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Effect of the variation of the gating system on the magnetic properties of injection molded pole-oriented rings

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Abstract: The demand for contactless and wear-free sensor systems for the measurement of different physical values, such as angle, position, or speed has increased over the past years and opened up new application areas for magnetically sensitive sensors. Polymer bonded magnets can be used as signal transmitters in these sensor applications. In general, a high precision and good repeatability of the magnetic field is required, whereas in particular, a high peak flux density and accurate pole length of each pole is demanded for precise measurement. These polymer bonded magnets can be produced economically using the injection molding process with an integrated magnetization of the particles, such that a second magnetization step is unnecessary. This article addresses the influences of the gating system on the magnetic properties of multipolar bonded rings. Further, the particle orientation as well as filler content at different locations, and along the pathway are investigated. It was evaluated that the gating system significantly influences the pole length accuracy, as well as the peak flux density. However, differences in the filler orientation and content cannot be analyzed quantitatively.

Keywords: gating system; injection molding; magnetic sensor; multipole wheel; polymer bonded magnet.

1 Introduction

The modification of polymers with ferro- or ferrimagnetic properties leads to compounds with magnetic properties, which can be processed in conventional polymer

processing technologies, such as injection molding or extrusion [1]. These so-called polymer bonded magnets can be produced with a thermoplastic, thermoset, or elastomeric matrix system [2–5]. Compared to conventional sintered magnets, polymer bonded magnets have a high freedom in design of the geometry, as well as the magnetic structure, small tolerances in the production process, as well as the possibility to integrate shafts or bushings in the production process [2, 6, 7]. Using the injection molding process, polymer bonded magnets can be cost-efficiently produced with very narrow tolerances in high quantities, such that post-processing steps are not required.

Polymer bonded magnets are mainly used for actuator and sensor applications. In conventional sensor technology, the turning of a shaft is detected with a multipolar magnet and an externally mounted sensor, such as a hall, anisotropic magnetoresistive or giant magnetoresistive sensor [2]. The sensor measures the variation of the magnetic field, which can be further processed, e.g. in terms of the rotation angle [8]. With regard to the application area and sensor type, specific requirements for the multipolar magnet have to be met, such as a small pole width for increasing accuracy [9], precise pole length [9, 10], or steep slope of the flux density in the pole pitch for more distance-resistant assemblies [9]. Often rings or flexible strips with a multipolar structure based on a thermoplastic [2, 9] or elastomeric material [11, 12] are used. Usually, the magnetization is conducted in a second processing step after the part production [2].

The properties of polymer bonded magnets are mainly influenced by the filler particle type, amount, and distribution in the polymer matrix [13] with complex interactions with the magnetic field inside the cavity, process parameters, and parts geometry. Due to the increase in the viscosity and, thus, lower degree of particle orientation when using compounds with higher filler degree, usually compounds with a filler volume content in between 50% and 65% are used [13]. Commonly used filler types are ceramic filler materials, as for example strontium or barium ferrite, or rare earth filler materials, such as neodymium iron boron or samarium cobalt. In order to increase the magnetic properties of bonded magnets anisotropic particles with preferred

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magnetic orientation are used. These particles have to be oriented during the injection molding process in the desired pole structure until the filler orientation is fixed by the polymer melt [14]. For the orientation and magnetization of the particles, a magnetic orientation field has to be included in the mold by using coils or sintered magnets [14]. Depending on the filler material as well as the magnetic field inside the cavity, the magnetization of the bonded magnets can be either conducted during the injection molding process or in a further processing step using a separate magnetization device [2]. The advantage of parts with a multipole particle orientation and magnetization in the mold are in particular higher peak flux densities, as well as lower process costs due to the integrated magnetization process [2].

Prior research on the production of bipolar as well as multipolar, rectangular shaped parts shows the influence of the processing conditions during injection molding. In general, the flux density in the cavity as well as the viscosity of the melt influences the degree of particle orientation [15, 16]. For the production of bipolar plates, the gating system and part thickness and, thus, the melt flow behavior have a big influence on the magnetic properties of the polymer bonded magnets [16]. Unsuitable melt flow can lead to faster melt flow in the edge area, open jet formation, or development of weld lines which results in magnetic inhomogeneity [16]. For multipolar magnets no influence of weld lines on the course of the flux density in a certain distance to the parts surface can be detected [15]. The influence of different gating systems for the production of multipolar magnets is not analyzed yet. Furthermore, it is shown that there is no difference in the filler content by means of part thickness [15], filler orientation for different flow lengths or different locations by means of location is not analyzed yet.

For multipolar rings the influence of different processing parameters, as well as different filler content on the major quality criteria for signal transmitter is analyzed [17]. For the pole length deviation, no influences of the processing parameters can be shown [17]. However, with different gating system and, thus, flowing conditions, a general effect of decreased pole length in the pole with injection point and increased pole length in the pole with weld line is shown [18]. Higher melt and mold temperature lead to a lower pole length deviation [18]. Furthermore, higher melt and mold temperature improve the peak flux density as well as the steepness of the slope in the pole pitch, high holding pressure decreases the different quality criteria, whereas the injection speed does not show any influence [17].

This article deals with the influence of the melt flow by varying the number of injection points and, thus,

flow length as well as number of developing weld lines on the magnetic properties of multipolar rings, such as flux density and pole length. In order to evaluate differences in the melt flow behavior, the particle orientation is optically analyzed. Furthermore, the filler content is evaluated for different flow lengths and locations in multipolar rings.

