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Progress in the Localization and Substitution of New Materials in Ultra-High Voltage (UHV) Equipment

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Abstract. Ultra-High Voltage (UHV) transmission technology, as a key method for global energy transmission, places higher demands on the performance of materials used in core equipment. This paper reviews the new materials employed in UHV equipment, including insulation materials, conductor materials, magnetic materials, and noise reduction materials. It analyzes the main characteristics, current research status, and limitations of each material, with a focus on the progress of domestic substitution for these materials. The aim of this paper is to provide a comprehensive reference for material development and equipment manufacturing, while proposing future directions to address the increasingly stringent service conditions and performance requirements of UHV equipment.

Keywords: Ultra-High Voltage Equipment; New Materials; Localization and Substitution; Insulation Materials; Conductor Materials; Magnetic Materials; Noise Reduction Materials

1. Introduction

With the rapid growth in energy demand, Ultra-High Voltage (UHV) transmission technology, with its large capacity and long-distance transmission capabilities, has become an indispensable part of modern power grid systems. The large-scale construction of UHV projects has made core equipment crucial. Despite the rapid development of China’s power transmission and transformation industry, the low level of localization of first-generation products of major technical equipment and the “hollowing out” of equipment have been significant obstacles to the transformation and upgrading of China’s equipment manufacturing industry. However, many key materials used in equipment manufacturing are heavily dependent on imports, particularly insulation, conductor, magnetic, and noise reduction materials [1-8]. To ensure the efficient and reliable operation of equipment, it is critical to develop new materials to increase the rate of localization. This paper provides a detailed analysis of the current applications, main characteristics, and limitations of each type of material, and discusses key directions for future research and development.

2. Progress and Challenges of Domestic Substitution of Materials

2.1 Insulating Materials

High-voltage insulation technology and devices are among the core factors limiting the development of power systems. The insulation materials used in high-voltage power equipment not only affect the operational stability of the equipment itself but also influence the overall safety of the high-voltage area where the equipment is located. According to incomplete statistics, more than half of equipment failures are directly or indirectly related to insufficient insulation levels. Polymer materials, known for their high molecular weight, ease of modification, and excellent comprehensive properties, are widely used in the field of insulation materials. By manufacturing and selecting more stable and reliable insulation materials, researchers aim to enhance the insulation level of high-voltage equipment, thereby improving its overall operational performance [9].

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The research and development trends of electrical insulation materials applied in the field of voltage insulation mainly focus on two aspects: (1) Achieving overall optimization of polymer composite materials through structural adjustments, interface optimization, and complex processing techniques. Special polymer materials tailored for specific working environments are gradually replacing traditional polymers that have been widely used [10]. (2) With the advancement of concepts and social ideals, non-toxic, harmless polymer materials that are recyclable or degradable are increasingly aligned with the vision of building a resource-efficient and environmentally friendly society in the future [11].

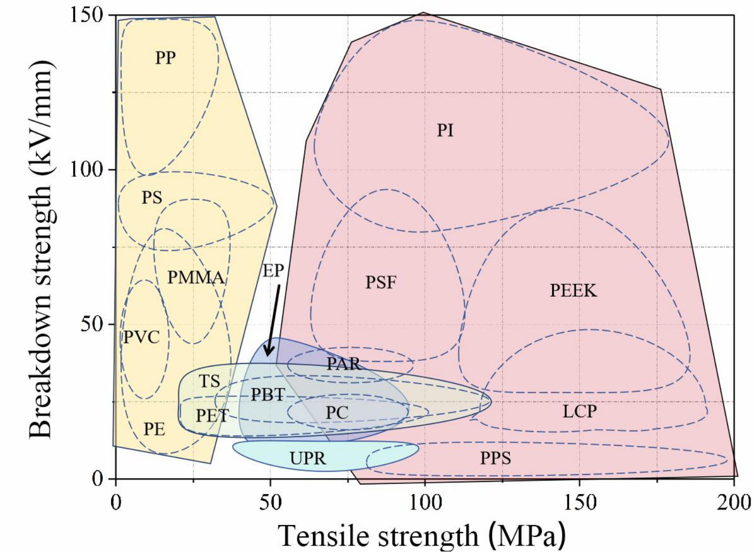

Fig. 1 Performance distribution of common polymer materials (data source: MatWeb.com)

2.1.1 Epoxy resin (EP) material

In the field of high thermal conductivity epoxy materials, filled high thermal conductivity epoxy resins are currently the mainstream epoxy materials used in industrial applications. These resins utilize polymers as the matrix and incorporate high thermal conductivity particles or hybrid fillers made from metals, inorganic materials, or carbon, resulting in composites that maintain the excellent sealing and processability of the polymer matrix while enhancing the thermal conductivity of the material [12]. Additionally, the thermal, electrical, mechanical, and magnetic properties of the material can also be tuned. The thermal conductivity of the composite materials is critically influenced by several factors, including the intrinsic thermal conductivity of the filler, its size, shape, surface morphology, and the filling amount, structural distribution, and interfacial interactions of the filler within the matrix. Therefore, selecting appropriate thermal fillers, effectively controlling the interface between the filler and the matrix, and constructing a thermal conductivity network are key to producing high-performance polymer-based thermal conductive composites. Common fillers for thermal conductive polymer composites include metals, ceramics, and carbon-based materials. Metal fillers such as copper nanowires, silver nanowires, silver particles, and aluminum fibers; ceramic fillers such as hexagonal boron nitride (h-BN), alumina (Al_2O_3), and silicon nitride (Si_3N_4); and carbon fillers including graphene, carbon nanotubes (CNTs), and carbon fibers (CF) are often added to a crosslinked network formed from epoxy resin monomers like diglycidyl ether of bisphenol A (DGEBA) [13, 14].Typically, the inherent electrical conductivity of metallic materials limits their use in environments where electrical insulation is required, thereby narrowing their application scope. In the high-voltage insulation field, high thermal conductivity epoxy resin materials predominantly utilize carbon-based fillers and ceramic materials. Fig 2 illustrates a specific scheme for preparing high thermal conductivity epoxy resin materials through traditional filler addition methods, showing a transition from conventional ceramic fillers to newly developed single-layer carbon-based fillers.

