Materials and Coatings Fabricated Using the Additive Manufacturing Technologies
Материалы и покрытия, получаемые методами аддитивных технологий

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Review article
Обзорная статья

Exploring 3D printing with magnetic materials: Types, applications, progress, and challenges

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Abstract. 3D printing, also known as additive manufacturing (AM), represents a rapidly evolving technological field capable of creating distinctive products with nearly any irregular shape, often unattainable using traditional techniques. Currently, the focus in 3D printing extends beyond polymer and metal structural materials, garnering increased attention towards functional materials. This review conducts an analysis of published data concerning the 3D printing of magnetic materials. The paper provides a concise overview of key AM technologies, encompassing vat photopolymerization, selective laser sintering, binder jetting, fused deposition modeling, direct ink writing, electron beam melting, directed energy deposition and laser powder bed fusion. Additionally, it covers magnetic materials currently utilized in AM, including hard magnetic Nd–Fe–B and Sm–Co alloys, hard and soft magnetic ferrites, and soft magnetic alloys such as permalloys and electrical steels. Presently, materials produced through 3D printing exhibit properties that often fall short compared to their counterparts fabricated using conventional methods. However, the distinct advantages of 3D printing, such as the fabrication of intricately shaped individual parts and reduced material wastage, are noteworthy. Efforts are underway to enhance the material properties. In specific instances, such as the application of metal-polymer composites, the magnetic properties of 3D-printed products generally align with those of traditional analogs. The review further delves into the primary fields where 3D printing of magnetic products finds application. Notably, it highlights promising areas, including the production of responsive soft robots with increased freedom of movement and magnets featuring optimized topology for generating highly homogeneous magnetic fields. Furthermore, the paper addresses the key challenges associated with 3D printing of magnetic products, offering potential approaches to mitigate them.

Keywords: 3D printing, additive manufacturing, additive technologies, magnetic materials

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Обзор 3D-печати изделий из магнитных материалов: виды, применение, достижения и проблемы

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Аннотация. 3D-печать, или аддитивное производство (АП), – это активно развивающаяся область техники, позволяющая изготавливать уникальные изделия практически любой сложной формы, которую зачастую невозможно получить традиционными технологиями. В настоящее время помимо работ с изделиями из полимерных и металлических конструкционных материалов востребованной также становится 3D-печать изделий из функциональных материалов. В данном обзоре представлен анализ литературных данных по 3D-печати изделий из магнитных материалов. Кратко рассмотрены основные технологии АП – фотополимеризация в ванне, селективное лазерное спекание, струйное нанесение связующего, моделирование методом наплавления, прямое написание чернилами, электронно-лучевая плавка, прямой подвод энергии и материала, синтез на подложке с помощью лазера, а также используемые в АП магнитные материалы – магнитотвердые сплавы Nd–Fe–B и Sm–Co, магнитотвердые и магнитомягкие ферриты, магнитомягкие сплавы типа пермаллоев и электротехнических сталей. Показано, что на данный момент материалы, изготовленные методами 3D-печати, пока уступают по своим свойствам аналогичным материалам, полученным более традиционными методами, однако основные преимущества 3D-печати – создание единичных изделий сложной формы и сокращение отходов материала, при этом ведутся работы по улучшению комплекса свойств. В некоторых случаях, например при использовании металл-полимерных композиций, магнитные характеристики 3D-изделий из них в целом уже сопоставимы с традиционными аналогами. В обзоре приведены основные направления применения 3D-печати магнитных изделий – в частности, показано, что весьма перспективно изготовление мягких роботов с быстрым откликом и высокой степенью свободы, а также магнитов с оптимизированной топологией, позволяющих генерировать магнитное поле с высокой степенью однородности. Также представлены основные проблемы 3D-печати магнитных изделий и возможные способы их решения.

Ключевые слова: 3D-печать, аддитивное производство, аддитивные технологии, магнитные материалы

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Introduction

Magnetic materials are capable of generating their own magnetic fields and are widely used in various electrical devices [1–3], such as generators, transformers, magnetic recording systems, and other units with specific geometries and architectures. Traditional methods for manufacturing such products are limited to simple shapes, requiring expensive tools and sophisticated post-processing. This pushes up the costs of low-volume production of unique items and leads to considerable waste. Consequently, an increasing number of studies are devoted to the development of new technologies, including 3D printing.