2 Materials and methods

2.1 Materials

The materials used in the experiments are a Polyamide 12 (PA12, Vestamid BS1636, Evonik Industries AG, Essen, Germany) as matrix material, as well as a strontium ferrite (SrFeO, OP-71, Dowa Holdings Co. Ltd., Japan). The PA12 and SrFeO are mixed in a twin screw extruder (Leistritz ZSE HP27, Leistritz Extrusionstechnik GmbH, Nuremberg, Germany) at standard processing parameters (nozzle temperature $T_N = 220^\circ\text{C}$) with a volume content of 55%. The extruded strands are further granulated to form suitable feed for the injection molding process.

2.2 Test specimen

For these investigations, multipolar rings are produced using the injection molding process. The mold contains integrated permanent magnets for the production of a ring geometry (mold dimensions: 30.6 mm; inner diameter: 22.6 mm; height: 5 mm) with a multipolar structure of 24 poles at the outer ring surface. Thus, the hard magnetic filler particles can be oriented and partially magnetized during the injection molding process. In order to evaluate the influence of the weld line, the gating system is varied systematically. The used gating systems are a film gate located centrally at the inner ring surface, as well as pin-point gating systems with two, four, eight and twelve injection points, each located at the rings side surface. The poles are numbered from 1 to 24, such that identical numbers are located at the same location in the mold. Thus, influences caused by differences in the flux density due to the molds setup can be eliminated. For the evaluation the location of the injection points and developing weld lines for all gating systems are shown in Figure 1. All injection points and weld lines are located centrally in a pole. However, for the 8-point gating system the weld line is located in the pole pitch due to the number of poles.

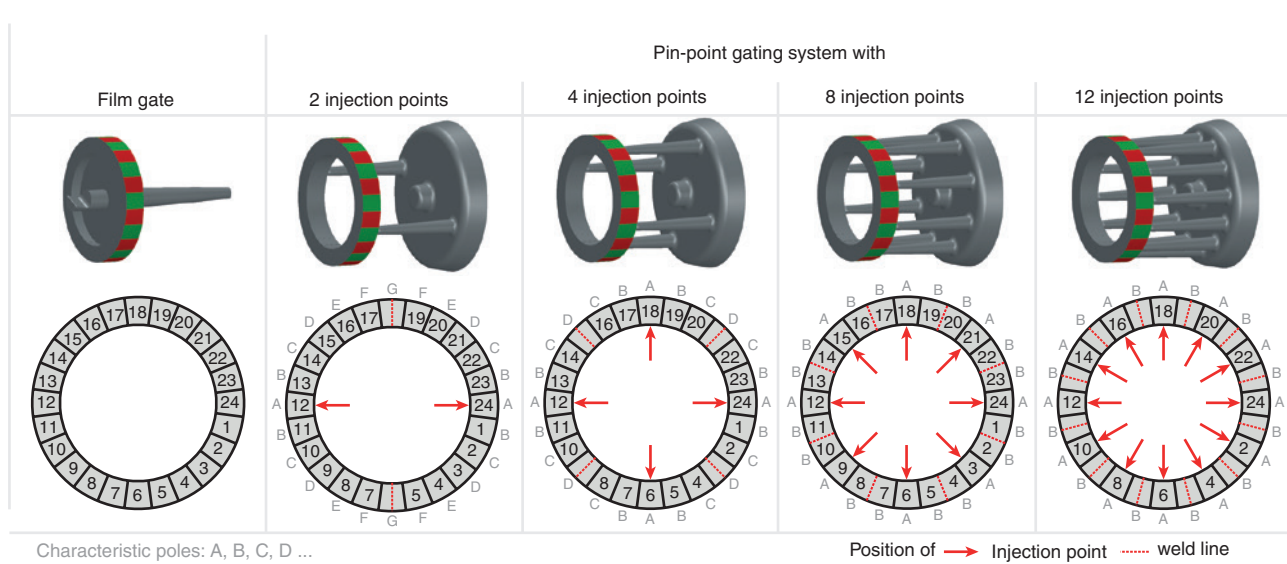


Figure 1: Multipolar rings with different gating systems with positioning of the injection points and developing weld lines, as well as definition of pole numbers.

2.3 Processing

For processing an injection molding machine (Demag 25/280-80, Sumitomo (SHI) Demag Plastics Machinery GmbH, Schwaig, Germany) with a screw diameter of 18 mm is used. All rings are processed with the same standard injection molding parameters, such as the melt temperature of 280 °C, mold temperature of 80 °C, and holding pressure of 500 bar. The injection speed is varied regarding the number of injection points, in order to keep a constant melt front speed inside the ring for all variations. Thus, an injection speed of 40 mm/s for the 2-injection point gating system, 80 mm/s for the 4-injection point gating and film gate system, as well as 160 mm/s for 8- and 12-injection point gating system is used. As there is no continuous melt front developing for the 12-injection point gating system, the same injection speed is used as for the 8-injection point gating system (compare Figure 2). Furthermore, Figure 2 shows that the melt flow of the magnetic compound is highly influenced by the magnetic field inside the cavity and is drawn to the outer ring surface at the melt front. The changeover to holding pressure is chosen position-dependent and is defined individually for each gating system.