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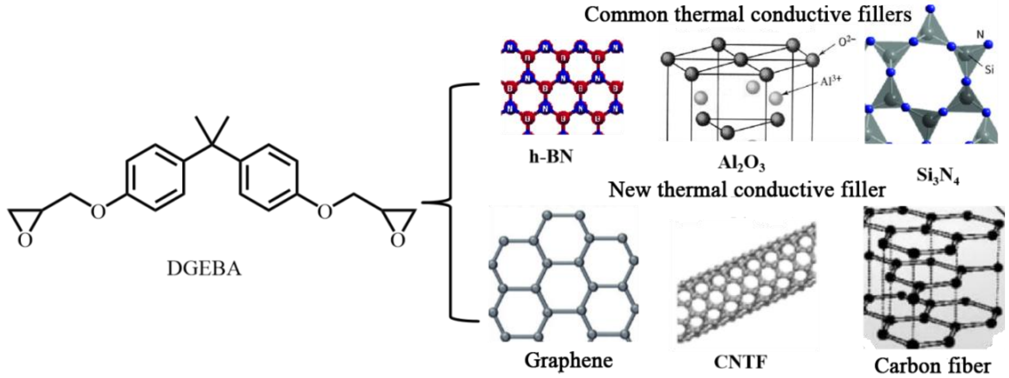

Fig. 2 Addition type and preparation scheme of high thermal conductivity epoxy resin filler

Currently, commercial high thermal conductivity epoxy resins are primarily produced by adding fillers into epoxy resin monomers to form a homogeneous structure, which is then combined with curing agents to create a crosslinked network with high thermal conductivity [15]. Domestically, China still relies on high thermal conductivity epoxy resins produced by foreign companies, such as Huntsman. For example, Huntsman's Aratherm® CW 2731 has a thermal conductivity of up to 3.0 $W \cdot m^{-1} \cdot K^{-1}$, although this performance comes at the cost of reduced dielectric and insulation properties. Its breakdown strength is only 7 kV/mm, and its power frequency dielectric constant is 16.9, significantly higher than the typical 3-4 range for conventional epoxy resins.

In terms of high thermal conductivity epoxy resins filled with ceramic or mineral materials, Huntsman produces monomers like Araldite® CW 5725-3, which achieve thermal conductivities between 0.6 and 0.75 $W \cdot m^{-1} \cdot K^{-1}$— a significant improvement compared to unfilled epoxy resins, which range from 0.2 to 0.3 $W \cdot m^{-1} \cdot K^{-1}$. Meanwhile, domestic manufacturers are actively developing localized alternatives to these high thermal conductivity epoxy resins. For example, Zhejiang Senfu produces the SF-S-8102 epoxy resin, which, after curing, reaches a thermal conductivity of 0.45-0.55 $W \cdot m^{-1} \cdot K^{-1}$. Similarly, Shanghai Xiongrun Resin's epoxy resin for use in saturated reactors, previously approved in a project, also achieves a thermal conductivity exceeding 0.5 $W \cdot m^{-1} \cdot K^{-1}$.

Table 1 presents the thermal conductivity data for Huntsman and domestic high thermal conductivity products, while Fig 3 illustrates a comparison between the performance of commercial high thermal conductivity epoxy resins and traditional epoxy resins. Based on this analysis, it is evident that domestic high thermal conductivity epoxy resins still require further research to achieve better performance, which is essential for advancing the localization and replacement of these materials. Developing specialty high thermal conductivity epoxy resins with independent intellectual property rights and superior comprehensive performance compared to foreign products remains a long-term goal.

Tab. 1 Commercial high thermal conductivity epoxy resin and its properties

Epoxy/curing	Aratherm ®CW 2731	Araldite® CW 5725-3 / Aradur® HY 5726	Araldite® CW 229-3/ Aradur® HW 229-1	SF-S-8102A/ SF-S-8102B	Shanghai Xiongrun
Thermal conductivity （$W \cdot m^{-1} \cdot k^{-1}$）	3.0	0.66	0.65-0.75	0.45-0.55	≥0.5
Tensile strength （MPa）	44	65	80	50-65	82.9
T_g（°C）	165	110	110	150-160	104
Breakdown strength（kV/mm）	7.0	38.0	18.0-22.0	18.0	31.6
Dielectric constant (power frequency)	16.9	4.3	4.2		3.25

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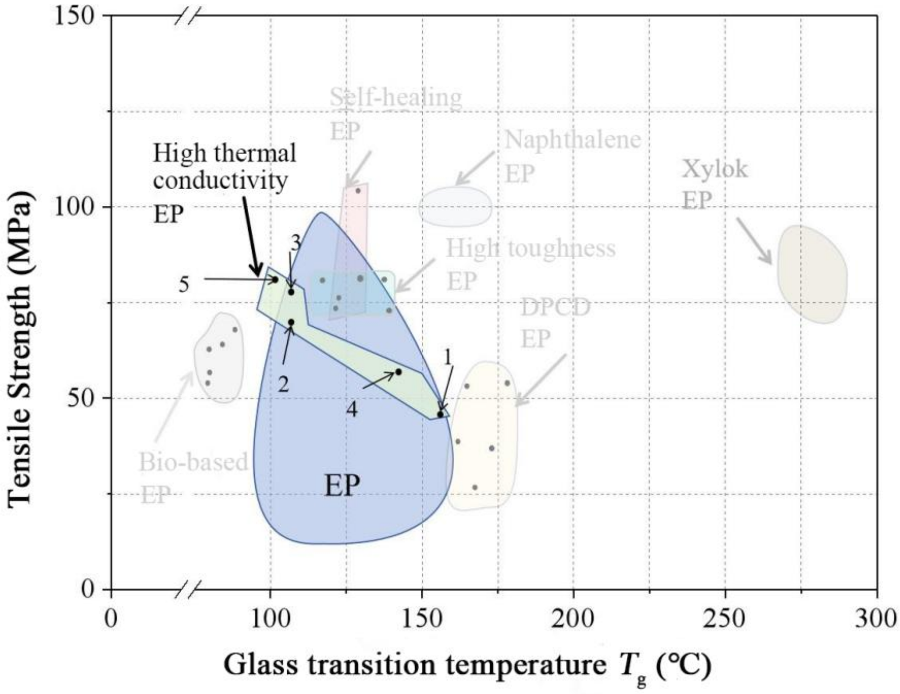

Fig.3 Tensile strength and Tg distribution of high thermal conductivity epoxy resin (data source: Huntsman official website, work acceptance data, etc.)

In the field of bio-based epoxy materials, bio-based polymers refer to a new class of polymers produced from renewable biomass through biological, physical, or chemical processes. These materials are characterized by their green, environmentally friendly, and renewable nature. Bio-based polymer materials have a vast market potential, offering partial substitutes for traditional petroleum-based plastics, alleviating the petroleum crisis, and reducing environmental pollution. They are poised to become a leading emerging industry driving global economic development and technological innovation. In recent years, researchers have designed and synthesized various bio-based compounds containing heterocyclic, alicyclic, and aromatic rings to replace petroleum-based bisphenol A (BPA) in the production of epoxy resins. However, the thermal stability and mechanical properties of currently reported bio-based epoxy resins still fall short of those of BPA-type epoxy resins [16].Thus, the design and synthesis of bio-based monomers capable of meeting the high-performance and functionalization requirements of bio-based epoxy resins remain a significant challenge. This is critical for broadening the application scope of bio-based polymer materials and enhancing their competitive advantage over petroleum-based polymers. Common bio-based raw materials for epoxy resins include castor oil, soybean oil, rosin, lignin, and vanillin. As competition intensifies in the traditional epoxy resin manufacturing sector, many chemical companies are now focusing on the development and production of bio-based epoxy resins. Currently, commercial bio-based epoxy resin manufacturers include Entropy, Spolchemie, Gougeon Brothers, Sicomin, and Wessex Resins, with bio-based content accounting for 30-40% of the epoxy resin composition.The primary application areas for commercial bio-based epoxy resins are epoxy laminates, coatings, and injection molding. To date, no reports have been found on the use of bio-based epoxy resins in high-voltage insulation applications, indicating that further research from manufacturers is needed before bio-based epoxy resins can be applied in this field.

