Fused Filament Fabrication (FFF) is a well-established additive manufacturing (3D printing) process using thermoplastic materials [1, 2]. Key advantages of FFF are: It is an affordable, fast and end-user friendly manufacturing process. This work deals with the 3D printing of polymer-bonded and magnetic anisotropic magnets. Polymer-bonded magnets are composed of magnetic powder and a polymer matrix. Therefore, the maximum energy product \((BH)_{\text{max}}\) of bonded magnets is limited compared to sintered magnets. Nevertheless, many applications need an accurate and complex magnetic field distribution instead of highest field strengths, for example in sensor and electric drive technology [3]. Polymer-bonded magnets can be produced from magnetic powder that is magnetically isotropic or anisotropic. If a high energy product \((BH)_{\text{max}}\) of polymer-bonded magnets is not the most important parameter, magnetic isotropic powder is preferred because it is associated with lower costs and more flexibility. On the other hand, anisotropic magnets can only be magnetized in one certain direction, which can be restrictive with respect to shape. For producing polymer-bonded magnets, magnetic powder is mixed with a binder such as a thermoplastic polymer. The resulted compound can be used for injection molding, compression and for extrusion. For the FFF process, thermoplastic or compounds are extruded into wire-shaped filaments. Due to the high filler content of the compound, the viscosity increases which can lead to filling and flowing problems. Polyamides such as PA6, PA11 and PA12 offer a good combination of viscosity, bonding and mechanical properties such as a high tensile- and impact strength [4, 5]. For 3D printing, PA6 is more difficult to process because the water absorption capacity is significantly higher compared to PA12: PA6 absorbs approximately 1.13 wt%, while PA12 absorbs 0.15 wt% [6]. To prevent printing errors, PA6 compounds have to be dried at around 90°C for 8h.

Certain applications of magnetic designs have complex requirements on the magnetic field distribution, for example highest possible magnetic field homogeneity in a certain volume. 3D printing of isotropic NdFeB magnets with focus on tailored the external stray field by topology optimisation of the magnet was successfully implemented [7–9]. With Big Area Additive Manufacturing (BAAM) isotropic NdFeB magnets were manufactured [10], where a special heat and extruding unit is needed and only large structures can be realized. Goal of this work is to produce magnetic anisotropic polymer-bonded magnets with the help of two different approaches by an end user 3D printer: Printing directly on the surface of a strong permanent magnet and investigating how the printing process itself affects the magnetic anisotropy of the sample.

Three different magnetic anisotropic compounds are investigated:

1. Strontium Hexaferrite inside a PA6 matrix (Sprox® 10/20p), fill grade: 49 vol%.

2. Strontium Hexaferrite inside a PA12 matrix (Sprox® 11/22p), fill grade: 53 vol%.

3. SmFe17N3 inside a PA12 matrix, fill grade: 44 vol%.

The two Sprox® compounds are prefabricated by the Magnetfabrik Bonn. SmFe17N3 and the thermoplastic PA12 are compounded with twin screw extruder at the University of Leoben, Austria [11]. The advantage of these ferrite powders is that they are inexpensive but have a lower \((BH)_{\text{max}}\) compared to rare earth materials. The volume filler constant for...
these materials is determined by the Loss on Ignition (LOI), whereby the sample is heated to 1100 °C and the plastic is evaporated [12].

Fig. 1 shows the hysteresis loops of all three materials in hard and easy axis, with samples printed at different external magnetic flux densities $\mu_0H_{ext} = 100$, 150 and 200 mT and Tab. II lists the corresponding ratio $m_i/m_s$ with the remanence $m_r$ and the saturation magnetization $m_s$. The internal field $\mu_0H_{int} = \mu_0H_{ext} - Nm$ is displayed on the x-axis, assuming a demagnetization factor of $N = 1/3$ and $m$ is the magnetization. This applies to a perfect cube and for real cubes small deviations are to be expected [17].

TABLE I: Best parameter settings for printer and Slic3r [16], empirically found.

| Parameter                  | Value          |
|----------------------------|----------------|
| Extruder temp              | 300 °C         |
| Layer height               | 0.25 mm        |
| Fill density               | 100 %          |
| Fill pattern               | rectilinear    |
| Printer speed              | 15 to 20 mm s$^{-1}$ |
| Build platform             | painter’s tape |
| Bed temperature            | 40 °C          |

For both Sprox® materials an external flux density of 200 mT is sufficient for aligning the particles because of their lower coercive field. However, 150 mT is the highest external field in which Sm$_2$Fe$_{17}$N$_3$ + PA12 can be printed, which is not enough for alignment. Larger flux densities destroy the
shape of the sample due to the larger remanence magnetization of the material compared to Sprox®. Also the density and therefore the remanence of the printed sample is reduced compared to the raw compound, Tab. III. All values in the table, measured and from the data sheet, refer to anisotropic samples.