2.4 Characterization

As the magnetic flux density and the resulting pole length are major quality criteria for multipolar signal transmitters in sensor applications, the magnetic characteristics of the specimens were analyzed and

evaluated. The magnetic flux density B_r oriented perpendicular to the surface was measured with a hall sensor (KSY-44, Siemens AG, Munich, Germany) at a distance of 0.5 mm from the magnets outer ring surface. In order to keep the same distance independent of the rings concentricity, the hall sensor is positioned flexibly on the rings outer surface. Due to the usage of a regularly replaced teflon tape, the abrasion of the sensor surface is prevented. During the measurement the angle of rotation is detected using a high accuracy angle encoder (RON 786, Dr. Johannes Haidenhain GmbH, Traunreut, Germany), which is further correlated to the measured flux density. In order to ensure the comparability of the measurements a reference ring is measured in between each sequence of rings and its results have to lie within the defined tolerance ranges, e.g. for the pole length of $\pm 0.03^\circ$ for a valid measurement.

For the evaluation of the influence of the gating system, the maximum B_r achieved for each pole $|B_{r,max}|$, as well as each pole length s is calculated (compare Figure 3). The pole length is defined as the section between two zero crossings, which is calculated by linear interpolation in between the two closest measurement points. The ideal pole length for all rings equals 15° or 4 mm. Due to variations of the pole length and maximum radial flux density inside the mold, these criteria are evaluated in regard to a defined reference in order to present the influences of the changed gating system in detail. As it was shown in previous research, the pole length of the rings with film gate correlate with the pole length of the mold [17]. Thus, the deviation of the pole

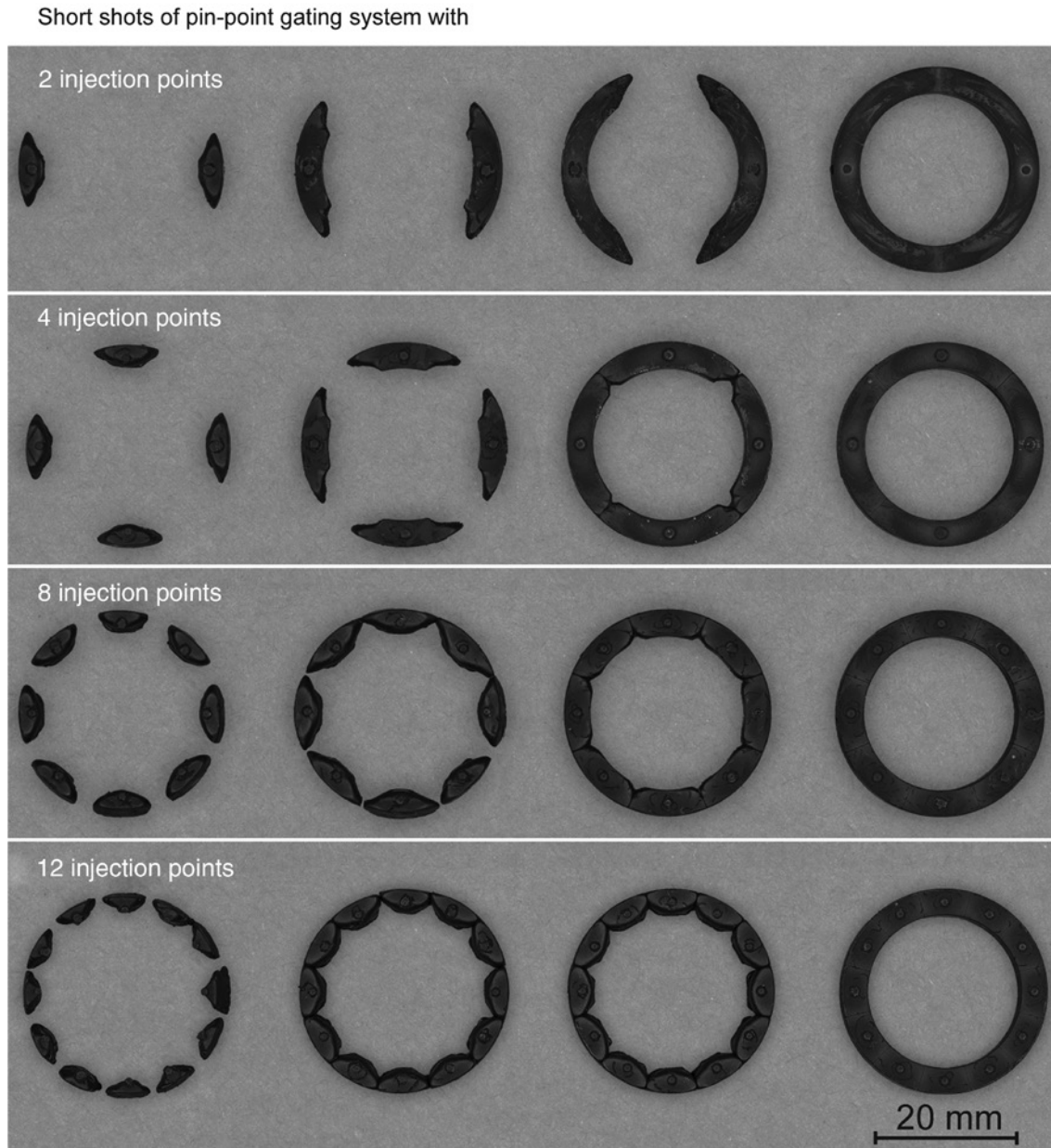


Figure 2: Short shots of multipolar rings with different gating systems.

length with regard to the pole length of the rings with film gate is presented. Furthermore, certain characteristic poles are summarized, such as all poles with centrally located injection point or weld line (compare Figure 1). For the evaluation of the maximum radial flux density the same procedure is conducted.