Fig 4 illustrates the structures of mainstream bio-based epoxy resin monomers and their crosslinked networks, revealing significant differences between the crosslinked network structures of commercial bio-based epoxy resins and traditional petroleum-based epoxy resins. These structural differences are the primary reason why the performance of bio-based epoxy resins is generally inferior to that of conventional epoxy resins. When comparing the performance of commercial bio-based epoxy resins to traditional epoxy resin materials, there remains a

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considerable gap. This is largely because the chemical structures chosen for the bio-based components, selected for cost and preparation feasibility, still fall short in terms of stability and chemical resistance when compared to petroleum-based resins. Despite these challenges, the current price of commercial bio-based epoxy resins is more than ten times that of conventional BPA-based epoxy resins.For example, bio-based epoxy resins from Entropy have a glass transition temperature (Tg) below 100°C, limiting their use in high-temperature and complex environments. Table 2 presents specific performance data for several commercial bio-based epoxy resins, while Figure 5 highlights the differences in tensile strength and Tg between bio-based and traditional epoxy resins. The performance distribution clearly shows that current bio-based epoxy resins are insufficient to meet the performance requirements needed to replace traditional epoxy resins.At present, bio-based epoxy resins account for only about 1% of the total output value of the epoxy resin industry. However, as costs decrease and performance improves in the future, it is expected that bio-based epoxy resins will gradually replace traditional epoxy resins and find applications in more fields.

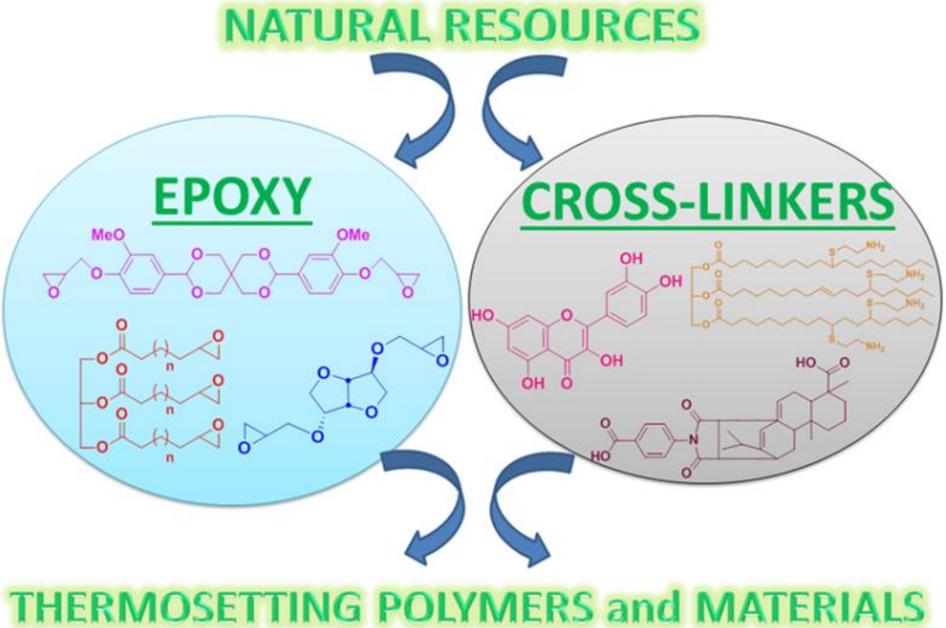

Fig.4 Structure of bio-based epoxy resin and the cross-linking network formed

In contrast, bio-based epoxy resins developed in laboratory settings have made significant advancements in terms of performance. Many epoxy resins with partial or fully bio-based components have been developed, exhibiting excellent thermal, mechanical, and electrical properties. However, due to limitations in cost or the complexity of synthesis, large-scale production under current industrial conditions remains challenging. The core research directions for bio-based epoxy resins currently see Tab 2.

Tab 2 Performance distribution of commercial bio-based epoxy resins (data source: Entropy, Ecopoxy, and Sicomin's official websites)

Bio-based epoxy resins	Entropy® BRT	Entropy® CLE	Entropy® CCR	Ecopoxy® Biopoxy36	Sicomin® Greenpoxy 56
Elongation at break（%）	5.0	6.0	6.5	2.8	4.3
Tensile strength （MPa）	65.5	67.6	54.5	57.9	68
T_g（°C）	56.0	63	52	54	79
Flexural strength （MPa）	96.5	93.1	76.5	76.5	-
Numbering	1	2	3	4	5

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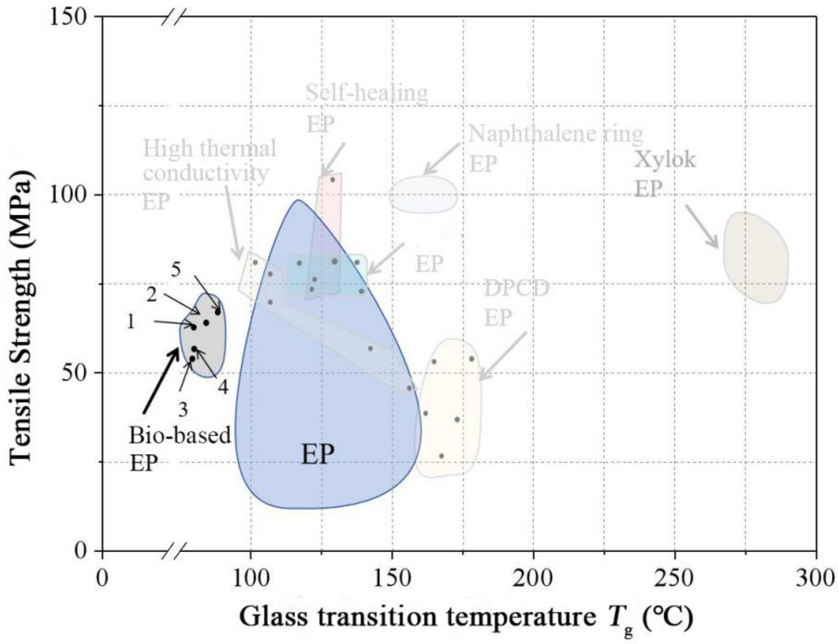

Fig. 5 Tensile strength and Tg distribution of commercial bio-based epoxy resins (data source: Entropy, Ecopoxy, and Sicomin's official websites).

2.1.2 Polyimide (PI) material

Polyimide (PI) is a polymer containing imide groups and belongs to the category of high-performance plastics. Due to its high heat resistance, PI is widely used in roles requiring durable organic materials, such as in high-temperature fuel cells, displays, and various military applications [17]. The core reason PI materials have garnered significant attention and are produced on a large scale is their outstanding thermal stability, coupled with excellent chemical resistance, superior mechanical properties, and excellent insulation capabilities.To date, commercial PI materials are primarily used in lightweight insulation or passivation protection layers. These materials utilize PI's excellent properties to protect metals or other materials, creating a barrier that prevents damage during transportation, while also maintaining structural integrity. In mechanical components, PI is typically fabricated into metal parts through hot pressing, with common PI grades including P84 NT, VTEC, Meldin, Vespel, and Plavis. Additionally, PI is used in filtration materials, such as in applications requiring insulation from overheated gases.As research into materials has advanced, PI has also begun to serve as a potential material in fields such as adhesives, flexible circuits, solar sails, and colorless transparent films [18].

