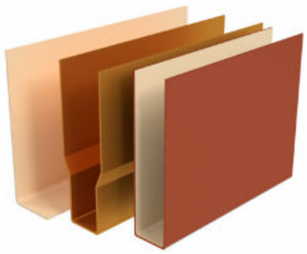
THE GUND COMPANY

MANUFACTURERS & FABRICATORS OF ENGINEERED MATERIAL SOLUTIONS

Generator Slot Liner Selection Guide



What is a Slot Liner?

A slot liner is a primary insulation component in a generator rotor, which provides an insulation barrier between the copper windings and the rotor forging.

The slot liner's primary role in the rotor is to protect the winding from an electrical ground during operation. It must also be strong enough to withstand the physical wear and tear of the assembly process during winding. During operation, the slot liner will endure large centrifugal forces of generator start-up, steady state, and shutdown. Additionally, the slot liner will experience a wide temperature variation, from ambient conditions up to 130°C in operation, depending on the design.

Generator slot liners are typically made of a composite construction. The composite layup of different materials provides both electrical and mechanical properties to meet the specific demands of the application. The following selection guide will provide information on the different constructions available, the unique advantages and disadvantages of each, and tips for best practices in slot liner design in order to help engineers make more robust slot liner insulation specifications.

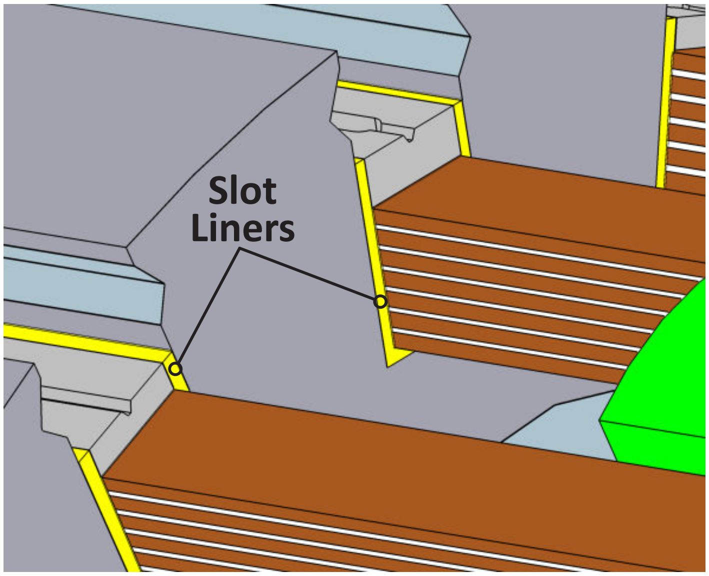
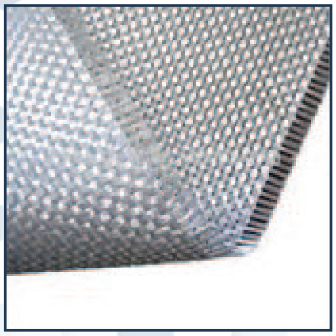


Figure 1 - Location of slot liners inside a rotor

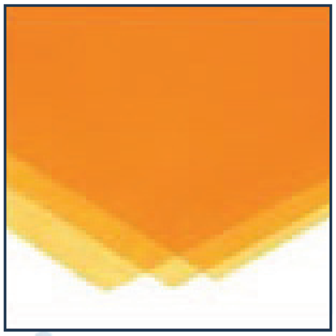
Slot Liner Construction

There are many choices of materials that can be used to build a composite slot liner. The most common materials used are:

Woven Glass Fabrics



Polyimide (i.e., Kapton®)