In order to determine the particle orientation, multipolar rings with all gating systems have been selected and optically analyzed using a scanning electron microscope with detection of secondary electrons (Ultra Plus, Carl Zeiss AG, Oberkochen, Germany). For

this purpose, cross-section polishes were made with the location of the cross section on the ring's half height. The polished surface is sputtered with platinum and palladium. For the ring with film gate different sections, such as the pole center and pole pitch right at the outer ring surface, as well as with a distance of 800 μm are analyzed. In order to analyze differences in the particle orientation for the parts with different gating system pole 24 is analyzed, which is a pole with centrally located injection point. Furthermore, the particle orientation in the weld line is analyzed in the pole center of

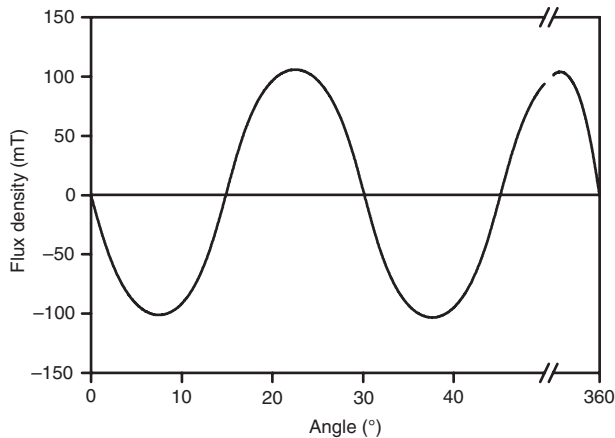


Figure 3: Resulting flux density curve with evaluated parameters.

pole number 6 (2 injection points), 3 (4 injection points), and 2 (12 injection points). The pictures are taken in a distance of 800 μm from the outer ring surface in the pole center. Prior to the optical analysis the rings have been demagnetized.

In order to detect variation in the filler content related to the parts thickness and the length of the flow path due to the magnetic pull of the mold integrated magnets or the flow length, samples in different locations are measured using thermogravimetric analysis (TGA Q 5000, TA Instruments, New Castle, USA). In this measurement, a sample is heated under inert conditions in order to evaporate the matrix material. By measuring the mass change during the complete measurement, the filler content of the samples can be determined. In order to show the influence of the longest flow path, a sample with 2-injection point gating system is chosen. Four characteristic locations are prepared; this includes the pole with injection point, the pole with weld line, the pole in the middle, and one pole pitch area. The samples are demagnetized for this measurement. Samples with a length of 2 mm are cut and embedded in a thermoset and then thin sections with a thickness of 30 μm are prepared for the complete part thickness (compare Figure 10). After preparing the thin cuts, the embedding thermoset is easily removed. In order to gain the necessary sample size of the TGA, five samples have been measured collectively. Samples at the surface and in a distance of approximately 1, 2, and 3 mm of the outer surface are selected for the measurements. During the measurement, the samples are heated in an inert atmosphere (nitrogen, 10 K/min) with a continuous measurement of the samples weight, such that the weight-related filler content can be identified as soon as the polymer decomposed completely.

3 Results and discussion

3.1 Pole length

In the following, the characterization of the pole length of the multipolar rings with different gating system is presented. Figure 4 shows the deviation of the pole length for all different gating systems compared to the reference, the pole length of the rings with fan gate. The deviation is shown for all characteristic poles, which indicates for example all poles with centrally located injection point. It can be seen that for all different gating systems, the pole length of all poles with centrally located injection point is lower and the pole length of all poles with centrally located weld line longer compared to the reference. Although the weld line is located in the pole pitch for the gating system with 8 injection points, the same characteristics can be detected. The poles in between these two characteristic poles show no significant distribution of the analyzed characteristics. This general effect is similar to the effect seen in Ref. [18] evaluating different processing parameters for a gating system with 4 injection points located at the inner ring surface.

Figure 5 shows the pole length deviation for the poles with centrally located injection point and weld line with regard to the reference for all number of injection points. As the weld line for the rings with a gate system with 8 injection points is located in the pole pitch, this result is not integrated in this summary. It can be seen that the deviation of the pole length in the pole with centrally located injection point, as well as centrally located weld line decreases with a higher number of injection points. Thus, the best reproduction of the pole length in the mold can be achieved using a high number of injection points. It is assumed that this general effect of lower pole length in the pole with centrally located injection point and higher pole length in the pole with centrally located weld line is caused by the filling behavior. Furthermore, due to the longer melt flow in the rings with a lower number of injection points this effect is increased. However, this has to be further evaluated in continuing research.

