DESIGN OF LIGHTWEIGHT PERFORATED COPPER FOIL FOR LIGHTNING PROTECTION OF FIBER REINFORCED PLASTIC

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1. ABSTRACT

Expanded foil wide area conductors have been successfully applied on the exterior of fiber reinforced plastic skins for protection from lightning strike. These materials have provided adequate protection to the vehicle, but the weight penalty of covering large regions of the skin surface is impactful. Very thin, lightweight, wide area foil conductors have been developed and embedded into lightweight epoxy surfacing prepregs to provide strike protection with significantly less weight penalty to the vehicle. This paper reviews the design, construction and test results achieved for conductors that have been designed in a digital environment and fabricated by plating and/or laser cutting to the digital definition.

2. ACRONYMS AND SYMBOLS

FRP = fiber reinforced plastic
LSP = lightning strike protection
r = radii
Ω = Ohm
mΩ = milli-Ohm
□ = square, unitless
µm = micro-meter

3. BACKGROUND

Fiber reinforced resin matrix composite materials are used in airplanes, wind generators, automobiles and other applications where stiff, light-weight materials, or parts consolidation are beneficial. The fibers are often made of carbon, glass, ceramic or aramid, and the resin matrix is an organic thermosetting or thermoplastic material. These composites are generally semi-conductive or insulating to electric current. To protect against lightning damage, a manufacturer often provides a low resistance pathway within the external skins to move the energy in a strike from one strike location to the other. Metallized materials have been used on the exterior surfaces of composite parts to provide the necessary electrically conductive region. Typical metallized materials include metal woven fabric, random non-woven mat, solid foil, and foraminous metallized sheet.

LSP material on the exterior of an aircraft is expected to:

- provide to the underlying composite structure a necessary measure of protection from strike induced damage,
- enhance the electrical conductivity of the underlying composite structure as required to support the enclosed systems,
- impact the weight of the aircraft minimally,
- conform to the contoured exterior surfaces,
- provide smooth, pin-hole free, paintable surfaces,
- resist corrosion and damaging effects from a suite of fluids and environments,
- integrate into the fabrication processes of the underlying composite structure, and
- be repairable.

Several of these objectives are exclusively or substantially controlled by the resin in the system. The resin-controlled objectives were not examined in this study.

A previous work, Engineered Lightning Protection Conductor [1], examined a design analysis approach to assess the conductivity, tear strength, conformability, weight and thermal expansion of candidate foraminous conductive foils using digital simulation software.

4. INTRODUCTION

Exterior surfaces of aircraft structure are made to be smooth and pin-hole free to provide an aerodynamic friendly painted surface that is appealing to the customer through the vehicle’s life cycle. Perforated foils are used as large area conductors on the exterior surfaces of FRP skins but because of their foraminous nature, they must be filled with a resin to create the surface quality expected. Thick foraminous foils require more resin to fill completely the voids generated by the foil perforation process than do thin foraminous foils. This creates an interdependency between the foil geometry and the amount of resin filler, which affects weight of the airframe; therefore, they are considered here together as a system. Some FRP part manufacturers apply the conductor and filling resin separately in the part fabrication process, but some manufacturers bring the conductor and filling resin together as an impregnated LSP surfacer prior to application. For purposes of this study, the system of the conductor and filling resin is referred to as an LSP surfacer, regardless of the method by which they are applied in the manufacturing process.

The demands on the conductor of an LSP surfacer vary greatly from application to application. The level of acceptable damage to the underlying structure varies with the location of the damage on the aircraft, and the function and composition of the structure. The required electrical conductivity of any protective conductor varies with the demands and proximity of the enclosed systems. Conformability is an important characteristic of a large area conductor for draping on skin surfaces with curvature in more than one plane. It is generally desired to optimize the lightning protection and the weight penalty.

