Stories From China

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3D Printing for Advanced Electrical Insulation: Recent Progress in China

3D printing is a manufacturing process to create three-dimensional objects directly from a computer designed model. The 3D-printed objects are fabricated by the gradual addition of point-wise, line-wise, or layer-wise material elements, making it also known as "additive manufacturing" [1]. Additive manufacturing technology was developed decades ago with Chuck Hull's invention of stereolithography in the 1980s. Due to its availability to improved performance, complex geometries, and simplified fabrication, additive manufacturing is now actively embraced by a variety of industrial sectors, e.g., automotive, aerospace, medical and dental care, education, art, culture, and so on. China has given great attention to the 3D printing technology. The Ministry of Industry and Information Technology and the National Development and Reform Commission have successively issued policy documents (in 2015, 2017, and 2020) to support the research and development of 3D printing. Moreover, 3D printing is also highlighted in the "Made in China 2025" program.

The application of 3D printing in the electrical power industry is also an emerging topic worldwide. Currently, various power system components have been 3D-printed for better product performance and higher fabrication efficiency, including electrical power fittings, substation buildings, battery electrodes, and downsized device models for engineering education [2]. Attention is also paid to the 3D printing of electrical insulation objects. However, most of the initial studies are based on generic, commercially available configurations, which cannot fully use the advantages of 3D printing. Fortunately, innovative progress in the 3D printing of advanced electric insulation was achieved by Chinese researchers and engineers, which can be categorized in the aspects of material, technique, and application.

Innovative 3D Printing Materials

The first progress is about the 3D printing materials. Generic printing materials usually have high dielectric loss, inadequate mechanical strength, and unsatisfactory thermal properties,

