounds.

Due to the increasing complexity and particularly due to the miniaturisation of electric and electronic devices highly filled soft magnetic plastics compounds become interesting for the enhancement of magnetic field strengths among other things.[4–6] The aim of a joint project

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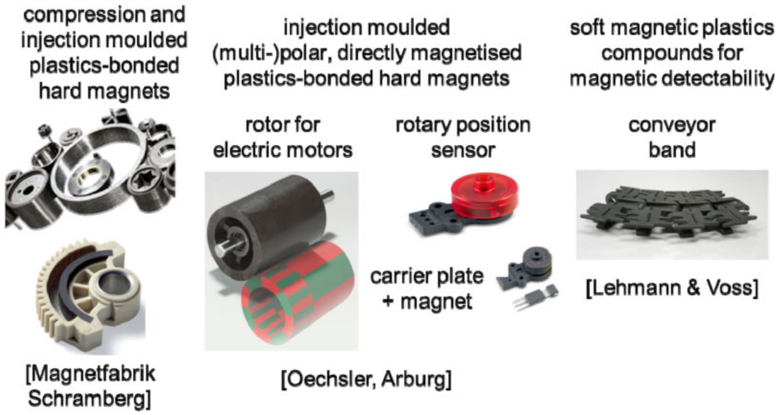

Figure 2.
Application of magnetic plastics compound.

with partners Arburg GmbH & Co KG, Lossburg, Germany, Oechsler AG, Ansbach, Germany and Siemens AG, Erlangen, Germany is to develop soft magnetic thermoplastic compounds for the production of electrical and electronic (micro-) components. Simulation results carried out from Oechsler AG show the potential of injection moulded soft magnets in combination with permanent magnets by using a multi-injection moulding process. Figure 3 on the left shows a possible application in the range of sensors (e.g. rotational angle detecting device). By the additional use of a soft magnet the measured magnetic flux density of a multipolar permanent magnet can be increased in a narrow range, which would considerably enhance the efficiency of an angle sensor. These simulation results will be verified by a demonstrator from Siemens AG (cp. Figure 3 on the right).

For these applications a considerably high relative permeability of approx. 20 is required and maximum soft magnetic filler content is needed. Whereas very small hard magnetic fillers can be used without any loss of magnetic properties, soft magnetic properties are generally reduced with decreasing particle diameter,[7] which makes the processing much more difficult.

The focus at the IKV is to develop the material compounding of highly filled soft

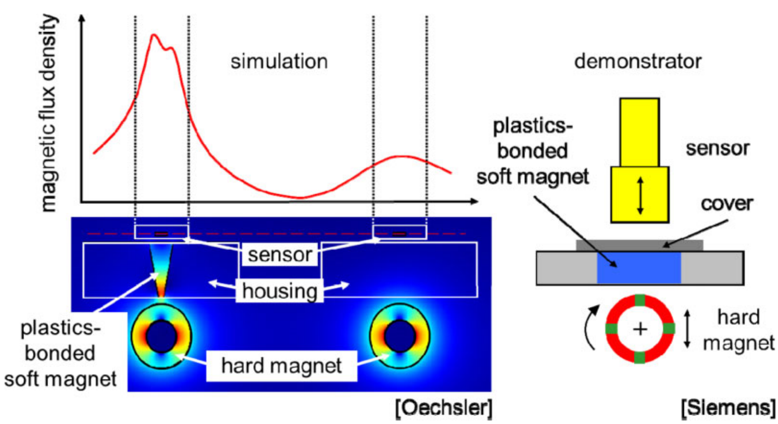

Figure 3.
Potential of soft magnetic plastics compounds.

magnetic compounds and to characterise the resulting magnetic part properties in dependence on material composition, part geometry and process parameters of the injection moulding process.

Materials

At IKV different soft magnetic iron and iron-silicon powders from Häganäs AB, Höganäs, Sweden, are incorporated into a low viscosity polyamide 6 (Schulamid 6 NV12) of A. Schulman GmbH, Kerpen, Germany. The used fillers are shown in Figure 4 by means of scanning electron microscopy (SEM) pictures. Investigated fillers differ in both shape and particle distribution. Whereas both iron fillers (AT 500 and ASC 100) are irregular- or flaky-shaped, the used FeSi 6.8 is spherically shaped. Different filler contents with a maximum filling degree of 90 wt.-% (approx. 57 vol.-%) have been produced and analysed.

