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Insulating and Metal-Ceramic Materials for Particle Accelerators

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Abstract

The properties of nitride and oxide ceramic materials, which find application for structural elements of accelerating facilities, are analyzed. The construction versions and technological aspects for manufacturing of the magnetic coils with current-leading buses made from copper or aluminum are considered. The designs of metalloceramics-based vacuum ceramic chambers, current leads and other elements of accelerating facilities are presented.

I. CERAMIC MATERIALS AND SOLDERS

Ceramic facilities are favoured for application in accelerating facilities because of their low susceptibility to ionizing radiation and an exceptional combination of mechanical, electro- and thermophysical properties. The methods of ceramic technology facilitate the manufacturing of products based on nonmetallic refractory compounds with a specified phase and chemical composition and structure, which determine the required properties and operational characteristics. Refractory nonmetallic silicon, aluminium or boron nitrides fall in a class of nonpolar dielectrics. High energy of directed bonds of atoms in grids contributes to stability of properties of these materials, rather large value of the forbidden zone width (4.6 eV for boron nitride; 6.2 eV for aluminium nitride and 4.1 eV for silicon nitride) determine a high value of electric resistance (up to $10^{16} Ohm \cdot cm$) and the total combination of the above characteristics determine their high radiation resistance.

Table 1: Properties of refractory nonmetallic nitrides

Parameter	Materials		
	silicon nitride	aluminium nitride	boron nitride
Bending strength, MPa	600-800	100-400	150-200
Compression strength, MPa	2500	500-1500	300
Decomposition temperature, K	2170	2720	2970
Thermal conductivity, W/m K (at 293 K)	25-60	40-140	15-30
Thermal expansion, $10^{-6} K^{-1}$	2.2	4.0	0.5-1.7
Electric resistance, Ohm.cm (at 293)K	1.10^{15}	1.10^{13}	$2 \cdot 10^{13}$
Electric strength, KV/mm	12	5-8	2-4
Swelling after irradiation, % ($\phi \sim 10^{21} n^0/cm^2 s$)	0.3	—	—

To develop the assembly technology of coils structural elements and to evaluate the possibility to manufacture full-scale constructions a series of experiments on manufacturing of scale models have been undertaken. A permanent gap between the magnet coil turns and a rigid joint of coil turns into a monoblock unit are provided by structural spacers from ceramics on the basis of silicon nitrides and aluminium oxide. During coils assembly two variants if joining the ceramic spacers with capper conductors have been tested: soldering by metallic solders and glueing by an epoxy compound with a filler. The main problem to be solved in soldering was a considerable difference in thermal expansion coefficients of soldered materials (thermal expansion coefficient of copper is $19.3 \cdot 10^{-6} K^{-1}$; silicon nitride — $2.2 \cdot 10^{-6} K^{-1}$; aluminium oxide — $4 \cdot 10^{-6} K^{-1}$;). The investigations were performed in two directions: metallization of ceramics based on plastic materials and subsequent soldering by low-temperature solders, as well as high-temperature soldering by active solders.

High-temperature soldering without pre-metallization by active solders with a compensator from plastic materials showed promise in developing the soldering technology. A solder based on titanium and niobium with a silver additive and a fluoroplastic interlayer has been tested. Soldering of copper buses with plates from silicon nitride and aluminium oxide has been performed. Solder is strong, weld is plastic spread of the solder is good. This method of joining provides the required ruggednes of the construction, but the control over electrical insulation between the turns is required, as the solder may spread over ceramics. It is necessary to weigh out the amount of the solder and to grind solder traces on the ceramics ends after soldering. The method of joining the copper buses with ceramics by an epoxy compound with a boron-nitride filler is free from the above disadvantage. Vacant gaps were filled with a lute from modified liquid glass or an epoxy compound with fillers from boron nitride or silicon nitride powders. Then the coils were wrapped with glass cloth and impregnated with a decorative protection layer.

II. DIELECTRIC COVER OF ALUMINIUM CONDUCTORS

Among the adaptable to streamlined production methods is the method of aluminium anode oxidation in chemically moderate-active electrolytes. The fact, the coating and substrate are chemically similar, results in formation of a low-stressed system resistant to mechanical and thermal conductivity of up to 30 W/m K. The growth of oxide films results from inner oxidation processes practically not changing the product geometry. Oxide films with 100 μm

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endure without damages thermal loads of up to 600 K.