3D printing enables the creation of arbitrarily-shaped structures with complex geometries using a variety of materials, including polymers [4; 5], metals [6–8], ceramics [9–11], composites [12–14], etc. This technology allows for reduced production time, lowered costs, controlled shapes, printing with multiple materials, and the production of structures that were previously impossible to obtain using traditional methods. The capabilities of 3D printing technology offer tremendous opportunities for manufacturing magnetic materials with irregular shapes, simultaneously reducing waste and enabling the creation of unique products unattainable through traditional methods. Further studies on materials and processes are required to fully explore the potential of 3D printing in manufacturing magnetic materials.

The aim of this paper is to review published works pertaining to the additive manufacturing of magnetic materials. It will specifically explore the 3D printing technologies employed for this purpose, the application scope of materials produced through this method, the potential and accomplishments of additive technologies in this domain, and finally, it will address current challenges and the prospects for their resolution.

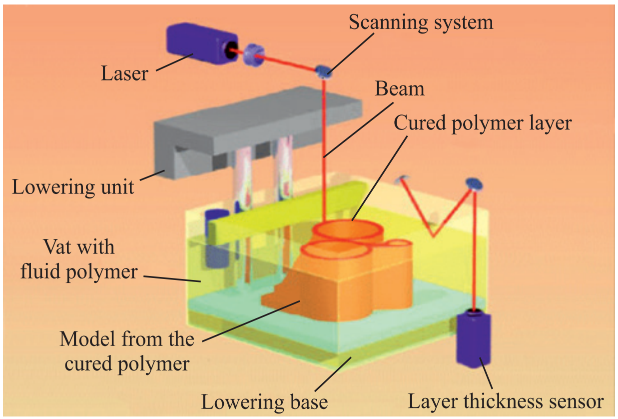
1. 3D printing technologies for manufacturing magnetic materials

A variety of technologies and materials are employed in the additive manufacturing of magnetic materials using 3D printing. Some of these techniques are discussed below.

Vat photopolimerization [15; 16] (Fig. 1, *a*) is a 3D printing technology that uses liquid polymers as initial materials along with a laser, projector, or liquid crystal display as a radiation source.

Stereolithography apparatus (SLA) technology operates by using a laser to illuminate photopolymer resin in the printer vat through point-by-point scanning. The laser beam targets the vat's bottom and, via mirror galvanometers, illuminates specific regions based on the developed 3D computer model of the product. This process forms a cured layer corresponding to the specified cross-section of the model. The platform then rises by the thickness of one layer, and the procedure repeats until the product is fully printed.

Digital light processing (DLP) technology [17] employs projectors to solidify photopolymer resin into three-dimensional objects. It simultaneously exposes the entire resin layer to optical range radiation, curing the entire layer with a single exposure, eliminating the need for scanning procedures. Digital micromirror devices (DMD), consisting of thousands of micro-



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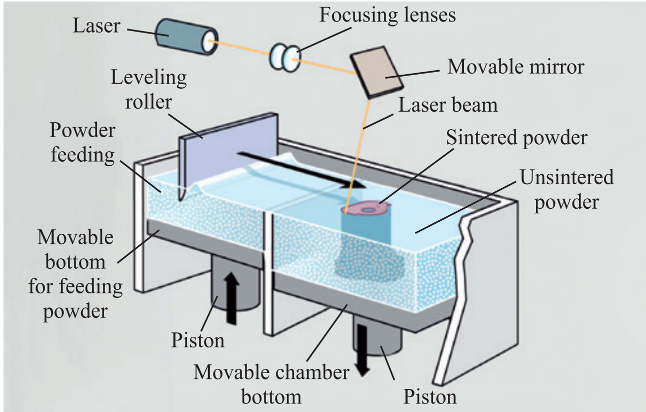

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Fig. 1. Vat photopolymerization method [21] (***a***) and SLS method [22] (***b***)

Рис. 1. Метод фотополимеризации в ванне [21] (***a***) и метод СЛС [22] (***b***)

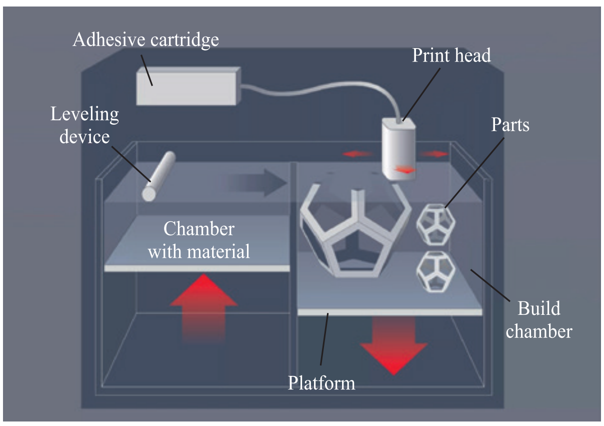
mirrors, control the reflection of light onto the resin surface, allowing the creation of images using pixels and voxels similar to conventional 2D or 3D cameras.