Currently, the commercial PI films available on the market are predominantly produced by large chemical enterprises. These include DuPont's Kapton, Toray's Vespel, Caplinq's PIT series, CEN Electronic Materials' CV and CF series, and NeXolve's Thermal Bright series, among others. Some commercial PI materials are enhanced with additives such as carbon fiber (CF), graphene, glass fiber (GF), molybdenum disulfide (MoS2), and polytetrafluoroethylene (PTFE). Due to the widespread application of PI materials, the majority of commercial PI films now have domestic alternatives with similar performance.Most commercial PI is sold in film form, and its properties vary depending on the thickness of the film. The data used in this study is sourced from PI films with a thickness of 50 μm. Table 2-3 presents the specific properties of current commercial PI films. From the data, it is clear that PI significantly outperforms epoxy resin in terms of mechanical properties and breakdown strength. Additionally, its dielectric constant and dielectric loss are comparable to those of epoxy resin. In terms of performance, the gap between domestic and imported PI films is relatively small.

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Tab. 3 Properties of different types of commercial PI films with a thickness of 50 μm (data source: official websites of each PI manufacturer)

Brand name	Manufacturer	Density (g/cm^3)	Mechanical properties			Electrical properties			Dielectric constant	Dielectric loss
			MD (MPa)	TD (MPa)	Elongation at break (%)	Breakdown voltage (kV/mm)	Surface resistance (Ohm)	Volume resistivity (Ohm·cm)		
Kapton @HN	Dupont	1.42	231		82	240		1.5×10^{17}	3.4(1KHz)	2×10^{-3}
P1T2N	Caplinq	1.42	165		45	197		10^{13}	3.9(1KHz)	3.610^{-3}
CEN	Electronic Material		160	150	55	180	8.0×10^{12}	8×10^{15}		
Thermalbright® N	Xelove	2.08	58		2.0		10^{9}	10^{12}		
Upilex	UBE	1.4	540		90	10.5	10^{15}	10^{14}	3.3	4×10^{-3}
WF-50	Shandong Wanda Microelectronics		180		70	260			3.5±0.4	
6501	Changshu Zhonghang Insulation Materials	1.42	≥135	≥115	≥35	150	10^{13}	2.8×10^{10}	3.5±0.4	2.8×10^{-3}
F-46			110		50	150			4	4×10^{-3}
Type F	Jiangsu Yabao Insulation Materials		90		40	120	10^{13}	10^{15}	3-4	10^{-3}
Type H			140		40	150	10^{13}	10^{15}	3-4	10^{-3}

Polyimide (PI) has found extensive applications in the field of high-voltage insulation due to its exceptional electrical insulation properties, resistance to high and low temperatures, flame retardancy, resistance to dry and wet arcs, wear resistance, dynamic cut-through resistance, hydrolysis resistance, radiation resistance, and chemical stability. PI's robust main-chain bond energy prevents it from easily breaking down, and it also boasts high tensile, bending, and compressive strength, along with excellent creep resistance and lightweight advantages. These characteristics allow PI to meet the special performance requirements of electrical wires and cables better than traditional materials.In cable materials, PI plays a crucial role as an impregnation varnish, coating insulation, and insulating layer material, especially in applications where high-performance insulation is needed. It is widely used in enameled wires rated at 200°C or above. Techniques such as the addition of silica (SiO_2) enhance its heat resistance, and using aluminum isopropoxide (AIP) or methyltriethoxysilane (MTES) improves the corona resistance of impregnation varnishes. In aerospace cables, PI is typically combined with PTFE (polytetrafluoroethylene) through composite wrapping to reduce weight, a key trend in producing lightweight aerospace insulation cables.PI materials are also applied in dielectric energy storage systems due to their excellent thermal stability, making them promising candidates to replace biaxially oriented polypropylene (BOPP) in high-temperature environments for new energy storage materials with better chemical resistance and higher energy density. Another use of PI is as an insulating and passivation layer in the manufacture of integrated circuits and micro-electromechanical systems (MEMS) chips. PI layers exhibit good mechanical elongation and tensile strength, aiding in the adhesion between PI layers or between PI and deposited metal layers. The minimal interaction between gold films and PI,

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combined with PI's high thermal stability, ensures reliable insulation under various environmental pressures.For these reasons, PI is considered the ideal material for high-voltage insulation and heat-resistant applications.

However, some challenges need to be addressed when using PI in insulation. One key issue is PI synthesis and cost. Currently, PI raw materials are in solid form and must be dissolved in N,N-dimethylacetamide (DMAc) to create a PI solution. This step leads to significant volume shrinkage during the transformation from PI solution to PI film, often exceeding 60%, making it difficult to manufacture large-scale insulation components in molds. To address this, PI is typically formed through hot pressing in electronic insulation applications. However, due to PI's excellent thermal stability, the process requires very high temperatures and pressures to shape PI films into complex components. Additionally, the cost of PI films remains relatively high, which should be factored in when considering their use in practical engineering applications [19].

2.2 Conductor Material

Currently, the primary conductor materials used in ultra-high voltage (UHV) equipment include aluminum and aluminum alloys, as well as copper and copper alloys. However, aluminum alloys have relatively high resistivity and insufficient electrical conductivity, leading to significant transmission losses [20]. UHV equipment demands high mechanical strength and ductility from the materials employed. Existing materials, however, are prone to fatigue and damage during long-term operation and under extreme environmental conditions, revealing deficiencies in their mechanical performance. During operation, UHV equipment generates substantial heat, and the performance of current conductor materials significantly deteriorates at elevated temperatures, potentially resulting in equipment failure. This makes the heat resistance of materials particularly critical in UHV grids.The electrical contact materials used in UHV equipment must exhibit both high electrical conductivity and excellent wear resistance. Presently, the contact materials in use tend to experience increased contact resistance and wear under high loads and extended operation, which undermines the reliability of the equipment. Therefore, developing new materials and improving existing ones can effectively enhance the performance and reliability of UHV equipment, ensuring it meets the growing demands of future power grids.

To address these issues, researchers worldwide are focusing on the following key areas:

(1) New conductor materials: This includes the development of high-performance electrical contact materials, new copper-based alloys, new aluminum-based alloys, and superconducting materials.

(2) High-performance electrical contact materials: Improving the electrical conductivity and wear resistance of these materials to ensure reliable performance under high loads and prolonged operation.

(3) New copper-based alloys: Copper has superior electrical conductivity compared to aluminum, but pure copper exhibits weaker mechanical strength at high temperatures. Therefore, research is concentrated on improving the high-temperature strength and oxidation resistance of copper-based alloys while maintaining their excellent conductivity.

(4) New aluminum-based alloys: Efforts are being made to enhance the electrical and mechanical properties of aluminum alloys by adjusting alloying elements and optimizing material design, thereby reducing transmission losses while preserving the lightweight advantages of aluminum.

