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BONDED STACKED-RING INSULATOR FOR THE ANTARES ELECTRON GUN

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INTRODUCTION

Antares is a high energy CO₂ laser under construction at the Los Alamos National Laboratory as part of the Inertial Confinement Fusion Program.

The electrical discharge in the laser gas is controlled by a low-current-density, large-area electron beam. The beam is produced by a cold-cathode, grid-controlled electron gun (Fig. 1) operating at voltages up to 500 kilovolts (kV). The coaxial cathode/grid assembly is 7.7 m long and weighs approximately 3000 kg. This assembly is supported at each end by bonded stack-ring insulators. The insulator between the cathode and grid is 81 cm diameter and 25 cm long, made up of six bonded sections; the unit between the grid and anode is the same diameter but 48 centimeters long and made up of 12 bonded sections. Both of these insulators are shown in Fig. 2. Between the two bushings is the grid connection ring. The insulator construction consists of 3.2 cm thick epoxy rings, bonded to .6 cm thick aluminum rings (Fig. 3). This bonded construction eliminates the multiple "O" rings and tie rods which are frequently used in high voltage insulators and also simplifies the support of the grid/cathode assembly in the electron gun shell (Fig. 4). Transformer oil fills the interior of the insulator, while the outside of the insulator has a 10^{-7} torr vacuum environment.

We have fabricated two complete sets of insulators for two Antares electron guns. One set has been installed in an electron gun which has been fired over 2000 times at voltages from 350 kV to 500 kV. In the following sections we describe the mechanical and electrical design and the fabrication techniques for these insulators.

MECHANICAL DESIGN

The insulators support a weight of 2950 kg (6,500 lbs.) resulting in bending stresses of .69MPa (100 psi) and shear stresses of .34MPa (50 psi) in the bond joints. In addition, there is an unknown shock load caused by the discharge.

In an effort to find the best material for the insulating rings, three impact and three tensile specimens were made of each of fourteen different formulations. The impact strengths ranged from .23 to .76 J/cm (.43 to 1.43 foot-lbs./in.). The selected formulation consisted of Epon 828, Armstrong flexibilizer and DEA. No filler material was used. The mechanical properties of this material are .73 J/cm (1.37 foot-lbs./in.) impact strength and 75.6 MPa (10,959 psi) tensile strength. The material was cured at 75°C for 16 hours. Additional samples were given a postcure of 140°C for 6 hours, and these averaged .76 J/cm (1.42 foot-lbs./in.) and 80.0 MPa (11,602 psi).

Having selected the material, efforts were focused on developing a workable fabrication technique. The rings were cast in thin fiberglass molds and machined to size. After initially experiencing significant breakage during machining, the residual stress pattern of the rings was examined using polarized light. Slow cooling of the rings over a 16 hour period resulted in a much improved residual stress pattern. In addition, a fixture was developed that held each ring with uniform pressure around the inside diameter during the machining operation. Using Cimcool as a lubricant, a cut of 3 mm (.12 in.) and a feed of 25 μ m (.010 in.) reduced the breakage of these slowly cooled rings to about 5 percent.

BONDING OPERATION

The bonding operation was performed in four basic steps: (1) surface preparation, (2) application of adhesive, (3) fixturing, and (4) cleanup. A fixture which held the epoxy and aluminum rings concentric within the prescribed tolerance of 0.030" was designed and fabricated. It also provided contact pressure of ~ 12 psi during the epoxy adhesive cure.

Surface preparation of the aluminum rings prior to adhesive bonding consisted of: (1) vapor degreasing, (2) bead blasting with glass beads at 80 psi pressure, and (3) acid etching for 10-15 minutes in chromic-sulfuric acid at 150°F followed by a water rinse and drying. The epoxy rings already had roughened surfaces from machining and were cleaned by solvent wiping with acetone.

The epoxy adhesive formulation was Epon 828 cured with Versamid 140 in a 1:1 ratio by weight. This formulation was chosen because of past experience regarding its adhesion to aluminum/epoxy, its reliability, viscosity, pot life, and the fact that it cures at room temperature within 24 hours. Adhesive was applied to both the aluminum and epoxy ring surfaces with a brush, the rings were assembled, and uniform pressure was applied to the joints by calibrated springs in the fixture. Considerable squeeze-out of adhesive occurred immediately after pressure was applied and continued for some time. Cleanup was started immediately on both the inside and outside surfaces of the stack. Acetone-damp rags were used, with care taken not to saturate the still-wet adhesive bond lines with solvent.

It should be noted that a maximum of four epoxy and four aluminum rings were bonded at any one time in the fixture. This allowed completion of all the bonding operations within the pot life of the adhesive.