The goal of this work was to fabricate and test alternative conductors which have been designed for possible improvement to existing conductors for LSP surfacers. This work seeks to build on the design analysis presented in a previous work, Engineered Lightning Protection Conductor [1], to exemplify conductive foils for LSP surfacers that have perforation patterns not constrained by traditional punch-and-stretch, or weaving fabrication processes. Foraminous foils with perforation patterns illustrated in Figure 1 and Figure 2 were fabricated by plating or lasing directly to the desired shape. These examples were compared to foils having patterns illustrated in Figure 3 that were fabricated by punch-and-stretch methods. The thickness and size parameters used in this study were chosen from an earlier analytical design work [1] to demonstrate a range of potentially useful parameters and are not intended to express limits of the fabrication technologies.

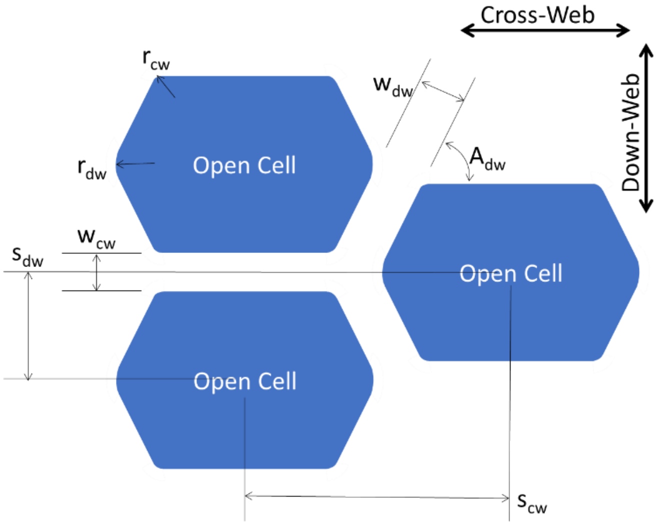


Figure 1 Rectangular / Hexagonal perforation patterns

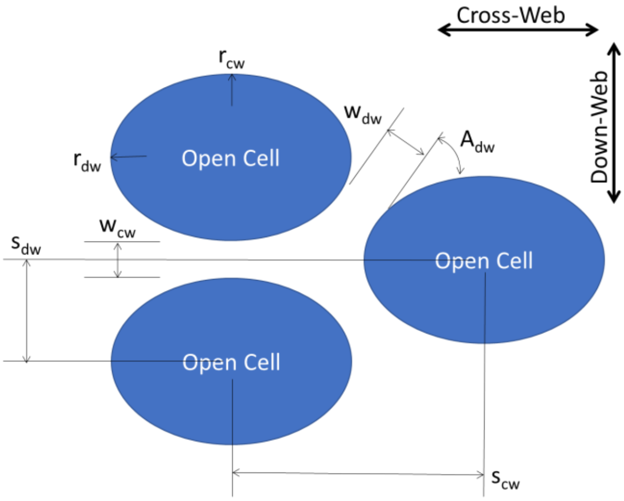
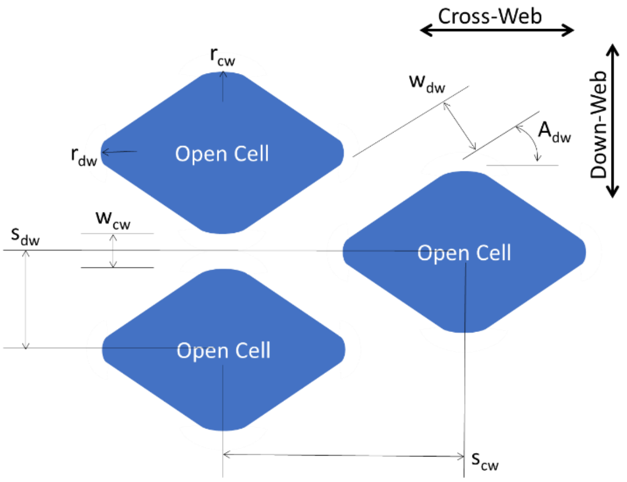


Figure 2 Oval / Circular perforation patterns

Figure 3 Diamond / Marquis perforation patterns



Although there are several materials found to be suitable for LSP conductors, such as copper, aluminum, and bronze, only copper was evaluated in this study.

To accomplish the goal of this work, it is necessary to select protection criteria that provide differentiation among the conductor configurations tested. Where lightning is concerned, the concept of protection is characterized with many criteria. For this work, protection was characterized as electrical conductivity (or resistance) of the LSP conductor, and as the ability to minimize damage to the underlying composite part. Damage to the underlying part was defined in terms of the depth and area of damage to the underlying composite structure.