(5) Superconducting materials: Superconducting materials, which exhibit zero electrical resistance at low temperatures, are considered ideal for future UHV grids. However, their application is currently limited by high costs, complex manufacturing processes, and stringent environmental requirements, necessitating further research.

Fig 6 summarizes the tensile strength and electrical conductivity ranges of various conductor materials used in UHV equipment [21]. The continued development and optimization of new

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conductor materials will likely lead to significant improvements in the performance and reliability of UHV equipment, addressing the growing demands of future power grid development.

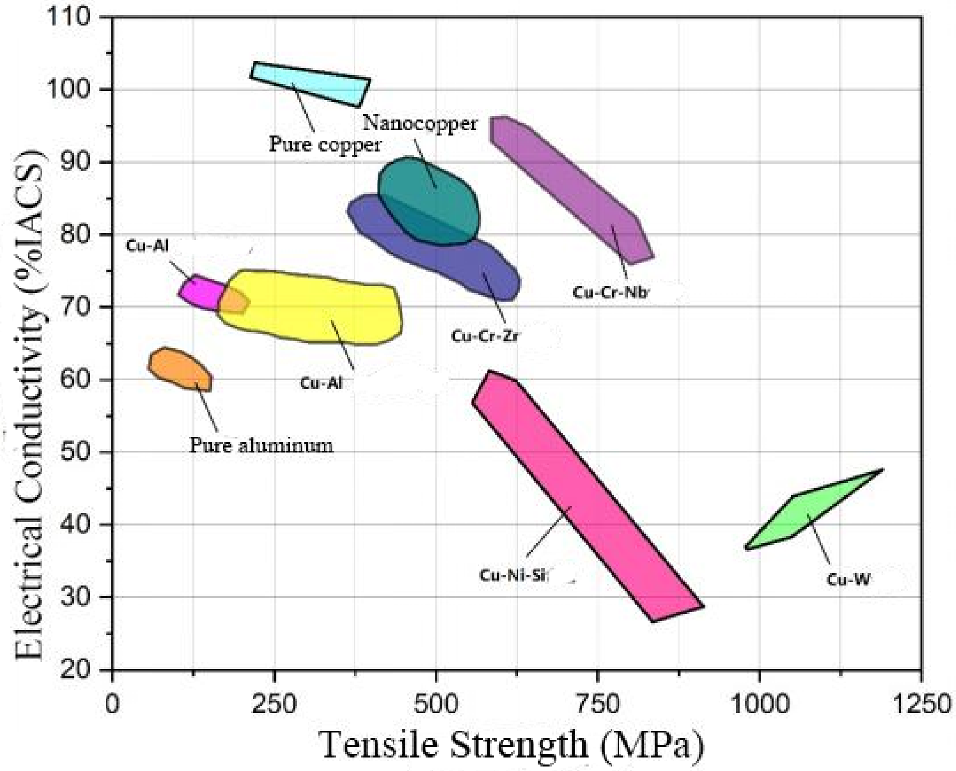

Fig.6 Tensile strength and electrical conductivity of conductor materials used in UHV equipment

2.2.1 Copper-tungsten alloy (Cu-W alloy)

Copper-tungsten (Cu-W) alloy is a material that combines the high melting point of tungsten (W) with the excellent electrical conductivity of copper (Cu), resulting in a material with high strength, temperature resistance, and superior electrical conductivity. It has become the primary material for ultra-high voltage (UHV) electrical contacts. Current research in this field is focused on three main areas: (1) optimizing the microstructure, (2) improving manufacturing methods, and (3) enhancing performance.

Cu-W alloy is a pseudo-alloy, formed by a uniform mixture of tungsten and copper phases that do not dissolve into each other or form intermetallic compounds. This alloy combines the outstanding properties of both constituent metals, such as tungsten's high-temperature resistance, strength, and density, and copper's high electrical and thermal conductivity as well as ductility. Moreover, the properties of Cu-W alloys can be adjusted by varying the proportion of the two components.

In China, Cu-W alloys are the primary material used for electrical contacts in high-voltage circuit breakers. However, with the ongoing development of power grids, there are increasing demands for improved arc erosion resistance and wear performance in electrical contacts. Current methods for strengthening copper-tungsten composite materials include:

(1) Alloy element strengthening: For example, Yang et al. prepared Cu-Zr-W composites by infiltrating a tungsten skeleton with Cu-Zr alloy. The addition of zirconium particles strengthened the Cu-W interface and the copper-rich regions while maintaining high electrical conductivity.

(2) Compound particle strengthening: Li et al. prepared W-25% (by mass) Cu-La_2O_3 bulk materials using a hydrothermal co-precipitation method. The material with 2.0% La_2O_3 exhibited the best overall performance, with electrical conductivity reaching 52.5% IACS, hardness at 288 HB, and tensile strength at 375.9 MPa.

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(3) Carbon nanotube (CNT) strengthening: Shi et al. produced multi-walled carbon nanotube (MWCNT)-reinforced Cu-W composites using hot-press sintering. The Cu-W composite with 0.4 wt% MWCNTs showed improvements in flexural strength and thermal conductivity by 8.8% and 27.8%, respectively.

(4) Graphene reinforcement: Compared to CNTs, graphene can be produced through relatively low-cost chemical and electrochemical methods and has a larger surface area, making it a promising reinforcing material. Zhou et al. fabricated graphene-reinforced W80Cu20 composites using infiltration technology and spark plasma sintering. The State Grid Research Institute's newly developed high-performance graphene contact material achieved major breakthroughs, with electrical conductivity reaching 46.1% IACS, hardness at 248 HB, and flexural strength at 1160 MPa, representing increases of 15.25%, 7.4%, and 10%, respectively, over the arc contact materials produced by Austria's Plansee. These performance metrics place the technology at an internationally leading level.

Tab 4 summarizes the performance indicators of domestic, foreign, and self-developed electrical contact materials. It is evident that the self-developed contact technology from the State Grid Research Institute has met the application standards.

Tab 4 Comparison of technical indicators

Products	The name of the metric	Foreign technology	Domestic technology	Self-developed technical indicators
CuW80 arcing contact	Flexural strength（MPa）	1050	1000	1160
	Electrical conductivity（%IACS）	40	38	46.1
	Hardness（HB）	/	230	248
550kV high voltage circuit breaker	Type	GIS	Tank circuit breakers	Tank circuit breakers
	Short-circuit currentkA	80	63	80
	The number of times the full blocking capacity is interrupted	12	16	21

2.2.2 Copper-aluminum alloys (e.g. Cu-Al alloys)

Copper-aluminum (Cu-Al) alloys, by introducing aluminum into the copper matrix, significantly improve the material's mechanical strength and corrosion resistance. Research in this area primarily focuses on optimizing the alloy composition and refining manufacturing processes to further enhance overall performance. For instance, by controlling the aluminum content and the processing techniques, the grain structure and phase composition of the alloy can be optimized.