Anodizing of aluminium buses in the oxalic acid solution allowed oxide films with a thickness of up to 100 μm to be obtained. Electrical strength of the coating amounted to 3 kV. Electroinsulating varnishes and siloxane sealing compounds were used as an additional electric insulation monolithic seal and moisture-protection coatings. Glyptal epoxy and organosilicon varnishes were chosen for testing. The best results were obtained with glyptal varnishes, thin films of which (80-100 μm) were applied to the aluminium buses with an oxide coating. Adhesion of films to the substrate is satisfactory. Electrical strength amounted to 25 kV/mm.For sealing compounds used to impregnate the constructions with narrow deep gaps (of accelerator coils type) critical is toughness determining the impregnability of a material. Sealing compounds based on liquid low-molecular siloxane rubber possess stable easy-to-manufacture properties with long-duration operation in a wide temperature range, preserve elastic properties for 2500 hours at 500 K, they are water-repellant, wet aluminium and its alloys well, have an electric strength of 6 kV/mm.

Model units compressing 9 and 18 alluminium buses were manufactured. Before being assembled the buses were anodized to obtain an oxide film 100 μm thick and impregnated by glyptal varnish. Then the buses with an assured gap (1 mm) were placed in a casing or fixed between each other by ceramic spacers 1 mm thick and the assembly was potted with a sealing compound. Tests for electric strength of the coils scale model showed the turn-to-ground and turn-to-turn insulation to withstand voltages of more than 6 kV.

In the technology of building up the protection coatings on aluminium and its alloys tested was the enamelling method based on a partial melting of glass powder uniformly distributed over the product surface. To apply dielectric coating to aluminium buses a low-fusible lead-borate glass (($T_{melt} \sim 720K$) with a thermal expansion coefficient of $\sim 13010^{-7}K^{-1}$ was chosen. The coating width amounted to 0.5-0.6 mm. The tests revealed, that the enamel coating had an electric strength of 8-10 kV per coating width.

III. METALLOCERAMIC COMPONENTS OF ACCELERATING FACILITIES

A number of metalloceramic units and components, such as vacuum ceramic chambers, electric decouplings, current leads etc, is used in accelerating facilities. To manufacture these components a superhigh-pure nonmagnetic vacuum-tight aluminium is used.

Vacuum ceramic chambers were assembled from segments up to 1000 mm long. The ceramic segments were soldered by fine-dispersed glass-ceramic solders, which provided vacuum tightness and required strength characteristics of the joint. The inner surface of the chamber was metallized by molybdenum-content pastes with the following firing-on, as well as by using the method of vacuum or plasma spraying of metallic films from titanium, copper, niobium and other metals. With the chamber surfaces treated mechanically quality 3 and asperity according to $R_a V0.025$ were achieved.

Ceramic vacuum chambers with different cross-sections, wall thickness and length were manufactured. On the chamber ends metal adapters were soldered to provided joining with the flanges. Tests performed showed, that the chamber ➤ ensured the vacuum inside the volume of up to 10^{-12} torr without pre-training and warming-up.

Ceramics, stainless steel, copper conductors should be used in the structure of the vacuum-tight joint in such metalloceramic units, as current leads and decouplings. The elements in the ceramic units were joined both by metallic solders with plastic additives and various glass-fiber reinforced cements. Tests performed revealed, that the metalloceramic units preserved vacuum-tightness of joints at room and cryogenic temperatures.

IV. CONCLUSION

The properties of ceramic materials of a nitride class have been analyzed. Ceramics based on silicon nitride and aluminium oxide is proposed to be used as a turn-to-turn insulation for electromagnet coils. Metallic solders have been chosen for a rigid joint of structural elements of copper buses. The regime of aluminium bus anodizing has been developed making it possible to produce anode-oxide films of a large thickness (up to 100 μm) with an electric strength of more than 3 kV. The properties of impregnating and sealing compounds have been tested, which allow for a qualitative potting of structures with narrow deep gaps. The scale models of the coils with the chosen insulation materials have been manufactured and tested for electric strength. The materials satisfy the requirements for electric strength. The ceramic vacuum chambers with inner metallization, as well as various metalloceramic elements complying with the operation condition for accelerating facilities have been started to be manufactured.