Photopolymerization can also be accomplished using a liquid crystal display (LCD) [18–20]. LCD printers, unlike the projection method, lack mirrors and instead employ powerful LCD panels. LEDs shine light onto the model, with the LCD panel blocking light in regions where photopolymer solidification is not needed. Only the necessary regions permit light to pass through onto the finished part. This approach simplifies the printing process, eliminating the need for mirrors or galvanometers. DLP and LCD technologies expedite the printing process, although the achievable level of detail is slightly lower compared to SLA.

Vat photopolymerization is known for its high accuracy and excellent feature detail, making it a preferred choice for manufacturing small complex parts, prototypes, and models. In this method, magnetic materials are obtained using magnetic fluid or ink.

Selective laser sintering (SLS) [15; 12–24] (Fig. 1, *b*) is a method that employs a laser to sinter powder. Unlike the vat photopolymerization method, SLS uses powders from specialized reservoir instead of liquid materials. The laser sinters the powder, forming a solid surface that corresponds to the specified cross-section based on the pre-designed 3D model. In the manufacturing of magnetic products via the SLS method, magnetic powders are used as the feedstock materials.

Binder jetting (BJ) [25–29] (Fig. 2, *a*) is an additive manufacturing process that involves depositing a liquid binder onto a layer of powder to selectively bind its particles. The powder layer is then densified,



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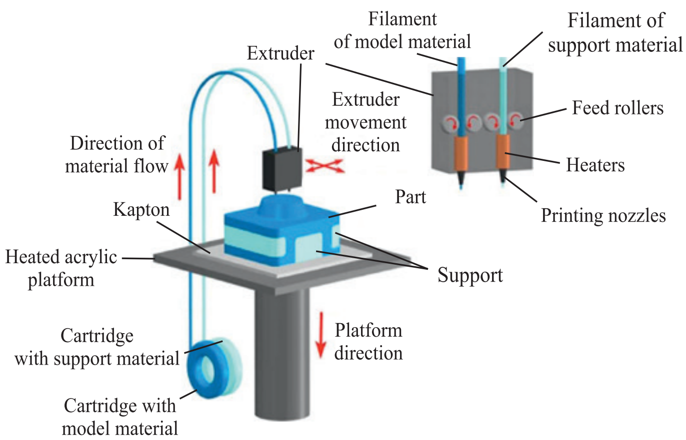

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Fig. 2. BJ method [33] (***a***) and FDM method [34] (***b***)

Рис. 2. Методы BJ [33] (***a***) и FDM [34] (***b***)

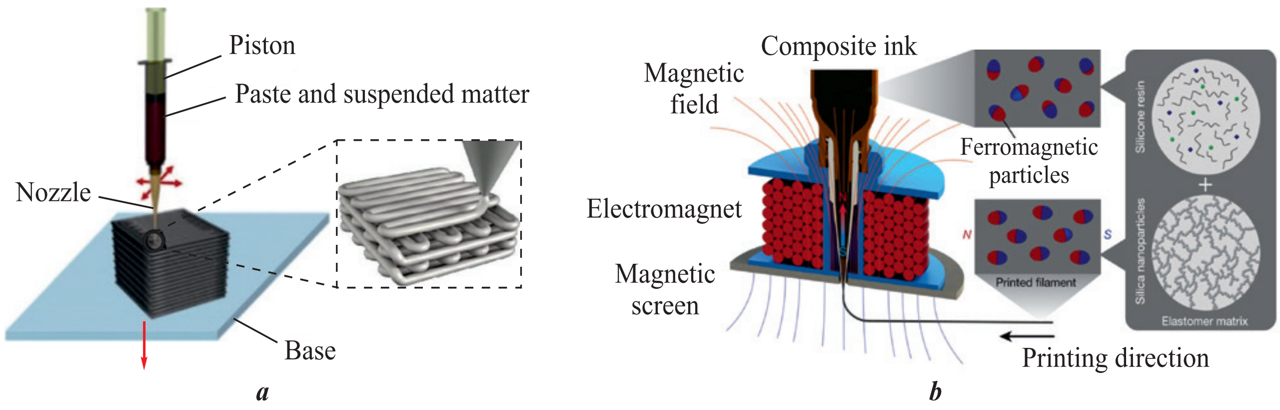

Fig. 3. DIW technique [32] (***a***) and magnetic field-assisted DIW technique [32] (***b***)

Рис. 3. Технология DIW [32] (***a***) и технология DIW с приложенным магнитным полем [32] (***b***)

and the process is repeated layer by layer until the part is fully fabricated. The unbound powder is removed, leaving the fabricated part behind. In order to print magnet materials by this method, magnetic particles are mixed with a binder during the printing process.