3.2 Flux density

Figure 6 shows the flux density for each pole for the rings with film gate system. It can be seen that the radial flux density varies for all poles with an average flux density of approximately 100 mT. These differences are caused by

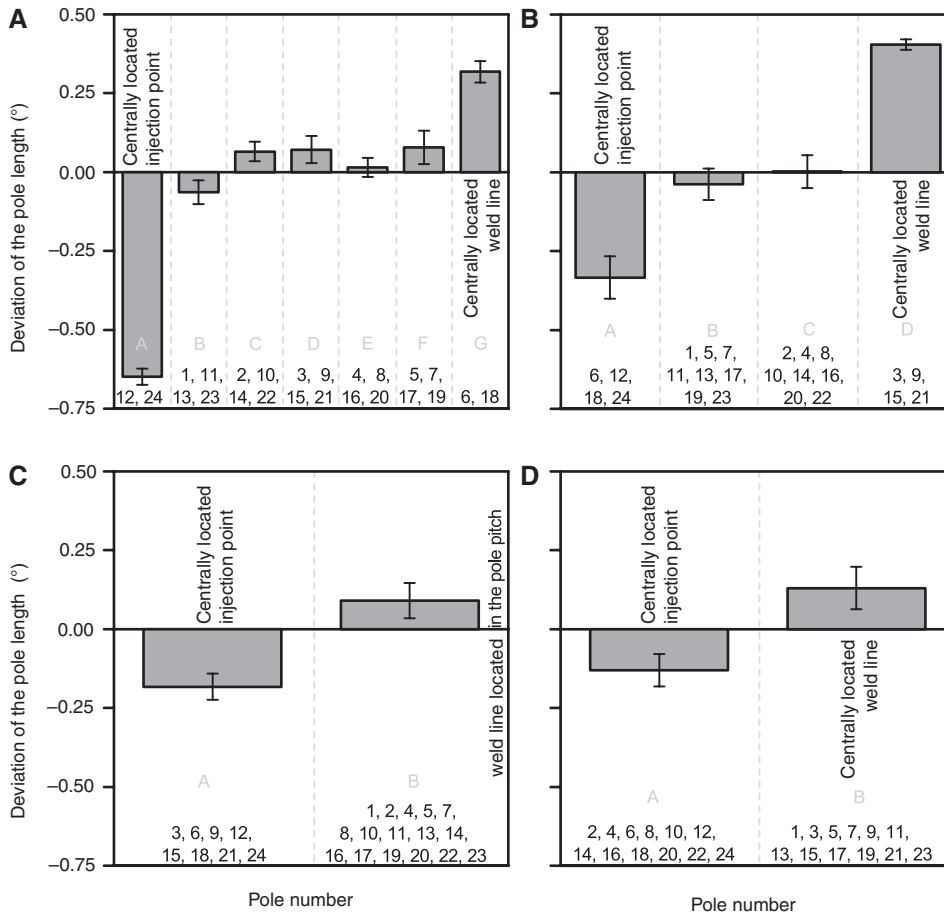


Figure 4: Pole length deviation of the rings with different gating system compared to the pole length of the rings with film gate for all characteristic poles.

(A) Gating system with two injection points. (B) Gating system with four injection points. (C) Gating system with eight injection points. (D) Gating system with twelve injection points.

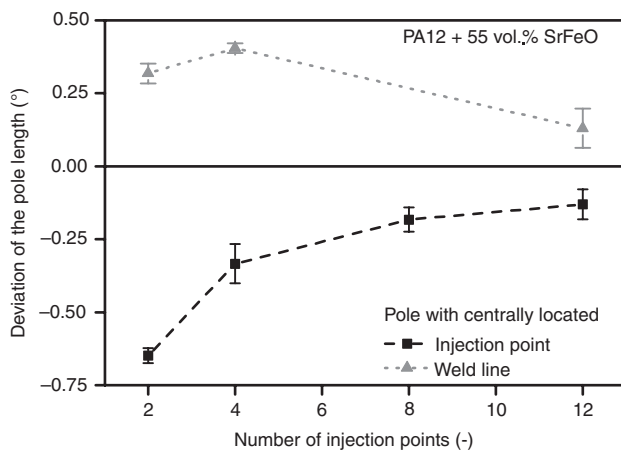


Figure 5: Pole length deviation of the rings with different gating system compared to the pole length of the rings with film gate.

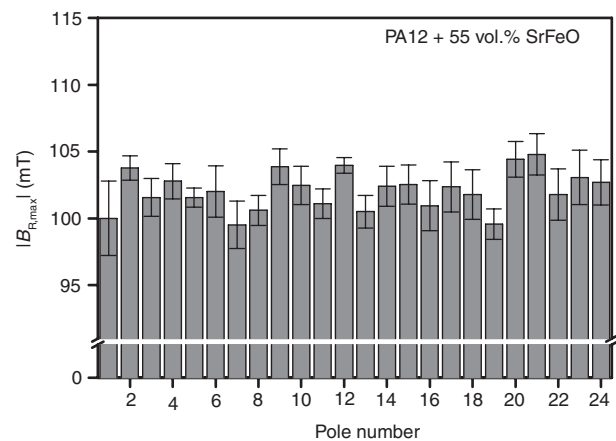


Figure 6: Radial flux density $|B_{R,max}|$ for the rings with film gate.

the inhomogeneity of the magnetic field inside the mold. In order to identify the process-related variations in the radial flux density, the deviation of the maximum radial flux density $|B_{R,max}|$ for the rings with different gating system is shown in Figure 7. It can be seen that the pole with centrally located injection point has the highest flux density, whereas the pole with centrally located weld line has the lowest. An exception is the flux density distribution in the rings with the two injection point gating system as the flux density deviation is not continually decreasing from the pole with injection point to the pole with weld line. It is assumed that the flux density decreases with longer flow path due to the cooling of the melt and and, thus, lower degree of orientation. Furthermore, it is assumed that the pole with centrally located injection point shows by far the highest flux density due to the fact that the

particles are magnetized for the first time and, thus, in the corresponding orientation. Incorrect oriented particles, e.g. due to the fast cooling of the material at the mold surface, which lead to a nonoriented surface layer are only magnetized regarding the magnetic field inside the mold. However, this has to be further analyzed in further research.