The compounding is conducted using a co-rotating twin screw extruder (type ZSK 26) of Coperion GmbH, Stuttgart, Germany, with a screw diameter of 26 mm. After the melting zone of the matrix material the soft magnetic fillers are dosed using a side feeder and an appropriate gravimetric powder dosing feeder. The fillers are dispersed by different kneading elements. Finally, the compound is degassed at the end and extruded to strands which are then pelletised. Improved strand qualities can be obtained with a screw speed $\geq$200 1/min and throughput $\geq$ 15 kg/h.

Soft Magnetic Measuring System

The used soft magnetic measuring system MPG 100 D of Dr. Bockhaus Messtechnik GmbH, Luedenscheid, Germany, is a micro-processor controlled hysteresis graph. The measuring system allows magnetic field strengths up to 23'000 A/m and frequencies between 3 Hz and 100 kHz. A maximum polarisation of 2 T can be measured. At IKV two different measuring coil systems are available. On the one hand injection moulded test rings can be measured according to IEC 60404–6. On the other hand small test plates (maximum cross section of 15×2 mm^2 and an optimum length of 30–32 mm) can easily be analysed using a specially developed yoke system (cp. Figure 5). The injection moulded test plates are positioned between an upper and lower yoke in an insertion which is provided with primary and secondary windings. This measuring method adequately allows process analyses of soft magnetic injection moulded parts.

Figure 6 on the left shows hysteresis curves of a pressed ring of AT 500 (approx.

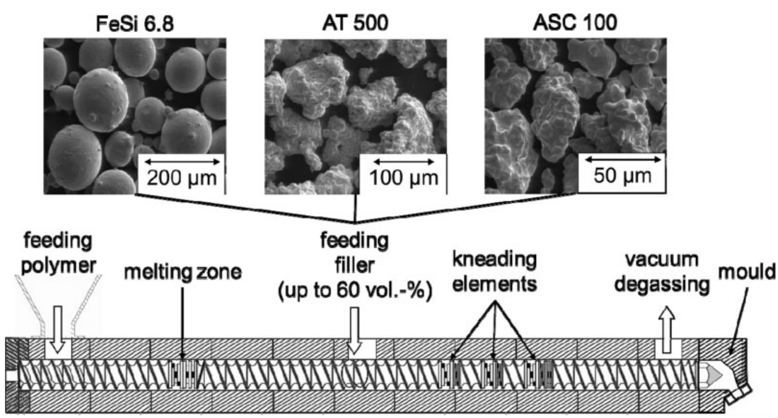

Figure 4.
Soft magnetic fillers and screw configuration.

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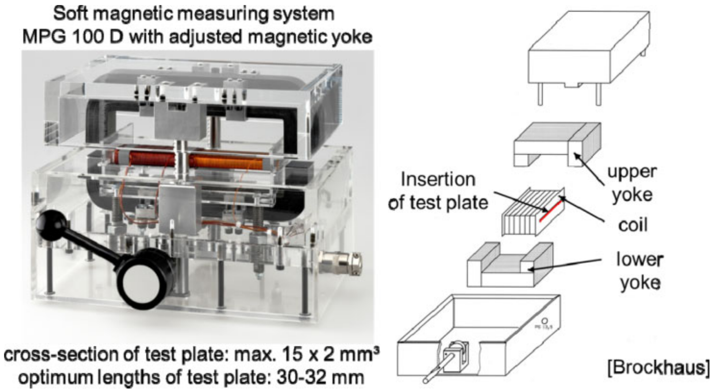

Figure 5.
Measuring system for soft magnetic plates moulded test plates.

99% pure iron) compared to injection moulded rings of AT 500 and FeSi 6.8 at a similar magnetic saturation induction of approx. 200 mT.