TABLE III: $B_{r1}$, $H_{c11}$ and $\rho_1$ measured properties of printed anisotropic sample, $B_{r2}$, $H_{c12}$ and $\rho_2$ according to datasheet. For Sm$_2$Fe$_{17}$N$_3$ + PA12 the printed anisotropic ($B_{r1}$) and printed isotropic ($B_{r2}$) samples are compared.

|          | Sprox 10/20p | Sprox 11/22p | Sm$_2$Fe$_{17}$N$_3$ + PA12 |
|----------|--------------|--------------|-------------------------------|
| $B_{r1}$ | 201          | 220          | 308                           |
| $H_{c11}$ | 162          | 281          | 565                           |
| $B_{r2}$ | 222          | 225          | 389a                          |
| $H_{c12}$ | 207          | 239          | 899                           |
| $\rho_1$  | 2.861        | 2.962        | 3.404                         |
| $\rho_2$  | 3.2          | 3.2          | 3.796b                        |
| $B_{r1}/B_{r2}$ | 0.91 | 0.98 | 0.79 |
| $\rho_{1}/\rho_{2}$ | 0.89 | 0.91 | 0.9 |

a calculated
b density measurement of compound, no data sheet available

A further functional principle is being investigated in which the printing direction is observed in relation to the orientation of the particles, the so-called "flow anisotropy". The magnetic hard and easy axis depend on the geometry: The magnetic easy axis of the Sprox® particles is perpendicular to the long side of their cuboid geometry. The orientation of the particles is shown with a light microscope in reflected light mode. Fig. 3 (a) shows an isotropic sample and Fig. 3 (b) a sample that is printed under an external field of 545 mT. By comparing the images in Fig. 3 one can see the alignment of the particles in the external magnetic field in vertical direction.

The cuboid structure of Sprox® allows mechanical orientation over the printing direction whereas the spherical structure of SmFeN remains unaffected. Fig. 4 (a) shows how this idea is realized: When a cuboid is printed consisting only of perimeters, areas arise where print direction is the same over the whole volume of the sample. For soft magnetic materials, the influence of the 3D printing process was investigated by Patton et al. [18].

Hysteresis loops with the applied field parallel to and orthogonal to the print direction were performed in the VSM with the $3 \times 3 \times 3$ mm$^3$ $(L \times W \times H)$ cubes. Fig. 4 (b) shows the hysteresis loops of the different samples. The SmFeN sample shows no difference between the two measured directions, whereas for the Sprox samples a difference is visible. This is a result of the Sprox aligned in the printing direction and no alignment of the SmFeN sample. The values of the normalized remanance $m_r/m_s$ are shown in Tab. IV.

TABLE IV: The ratio $m_r/m_s$ in parallel and perpendicular direction of print - movement.

|          | - direction | - direction |
|----------|-------------|-------------|
| Sprox 10/20p | 0.58       | 0.39       |
| Sprox 11/22p | 0.62       | 0.4        |
| SmFeN      | 0.66       | 0.67       |

This paper presents two methods for aligning the easy axis of magnetic particles during 3D printing. A ferromagnetic powder inside a thermoplastic matrix is processed. The described techniques allow the printing of samples with a higher remanence $B_r$ than isotropic powders. Compared to the presented approaches, providing an external alignment field produces better results in terms of $m_r/m_s$ but the observed flow anisotropy shows, that the print process itself has an influence on the alignment of the particles. The results show that

FIG. 2: Hysteresis loops in hard- and easy axis of three samples measured with the VSM, where $H_{int}$ is the internal field, considering a demagnetization factor of $N = 1/3$. The samples are aligned with different magnitudes of the external field.

FIG. 3: Reflected light microscope images: (a) Isotropic Sprox® 11/22p (b) aligned anisotropic particles of the printed magnet in an external magnetic field of 545 mT.
a magnetic field $B_z$ of approximately 200 mT is sufficient for aligning the hardmagnetic Strontium Hexaferrite particles in the Sprox® compound materials. For SmFeN the threshold value stays unknown, since printing above external fields bigger than 150 mT is not possible right now. An improved cooling could contribute to the increase of the magnetic field during printing SmFeN. As a next step the results motivate the development of a customized 3D printer capable of aligning the particles arbitrarily during printing by applying a variable external magnetic field of 200 mT in the desired direction for the alignment of the particle. After successfully implementing this design, complex structures with special magnetic capabilities should be printable. This would be a breakthrough in the development and manufacturing of magnets with varying local magnetization direction that can not be produced by fabrication techniques that are state of the art.

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