DOI: 10.54254/2755-2721/2025.GL27143

Research Progress of Volumetric Additive Manufacturing

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Abstract. Volumetric Additive Manufacturing (VAM) is a new additive manufacturing (AM) technology. As a layer less manufacturing technique, VAM offers faster printing speeds, no support requirements, and greater design freedom compared to traditional AM. In recent years, VAM has made significant progress in printing equipment improvements and material diversity. This article reviews the technological development of VAM from three perspectives: equipment, manufacturing processes, and materials. It evaluates and analyzes the status of each dimension and compares the technologies and research results in each. VAM's printing equipment and manufacturing processes have been improved in terms of exposure mechanisms and light projection efficiency, resulting in the development of automated exposure AM and full-scale tomography volumetric AM. Regarding printing materials, more biomedical materials are now being used in VAM, and VAM technology can process living cells and cell-laden materials. These advancements not only demonstrate the immense potential of VAM in revolutionizing manufacturing paradigms but also open up new possibilities for applications in regenerative medicine and personalized healthcare.

Keywords: Volumetric additive manufacturing, additive manufacturing, Tomographic volumetric additive manufacturing

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, can process more complex parts and provide greater freedom in mechanical design compared to traditional subtractive manufacturing. It is now widely used in aerospace, automotive manufacturing, biomedicine and other fields. Volumetric Additive Manufacturing (VAM) is a new type of additive manufacturing technology. In 2019, Brett et al. developed the computed axial lithography (CAL) method [1]. Instead of relying on traditional layered printing and support, it superimposes 2D optical images onto the material at multiple angles, selectively solidifies high-viscosity fluids within a limited volume, and completes the generation of objects in one go. Compared with traditional additive manufacturing, VAM allows for higher geometric freedom and significantly improves printing speed [2]. In recent years, in the field of VAM printing equipment, Antony et al. developed Automatic Exposure Volumetric Additive Manufacturing (AE-VAM), a technology that improves VAM exposure mechanisms by adopting automated exposure, eliminating the need for manual control. Andreas et al. developed Holographic tomographic volumetric additive manufacturing in 2025, significantly improving the light projection efficiency of VAM printing. Ribin et al. designed a VAM printing device in 2022 that utilizes

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tomographic reconstruction, significantly improving VAM printing accuracy by optimizing the projection required for target object aggregation.

This study analyzes VAM material properties, commonly used materials, and emerging materials from three perspectives: materials used in VAM, VAM processes, and VAM printers. From the perspective of VAM processes, VAM is compared with traditional point-by-point and layer-by-layer printing. Three major VAM processes and their optimization are introduced, along with the development and current commercially available VAM printers. Preparing your paper

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2. Materials for volumetric additive manufacturing

2.1. Requirements for the properties of vam materials

2.1.1. Optical transparency

Since VAM prints by stimulating the entire volume with light at once rather than layer by layer, the materials used for VAM must have high optical transparency [3]. Therefore, the photoinitiator used in VAM must be at a low concentration, otherwise the light will decay exponentially according to the Beer–Lambert–Bouguer law. Ideally, the photoinitiator for VAM has a low extinction molar coefficient but a high polymerization yield. However, most photoinitiators are toxic and must be used at low concentrations in certain special printing situations to reduce toxicity, such as bioprinting [3].

2.1.2. Resin viscosity

In VAM, objects are not built layer by layer, and the resin does not need to flow during each printing step like in traditional additive manufacturing stereolithography (SLA), so VAM can use resins with higher viscosities. This allows VAM to use solvent-free formulations, which have higher monomer concentrations and polymerize faster, resulting in stronger objects [3]. However, VAM is not limited to printing with high-viscosity materials; when printing with low-viscosity materials, this can be achieved by shortening the printing time.

2.2. Commonly used materials for volumetric additive manufacturing

2.2.1. Acrylates

Acrylates were the first materials used in VAM because they are highly reactive, low-cost, and easy to use in commercial coatings and 3D printing applications. Acrylates are highly transparent, even in near-UV light, have adjustable mechanical properties, can polymerize rapidly, and propagate reactions initiated by free radicals in the photoinitiator. The commonly used photoinitiator for acrylates is Diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (TPO), and the wavelength of light is about 405 nm. Objects printed with acrylates have sufficient strength to maintain their shape, and while ensuring sufficient strength, they can also be made soft enough, so they can be used to print elastomers. Elastomers can be used in many industrial fields, for example, they can be used to make dental retainers and hearing aids [3]. Printing this material with VAM can diversify the design of

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elastomers, and VAM printing can provide more geometric freedom and increase the production speed.