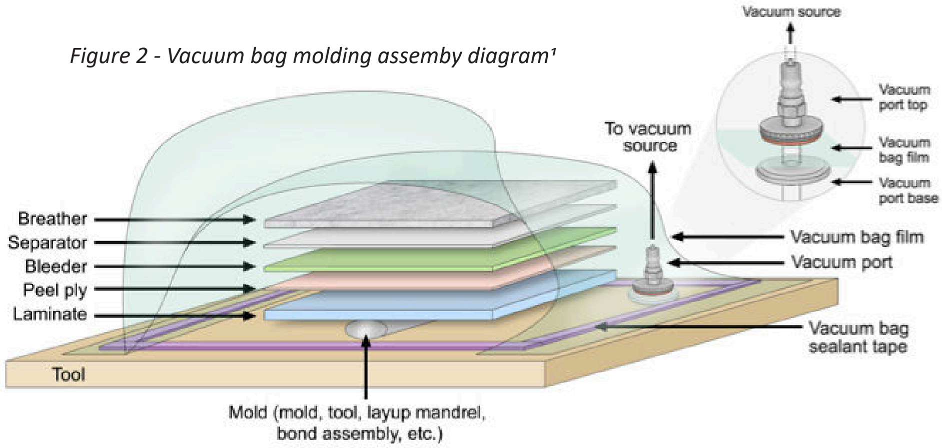


Aramid Paper (i.e., Nomex®)

High Temperature Epoxy Resin

Each of these materials has specific electrical and mechanical properties that create a unique set of characteristics when combined during the slot liner composite fabrication. Epoxy has historically been used as the primary adhesive in slot liner composites due to its high-temperature electrical and mechanical properties. Woven glass fabric is often pre-impregnated with the epoxy resin and stabilized for further processing. This material is commonly known as glass-epoxy prepreg or b-stage. When heated and put under pressure, the epoxy prepreg resin will flow and bond the composite laminate layers.

Figure 2 - Vacuum bag molding assemby diagram[1]



Several methods can be used to mold slot liners, including compression molding, bladder molding, vacuum bag molding (see Fig. 2), and autoclave molding. Methods that incorporate a vacuum, such as vacuum bag molding and autoclave molding, will typically produce composites with fewer voids and greater uniformity.

When properly used, a vacuum will evacuate entrapped air within the layers of the composite and produce a composite with higher electrical and mechanical performance and fewer defects.

The construction of the composite laminate and the pressing operation will determine the final properties of the slot liner. As previously mentioned, the glass epoxy b-stage acts as the laminate's backbone while other materials enhance the electrical and mechanical properties. For example, aramid paper provides tear resistance. Polyimide film provides puncture resistance and also increases dielectric strength.

Some typical constructions for slot liners are listed in the table below, along with the relative characteristics of each:

Type	Construction Type	Relative Cost	Installation Toughness	Mechanical Strength	Flexibility	Dielectric Strength	Thin Wall (<0.030")	Thick Wall (>0.030")
O	All Epoxy Glass (EG)	$	Low	High	Low	Low	X	X
I	EG - Nomex® - EG	$$	Medium	Med-High	Medium	Medium	X	X
II	Nomex® - EG - Nomex®	$$$	Med-High	Medium	Med-High	Medium	X	X
III	Glass - Nomex® - EG- Polyimide - EG - Nomex® - EG	$$$$	High	Medium	Med-High	Med-High		X
IV	Nomex® - EG - Polyimide - EG - Nomex®	$$$$	High	Medium	Med-High	High		X
N	Nomex®	$$	Medium	Low	High	Medium	X	

Typically slot liners will be designed in either an L or U format. If an L format is used, two Ls are used to make a U shape by having them in opposing directions. The rotor slot diagram (see Fig. 3) shows two L slot liners used along with sub-slot insulation. Sub slot insulation is placed at the bottom of the slot providing insulation between the windings, and the rotor forging.

If a full U shape format is used, the sub slot insulation does not have to be used since there is no gap to fill. The U format is more common with smaller rotors since mold costs increase, and manufacturability decreases considerably at longer lengths, making it more difficult to specify the U format for larger rotors. Each "type" of construction can be used for various wall thicknesses. The above table shows what range of thickness the market tends to use broken down into a "thin wall" or "thick wall," with 0.030 inches (0.77mm) being nominal.

The overall fit within the slot is very important when designing and producing slot liners. If the slot liners do not mate up to the shape of the slot, specifically the radius of the slot, the force of the coil will easily crack or sever any liner once in operation. Likewise, if the liner shape does not match the initial layer of copper's shape, the likelihood of failure increases tremendously. One common failure occurs when slot liners are not straight. This results in damage to the slot liner when winders struggle to install the copper in the slot. A second common failure occurs when the liner angle is incorrect and bends inward towards the slot opening. This failure typically results in damage to the ends of the slot liner during the winding process.