The threshold for each criterion cannot be determined independent of the specific application of the LSP surfacer; therefore, general principals were applied to guide the selection. Minimizing electrical resistance was considered desirable improvement for protection of electrical systems. Minimizing both depth of damage and the area of damage to the underlying composite structure was considered desirable for protection of structure and other systems.

Standardized testing for evaluating lightning strike protection of structure has been developed. These tests require the specimen be subjected to a simulated strike. Industry accepted simulated strikes are described in ARP5412 [2] and ED-84 [3]. Strike profiles were chosen to represent regions of the aircraft as described in ARP5414 [4] and ED-91 [5]. For this study, weight minimization was a significant selection criterion. To maximize the benefit of any weight improvement opportunities, the test waveform was chosen to represent the largest surface area of the airframe. For transport aircraft, Zone 2A [4][5] covers the greatest amount of surface area.

5. CONDUCTOR CONFIGURATIONS

Copper foil conductors having perforations shaped as circles, diamonds, hexagons, and elongated hexagons were fabricated and evaluated in LSP surfacers. The geometric parameters of each perforation pattern are listed in Table 1.

Table 1 Conductor Patterns

Pattern[i]	Cell Spacing (mm) S_{dw}	Cell Spacing (mm) S_{cw}	Strand Width (mm) W_{dw}	Strand Width (mm) W_{cw}	Radii (mm) R_{dw}	Radii (mm) R_{cw}	Strand Angle A_{dw} (°)	Open Area (%)
Circle 97.10a	1.78	3.05	1.53	1.56	1.27	1.27	60	38
Circle 97.10b	1.78	3.05	1.53	1.56	1.47	1.47	60	44
Circle 97.23	1.73	1.00	0.86	0.86	0.57	0.57	30	29
Diamond AE175	1.36	2.54	N/A	N/A	0	0[ii]	28	55
Diamond AE142	1.40	2.54	N/A	N/A	0	0[ii]	29	84
Diamond AE73	1.23	2.54	N/A	N/A	0	0[ii]	26	84
Hexagon 97.7	2.10	4.00	1.88	1.88	0.1	0.1	60	34
Hexagon 97.8	1.80	3.11	1.05	1.05	0.1	0.1	60	50
Elongated Hex 97.38	1.80	3.75	0.65	0.80	0.4	0.1	51	59
Elongated Hex 97.20	1.25	2.13	0.78	1.36	0.1	0.1	38	37

These patterns were perforated into copper foils of thicknesses ranging from 12 µm to 76 µm. Direct-pattern electroplating, as described in [6], was used to fabricate foils having circular and hexagonal shaped perforations with tin binding layers on each face. Foils having perforations shaped as circles and elongated hexagons were fabricated by lasing the patterns directly into treated copper foils as described in [7]. The foils having diamond (marquise) shaped perforations were fabricated by Bender GmbH applying punch-and-stretch forming methods to copper foil. The resultant conductors are described in Table 2.

Table 2 LSP Conductors

Conductor	Pattern	Fab Process	Foil (µm)	Weight (gsm)	Resistance (mΩ/□) Cross -web	Resistance (mΩ/□) Down -web
C10a-20	Circle 97.10a	Plate	20	110	1.5[iii]	1.5[iii]
C10b-20	Circle 97.10b	Plate	20	100	1.5[iii]	1.5[iii]
C23-18	Circle 97.23	Lase	18	115	1.9	3.4
AE175	Marquise AE175	Expand	45	175	1.3	3.7
AE142	Marquise AE142	Expand	76	142	1.6	4.8
AE73	Marquise AE73	Expand	51	73	3.1	12
H7-12	Hexagon 97.7	Plate	12	69	2.8[iii]	2.8[iii]
H7-16	Hexagon 97.7	Plate	16	93	2.1[iii]	2.1[iii]
H7-25	Hexagon 97.8	Plate	25	108	2.0[iii]	2.0[iii]
EH38-18	Elongated Hex 97.38	Lase	18	60	3.1	6.0
EH38-33	Elongated Hex 97.38	Lase	33	115	1.6	3.2
EH20-17	Elongated Hex 97.20	Lase	17	96	1.8	3.1