Ultimate stack height is controlled to some extent by careful measurement of all individual components prior to assembly. Bond line thickness appears to be less

than 0.001" on each ring surface, but an accurate determination has not been made because of dimensional variations in the components. Final stack height and parallelism was achieved by bonding the stack slightly over-height and then machining the top insulating ring prior to bonding the top flange.

ELECTRICAL DESIGN

The Antares electron gun must withstand approximately 300 kV between the cathode and grid for the first few hundred nanoseconds until the cathode blades begin to emit. Once the gun begins to draw current, the grid voltage rises to within a few tens of kilovolts of the cathode voltage. Thus, the majority of the gun voltage appears between the grid and anode during the 5- μ s pulse width (across insulators 1 and 4, Fig. 1). The cathode voltage wave shape (Fig. 5), shows the initial voltage spike when blade ignition occurs, the rise to peak and the chop of the tail when the voltage is diverted.

As is common with many other high-voltage vacuum devices (accelerators, x-ray tubes, etc.), the weakest link per unit length in voltage holdoff strength is surface flashover of the vacuum insulators. To achieve a maximum safety factor in flashover strength, as well as provide a simple mechanical configuration, a stacked-ring bonded insulator design was chosen.

The primary factors affecting the surface flashover of a stacked-ring vacuum insulator are the pulse shape (risetime and width), the insulator material, the thickness of the insulator rings and the angle that the dielectric makes with the field [1], [2], [3]. The pulse parameters were fixed by gun performance requirements. The other variables were established by tradeoffs between surface flashover, mechanical strength and fabrication considerations.

Mechanical and fabrication aspects suggest that a minimum angle should be used to give a maximum bond joint width for a given chosen insulator width, and that a maximum insulator thickness is desired to give a minimum number of bonding operations.

The insulation material has been shown to have a flash-over voltage of ~ 225 kV across a 1.27 cm sample with an angle between the field and insulator surface of 45° and a pulse risetime of $5 \mu\text{s}$ [3]. The broad maxima of flash-over voltage as a function of angle for various insulating materials, as given by Milton, indicate that the flashover voltage for epoxy at 35° should not be significantly different from that obtained at 45° . Also, his data indicates that the flashover field for a constant angle varies as the inverse square root of the insulator thickness.

With the above constraints and data points in mind, an initial design was selected which had an insulation thickness of 3.2 cm and an angle of 35° .

To obtain an approximation of the insulator material vacuum flashover characteristics under pulsed conditions, a series of tests on small epoxy ring samples was conducted. In all cases the angle on the vacuum side of the test specimen was maintained at 35° . Three sample thicknesses were tested: 1.27 cm, 1.9 cm, and 3.175 cm. The applied voltage had a risetime of approximately 100 ns and a $6 \mu\text{s}$ RC decay. The voltage was raised in small steps to assure that the flashover always occurred on the pulse decay. The vacuum surface flashover voltage and average field for the three sample thicknesses is shown in Fig. 6.

Static field plots of the final stacked-ring insulator configuration were made to determine the worst case field. This was compared with the sample test results to give an approximation of the operational safety margin. The highest field occurs at the ground (anode) end of the No. 1 insulator and is approximately 35 kV/cm (Fig. 7). This field is approximately a factor of 4 below the flashover stress of the 3.175 cm sample. The static field distribution across the entire bushing is forced by the electron gun geometry and the presence of metal rings in the stacked-ring bushing configuration was found to have only a slight effect.

CONCLUSION

In conclusion, we have developed a large diameter insulator utilizing epoxy bonding which has sufficient mechanical strength to support the 3000 kg cathode/grid assembly. Bonding the insulator simplifies the handling and reduces the number of O-ring seals to a minimum. We have described the material selection, bonding techniques and electrical design approach.

- [1] I.D. Smith, "Pulse breakdown of insulator surfaces in a poor vacuum," Proc. 1st Int. Symp. Insulation of High Voltages in Vacuum, p. 261, Oct. 1964.
- [2] A. Watson, "Pulsed flashover in vacuum," J. Appl. Phys., vol. 38, p. 2019, 1967.
- [3] G. Milton, "Pulsed flashover of insulators in vacuum," IEEE Transactions on Elect. Insulation, vol. E1-7, No. 1, p. 7-15, March 1972.

Fig. 1. Antares electron gun configuration.

Fig. 2. One end of cathode with grid/anode and grid/cathode insulators installed.

Fig. 3. Insulator construction.

Fig. 4. Grid/cathode assembly, including insulators being inserted into vacuum shell.

Fig. 5. Cathode voltage wave shape.

Fig. 6. Flashover voltage and average field for three insulator thicknesses.

Fig. 7. Typical field plot of highest stress insulator.