Fused deposition modeling (FDM) [29; 30] (Fig. 2, *b*) is a type of 3D printing based on depositing plastic material, usually thermoplastic polymers, onto existing layers. The filament is fed into a heated nozzle where it melts and is deposited onto the assembly platform in the exact order determined by the 3D model, thus creating layers of material that cool and solidify to form a part of the desired shape. Special composite filaments containing magnetic particles are used to manufacture magnetic materials.

Direct ink writing (DIW) [31; 32] (Fig. 3) represents one of the 3D printing techniques capable of producing intricate structures with exceptional accuracy and detailed features. The DIW method utilizes materials in the form of liquid paste (Fig. 3, *a*), that is subsequently solidified during post-printing. The solidification occurs either through water evaporation, in the case of a water-based binder, or via polymerization induced by exposure to high temperatures around 100 °C or a UV source. Various methodologies exist for governing the shape and properties of the printed materials, one of which involves the application of a magnetic field (Fig. 3, *b*). Employing a magnetic field allows for the deliberate orientation of material particles, enhancing magnetic properties and facilitating precise control over the shape of the printed products.

Electron beam melting (EBM) (Fig. 4, *a*) [25; 32; 35; 36] is a printing method that utilizes an electron beam to fuse metal powders into a three-dimensional part. In the EBM process, an electron beam is generated within a vacuum chamber and directed at the powder

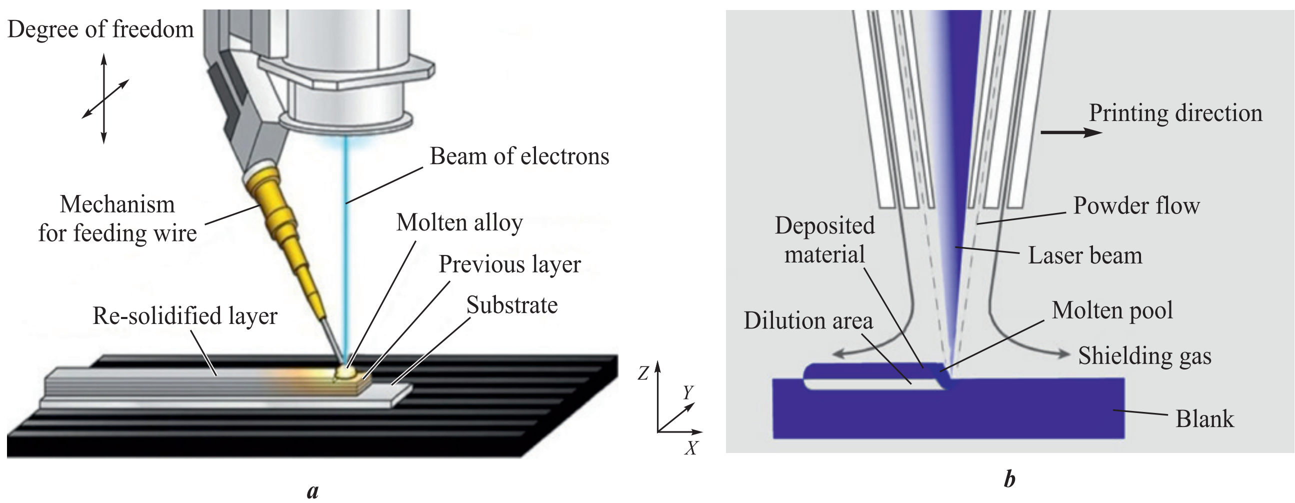

Fig. 4. EBM method [37] (***a***) and DED method [38] (***b***)

Рис. 4. Методы EBM [37] (***a***) и DED [38] (***b***) bed, causing the powder to melt. Metal parts are fabricated using this method. Powders containing magnetic particles are employed to create magnetic materials.

Directed energy deposition (DED) (Fig. 4, *b*) [32; 39; 40] is a printing method that employs a laser or plasma to fuse metal powders and create three-dimensional parts. In the DED process, the material is heated until it begins to melt, and its controlled flow is fused with the layer below. This printing method is well-suited for fabricating parts made of metal and ceramics. In order to produce magnetic materials using this method, powders containing magnetic particles are used as feedstock materials.

Laser powder bed fusion (L-PBF) [15; 22; 32] (Fig. 5) is a technique similar to the SLS method. However, in this case, the laser is not utilized for sintering but for powder melting.