6. TEST SPECIMEN FABRICATION

6.1 Lightning Strike Protection Surfacer

The perforated conductor foils were laminated into B-staged epoxy films for use as a LSP surfacer on the test panels. The thick foils generally required thick epoxy films to fill completely the voids generated by the foil perforation process. Epoxy films were made in sheets from 67 gsm to 150 gsm with a light weight (6 gsm to 8 gsm) glass non-woven scrim included. The resulting perforated foil/epoxy film prepregs are described in Table 3.

Table 3 LSP Surfacer

Specimen	Conductor	Pattern	Foil (µm)	Weight (gsm) Foil	Weight (gsm) Film	Weight (gsm) Prepreg
0829-121	C10a-20	Circle 97.10a	20	110	150	260
0829-131	C10b-20	Circle 97.10b	20	100	150	250
0121-3	C23-18	Circle 97.23	18	115	67	182
0121-7	AE175	Marquise AE175	45	175	87	262
0916-18	AE142	Marquise AE142	76	142	143	285
0916-22	AE142	Marquise AE142	76	142	93	235
0916-26	AE142	Marquise AE142	76	142	93	235
0916-15	AE73	Marquise AE73	51	73	143	216
0916-19	AE73	Marquise AE73	51	73	143	216
0916-23	AE73	Marquise AE73	51	73	143	216
0916-17	AE73	Marquise AE73	51	73	143	216
0916-21	AE73	Marquise AE73	51	73	143	216
0121-5	AE73	Marquise AE73	51	73	100	173
0829-110	H7-12	Hexagon 97.7	12	69	72	141
0829-105	H7-16	Hexagon 97.7	16	93	96	189
0829-119	H7-25	Hexagon 97.8	25	108	112	220
0916-16	EH38-18	Elongated Hex 97.38	18	60	70	130
0916-20	EH38-18	Elongated Hex 97.38	18	60	70	130
0916-24	EH38-18	Elongated Hex 97.38	18	60	70	130
0121-1	EH38-33	Elongated Hex 97.38	33	115	83	198
0121-4	EH20-17	Elongated Hex 97.20	17	96	69	165

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[i] *See Figure 1, Figure 2, and Figure 3 for pattern feature definitions.*

[ii] *This radius is as-formed during the stretching process.*

[iii] *This resistance was estimated by finite element analysis as described in [1].*

6.2 Lightning Strike Test Panels

The test panels were constructed of unidirectional carbon fiber epoxy prepreg. Plies of M21/34%/UD194T800S prepreg, from Hexcel Corporation, were vacuum laminated to form a consolidated panel 460 mm square. Most plies were arranged [45, 0, 135, 90, 0, 90]s to be 2.29 mm thick after curing. On one panel, 0829-110, the plies were arranged [45/90/135/0/90/0/135/90/45] to be 1.7 mm thick after curing.

Each LSP surfacer sheet was vacuum laminated to a consolidated panel with the face of the LSP conductor placed against the panel. See Table 4 for the characteristics of each test panel. Each consolidated panel was applied to a flat invar tool that was treated on the surface with a release agent[iv]. The tool and panel were then placed in a vacuum bag under a vacuum of approximately 28 inches of mercury (94.8 kPa) and the bag was placed in an autoclave at 60 psi (414 kPa). The panels were cured at 350°F (177°C) for 120 minutes.

After curing, the panels were separated from their tools and machined to 430 mm square. 12 holes 8.992 - 8.687 mm diameter were drilled equidistant apart on a 370 mm diameter circle to align with holes in the test fixture as illustrated in Figure 4.