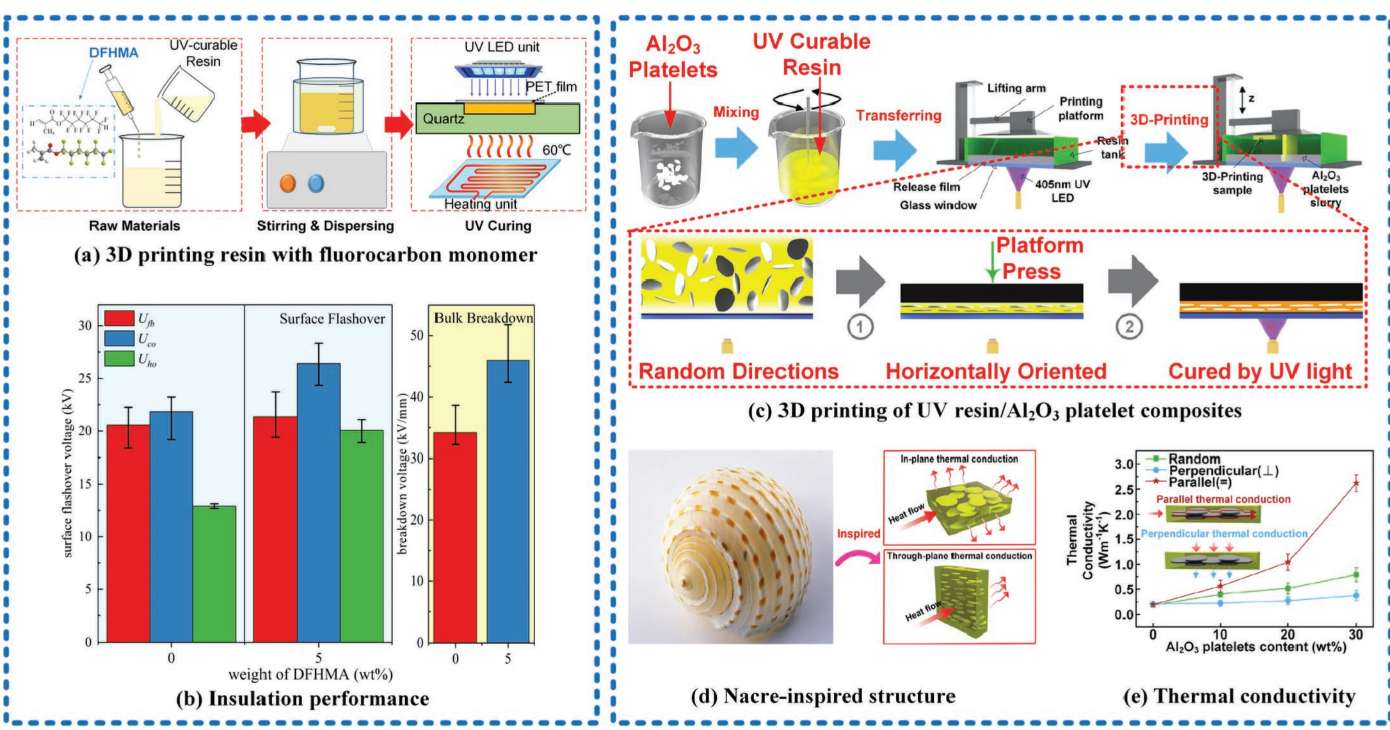

Figure 1. 3D printing materials with elevated properties. (a) and (b) are the fluorocarbon-modified 3D printing material (UV resin) [3]. (c) through (e) are the 3D printing composites with bioinspired structure and high thermal conductivity [5].