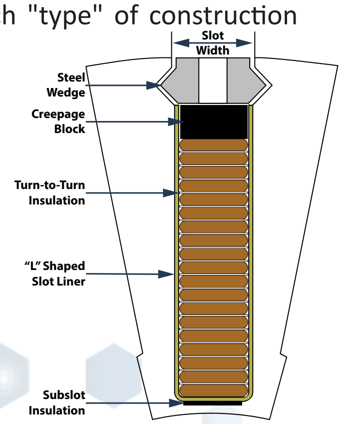


Figure [3] - Rotor Slot Diagram

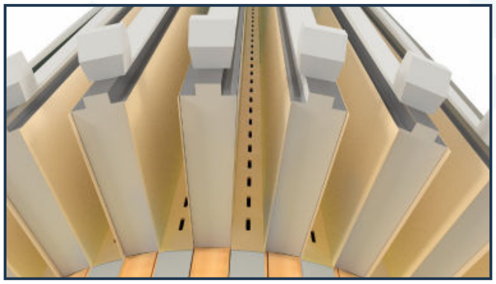


Figure 4 - slot machined into slot liner

Another typical enhancement found in many slot liners is low-friction materials that are applied to the inside surface. Low friction additives such as PTFE can be applied to the slot liner's inner surfaces to allow copper coils to slide easily into the liner without damaging the insulating material. Some PTFE materials can be bonded onto the liner to create a permanent slip plane that can increase liner life by decreasing friction wear during generator cycling.

Lastly, slot liners can be vented with holes in the bottom to match the rotor's cooling slots. Some ventilated rotor coils require slot cells with ventilation slots that must be carefully measured to match up with the copper coils and rotor slot vents. The axial growth of the copper and abrasion against the insulation can cause ventilation slots to be partially covered, potentially causing localized hot spots in the rotor. Ventilation hole designs must consider the movement of the copper in order to prevent the ventilation holes from being blocked.

Typical Testing and Properties

Many of the tests performed on slot liners are primarily for electrical and mechanical purposes. These tests typically follow ASTM or ISO standards. Additional tests on the slot liners are performed outside of ASTM and ISO standards for other operation and quality reasons.

Electrical Testing

- **Dielectric Strength** – ASTM D149 Method B with a choice of electrode shape and diameter.
- **Voltage Endurance** – Electrode sizes are called out and referenced to ASTM D149, and the test is conducted to determine if partial discharge occurs on the surface of the slot liner over a period of time when a specified voltage is applied.
- **Voltage Withstand (Hipot)** – Electrodes can be designed for a pass-through test or full slot liner test. The test was designed to detect flaws or weak spots in the liner.
- **Electrical Creepage** – Measures the resistance to forming a current path across the material's surface or around an edge. It is tested by applying a voltage across two electrodes on the sample surface and then gradually increasing the voltage to a specified maximum current flow.

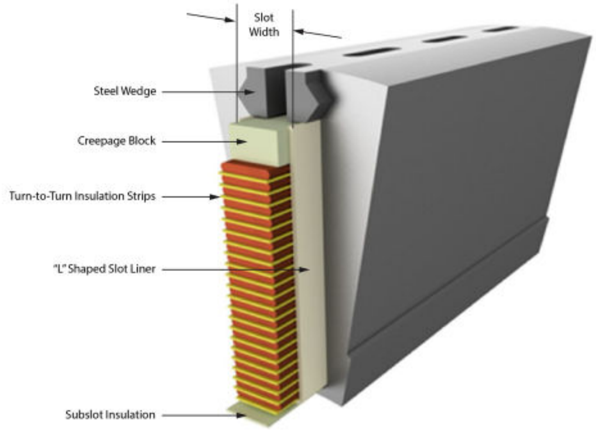
Mechanical Testing

- **Impact Resistance** – ASTM D5420 and a specific striker diameter called out to be used in the test.
- **Flexural Strength** – ASTM D790 or ISO 178 with specific instructions called out.
- **Flexural Modulus** – ASTM D790 or ISO 178 with specific instructions called out.
- **Water Absorption** – ASTM D570.
- **Tensile Creep** – ASTM D2990 with a high tensile load for an extended period of time at temperatures near the typical rotor operating temperature.
- **Static Coefficient of Friction** – ASTM D1894.
- **Shrinkage in the Length Direction** – Conducted to see if shrinkage occurs after a high temperature is applied to a sample for an extended period of time. A sample is measured before and after temperature application to calculate a percentage of shrinkage.
- **Thermal Endurance** – Can be done in accordance with ASTM or ISO standards, but generally, a group of multiple samples are placed in an oven at the high end of the operating temperature for up to 8 weeks. Samples are removed each week and tested to see how they perform mechanically.
- **Resistance to Compressive Buckling, Ball-On-Cavity Compression Test, and Shear Test** – These tests are less common but are used to test the slot liners' ability to withstand the stresses of field assembly.