2.2.2. Sintered materials

Sintered materials mainly refer to glass and ceramics. Glass and ceramics have excellent properties such as hardness, heat resistance, chemical resistance and inertness [3]. Glass has optical transparency and refractive index. However, due to its high mechanical strength and brittleness, traditional subtractive manufacturing technology finds it difficult to process such materials.

However, with the development of additive manufacturing, technical support has been provided for the manufacture of glass and ceramic products. Glass and ceramic manufacturing require high temperature or high pressure to obtain the required mechanical and chemical properties of the materials. Polymer-derived ceramics are obtained by pyrolyzing organic silicon polymers to prepare polymer-derived silicon-based objects, which are obtained by pyrolyzing these polymers into ceramic parts [3]. Although ceramics can be formed by mold shaping or heat-induced gelation, the use of photocurable materials can make ceramic molding with higher precision and greater flexibility. Kollep et al. developed an optically transparent resin using commercial polysiloxane and 1,4-butanediol diacrylate as crosslinkers and diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (TPO) as a photoinitiator.

Using VAM printing technology, polymer-derived ceramics can be printed. The crosslinker reduces printing time, and the resolution of the resulting printed green body is only 80 μm. After pyrolysis at 1000°C, a smooth surface ceramic part is obtained [3]. VAM has advantages for glass printing. Because there is no fluid movement in VAM, high solid loading and high viscosity precursor liquid can be printed in one go. As mentioned above, in VAM printing, the transparency of the material is a necessary condition for tomographic VAM. Therefore, the solid silica nanoparticles and liquid monomer binder of the particle-loaded precursor should have refractive index matching properties [3]. This strategy was used in the first demonstration of tomographic VAM printing of transparent glass [3], and complex structures, including periodic lattices and 3D branched microfluidic channels, were fabricated with a minimum feature size of only 50μm. The lens system showed a minimum Ra roughness of 6nm and had good optical performance [3].

2.3. Exploration of VAM materials in the field of biomanufacturing

Aside from the traditional manufacturing field, in the field of biomedical manufacturing, volumetric additive manufacturing technology has been designed to process living cells and cell-laden materials. These materials are usually in the form of hydrogels, which are aqueous networks composed of hydrophilic polymers that can embed cells and maintain their vitality and function. Cell-laden hydrogels are called bio-inks or bio-resins.

Biomanufacturing technology could control cells and bioactive molecules. Today, biomedical scientists are using it to design major functional tissues that simulate natural organs and biological systems. It is mainly used in living transplants in biomedicine, generating tissue models as substitutes in biomedical experimental research, and engineering living materials [3]. The bioprinting process needs to be carefully designed to avoid damaging cells during and after printing. Bernal et al. first proposed the concept of volumetric bioprinting (VBP), which generates cell-laden functional tissues in seconds through tomographic printing technology.

VBP is simply VAM used to manufacture cell-laden structures for tissue engineering and tissue modeling. As a photoresponsive bioresin component, gelatin methacryloyl (GelMA) was used in this

DOI: 10.54254/2755-2721/2025.GL27143

first study. Since then, the library of materials available for volumetric bioprinting has expanded rapidly. Gelatin is a biopolymer obtained by denaturing collagen and has been widely used as a biomaterial for tissue engineering and bioprinting. This is due to the material's good biocompatibility, controllable degradation properties, and its ability to promote cell adhesion and various cell functions. Bernal et al. developed a GelMA-based bioresin for volumetric bioprinting. In addition, a low-stiffness (compression modulus < 2 kPa) GelMA bioresin for VBP has also been optimized for culturing organoids [3].

3. Manufacturing processes for volumetric additive manufacturing

3.1. The difference between VAM process and traditional additive manufacturing process

Traditional additive manufacturing processes are divided into two types: point-by-point printing and layer-by-layer printing. VAM printing is very different from them. In point-by-point printing, printing starts from one point at any given time and proceeds in a construction order. Layer-by-layer printing goes a step further. This printing process places the entire layer under an energy source (usually ultraviolet light) to solidify the entire layer in each step. VAM is different. It represents a holistic idea that goes beyond the traditional point and layer process.