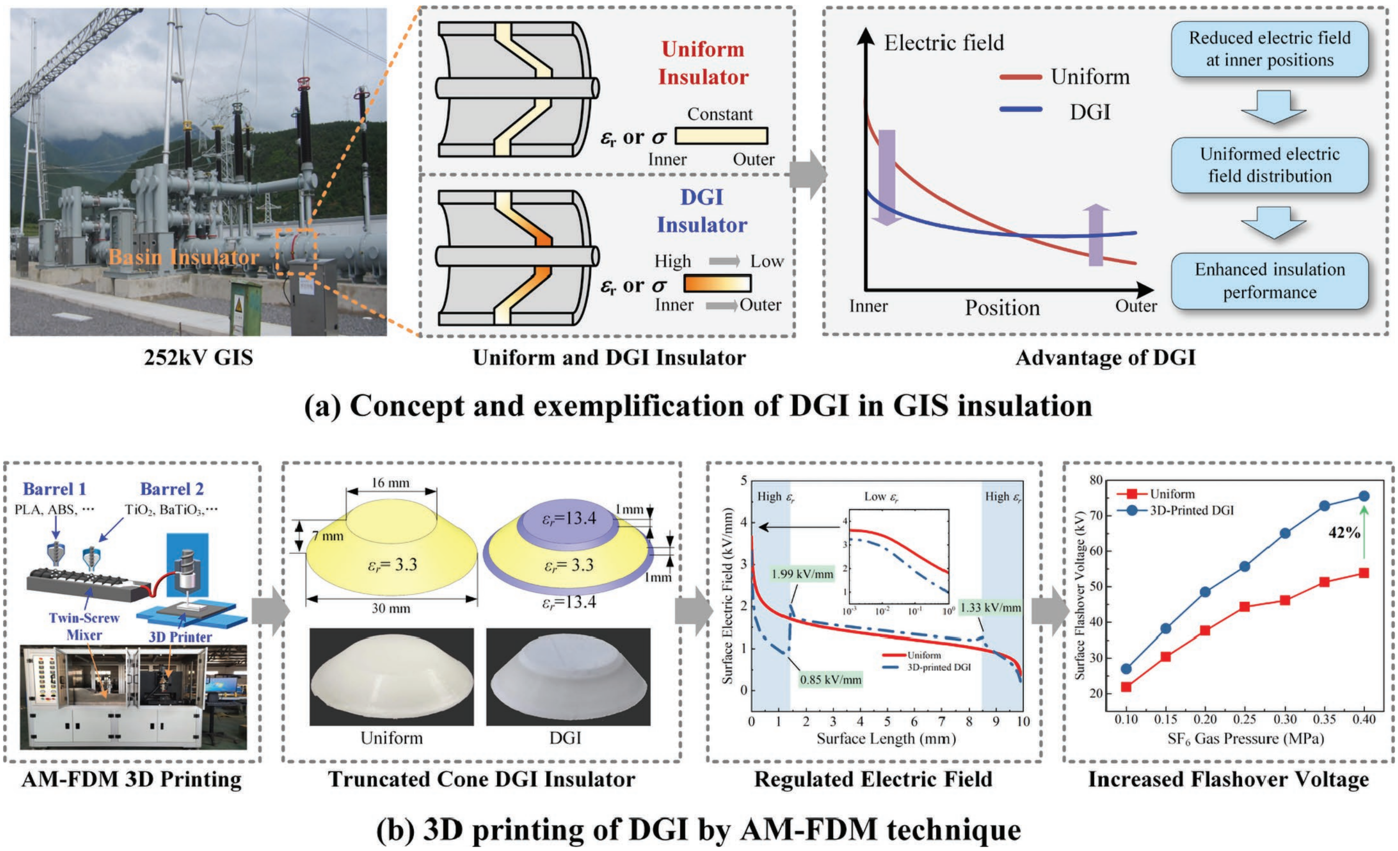

Figure 2. 3D printing of dielectrically graded insulation (DGI). The active-mixing fused deposition modeling (AM-FDM) description is from [12]. The photo of 252-kV gas-insulated switchgear (GIS) is provided by Shandong Taikai High Voltage Switchgear Co. Ltd.

restricting their use in electrical insulation. Recently, Zhang's group from Xi'an Jiaotong University [3] doped 5 wt% of fluorocarbon acrylate modifier (dodecafluoroheptyl methacrylate) into the photocurable, 3D printing material, which significantly increase the bulk breakdown strength (34.7%) and surface flashover voltage (21.1%) due to the introduction of electron trap sites, i.e., F atoms. Huang's group in Chongqing University [4] developed a dual-curing 3D printing material, in which reduced dielectric loss and increased impact strength is found. Another interesting research topic [5] is the 3D printing of bioinspired nacre-like insulation materials. The layer-by-layer formation process makes 2D Al_2O_3 platelets well-oriented in the UV resin and increases the thermal conductivity of 3D printing material 14 times. These studies confirm that when a proper modification strategy is used on the 3D printing material, the applicability of 3D printing in electrical insulation can be largely improved, and some novel insulation material (i.e., thermally conductive by electrically insulative) can be achieved (Figure 1).

Innovative 3D Printing Techniques

The progress in novel 3D printing techniques also facilitates the implementation of advanced insulation components. A promising example is the 3D printing of dielectrically graded insulation (DGI), which is also known as the electric insulation using functionally graded material. The distinctive feature of DGI is the nonuniform spatial distribution of electrical permittivity or conductivity (i.e., dielectric gradient), which offers the ability of electric field regulation inside or along the surface of solid insulators. Previous studies [6] have verified the effectiveness of DGI in enhancing the insulation performance, elevating the reliability and life-span of insulation devices [Figure 2(a)]. However, fabrication of DGI is challenging due to the complexity and difficulty in precisely building the dielectric gradient.

In 2015 Li et al. from Xi'an Jiaotong University [7] proposed that 3D printing can be used to build DGI and pointed out that the key issue in developing DGI-applicable 3D printing methods is the ability to change the dielectric parameters of each geometrical element (e.g., layers or voxels). Thereafter, two novel 3D printing techniques, including the active-mixing fused deposition modeling [8] and multi-material 3D printing with constraint sacrifice layer [9], were developed to build DGI using thermoplastic and UV curable materials, respectively. Based on the corresponding 3D printing device and customized control program, truncated cone DGI spacers were fabricated, which has significantly increased (42% maximum) surface flashover voltage [Figure 2(b)]. The above research progress indicates that 3D printing can become an effective approach for the realization of next-generation, high-performance insulation components, especially when complex outline geometry or internal structure is involved.