The slope and thus the relative permeability is considerably reduced by plastics compounds. Furthermore, the filler content and also the filler material itself has a strong impact. However, the narrow hysteresis curves indicate similar hysteresis losses for plastics compounds at a similar magnetic saturation induction. On the right side in Figure 6 the relative permeability is shown depending on the magnetic field strength, exemplified for AT 500. Besides the different level of permeability the measured maximum of permeability occur at similar magnetic field strength of 400–800 A/m.

Filling and Flowing Behaviour

The filling behaviour of highly filled soft magnetic materials is significantly changed compared to unfilled plastics which is already known from investigations of electrically conductive compounds.[8] On the one hand the filler content increases continuously along the flow path. The filling behaviour can be well explained by a filling

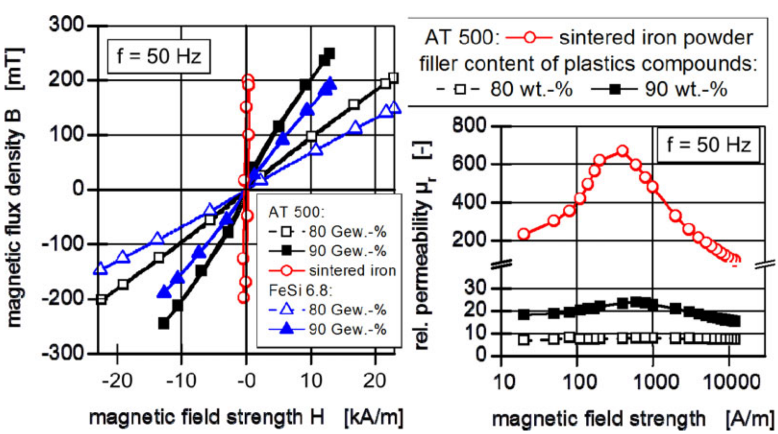

Figure 6.
Comparison of soft magnetic properties of sintered iron and injection moulded soft magnetic plastics compounds.

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study of test plates ($80 \times 80 \times 2$ mm^3) shown in Figure 7 on the left. In contrast to unfilled plastics the part filling is not even and an uncompressed flow front can be detected. The higher metal content at the flow front can be explained by the flow behaviour of filled compounds, since fillers tend to locate themselves in the middle of the flow channel and are therefore more carried to the end of the flow path. Furthermore, a compression of the material with wall adhesion is detected a few centimeters behind the flow front. The metal distribution over the part thickness at different positions along the flow path confirms the increased agglomeration of fillers in the middle (cp. Figure 7 on the right).

In addition the flowability of highly filled compounds is significantly reduced. This is analysed using flow spirals with a cross section of 14×1.5 mm^2 and a maximum flow length of 445 mm. In Figure 8 the maximum flow length of different compounds and the maximum loss of pressure (difference between pressure in front of the screw and cavity pressure near the sprue) are shown. A maximum injection pressure of 1600 bar is used.

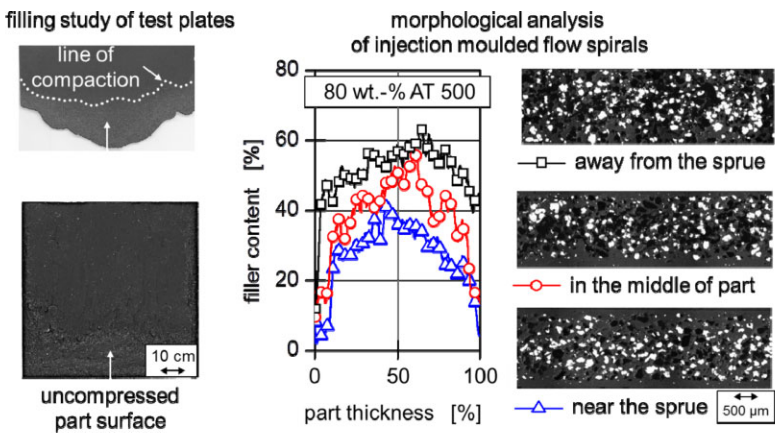

Figure 7.
Filling behaviour and filler distribution of highly filled soft magnetic plastics compounds.