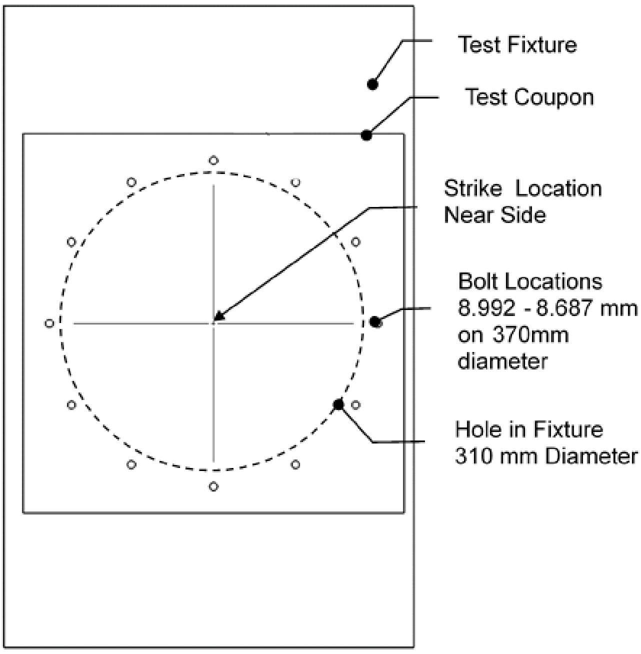

Figure 4 Test Specimen in Fixture

The face of each panel was washed clean with soap and water to remove any machining fluids and other contaminates. The surface was scuffed with 3M™ Scotch-Brite™ Ultra Fine Pad 7448 on an orbital sander with deionized water until the surface exhibited a dull appearance. All abrading residual, debris, and/or cleaner residue was removed with isopropyl alcohol and a clean lint-free towel. A mask was applied to the face of the panel around each drilled hole to create a paint-free region around each hole. To each panel, three box coats of epoxy primer[v] were applied to a dry-film thickness of approximately 20 µm followed by heavy box coats of paint[vi], each averaging approximately 25 µm per box coat until the final thickness of paint was achieved. See Table 4 for the thickness of paint measured on each test panel.

Table 4 Lightning Strike Test Specimen

Specimen	Conductor	Pattern	Foil (µm)	Foil Weight (gsm)	Panels Thick (mm)	Paint (µm)
0829-121	C10a-20	Circle 97.10a	20	110	2.29	198
0829-131	C10b-20	Circle 97.10b	20	100	2.29	334
0121-3	C23-18	Circle 97.23	18	115	2.29	361
0121-7	AE175	Marquise AE175	45	175	2.29	356
0916-18	AE142	Marquise AE142	76	142	2.29	330
0916-22	AE142	Marquise AE142	76	142	2.29	330
0916-26	AE142	Marquise AE142	76	142	2.29	330
0916-15	AE73	Marquise AE73	51	73	2.29	330
0916-19	AE73	Marquise AE73	51	73	2.29	330
0916-23	AE73	Marquise AE73	51	73	2.29	330
0916-17	AE73	Marquise AE73	51	73	2.29	330
0916-21	AE73	Marquise AE73	51	73	2.29	330
0121-5	AE73	Marquise AE73	51	73	2.29	355
0829-110	H7-12	Hexagon 97.7	12	69	1.7	348
0829-105	H7-16	Hexagon 97.7	16	93	2.29	191
0829-119	H7-25	Hexagon 97.8	25	108	2.29	215
0916-16	EH38-18	Elongated Hex 97.38	18	60	2.29	330
0916-20	EH38-18	Elongated Hex 97.38	18	60	2.29	330
0916-24	EH38-18	Elongated Hex 97.38	18	60	2.29	330
0121-1	EH38-33	Elongated Hex 97.38	33	115	2.29	378
0121-4	EH20-17	Elongated Hex 97.20	17	96	2.29	369

The mask was removed from each drilled hole, and the epoxy surface was abraded from the copper conductor in a region around each drilled hole to a diameter large enough to mate with the attachment fasteners.

[iv] *FreKote 700-NC™ from Henkel Corporation*

[v] *Aviox CF Primer 37124 system from AkzoNobel*

[vi] *Aviox Finish 77702 urethane paint system from AkzoNobel*

7. TESTING

7.1 Electrical Conductivity (Resistance) Testing

The resistance of foraminous foils used for aircraft lightning protection and electromagnetic shielding is typically represented in terms of sheet resistance as Ohms per Square (Ω/□). The resistance of the foil was measured on rectangular specimens per ASTM 4496 [8] and normalized to the surface area according to (1).

$$R_S = \frac{\Delta V}{I}.\frac{w}{d} = R.\frac{w}{d} \tag{1}$$

Rs = Sheet Resistance
w = Width of test region
d = Length of test region
ΔV = Potential (voltage) drop
I = Current

The perforation pattern on the foil is axisymmetric in the down-web direction and the cross-web direction, so resistance values are measured and reported separately in those orientations.