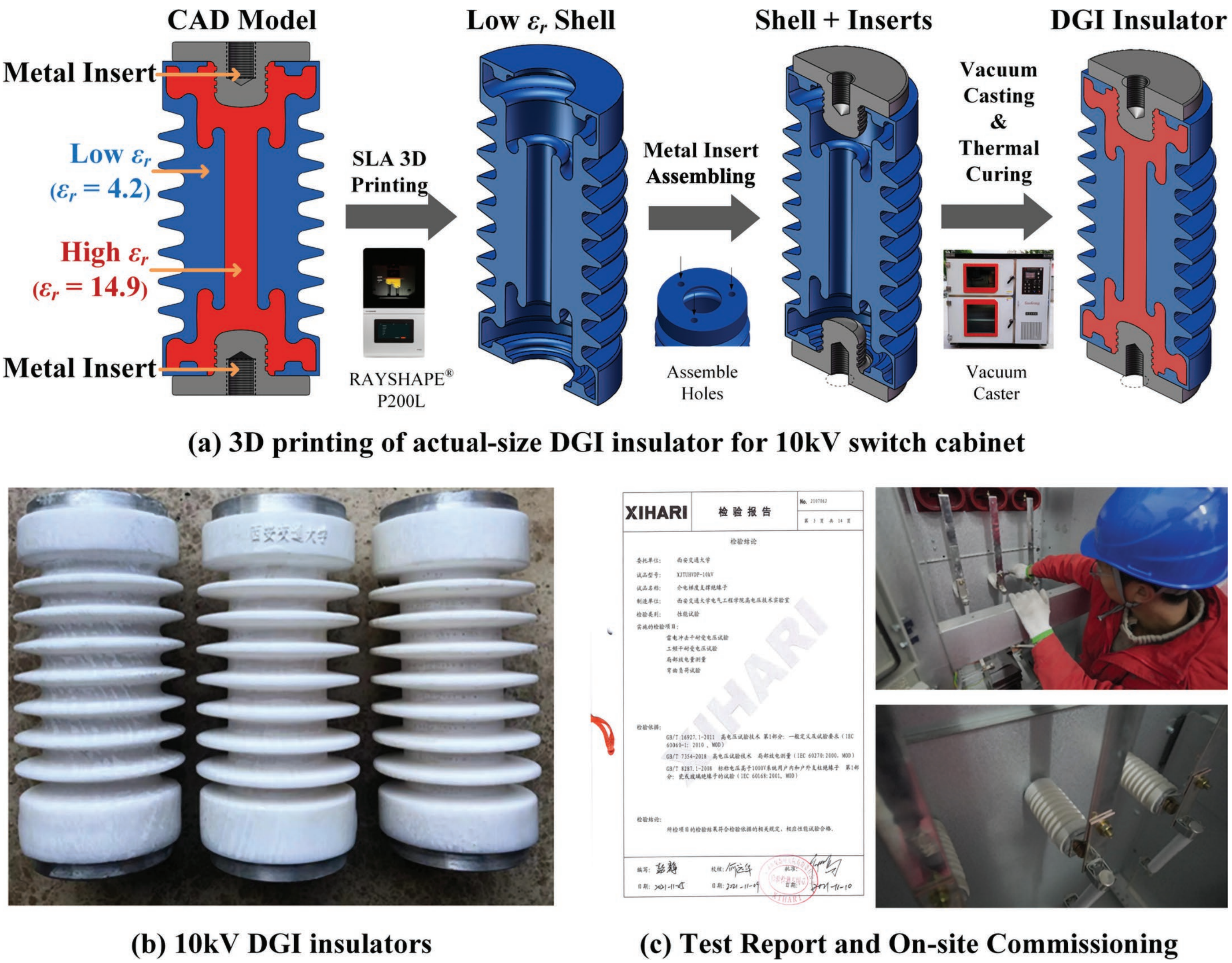

Figure 3. Fabrication and on-site commission of 10-kV dielectrically graded insulation (DGI) insulator.