2. Overview of magnetic materials in additive manufacturing

Magnetic materials [42; 43] are commonly classified into two groups: hard and soft magnetic materials. This classification depends on the material's coercive force (H_c). Soft magnetic materials possess a coercive force lower than 4 kA/m, whereas hard magnetic materials have a coercive force higher than 4 kA/m. Soft magnetic materials are often employed in manufacturing transformer cores, magnetic shields, microwave devices, and so on, while hard magnetic materials find application in producing permanent magnets, various sensors, an so on.

2.1. Soft magnetic materials

Soft magnetic materials [42–44] possess the ability to magnetize and demagnetize easily. They exhibit low coercive force (H_c), resulting in lower losses associated with magnetization reversal. These materials are well-suited for applications requiring rapid changes in magnetic fields. Additionally, soft magnetic materials should often possess high saturation induction (B_s) and high magnetic permeability, even at high frequencies. They find usage in diverse devices such as electric motors [45; 46], transformers [47; 48], magnetic sensors [49], and magnetic shields [50; 51].

Permalloys [52; 53] constitute a group of iron- and nickel-based alloys with high magnetic permeability. They serve as the foundation for numerous parts in electrical equipment. Permalloys have widespread industrial applications, including the production of motors, generators, inductors, transformers, and other devices. Due to their magnetic properties, permalloys can be effectively employed in 3D printing to fabricate intricate magnetic structures. For example, in [52], 3D printing with L-PBF was utilized to directly manufacture permalloy magnetic shields based on Ni–Fe fiber-optic gyroscopes in spacecraft. Comparative evaluations of the soft magnetic properties of printed Ni–15Fe–5Mo permalloy, with and without annealing, demonstrated similarity to traditionally processed permalloy parts, indicating the feasibility and applicability of the L-PBF method.

Fe–Si electrical steels (with varying proportions of iron and silicon, e.g., 6.9 % Si) [54] exhibit high magnetic permeability, low coercive force, and high

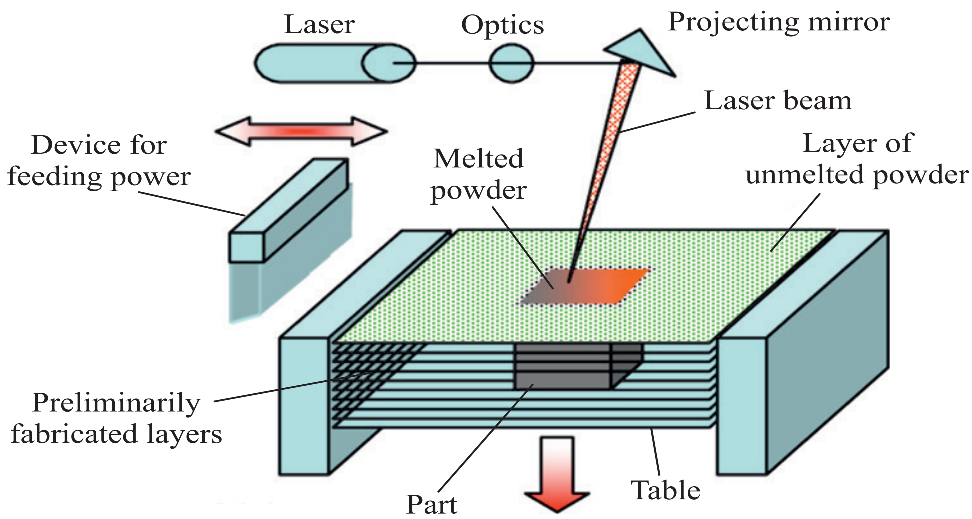

Fig. 5. L-PBF technique [41]

Рис. 5. Метод L-PBF [41]

electrical conductivity. These characteristics make them suitable for diverse fields such as electronics, automotive, and microelectronics. The L-PBF method in additive manufacturing can produce magnetic components like toroids, transformer cores, magnetic conductors, and other elements using these alloys [54].

Soft magnetic ferrites (such as $NiFe_2O_4$, Fe_3O_4, Ni–Zn and Ni–Zn–Cu ferrites) are used in manufacturing transformer cores, elements of microwave devices, and as magnetic fillers for producing soft robots and manipulators.

2.2. Hard magnetic materials

Hard magnetic materials [32; 55–59] retain a strong magnetic field even without an external magnetic force and are commonly used in manufacturing permanent magnets. These materials are challenging to magnetize but can retain their magnetization after the external magnetic field is removed. Essential characteristics for such materials include high values of H_c, B_r and maximum magnetic energy product $(BH)_{max}$. They find applications in producing items requiring a constant strong magnetic field, such as motors, generators, magnetic storage devices, and various sensor types. Common materials utilized for fabricating permanent magnets include alloys based on the Nd–Fe–B and Sm–Co systems, along with hard magnetic ferrites.