7.2 Lightning Strike Testing

The test panels were loaded to aluminum test fixtures as shown in Figure 4, and the protruding fasteners were covered with tape to prevent unintended arc attachment. All simulated strikes were conducted by Lightning Technologies, NTS Pittsfield in Pittsfield, Massachusetts, USA. The test was accomplished per SAE ARP5416 Aircraft Lightning Test Methods section 5.2 High Current Physical Damage Tests using current components as prescribed in SAE ARP5412 Aircraft Lightning Environment and Related Test Forms for Zone 2A consisting of current components D, B and C*, in that order (omitted component H). A jet diverting test electrode was used to inject the current. Waveform characteristics were recorded for each discharge, including Charge Voltage, Action Integral, Charge Transfer, Peak Current, Average Current and Pulse Width as appropriate to the current component.

To assess the damage inflicted by the simulated strike, each panel was fully immersed in water, and scanned on a Mistras ultrasonic scanning gantry with UTWin Version E3.44 software. The transducer operated with a 19 mm focal length and scanned uni-directionally. Pulser settings were: 400 V, 820 pf, 2000 ohms, 15 MHz, in pulse-echo mode. Receiver settings were: 100 MHz sampling, 0.1 microsecond envelope, 4.2 microsecond delay, 20.977 microsecond width. Scans were made from the back side of the panel. Post-scan replay gating was used to locate the deepest detectable damage and the damage area. Damage area was determined by planimeter measurement of a circumscribed region containing the damage to the underlying composite. Results of the direct attachment tests and the subsequent ultrasound microscopy are described in Table 5.

Table 5 Lightning Strike Test Results

				Damage to Composite		
Specimen	**Perforation Pattern**	**Foil (µm)**	**Foil Weight (gsm)**	**Max Depth (mm)**	**Ply Area (mm)**	**Back-Side Crack**
0829-121	Circle 97.10a	20	110	1.60	28	No
0829-131	Circle 97.10b	20	100	1.70	38	No
0121-3	Circle 97.23	18	115	0.19	89	Yes
0121-7	Marquise AE175	45	175	0.62	38	Yes
0916-18	Marquise AE142	76	142	1.54	86	No
0916-22	Marquise AE142	76	142	1.54	81	No
0916-26	Marquise AE142	76	142	1.54	94	No
0916-15	Marquise AE73	51	73	1.84	62	No
0916-19	Marquise AE73	51	73	1.80	80	No
0916-23	Marquise AE73	51	73	1.83	50	No
0916-17	Marquise AE73	51	73	1.96	59	No
0916-21	Marquise AE73	51	73	1.91	82	No
0121-5	Marquise AE73	51	73	2.00	101	No
0829-110	Hexagon 97.7	12	69	0.80	28	No
0829-105	Hexagon 97.7	16	93	0.50	40	No
0829-119	Hexagon 97.8	25	108	0.3	20	No
0916-16	Elongated Hex 97.38	18	60	1.45	7	No
0916-20	Elongated Hex 97.38	18	60	1.52	3	No
0916-24	Elongated Hex 97.38	18	60	1.65	3	No
0121-1	Elongated Hex 97.38	33	115	0.19	57	No
0121-4	Elongated Hex 97.20	17	96	0.48	106	No

See Figure 5 for a graphical illustration of the results in Table 5. In Figure 5, the size of the bubbles corresponds to the weight of the conductor, and the data labels are the arithmetic average of the cross-web resistance and the down-web resistance.