Unlike point-by-point printing and layer-by-layer printing, which divide the object into point-activated layers for step-by-step printing, VAM generates an energy dose distribution field (EDDF) in a specific medium. EDDF can be effectively represented as a set of 2D optical images to guide the desired 3D shape inside the medium. EDDF is generated based on the energy threshold of the photoinitiator used, and the specific part is formed by initiating and controlling polymerization of the photoinitiator [2]. Another major advantage of VAM is that no auxiliary materials or media need to be added during the printing process to complete the printing. VAM uses pre-assembled media that can be printed after being activated by the energy emitter. This eliminates the need to add additional material during the manufacturing process, which is in stark contrast to traditional additive manufacturing processes. For example, in some tank polymerization techniques, the build platform needs to be repeatedly immersed in a medium to produce the material layer by layer [2].

3.2. Three main VAM manufacturing processes

3.2.1. Additive light superposition

The first VAM system was developed by Shusteff et al. in 2017 and is called Additive Light Superposition. It can produce complex, non-periodic 3D parts in 10 seconds. The technology uses a resin with nonlinear polymerization initiation behavior as the printing material, superimposes three laser beams, divides the holographic 3D image into multiple 2D patterns and projects them onto the printing material to achieve the printing of the object. The threshold behavior of the photopolymer resin is utilized to limit the formation of the polymer under single laser exposure, and polymerization is completed only when the voxel is simultaneously exposed to the intersection of all three laser beams. [2].

3.2.2. Subtractive light superposition technology

In 2019, Van der Laan et al. proposed a new technology of light-reduction superposition, called dual-wavelength volume polymerization. This technology uses specific wavelengths of light to initiate and control the polymerization of resins. The light-reduction superposition method was

DOI: 10.54254/2755-2721/2025.GL27143

successfully achieved by using a combination of camphorquinone (CQ)/ethyl 4-(dimethylamino) benzoate (EDAB) as a photoinitiator and butyl nitrite as a photoinhibitor in the resin formulation [2]. The photoinitiator initiates polymerization through visible light, and the photoinitiator responds to near-ultraviolet wavelength light to limit polymer growth. EDDF is generated by two projectors, which convert the digital 3D model into a cross-section, and the projector projects light of different wavelengths onto the material, and the inhibitor and initiator react to combine to finally print the part.

3.2.3. Tomographic volumetric additive manufacturing

Tomographic volumetric additive manufacturing is the most widely used VAM method. Kelly et al. first proposed this method in 2019. Tomographic VAM transmits light into the resin tank from multiple angles in the form of a set of 2D images. First, the Radon algorithm is used to convert the 3D model into a set of 2D images, called "sinograms". These images represent the model from different angles, and the required 3D light intensity distribution is calculated by calculating these sinograms.

When these patterns are projected into the photosensitive resin through a light projector, the final part can be manufactured [2]. In 2021, Bhattacharya et al. improved the accuracy of energy dose calculation by improving the gradient descent based on the effective loss function, which is a new tomographic technology projection method to reduce the dose violation penalty of high-fidelity printing [4]. Rackson et al. proposed a simple and high-performance algebraic image computation method for tomographic volumetric additive manufacturing, called object space model optimization (OSMO), which significantly improved the accuracy of complex parts printed by tomographic volumetric additive manufacturing by improving the optical dose contrast between the printed target and the surrounding area without relying on high-precision optical and material accuracy [5].

3.3. Optimization of VAM manufacturing process

The volumetric light patterning of tomographic VAM has a disadvantage. The exposure window is small, and overexposure can lead to voxels outside the solidified part. Therefore, it is very important to control the exposure time for VAM. However, in most VAM printing, the exposure time is manually controlled, which is very complicated and prone to human errors. In 2025, Antony et al. developed an automatic exposure volumetric additive manufacturing technology (AE-VAM). This technology does not require the user to intervene in the printing process. It determines the exposure endpoint of each print that is independent of the rain geometry by monitoring the total scattered light signal of the imaging system during printing [6]. In addition, this method can achieve resin recycling. The printing quality will not be significantly reduced after at least 4 reuses. The system achieves very high repeatability and significant printing fidelity. The AE-VAM system is shown in Figure 6. The projector projects a set of images through a rotating light curing bottle. The LED above illuminates the resin. The camera records the sample image during the printing process. The light dose distribution absorbed by the resin will match the shape of the printed object. The AE-VAM system also outperforms conventional VAM printers in terms of printing speed. Compared to the fastest commercial printer (Form4, 492 seconds), the AE-VAM's standardized printing time is only about 40-55 seconds, which is about 10 times faster [6].