3.3 Scanning electron microscope (SEM)

The filler particle orientation at different areas of the rings and rings with different gating system are shown in Figures 8 and 9. The predominant magnetization direction is perpendicular to the large surface of the mainly platelet-shaped particles. This leads to a horizontal alignment of

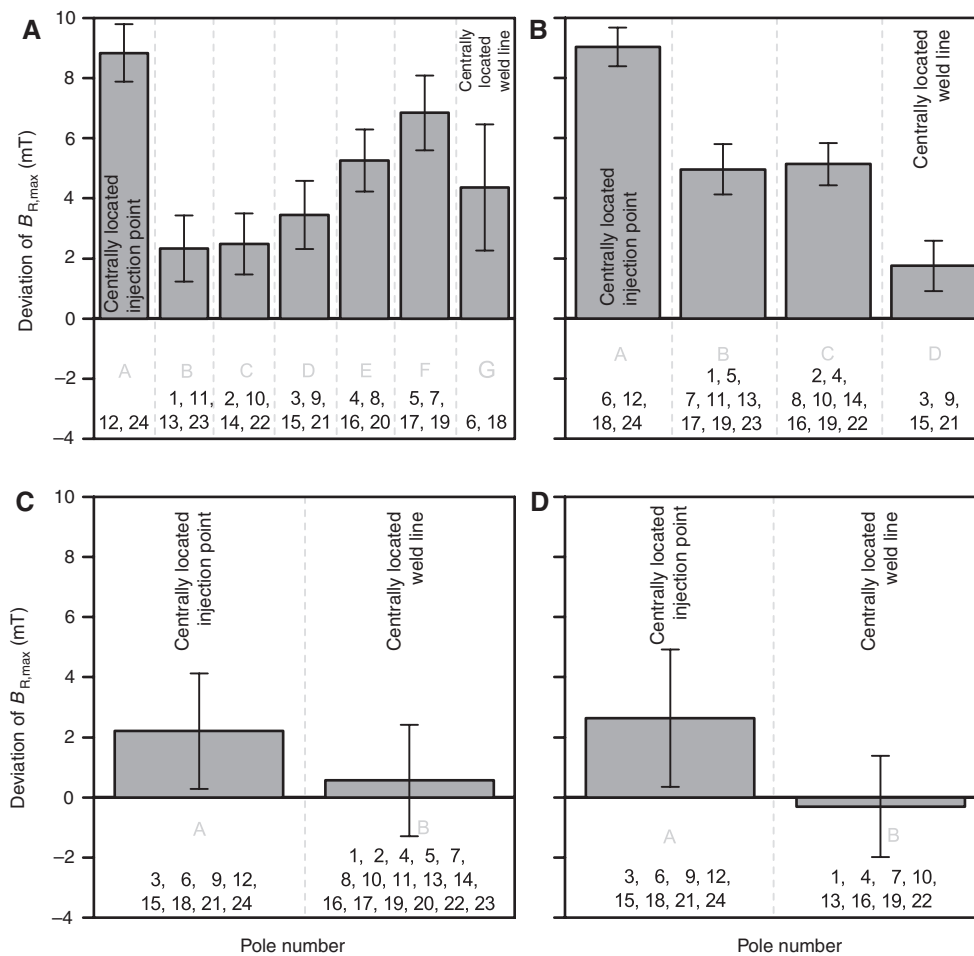


Figure 7: Deviation of $|B_{R,max}|$ of the rings with different gating systems compared to $|B_{R,max}|$ of the rings with film gate for all characteristic poles.

(A) Gating system with two injection points. (B) Gating system with four injection points. (C) Gating system with eight injection points. (D) Gating system with 12 injection points.