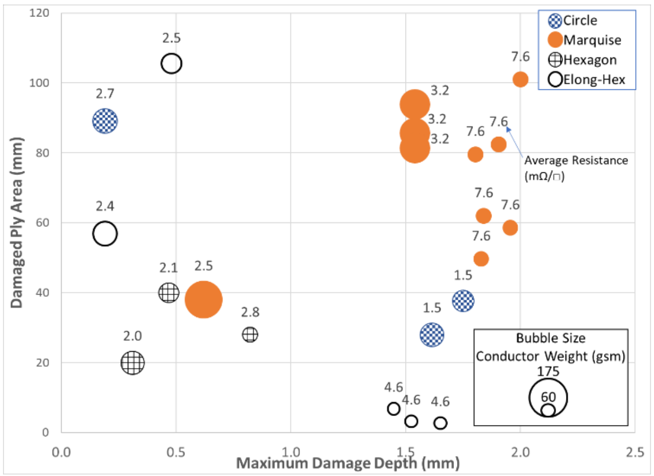

Figure 5 Lightning Strike Test Results

7.3 Conformability Testing

To assess the conformability of a wide area foil, each LSP surfacer was applied to the surface of an aluminum tool having a 3 meter radius of curvature in any two orthogonal planes. A 50 cm x 50 cm sheet of each prepreg was expected to conform wrinkle free to the surface. Test results are displayed in Table 5.5.

Table 5.5 Conductor Conformability

Conductor	Pattern	Foil (μm)	Weight (gsm)	Conformable
C10a-20	Circle 97.10a	20	110	Fail
C10b-20	Circle 97.10b	20	100	Fail
C23-18	Circle 97.23	18	115	Fail
AE175	Marquise AE175	45	175	Pass
AE142	Marquise AE142	76	142	Pass
AE73	Marquise AE73	51	73	Pass
H7-12	Hexagon 97.7	12	69	Fail
H7-16	Hexagon 97.7	16	93	Fail
H7-25	Hexagon 97.8	25	108	Fail
EH38-18	Elongated Hex 97.38	18	60	Pass
EH38-33	Elongated Hex 97.38	33	115	Pass
EH20-17	Elongated Hex 97.20	17	96	Pass

8. ANALYSIS

The goal of this work was to fabricate and test alternative conductors which have been designed as possible improvements to existing conductors for LSP surfacers. The ability to conform to surfaces of complex contours is deemed to be a significant attribute of a useful LSP surfacer. The conductors having circular and hexagonal perforations were not deemed to have adequate conformability to be fully useful for all aircraft fabrication (reference Table 5.5), so these conductors were not further considered in this analysis. Although there are many other design parameters for LSP surfacers, this analysis is limited to the strike protection capability and electrical conduction, with associated weight impact of the conductors.

To compare the weight impact of the conductor configurations, it was desired to account for the resin needed to fill the perforations in the conductors. This comparison is illustrated by using the prepreg weight to establish the size of the bubbles in Figure 6.

8.1 73 gsm Class of Conductors

It was useful to identify an industrializable conductive foil for an LSP surfacer that could enhance the performance of the 73 gsm class of conductors represented by ECF made from 51 μm thick copper. A configuration of conductor with perforations shaped as elongated hexagons (See Figure 1) cut from copper foil 18 μm thick demonstrated lower electrical resistance and equivalent or better protection of the underlying part. This conductor configuration is identified in Table 2 as EH38-18 with elongated hex pattern 97.38 as shown in Figure 5.5, and the design path is illustrated as “73 gsm Class” in Figure 6. These improvements were obtained in a conductor configuration weighing 60 gsm. This is an 18% (13 gsm) weight improvement in the conductor.