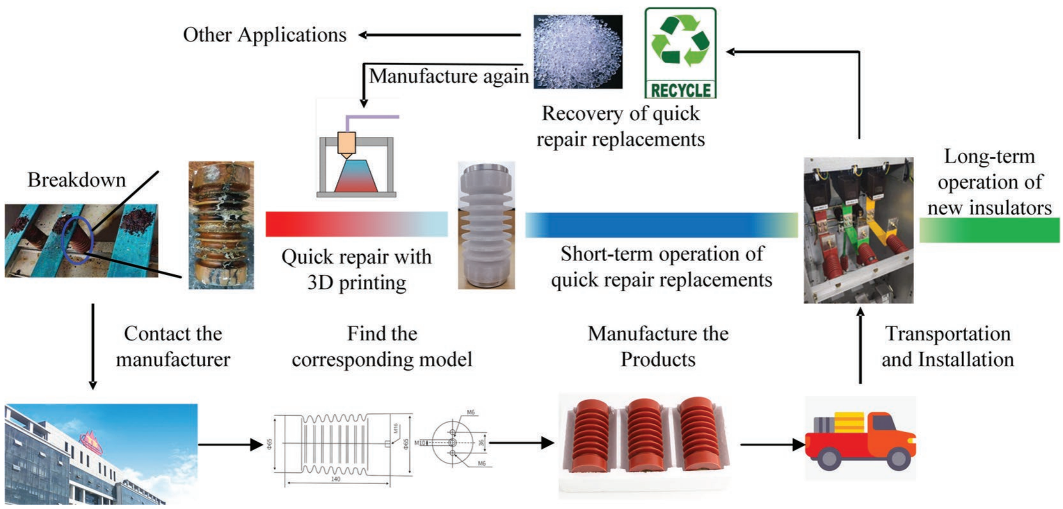

Figure 4. Quick repair of solid insulators assisted by 3D printing technology.

Innovative 3D Printing Applications

With the development of both materials and techniques, the application of 3D printed insulators is also realized in some most current studies. One is the application of a DGI support insulator developed for the switch cabinets in distribution networks (Figure 3). This insulator is made by a combination process of photocuring-based 3D printing and vacuum casting and has a three-region dielectric gradient as shown in Figure 3(a). The uniformity of electric field is improved by this permittivity gradient. Standardized test results according to DL/T 404 indicate that the 3D printed DGI insulator satisfies the requirements of industrial-grade 10-kV electric equipment. Moreover, the partial discharge inception voltage is increased by 17.5%. In November 2021, the on-site commissioning of the DGI insulator was conducted in a 10-kV switch cabinet in Anji, Zhejiang province, which has been in stable operation ever since.

Another application of a 3D printed insulator is as a 10-kV support insulator used for quick repair. The economic losses caused by insulation accidents are strongly dependent to the repair time, but the speed of repair is often limited by manufacturing and transportation in the absence of field replacements. In a report from Xi'an Jiaotong University [10], a 10-kV support insulator was built using a desktop 3D printing device and polycarbonate (PC) material. Experimental results show that the flashover voltage and partial discharge inception voltage of the 3D printed PC insulator were close to the epoxy control, and the total manufacturing period took only 1 to 2 days for the 3D printed PC insulator, which is much less than epoxy insulators because the time-consuming fabrication of casting molds is no longer necessary. This study is meaningful for reducing power black-out and economic loss caused by insulation accidents (Figure 4).

In summary, by continuous R&D from Chinese researchers and engineers, the material restrictions in the electrical insulation use of 3D printing can be overcome, and the advances in 3D printing techniques enable the implementation of conventionally unavailable insulation components (e.g., dielectrically graded insulation). All this progress leads to successful deployment of 3D printed support insulators in 10-kV on-site equipment, expanding the applicability of 3D printing technology and improving the comprehensive performance and fabrication efficiency of electrical insulation components.

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