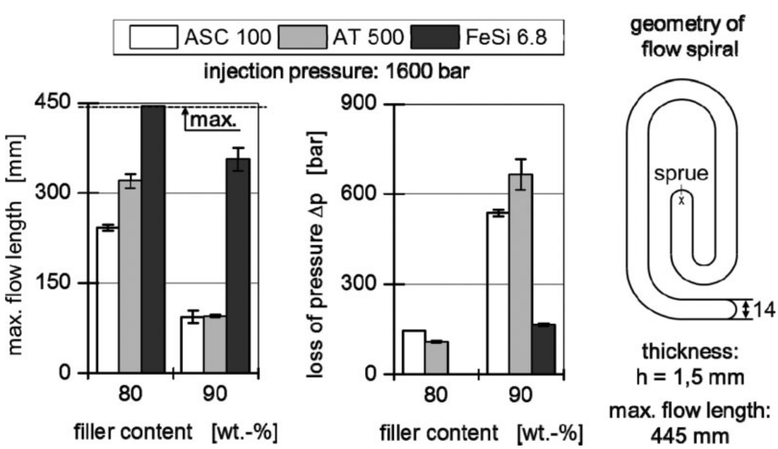

Figure 8.
Flow behaviour of soft magnetic plastics.

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Compounds based on iron-silicon show considerably improved flowability due to the spherically-shape of the filler. The loss of pressure increases with higher filler content since the high thermal conductivity of higher filled compounds exhibit a fast heat dissipation.

Magnetic Properties Depending on Part Position

As mentioned above, the filler distribution is not homogeneous within an injection moulded part. In general, the density and thus the metal content increases continuously along the flow path (cp. Figure 9 on the left). Since the magnetic properties are strongly depending on the filler content, the local increase in density influences the local magnetic properties.

In Figure 9 on the right the maximum relative permeability depending on part position is shown. The permeability increases along the flow path analogous to the density. In general, the measured values of test plates are reduced compared to ring-shaped test geometries which can be explained by the lines of magnetic flux in the yoke system. Whereas the magnetic flux is only located in the inner part in the ring system, the magnetic flux is generated by the upper and lower yoke in the plate system. Thus, the surface layer of the plate with a lower filler content and possible air gaps reduce the magnetic properties by a factor of 1.1 - 2 depending on part position and magnetic field strength. However, the used system is well suited for comparative measurements.

Conclusion

Soft magnetic plastics compounds can be injection moulded up to a maximum filling degree of 60 vol.-%. On the one hand the filling behaviour of highly filled compounds differs considerably compared to unfilled plastics. On the other hand the maximum flow lengths of irregular- or flaky-shaped metal particles are significantly reduced compared to spherically shaped particles. Further investigations will focus on both smaller and spherically shaped fillers. The magnetic properties are not only depending on the filler material or content itself but also on the local part position. However, relative permeability values of approx. 20 can be reached with appropriate fillers and filler contents. The influence of an injection mould with integrated magnetic coils on the filler distribution and thus on the magnetic properties is investigated. By aligning the fillers by a magnetic field the magnetic properties can perhaps be locally increased.

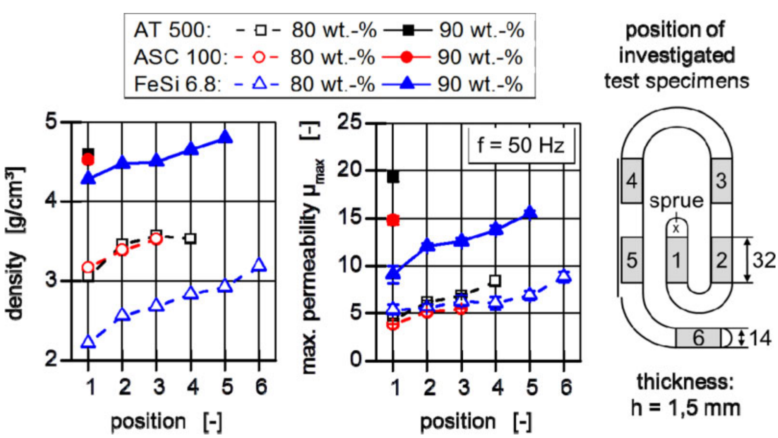

Figure 9.
Density and relative permeability depending on part position, filler and filler content.

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