Copper-aluminum composite materials combine the excellent electrical conductivity of copper with the light weight and cost-effectiveness of aluminum. In these composites, aluminum serves as the core material, with copper layers metallurgically bonded on both sides. This structure achieves electrical conductivity comparable to standard copper busbars, while significantly reducing weight. This makes copper-aluminum composites highly suitable for high-current equipment, where they effectively mitigate issues like excessive heat generation and high energy loss.

Cu-Al alloys hold significant potential for application in ultra-high voltage (UHV) transmission lines, especially in environments that require high strength and corrosion resistance. Table 2-5 compares the performance indicators of pure copper, pure aluminum, copper-aluminum composites with pure aluminum cores, and copper-aluminum composites with aluminum alloy cores. While the electrical conductivity of Cu-Al composites is slightly lower than that of pure copper, their mechanical strength and corrosion resistance make them well-suited for use in high-stress components such as conductors and busbars. Further improvements in electrical conductivity are needed to reduce transmission losses and improve stability in high-temperature and extreme conditions.

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However, current applications of Cu-Al composites face significant challenges due to the weak bonding at the copper-aluminum interface, where interfacial reactions are difficult to control. The key technical challenge in producing high-performance aluminum-clad copper composite busbars lies in overcoming the weak interfacial bonding between the two metals. This requires breaking through the technical bottleneck of achieving strong copper-aluminum metallurgical bonds while ensuring the stabilization and homogenization of the composite material.

Tab 5 Comparison of technical indicators

Performance		Pure copper	Pure aluminu m	Copper-aluminum composite (Pure aluminum core).		Copper-aluminum composite (Aluminum alloy core material).		
Copper volume ratio %		100%	0%	25%	30%	20%	25%	30%
Densityg/cm^3		8.9	2.7	4.25	4.56	3.94	4.25	4.56
Electrical conductivity % IACS	Hard	≥99	≥61	≥70.5	≥72.2	≥66.2	≥68.3	≥70.3
	Soft	≥102	≥62	≥72.0	≥73.5	≥68.4	≥70.5	≥72.6
DC resistivity $\Omega \cdot mm^2/m$	Hard	0.01742	0.02826	0.02446	0.02387	0.02604	0.02526	0.02452
	Soft	0.01690	0.02781	0.02395	0.02346	0.02521	0.02446	0.02375
Tensile strength MPa	Hard	≥380	≥121	≥180	≥185	>410	≥410	≥410
Elongation %	Soft	≥220	≥73	≥120	≥125	≥190	≥190	≥190
	Hard	3	≥6	≥3	≥3	≥2.5	≥2.5	≥2.5
	Soft	≥35	≥20	≥30	≥30	≥25	≥25	≥25

2.2.3 High conductivity and high strength aluminum alloy conductor material

Developed countries such as those in Europe, the United States, and Japan have conducted extensive systematic research in the field of high-strength aluminum alloy conductor technology. These nations have mastered a wide array of key technologies and have successively developed and produced various grades of high-strength aluminum alloy conductors. As global leaders, they have also set the industry standards for high-strength aluminum alloy conductors. The performance comparison of several typical conductors is shown in Tab 6.

Tab 6 Comparison of the performance of several typical conductors

	CuW80 arcing contact	Cu-Cr-Zr alloy	Novel nanostructured copper alloys	Cu-Ni-Si	High conductivity heat-resistant aluminum alloy conductor material	High conductivity and high strength aluminum alloy conductor material
Flexural strength（MPa）	1160	400-600	600-800	600~860	61.5	≥55.5%
Electrical conductivity（%IACS）	46.1	72-86	78-95	30%~60		≥300

In the year 2000, the UK (as part of the EU) implemented the standard BS EN 50183:2000, which stipulated that the conductivity of aluminum-magnesium-silicon alloy conductors for overhead lines must reach at least 55.25% IACS. This improvement in conductivity significantly

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boosted the usage of high-strength aluminum alloy energy-saving conductors internationally, with their adoption increasing year by year.

Currently, China's high-strength aluminum alloy conductor materials are mainly classified into two types: LHA1 single wire (with strength ≥ 315 MPa and conductivity ≥ 52.5% IACS) and LHA2 single wire (with strength ≥ 295 MPa and conductivity ≥ 53% IACS). These domestic standards are equivalent to the international standard IEC 60104:1987 and have been formalized in the national standard GB/T 23308-2009, titled Aluminum-Magnesium-Silicon Alloy Conductors for Overhead Lines. However, the conductivity and mechanical performance of LHA1 or LHA2 stranded conductors do not offer significant advantages over traditional steel-reinforced aluminum conductors, which are still predominantly used in overhead transmission lines in China.

The dual requirements for high strength and high conductivity in aluminum alloy conductors present a significant challenge in material research and development. Research institutes in France and Russia have studied the effects of ultrafine grains and nano-precipitation phases in the aluminum-magnesium-silicon system to optimize strength and conductivity. Through severe plastic deformation and optimized aging heat treatment, they have successfully increased the conductivity of high-strength aluminum alloy conductor materials to over 54% IACS.

In recent years, companies such as Pirelli (Italy), Nexans (France), and General Cable (USA) have led efforts in developing Al-Mg-Si high-conductivity, high-strength aluminum alloy energy-saving conductors, which have seen further performance improvements. These conductors now achieve conductivity exceeding 55.25% IACS, placing European and American cable companies at the forefront of the international market in the research and application of high-strength aluminum alloy conductors.

In China, many aluminum alloy conductor manufacturers and research institutions have actively explored ways to improve the conductivity of high-strength aluminum alloys, with some products now reaching conductivity levels above 54% IACS. However, widespread adoption has yet to occur. For instance, Far East Cable Co., Ltd. produces high-strength aluminum alloy conductors with tensile strength ≥ 340 MPa and conductivity ≥ 54% IACS (at 20°C), suitable for industrial production, although their electrical performance still needs improvement. Henan Jiutong Cable Co., Ltd. has increased the conductivity of high-strength aluminum alloy conductors to 56% IACS, but at the expense of strength, with tensile strength dropping to 288 MPa.

Despite these advancements, China is still in a catch-up phase compared to developed countries in Europe and North America. Nevertheless, State Grid Liaoning Electric Power Co., Ltd. and State Grid Smart Grid Research Institute have overcome the challenge of simultaneously improving both conductivity and strength, breaking through key precision control technologies in the manufacturing process. They have successfully developed high-conductivity, high-strength aluminum alloy conductor materials with conductivity ≥ 55.5% IACS, tensile strength ≥ 300 MPa, and elongation ≥ 3.0%, and have achieved the production of 55.5% IACS high-conductivity, high-strength aluminum alloy conductors, which have been applied to grid installations in Liaoning. The performance comparison is summarized in Tab 7.