Nd–Fe–B magnets [60–62] are known for their exceptional magnetic performance and possess a high energy density, enabling the generation of intense magnetic fields. These magnets are highly sought after in electronics, electromechanics, and medical equipment. Conventionally, magnets based on the Nd–Fe–B system are manufactured by sintering a blank pressed from initial powder, followed by infiltration with a low-fusible alloy based on the Pr–Cu system to enhance coercivity. In [63], the authors proposed applying the L-PBF method to a mixture of Nd–Fe–B powder and eutectic alloy powder $(Pr_{0.5}Nd_{0.5})_3(Cu_{0.25}Co_{0.75})$ to obtain a magnet with $Nd_2Fe_{14}B$ magnetic grains and a non-magnetic intergrain layer in a single manufacturing operation.

However, a distinctive feature of 3D printing using metallic materials, especially Nd–Fe–B magnetic alloys, is porosity. This arises due to both insufficient injected radiation energy causing lack-of-fusion zones and excessive energy leading to intense metal evaporation in the laser beam zone. By varying laser power and scanning speed using L-PBF technology, the authors [64] identified optimal modes to ensure the stability of the Nd–Fe–B-based alloy melting process and obtain high-quality fused track for competitive permanent magnet fabrication.

The Nd–Fe–B-based magnets produced by metallic 3D printing methods are also prone to cracking and brittleness. In [65], the double scanning method was proposed, involving scanning each layer twice – initially with full laser power and then with half the power. This approach, involving partial remelting of the already deposited layer, resulted in denser samples with fewer defects in the form of pores and cracks, thus preventing their destruction when separated from the substrate.

Polymer-bonded magnets [66; 67] consist of polymers infused with magnetic particles, typically ferrites (such as $SrFe_{12}O_{19}$, $BaFe_{12}O_{19}$, $CoFe_2O_4$). While they possess lower energy compared to traditional sintered iron, nickel, or cobalt-based magnets, polymer-bonded magnets serve purposes where a lightweight and flexible magnetic solution is required. Moreover, they are relatively cost-effective and easy to manufacture. The utilization of 3D printing for producing ferrite-based magnets offers numerous advantages. It allows the creation of magnets in diverse sizes, shapes, and intricate geometries that might be inaccessible via traditional methods.

A prevalent technique for fabricating ferrite-based magnets using 3D printing involves extruding the material while applying an external magnetic field. During this process, molten plastic is dispensed through a nozzle onto a special platform, and an external magnetic field – created using a permanent magnet or a current-carrying coil – is directed at the composite of polymer and magnetic particles. This field aligns the magnetic particles in the polymer, resulting in an anisotropic magnet when the polymer cools and solidifies.

These magnets find widespread applications in work surfaces, storage devices, magnetic toys, and can even be customized into specific shapes like logos.

Currently, polymer-bonded magnets [68–70] are gaining attention in industries due to their comparable magnetic properties (in contrast to traditional pressing and injection molding methods), mold flexibility, low cost, and acceptable mechanical properties [71; 72].

The manufacturing of magnets has shifted from traditional pressing and injection molding techniques to the widespread utilization of 3D printing methods. An illustrative instance is the application of the BJ method, used to 3D print isotropic magnets based on polymer-bonded Nd–Fe–B. These magnets were shaped using initial materials of approximately 70 μm particles [26]. Upon completion of the printing process, the resulting green model underwent curing at temperatures ranging from 100 to 150 °C. Subsequently, the surface underwent infiltration with urethane resin, achieving a magnet density of 3.47 g/cm^3. This density corresponds to 46 vol. % of the Nd–Fe–B density (7.6 g/cm^3). It's noteworthy that the residual induction of the magnet samples produced by binder jetting, reaching approximately 0.3 T, aligns closely with residual induction values of 0.5 and 0.65 T typically achieved in standard isotropic magnets through conventional pressing and injection molding methods [26]. Furthermore, this approach enables precise control of the magnetic characteristics during the printing process, leading to maximum efficiency gains.

Sm–Co magnets [73] possess notably high coercive properties, trailing only behind NdFeB-based magnets in terms of their characteristics. They prove advantageous in 3D printing applications, particularly in scenarios requiring high-temperature resistance. These magnets, based on the Sm–Co system, often consist of multiple components, incorporating elements such as Fe, Cu, and Zr. Notably, they exhibit a high energy density, exceptional temperature stability, and resilience to mechanical stresses. These distinctive traits render Sm–Co magnets indispensable across various industrial fields, spanning from medical devices to electronics and the automotive industry.