What construction is right for your design?

The construction of a slot liner depends on the type of rotor that one is designing or repairing. OEM's and repair companies have different requirements. The operating environment of the liner will influence the materials used in the composite. In any case, the design variations are nearly endless. From simple liners for small rotors to large, complex liners with venting, TGC can help with the fabrication of almost any design. Our aerospace-grade autoclave process produces the straightest void-free slot liners in the world.

Be confident in your selection of RotoGuard® slot liners, and contact one of our customer service specialists today to see how we can help you with your needs.



RotoGuard® Rotor Insulation

For more information on Rotoguard® slot liners, please visit https://thegundcompany.com/rotoguard

For more details on The Gund Company, go to https://thegundcompany.com/

References:
1."Composites Technology - NSC STEM Pathways". Open Learning Initiative. 2020: https://oli.cmu.edu/courses/composites-technology-nsc-stem-p`athways/.

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Item:	RotoGuard® Slot Insulation	
Description:	RotoGuard® Slot Insulation from The Gund Company is a high performance glass epoxy laminate. It can be produced in five standard constructions as well as custom constructions. The aerospace manufacturing technology used to produce this insulation provides uniform, high quality thickness and straightness down the entire length of each part. Every part is 100% inspected for quality and can be hipot tested up to 20kV.	

Dimensions:			
	Standard Inside Radius	.100” +/- .010”	2.54 +/- .25 mm
	Radius Range Available	.027” - .125”	.7 - 3.2 mm
	Angle	90 +/- 3° Standard	
	Max Leg Dimensions	7” x 1.8” +/- .008	177.8 x 45.7 +/- .2 mm
	Available Thickness	.030” - .125” +/- .003”	.78 mm - 50.8 mm +/- .076 mm
	Shapes	Standard “U” and “L” shapes are available. Custom shapes available upon request.	

Construction:		
	Type O	All Epoxy Glass
	Type I	Glass - Nomex® - Glass
	Type II	Nomex® - Glass - Nomex®
	Type III	Glass - Nomex® - Glass - Polyimide - Glass - Nomex® - Glass
	Type IV	Nomex® - Glass - Polyimide - Glass - Nomex®
	Type N	Nomex®
	Special Requests	Custom construction available to meet most customer requests

Key Characteristics [1]	Units	Test Method	Condition	Type 0	Type I	Type II	Type III	Type IV	Type N
Apparent Density	g/cm¹	ASTM D-792	A	2.0	1.7	1.7	1.6	1.7	1.08
Water Absorption	%	ASTM D-570	D-24/23	0.4	1.3	4.0	1.5	3.7	-
Tensile	ksi	ASTM D-638	A	32.9	26.6	18.3	26.0	17.5	15.6
Flexural Strength	ksi	ASTM D-790	A	87.70	54.70	50.60	65.20	60.10	-
			E-1/160 T160	46.60	50.60	32.70	52.50	41.40	-
Dielectric Strength	V/mil	ASTM D-149	A	1,050	1,050	1,400	1,200	1,200	680
Permittivity	-	ASTM D-150	A	4.6	4.2	3.8	4.2	3.8	3.7
Dissipation Factor	-	ASTM D-150	A	0.03	0.02	0.02	0.022	0.02	0.007
Compressive Strength (1/2”)	ksi	ASTM D-695	A	-	-	40	48	-	-
Thermal Conductivity	W/(m.K)	ASTM E-10461	-	0.25 - 0.21	0.23- 0.19	0.25 -0.21	0.25 - 0.21	0.24 - 0.20	0.20 - 0.14
Comparative Tracking Index	-	IEC-60112	-	200	200	250	200	250	250

[1] Indicates a thickness of 0.050”