Tab 7 Comparison of the properties of the main aluminum alloy conductor materials

Production units	Far East Cable Co., Ltd	Henan Jiutong Cable Co., Ltd	State Grid Liaoning Electric Power Co., Ltd., State Grid Smart Grid Co., Ltd
Electrical conductivity/ %IACS	≥54（20 °C）	56	≥55.5
Tensile strength/MPa	≥340	288	≥300

2.3 Magnetic Materials

Ultra-high voltage direct current (UHVDC) transmission technology is currently the most advanced power transmission technology in the world, characterized by the highest voltage levels,

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the largest transmission capacity, and the longest transmission distances. It is also the primary technical means for achieving large-scale power transmission. In transformers operating at 110 kV and above, especially large-capacity transformers, the operating conditions are complex. For example, UHVDC converter transformers experience heavy loads, high harmonic content, and significant vibration, placing much higher demands on the magnetic properties, service performance, and processing design of grain-oriented silicon steel compared to distribution transformers.When considering low losses under complex operating conditions, long-term service reliability, overall quality, and processing performance, the technological development for grain-oriented silicon steel used in large power transformers should focus on achieving excellent overall performance in products with a thickness of 0.20 mm. However, the performance of core materials used in existing high-voltage, large-capacity power transformers in China does not align with the requirements for the development of high-efficiency power transformers. Due to the limitations in the performance of grain-oriented silicon steel materials, manufacturing level-1 high-efficiency large power transformers using the highest grade of current grain-oriented silicon steel still presents challenges such as low magnetic flux density, large volume, and high costs, as shown in Tab 8.Additionally, transformers using high-loss grain-oriented silicon steel tend to experience increased core temperature rises. Under conditions of high summer loads and elevated ambient temperatures, this can easily lead to core overheating, posing a safety risk to the transformer [20].

Tab 8 Technical and economic analysis of top-grade oriented silicon steel for high-efficiency power transformers

Transformer type	Different thickness specifications The highest grade of silicon steel	Energy efficiency rating	Design magnetically dense	The cost of the main material (silicon steel sheet + magnet wire + oil) (10,000 yuan).	Volume ratio
110kV/50MVA alternating currently	20/70	Level	1.699	139.0	1.031
	23/75	Level	1.640	139.9	1.041
	27/85	Level	1.580	141.4	1.058
±400kV/415 MVA DC commutation	20/70	There is no energy efficiency standard requirement, and the design is designed to reduce no-load losses by 20% compared with the current level	1.628	1296.2	1.049
	23/75		1.494	1339.6	1.108
	27/85		1.447	1375.7	1.134

In direct current (DC) transmission, alternating current (AC) is converted to DC for transmission to the load side, and then converted back to AC for user consumption. The key equipment used to achieve the AC-DC conversion is the converter valve. As the core system of ultra-high voltage direct current (UHVDC) transmission projects, the converter valve is equipped with components such as thyristors, damping capacitors, damping resistors, gate units, and saturated reactors. The saturated reactor plays a critical role by suppressing the rate of current rise (di/dt) when components within the valve are conducting and smoothing out surge currents caused by line faults, thus

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protecting the thyristors.Ultra-thin grain-oriented silicon steel with a thickness of no more than 0.1 mm (with iron loss P1.5/400 <11.5 W/kg and magnetic flux density B800 ≥1.80 T) is the key core material for manufacturing saturated reactors in UHVDC converter valves. For a long time, high-quality ultra-thin grain-oriented silicon steel has been monopolized by Japan's Metal Company, posing a significant threat and challenge to China's UHVDC project development due to the reliance on foreign technology [21].

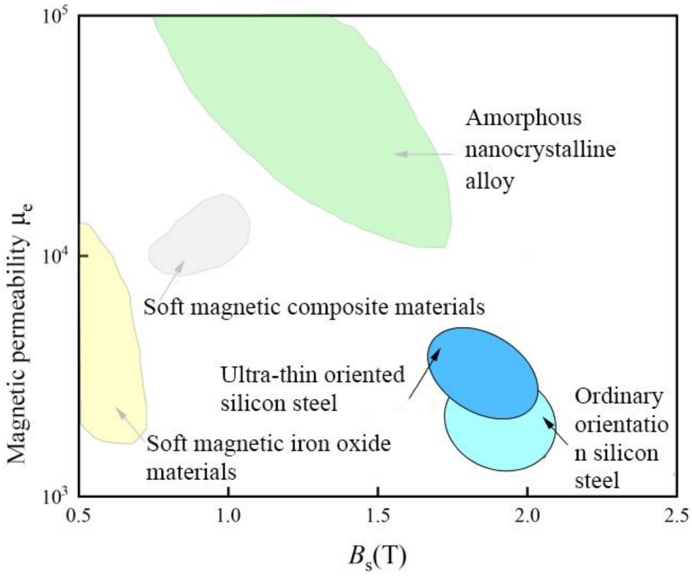

Fig.7 Relationship between saturation flux and effective permeability of oriented silicon steel material

In the field of grain-oriented silicon steel for high-efficiency transformers, Japan's Nippon Steel and Korea's POSCO have been leading enterprises in the development of grain-oriented silicon steel technology. They have mastered production and preparation techniques for various types of grain-oriented silicon steel products, including thin-gauge silicon steel and high-magnetic-induction grain-oriented silicon steel. Regarding thin-gauge, low-loss grain-oriented silicon steel, Nippon Steel has the capability to produce products with thicknesses of 0.18 mm and 0.20 mm. The 0.20 mm products are available in the ZH (non-scribed) and ZDKH (scribed) series, with several grades including 20/70, 20/75, 20/80, and 20/85. Although Nippon Steel developed 0.18 mm thickness products several years ago, they are still under strict confidentiality, and no related research has been reported. The stability and performance of product batches remain bottlenecks restricting large-scale application.

For high-magnetic-induction grain-oriented silicon steel, Nippon Steel has conducted laboratory research on materials with magnetic induction B800 values between 1.94 T and 1.98 T by adding grain-boundary segregation elements such as Se, Sb, Bi, and B. By controlling the normalization temperature and enhancing the inhibitory force with Bi and BN, the company has increased the size of secondary grains, though mass production has not yet been achieved.

In the area of low-loss grain-oriented silicon steel for large power transformers, Nippon Steel and POSCO have the capability to produce grades such as 20/70 and 20/75. They have conducted experimental applications in transformers of 110 kV and above, but only pilot-scale production research has been conducted for grades like 20/65 and higher, with no large-scale production or application achieved yet.

Domestically, China's grain-oriented silicon steel industry is transitioning from rapid development to a focus on high-quality production, with products generally meeting the design requirements for power transformers. As of 2021, the total production of grain-oriented silicon steel in China reached 1.832 million tons, but high-end products with 0.20 mm thickness accounted for only 4.2% of the total output. Although domestic production capacity is large, it is still dominated

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by medium-to-low-end products with thicknesses ranging from 0.23 to 0.30 mm. Only leading companies like Baosteel and Shougang have the capability to research and produce low-loss, high-end grain-oriented silicon steel with a thickness of 0.20 mm. Under the national "dual carbon" strategy, 0.20 mm high-end grain-oriented silicon steel is expected to be the future trend for technological development and application, while lower-end grades will gradually be phased out.

Baosteel, as the leading domestic producer of high-magnetic-induction grain-oriented silicon steel, continues to optimize slab low-temperature heating and nitriding processes. The quality and performance of products such as B23R075 and B27R085 are comparable to international counterparts. Baosteel has successfully developed higher-grade products like B20R070 and B20R075, with losses below 0.70 to 0.75 W/kg, reaching world-class standards.