Figure 5.5 Elongated Hex Conductor

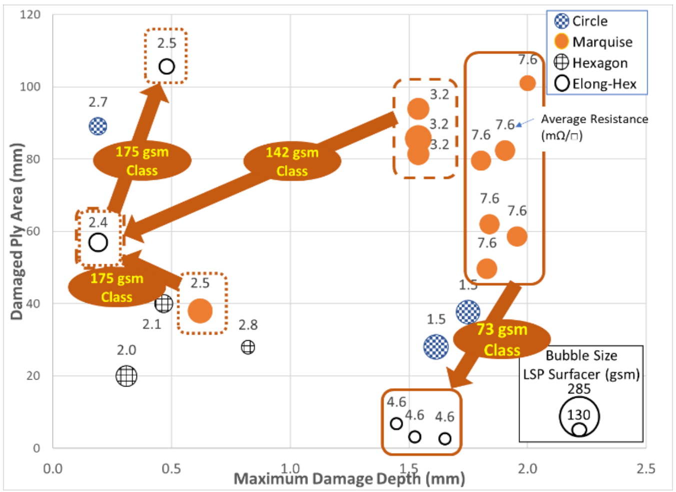

Figure 6 Design Migration

8.2 142 gsm Class of Conductors

It was useful to identify an industrializable conductive foil for an LSP surfacer that could enhance the performance of the 142 gsm class of conductors represented by ECF made from 76 µm thick copper. A configuration of conductor with perforations shaped as elongated hexagons (See Figure 1) cut from copper foil 35 µm thick demonstrated lower electrical resistance and equivalent or better protection of the underlying part. This conductor configuration is identified in Table 2 as EH38-33 with elongated hex pattern 97.38 as shown in Figure 5.5, and the design path is illustrated as “142 gsm Class” in Figure 6. These improvements were obtained in a conductor configuration weighing 115 gsm. This is 20% (27 gsm) weight improvement in the conductor.

8.3 175 gsm Class of Conductors

It was also useful to identify an industrializable conductive foil for an LSP surfacer that could enhance the performance of the 175 gsm class of conductors represented by ECF made from 45 µm thick copper. Two interesting configurations emerged from this objective. The design path for both is illustrated as “175 gsm Class” in Figure 6.

The first conductor of interest was a configuration of conductor with perforations shaped as elongated hexagons (See Figure 1) cut from copper foil 33 µm thick that demonstrated lower electrical resistance with reduced strike damage depth but exhibited larger strike damage area. This conductor configuration is identified in Table 2 as EH38-33 with elongated hex pattern 97.38 as shown in Figure 5.5, and is the same conductor identified above as a useful configuration for the 142 gsm class of conductor. These improvements were obtained in a conductor configuration weighing 115 gsm. This is 34% (60 gsm) weight improvement in the conductor.

A second conductor of interest for this class of conductors was a configuration of conductor with perforations shaped as elongated hexagons (See Figure 1) cut from copper foil 17 µm thick that demonstrated approximately equivalent electrical resistance and strike damage depth but exhibited larger strike damage area. This conductor configuration is identified in Table 2 as EH38-17 with elongated hex pattern 97.20 similar to the image in Figure 5.5. These improvements were obtained in a conductor configuration weighing 96 gsm. This is 45% (79 gsm) weight improvement in the conductor. This conductor captured interest because of the additional 9% (19 gsm) weight improvement in the conductor.

9. CONCLUSIONS

By employing design methods from earlier work [1] and disassociating the conductor configuration from preconceived perforation methods, conductor options were designed, fabricated, and tested which demonstrated performance suitable for 73 gsm, 142 gsm, and 175 gsm classes of conductors for LSP surfacers, with weight advantages of 9% to 45% from the existing conductor options.

This work used existing conductor classes as the performance baseline. The electrical resistance of the existing classes of conductors are biased, in some cases significantly biased, between the down-web and cross-web directions. That bias is a consequence of the punch-and-stretch process used to fabricate the expanded foils, not necessarily the conductivity needs of the airframe. The conductors that were fabricated and tested in this work were not constrained by the stretching process; therefore, a wide spectrum of biased and unbiased conductivity was achieved. This design work suggests additional weight reduction may be possible if the perforated conductor were designed to meet more closely the electrical resistance objectives of the target airframe.

The minimum amount of resin needed, and consequently the optimum weight of the LSP surfacer, is affected by the thickness of the conductor and the amount of open area in the conductor that must be filled by resin. This affect can be observed in Table 3 and Figure 6, where thinner foils allow lighter weight LSP surfacers. Additionally, the minimum amount of resin needed for a usable LSP surfacer may also be limited by expectations for surface quality, fluid resistance and environmental resistance. Additional work to optimize the resin quantity and associated conductor configuration (perforation pattern and foil thickness) may be beneficial to further optimize the weight impact of an LSP surfacer system.

10. REFERENCES

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