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4. Printing equipment for volumetric additive manufacturing

4.1. Structure of VAM printing equipment

The equipment required for VAM printing includes a light source, a light modulator with a projection system, and a rotating stage for photocuring resin. The light source can be a laser or an LED, and the wavelength of the light it emits must match the absorption spectrum of the photoinitiator used. LEDs are generally cheaper than lasers, but they have a higher divergence, which reduces resolution [3]. The light modulator is usually composed of a digital micromirror, which can display the calculated pattern. The printing process is carried out in a sealed vial, which reduces the possibility of contamination during the printing process. No refractive tank is required around the vial. This design simplifies the system because the refractive index of the immersion tank must be the same as that of the material, avoiding the time-consuming process of matching the tank characteristics when using a new material [7].

4.2. Commercial tomography VAM printers

The supply of commercial VAM printers is limited. The Tomolite v1.0 is a widely accepted commercial VAM printer that uses non-contact tomographic illumination technology to create biological systems from sensitive cells and biomaterials without compromising their viability [2][8]. The Tomolite v1.0 has a very fast printing speed, with a maximum rotation speed of more than 60° per second. Depending on the printed material and design, the printing time is typically between 30 seconds and 120 seconds. Centimeter-scale structures can be produced in tens of seconds. Due to the ultra-fast printing speed, the cells are exposed to air for a very short time, and the low photoinitiator content also significantly reduces cytotoxicity. The Tomolite printer can print human liver organoids in 15.5 seconds, with strong cell viability and a stock of more than 95% after 10 days [8].

4.3. Optimization direction of VAM printer

The accuracy of manufactured objects, printing cost and light projection efficiency of VAM printers are the main goals of optimizing VAM printing equipment. In 2022, Ribin et al. designed a VAM printer based on the concept of tomographic reconstruction. The optimized projection required for the target object aggregation was used to generate objects by adjusting the tree container rotation speed and projection rate. The printer can print centimeter-level objects in 30 seconds. The surface roughness of the object is extremely low, and the size deviation from its designed CAD model is less than 5% [9]. In terms of reducing printing costs, the AE-VAM printing system uses reusable resin materials for printing. This technology is very important for reducing the cost of VAM printing. Since the printing system does not need to align the projection coordinates with the reference coordinate system, it will not be affected by artifacts caused by debris in the resin. Therefore, it can adapt to larger exposure time changes when using reusable resin materials for printing. AE-VAM allows the resin material to be reused up to the fifth generation of resin. When the amount of resin is sufficient for printing requirements, the printing quality will not be affected when mixing resins after the fifth generation for printing. This technology greatly reduces the printing cost [6]. In terms of improving light projection efficiency, the holographic tomographic volumetric additive manufacturing developed by Andreas et al. in 2025 has greatly improved the light projection effect of VAM printing and has high flexibility. It can perform precise light control throughout the printing process. The technology can use a 40-mW light source in less than 1 minute to create a millimeter-

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scale 3D object with a negative feature of 31 μm in acrylic and scattering materials (such as hydrogels loaded with soft cells at a concentration of 0.5 million cells per milliliter) [10]. This technology uses a light engine (HoloVAM) that utilizes the phase characteristics of the light beam. By achieving 3D control of the light beam and effectively creating low-divergence projections, it can be printed in scattering materials to improve light projection efficiency.

5. Conclusion

Nowadays, after years of development, volumetric additive manufacturing has been increasingly used in various manufacturing fields, but it also faces many problems, such as exposure control, light projection efficiency, and printing cost. Compared with layer-by-layer 3D printing technology, tomographic VAM must reduce the contrast of the object exposure. The stricter exposure control requirements are contrary to the highly variable situation of the ideal exposure of VAM. The automatic exposure system achieves the goal of printing without user intervention through the printing progress measurement method and has also significantly improved the printing speed. However, this technology is only implemented and extensively characterized for a fixed resin formula AE-VAM and used in combination with similar acrylic resins. However, for other VAM printing materials, this automatic exposure technology has not been verified. In the future, to improve the overall technical level of VAM printing, it is necessary to study the control of automatic exposure in more materials. In addition, the emerging holographic tomographic VAM technology has greatly improved the light projection efficiency through holographic phase encoding technology. In the future, a five-lens projection system can be designed to improve the spatial resolution of tomographic VAM. To control the cost of VAM printing, researchers have already experimented with the fifth generation of reusable resins in the development of AE-VAM printing equipment. In the future, they can go a step further and conduct more research on reusable materials to enable the printing materials to be reused multiple times.

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