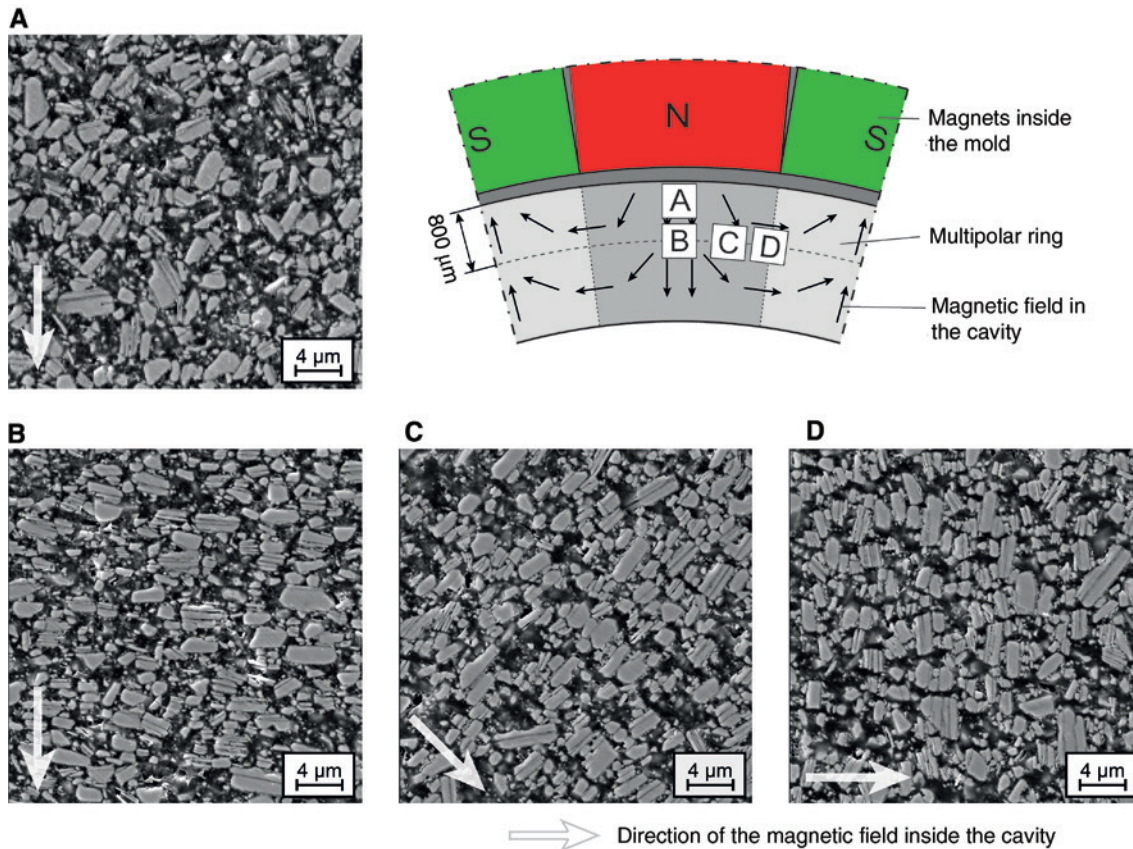


Figure 8: SEM analysis of the particle orientation (multipolar ring with film gate, filler volume content: 55%). (A) Edge layer, pole center. (B) Pole center. (C) Intermediate area. (D) Pole pitch.

the filler particles with a horizontally orientated magnetic field, as shown in Figure 8, picture B. However, a quantitative evaluation of the filler orientation is difficult, due to the irregular particle shape which results from the manufacturing process of the ferrite particles. Furthermore, it can be seen that there is no orientation at the edge layer (A). The development of the nonoriented edge layer can be explained by the fast cooling due to the cold mold (80°C). The viscosity of the melt increases, such that the filler particles do not have sufficient time for orientation or the solidification takes place before the orientation process. At a distance of approximately 800 μm, an orientation of the particles along the arcuate magnetic field inside the cavity can be identified. The filler particles align in the area of the pole pitch (D) vertically and in the pole center (B) horizontally. In between diagonally aligned filler particles are determined (C). However, single nonoriented particles can be identified, which are hindered from complete orientation due to the high filler content and interactions among the filler particles themselves.

Figure 9 shows the particle orientation for rings with different gating system in the pole with centrally located injection point. Exemplarily, for the 2-injection point

gating system, the filler orientation in the pole with centrally located weld line is pictured. However, the exact location of the weld line cannot be determined optically by analyzing the filler orientation as the magnetically induced particle orientation is dominating. In summary, no differences in the appearance of the orientation in the poles with centrally located injection point, weld line or intermediate located poles can be identified. However, differences in the degree of orientation cannot be defined optically.

3.4 Filler particle content

The filler particle distribution was evaluated by measuring the filler content at different flow lengths and by means of the thickness of the part in order to analyze a possible separation due to the magnetic pull of the particles in direction of the magnets or flow induced filler matrix separation. The results shown in Figure 10 show slight deviations in the filler content, but neither show a trend of higher filler content close to the outer ring surface nor with regard to the length of the flow path.