However, the conventional manufacturing process for Sm–Co magnets is notably expensive and labor-intensive, thereby posing challenges for smaller manufacturers to affordably engage in production. This issue finds a potential solution through the application of 3D printing technology. Employing 3D printing for the fabrication of Sm–Co magnets offers a significant advantage in cost reduction, particularly when producing magnets in smaller batches.

Despite its numerous advantages, utilizing 3D printing techniques like L-PBF for fabricating Sm–Co magnets presents certain drawbacks. Notably, the magnets produced through this method often exhibit relatively low mechanical strength, potentially limiting their application in specific sectors, particularly within aviation and marine transportation industries. Nevertheless, the realm of 3D printing Sm–Co alloys holds immense promise and signifies a compelling avenue for the future development of magnetic material production. The prospect of reduced manufacturing costs while maintaining quality and productivity, alongside the capacity to fabricate more intricate products, positions the 3D printing of Sm–Co magnets as a prospective mainstream industrial method [74].

Hard ferrites [75; 76], also referred to as ceramic or ferrite magnets, represent a class of permanent magnets composed of iron oxide and ceramics ($BaFe_{12}O_{19}$, $SrFe_{12}O_{19}$, $MnZnFe_2O_4$) [77].

Despite their relatively modest magnetic properties, hard ferrite ceramic materials boast exceptional resistance to corrosion and mechanical impacts, rendering them the most cost-effective type of magnetic materials available. They are widely utilized in manufacturing of electronic devices, magnetic systems, motors, transformers, and various other equipment.

Typically, the production process for hard ferrite ceramic materials involves blending corresponding powders, subjecting them to pressure, and subsequent sintering at elevated temperatures. However, with the advent and advancement of 3D printing technologies, ferritic components can now be fabricated using innovative methods such as the DIW technique [77]. This technological approach allows for the adjustment of their magnetic properties by varying the ratio of magnetic iron oxide and incorporating additional magnetic metals.

While hard ferrite ceramic materials possess inferior magnetic properties compared to other types of magnets such as Nd–Fe–B and Sm–Co, their superior stability and versatility make them a compelling option for a diverse array of applications across various fields.

3. Application scope of 3D printing with magnetic materials

3D printing has transformed the manufacturing industry, facilitating the creation of intricate shapes and designs previously unattainable through conventional manufacturing methods. When combined with magnetic materials, 3D printing technology opens doors to a wide array of innovative products.

3.1. Magnetic sensors

Magnetic materials find extensive use in the production of sensors. These sensors serve various purposes, including determining the position of moving objects, measuring the speed of rotating objects, and detecting the presence of metal objects. Utilization of 3D printing technology allows for the production of sensors with intricate shapes and precise dimensions, customizable to meet specific requirements. Certain applications, such as medical diagnostics, necessitate irregularly shaped sensors, enabling insertion into the body to monitor indicators such as temperature, blood pressure, and blood oxygen levels. Magnetic sensors can be manufactured using FDM technology [68; 78; 79].

3.2. Magnetic drives

Magnetic drives utilize the interaction between magnetic fields and magnetic materials to generate motion. They find widespread applications, particularly in robotics, automation, and the automotive industry. 3D printing technologies such as SLA and FDM [80; 81] enable the production of intricately designed magnetic drives [82], tailored to specific requirements. Magnetic drives created through 3D printing exhibit advanced features [83] and enhanced efficiency compared to their traditional counterparts. For instance, a publication [83] details the printing of a magnet with optimized topology via the FDM process. This production method offers advantages such as rapid and cost-effective fabrication, increased distortion power factor, and high power output. Optimizing the magnet's topology allows for the creation of magnets generating a homogeneous magnetic field, crucial in applications such as nuclear magnetic resonance, magnetometers, sensors, and magnetic traps, among others. Additive technologies, particularly FDM, enable the replication of a pre-designed computer 3D model with remarkable accuracy.

3.3. Soft robots

Soft drives and robots represent a significant advancement in human-machine interaction, offering unrestricted movement due to their pliable nature [84]. Unlike conventional rigid robots, soft robots typically utilize gels [85; 86], elastomers [87], and other flexible materials, allowing them to adapt to their surroundings [88]. Furthermore, integrating magnetic particles into the polymer matrix [89; 90] or applying magnetic coatings onto polymer frameworks [91; 92] enables these soft robots to function within magnetic fields. However, achieving multiple functionalities without intricate geometry remains challenging [93; 94]. 3D printing plays a pivotal role in producing complex designs using multiple materials. For example, studies detailed in papers [95; 96] highlight the creation of a soft worm-like robot through SLA technology. This robot, comprised of composites involving magnetic particles and polymer, demonstrates both linear and rotational motion (see Fig. 6) [95]. This magnetically driven robot shows promise, particularly in controlled medicine delivery [32].