Grain-oriented silicon steel products from Baosteel and Shougang have made significant progress in areas such as low-loss, high-magnetic-induction, low-noise, and substrate-free types. These high-grade products have been extensively applied in China's 1000 kV ultra-high voltage AC transformers and ±800 kV ultra-high voltage DC converter transformers, achieving large-scale localization [24].

2.4 Noise-Reducing Materials

At present, key ultra-high voltage (UHV) equipment such as converter transformers and shunt reactors primarily use box-in soundproof enclosures and sound barriers for noise control, with core noise reduction materials being predominantly mineral wool and metal soundproof panels. These materials have been in use for over a decade, and their performance improvements have reached a plateau. Overseas manufacturers of noise reduction materials have started using acoustic metamaterials to replace traditional materials, manufacturing box-in soundproof enclosures, sound barriers, and soundproof panels for direct noise reduction, significantly improving noise control effectiveness. To achieve domestic substitution with advanced acoustic metamaterials, research must be conducted on the noise characteristics of UHV equipment, along with theoretical studies, structural design, and application analysis of acoustic metamaterials.

In the area of acoustic metamaterials, to improve the low-frequency noise reduction performance of noise-reduction devices for UHV equipment, domestic manufacturers have focused on mineral wool materials such as glass wool, rock wool, and aluminum silicate. By increasing the thickness and density of these materials, the sound absorption coefficient at 125 Hz has been raised to above 0.35, with a noise reduction coefficient reaching 1.00p. Using these materials in combination with galvanized steel plates to manufacture box-in soundproof enclosures has achieved a maximum insertion loss of 15 dB. However, this approach significantly increases the size, thickness, and weight of the soundproof panels, complicating installation, transport, and construction. In some cases, the limited distance between UHV equipment and firewall structures makes it difficult to meet safety clearance requirements when installing box-in enclosures, necessitating a reduction in panel thickness, which weakens soundproofing performance.

Although domestic mineral wool noise-reduction materials have been optimized, their low-frequency acoustic performance still lags behind that of foreign acoustic metamaterials. Despite a later start, domestic research and development of acoustic metamaterials has made good progress. The noise of UHV transformers and reactors primarily consists of the 100 Hz fundamental frequency and its second to fourth harmonic components. By applying theories such as effective medium, long-short-range coupling, and bandgap, researchers have optimized the acoustic elements and artificial structures of acoustic metamaterials. These metamaterials can achieve highly efficient noise control at specific spectral frequencies, thereby effectively controlling noise propagation in UHV equipment. Institutions such as Nanjing University, the Chinese Academy of Sciences' Institute of Acoustics, and the State Grid Electric Power Research Institute have mastered key technologies in the theoretical analysis, structural design, sound impedance optimization, and precision manufacturing of acoustic metamaterials. They have developed various types of acoustic metamaterials, including Helmholtz-type, coiled space-type, and membrane-type materials. The

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table below lists major acoustic metamaterials developed domestically and internationally. However, most of these materials remain at the experimental stage, and due to their complex structures, high-precision 3D printing technology is required for production, leading to high manufacturing costs. To fully replace advanced foreign noise reduction materials with high-performance acoustic metamaterials, further research is needed to deepen the theoretical understanding, structural design, and manufacturing processes of these materials.

Tab 9 Comparison of the effects of sound-absorbing metaproducts

Serial number	Research institutes	Metamaterial type	Frequency band	Sound absorption coefficient
1	The Hong Kong University of Science and Technology	Thin film type	180、370、780 Hz	0.5-0.7
2	The Hong Kong University of Science and Technology	Thin film type	164、376、511、645、827、960 Hz	1.0
3	U.S. Navy Laboratory	Thin film type	50~1600 Hz	≥0.8
4	National University of Defense Technology	Helmholtz type	600~1000 Hz	0.9
5	Nanjing University	Helmholtz type	298~479、870~3244 Hz	1.0
6	Intellectual Research Institute	Helmholtz type	100 Hz、200 Hz、300 Hz	≥0.9
7	Mit	Helmholtz type	50~1600 Hz	0.9
8	Nanjing University	Curly type	228~319 Hz	0.95
9	University of Lorraine, France	Curly type	49~53 Hz	1.0

In addition to acoustic metamaterials, domestic institutions have led the research and application of sound-vibration decoupling noise reduction materials and devices to achieve effective noise control for ultra-high voltage (UHV) equipment. Sound-vibration decoupling noise reduction devices, developed from Japan’s soundproof walls, involve installing a body noise reduction system composed of elements such as support beams, sound-absorbing and insulating panels, vibration-damping supports, fireproof partitions, and monitoring systems on the outside of the equipment’s oil tank and inside the radiators. The main structure of this system consists of multiple detachable decoupling sound-absorbing panels. Compared to traditional box-in devices, this system does not interfere with firefighting equipment and significantly reduces installation time.The sound-vibration decoupling device uses the principle of acoustic impedance matching and a multi-layer composite panel design to enhance low-frequency noise reduction performance. By optimizing the density, thickness, and acoustic impedance properties of the multi-layer materials, the panel thickness is controlled to achieve efficient low-frequency noise control in confined spaces. The design of panel seams, sealed openings, and prefabricated frame structures enables a modular configuration that can accommodate the surface components of the equipment oil tank, while quick assembly and disassembly technologies significantly improve installation efficiency.To meet the maintenance and operational needs of UHV equipment, the system addresses the shielding effect of the sound-vibration decoupling panels on the oil tank surface. A contact-based oil tank surface leakage monitoring system and a temperature rise monitoring system were developed, replacing traditional manual inspections and infrared temperature measurement methods. These systems enable real-time, accurate monitoring of reactor operational status, ensuring the reliable operation of the equipment.

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The sound-vibration decoupling noise reduction panels are currently being installed and applied at the 1000 kV Ximeng UHV substation, where they have achieved a noise reduction level of approximately 15 dB.

3. Summary

The large-scale construction of UHV projects relies heavily on the development of core equipment. As China's power transmission and transformation industry experiences rapid growth, the low rate of localization of major technical equipment and the "hollowing out" of key equipment remain significant factors constraining the transformation and upgrading of the country's manufacturing sector. Although China is a global leader in UHV grid construction, key materials in certain UHV electrical equipment still rely on imports. With increasing demands for transmission capacity and stability in the future, even imported materials may struggle to meet requirements for high thermal conductivity, long lifespan, and environmental sustainability. This creates an urgent need to develop new electrical materials that can achieve "leapfrogging" technological advancements.

Building ordered structures within materials to enhance their performance and functionality has become an important trend in the development of next-generation advanced materials. Ensuring that these materials maintain stable performance under extreme operating conditions will be a key focus for future research in UHV insulation equipment. International chemical manufacturers are significantly increasing their investments in the development of specialized materials and, given their first-mover advantage, they have captured a large share of the market. In response, some domestic manufacturers have been able to develop comparable localized alternatives for certain products, but substantial differences remain in other areas, requiring greater support and research efforts.

Furthermore, optimizing traditional manufacturing processes by controlling material structure and enhancing performance remains highly valuable. Process optimization can effectively reduce production costs, making it feasible for some high-performance new materials to be applied in high-voltage equipment, which holds considerable practical significance.

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