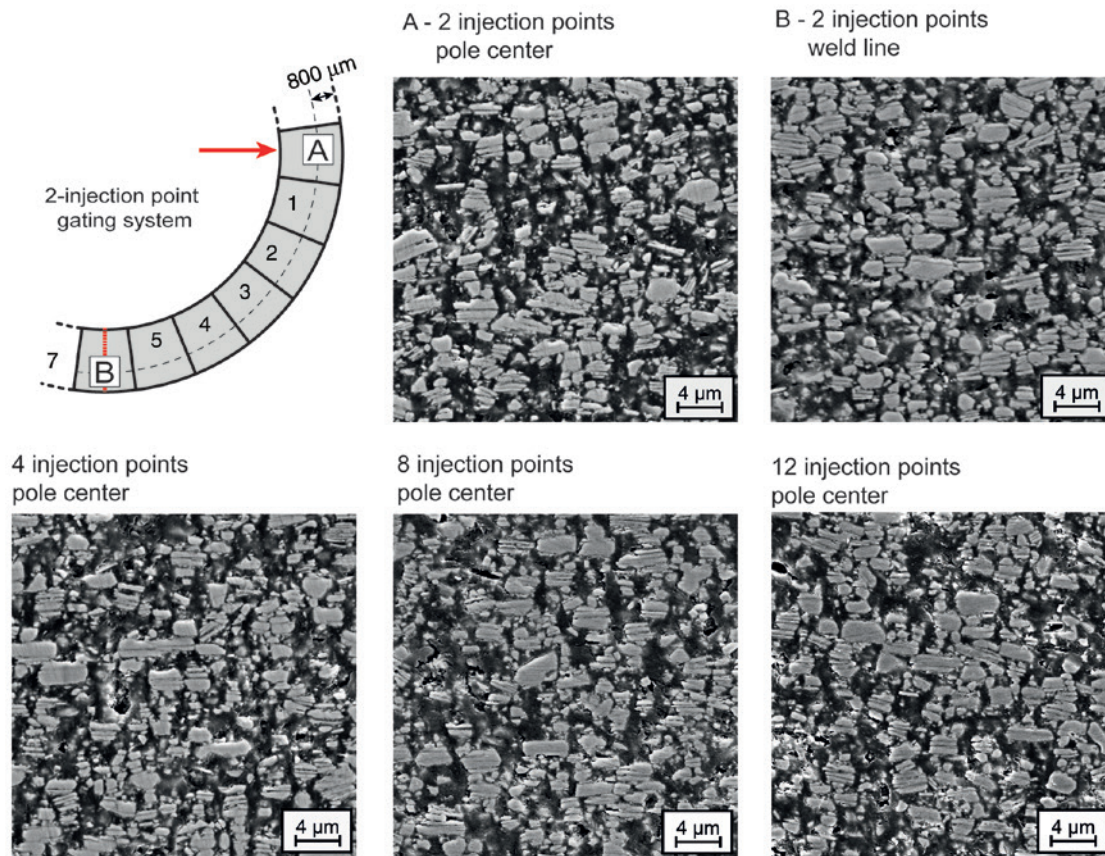


Figure 9: SEM analysis of the particle orientation (multipolar rings with different gating systems and location inside the ring, filler volume content: 55%).

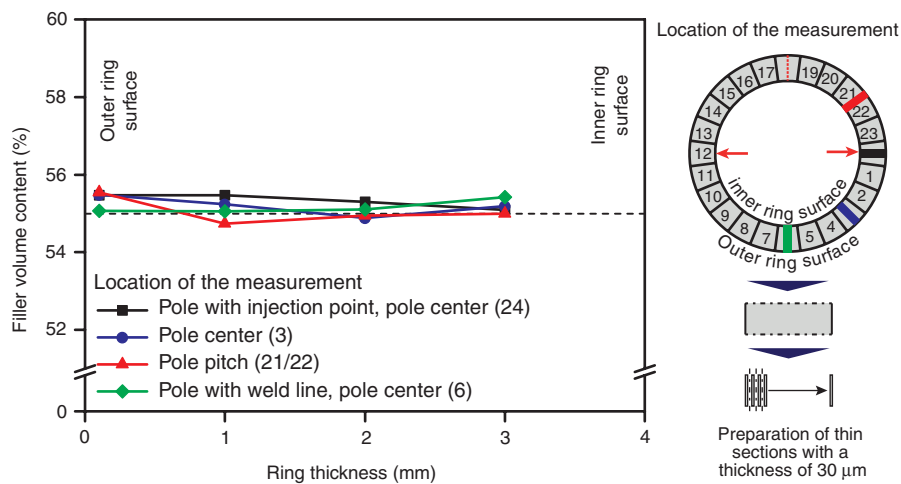


Figure 10: Filler volume content at different locations in the ring.

4 Conclusion and outlook

The investigations show that the magnetic properties of pole-oriented magnets significantly depend on the gating

system. An increasing number of injection points and weld lines improve the quality of the pole length accuracy, as well as the uniformity of the peak flux density. It is assumed that this result is caused by flowing effects,

but has to be further studied in continuing research. Thus, a longer flowing path as in the gating system with 2 injection points leads to high deviations in the pole length as well as peak flux density. Both properties are important quality criteria for the application as signal transmitter. It can be shown that the differences in the peak flux density and pole length deviation are not caused by variations of the filler volume content, as the filler volume content is equal in the scope of the tolerance area and does not depend on the flow length or the location in regard of the thickness of the part. Furthermore, it can be shown that the particle orientation qualitatively does not depend on the gating system. However, the evaluation of the degree of the particle orientation is optically not evaluable.

In further research, the reason for the occurring effects during the injection molding process will be questioned. It is assumed that the shown influences are caused by flowing effects, which shall be confirmed by additional experiments. For this, the influence of the filling and holding phase on the magnetic properties will be studied by producing short shots as well as parts with varied holding pressure. Further, the influence of the fast cooling of the polymer melt at the mold surface and its influence on the magnetic characteristics of these parts have to be evaluated. In this connection, different processing conditions will be identified by measuring the pressure distribution during the molding process inside the parts for different gating systems. Furthermore, the influence of the position of the injection points with regard to the pole structure, as well as the influence of a different number of poles with equal circumference will be analyzed.

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Conflict of interest statement: The authors declare that they have no conflicts of interest.

[Correction added after online publication October 24, 2016: Conflict of interest statement: The authors declare that they have no conflicts of interest.]

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