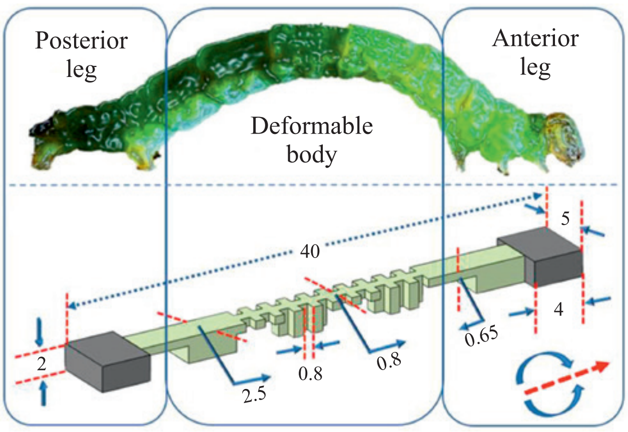

Fig. 6. Soft robot structure [95]

Рис. 6. Конструкция мягкого робота [95]

The evolution of 3D printing technologies has expanded horizons for manufacturing magnetic materials and related products. The ability to fabricate parts with advanced features and increased efficiency, owing to complex shapes and high accuracy, showcases the potential of 3D printing in this field. Magnetic materials produced via 3D printing find applications across various sectors – from sensors and drives to medical devices and data storage systems. As 3D printing continues to advance, more innovative uses of magnetic materials are anticipated in the future.

4. Prospects for the development of 3D printing with magnetic materials

While modern 3D printing offers numerous advantages, certain inherent features pose challenges in creating magnetic materials. The key current issues and potential solutions associated with 3D printing of magnetic materials are listed below [32].

4.1. Low magnetic properties

3D-printed magnetic materials often exhibit lower magnetic properties compared to traditionally manufactured ones. This discrepancy arises due to the inherent porosity in materials produced through 3D printing, resulting in slightly reduced material density and subsequently lower magnetic performance.

One potential solution involves the development of improved magnetic powders and further optimization of technological parameters in the 3D printing process.

4.2. Limited accuracy

Another characteristic challenge in 3D printing magnetic materials is the limited accuracy of the printing process. Despite significant advancements in accuracy and surface quality, 3D printing still falls short compared to traditional methods like CNC machining. This limitation becomes critical when intricate micro-sized parts from magnetic materials are necessary. Minor alterations in the geometry of a printed part can substantially impact the material's magnetic properties, potentially restricting its utility in specific applications.

Selecting a 3D printing method based on desired surface quality and detail, with minimal post-processing, could mitigate this issue to some extent.

4.3. Requirements for post-processing

A notable challenge in 3D printing magnetic materials is the necessity for post-processing to attain the desired magnetic properties. This often involves subsequent heat treatments and mechanical adjustments, particularly for enhancing surface quality. However, it's worth noting that traditional methods also frequently require substantial post-processing.

4.4. Limited scalability

One of the significant unresolved challenges in 3D printing magnetic materials pertains to the limited scalability of the process. Despite its flexibility and customization capabilities, 3D printing is currently unable to match the scale or speed of traditional manufacturing technologies.

While 3D printing excels in small batch production and prototyping, it might not be suitable for large-scale manufacturing due to its restricted scalability. Additionally, the limited range of available materials and the need for post-processing can further hinder the scalability of 3D printing for magnetic materials. Nonetheless, emerging technologies like *Big Area Additive Manufacturing* (BAAM) and *Wire Arc Additive Manufacturing* (WAAM) [97] are starting to enable the printing of virtually unlimited sizes, potentially addressing this limitation [97].

Conclusion

In conclusion, the utilization of 3D printing for magnetic materials holds the potential to transform numerous industries by facilitating the creation of intricate designs with complex geometries previously unachievable through conventional manufacturing methods. The combination of 3D printing with magnetism integration presents remarkable possibilities for manipulating and controlling soft robots and drives, particularly in highly demanding environments such as targeted medicine delivery within the body. Nevertheless, several challenges currently impede the seamless implementation of 3D printing for magnetic materials, including lower magnetic properties, limited printing accuracy, post-processing requirements, and scalability limitations. Despite these obstacles, the advancement of 3D printing technology for magnetic materials remains an extremely promising area of research. Overcoming these challenges could unlock even greater opportunities in the future, fostering innovation and opening doors to new applications and advancements across various industries.

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