ENHANCED EROSION PROTECTION FOR ROTOR BLADES

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ABSTRACT

The deployment of rotorcraft to desert locations in southwest Asia has resulted in a significant increase in maintenance cost due to sand erosion. In these extreme environmental conditions, existing rotor blade erosion protection systems, typically metallic leading edges, are being replaced more frequently, resulting in costly repairs, lower sortie rates, and abbreviated blade life. Through previous efforts, Hontek Corporation has developed a sprayable erosion protective coating that has been validated in a field trial on two Black Hawk helicopters deployed to southwest Asia. This paper discusses the requirements definition process used to investigate the effects of the Hontek coating material on blade dynamics, ice protection, and lightning strike protection in a rotary-wing operating environment. Latest test results and status of its evaluation on a Bell rotorcraft will be discussed.

INTRODUCTION

The deployment of rotorcraft to desert locations in southwest Asia has resulted in a significant increase in maintenance cost due to sand erosion. Due to the complex flow of the sand particles over the blade, erosion damage is often seen on the metallic leading edge as well as on the blade body aft of the leading edge. This erosion damage is especially evident on the outboard sections of rotor blades, where tip speeds approach Mach 1. In these extreme environmental conditions, existing rotor blade erosion protection systems, typically metallic leading edges, are being replaced more frequently, resulting in costly repairs, lower sortie rates, and abbreviated blade life.

Through previous efforts, Hontek Corporation has developed and validated a sprayable erosion protective coating on two Black Hawk helicopters deployed to southwest Asia. While considerable study of the coating system was performed in advance of the field trial, a number of questions remain to be considered in extending this erosion protection system on other rotorcraft platforms with different blade designs and requirements. This paper discusses the requirements definition process used to investigate the effects of the Hontek coating material on blade performance, including dynamics, ice protection, and lightning strike protection in a rotary wing operating environment.

ROTOR BLADE EROSION DAMAGE

Rotor blades are complex structures designed to balance a number of competing requirements. The structure is generally defined to maximize aerodynamic performance, carry flight loads, and ensure aeroelastic stability. Additional requirements include the ability to safely fly in weather conditions where icing and lightning strikes may occur. Advanced, lightweight rotor blades are composed of a fiberglass composite structure. To prevent damage from rain or sand erosion, metallic abrasion strips, typically composed of stainless steel or titanium, are bonded to the blade leading edge to serve as a hard surface that absorbs the kinetic energy of the rain drop or sand particle. Metallic structures are especially good at rain erosion protection. Impacting sand particles, however, slowly erode away the metallic material. This is especially true near the outboard blade tip, where the high blade velocity ensures that the sand particles impact with greater kinetic energy. In this area, a metallic cap that is more durable to sand erosion, often composed of electroformed nickel, is often bonded to the abrasion strip. Damaged abrasion strips and caps may be replaced to refurbish rotor blades; but this requires removal and repair at a depot, increasing maintenance cost and reducing fleet operational readiness. A secondary concern with the erosion of metal abrasion strips pertains to the visible signature that occurs when microscopic metallic pieces are eroded away. In the

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erosion process, they often oxidize, giving off a visible spark and causing a corona effect in sandy environments.

Prolonged rotorcraft service in sandy environments, as seen in Operation Iraqi Freedom and Operation Enduring Freedom, has accelerated the sand erosion damage that rotor blades experience. The increased sand erosion is occurring for two reasons. In southwest Asia, the fine sand particles are easily entrained in the downwash and are light enough to remain suspended in air for a considerable time. Rotorcraft blades moving through such an environment are continually bombarded by the entrained sand particles, causing uniform erosion damage. Additionally, rotorcraft landing in unimproved areas tend to kick up larger pebbles, which then strike the rotor blades, causing more severe damage in localized areas.

Figure 1 shows erosion damage on the outboard section of a rotor blade. In this image, it can be seen that the damage is not confined to the metallic abrasion strip, as the paint on the composite body has been eroded to the green primer.

If not caught in a timely manner, the sand may erode into the fiberglass blade skin, degrading its structural integrity. Additionally, since expanded copper mesh is often embedded on the surface of the composite skin for lightning strike protection, the erosion damage may locally remove the copper mesh and jeopardize the lightning strike protection for the blade. Since lightning strikes tend to be concentrated at the outboard section of the blade, erosion damage may degrade lightning strike protection in an area where it is most necessary.

Figure 2 shows the erosion damage incurred on a nickel cap at the outboard tip of the blade. For aerodynamic performance, the nickel cap is thickest at the leading edge and the thickness tapers down chordwise to blend with the abrasion strip. In this image, the nickel cap is eroded uniformly, but the erosion damage is most noticeable at the back edge of the nickel cap, where it is thinnest. In this area, it can be seen that the sand impacts have eroded away the nickel. Additional damage is seen around the tip light and the weight pocket bolts.

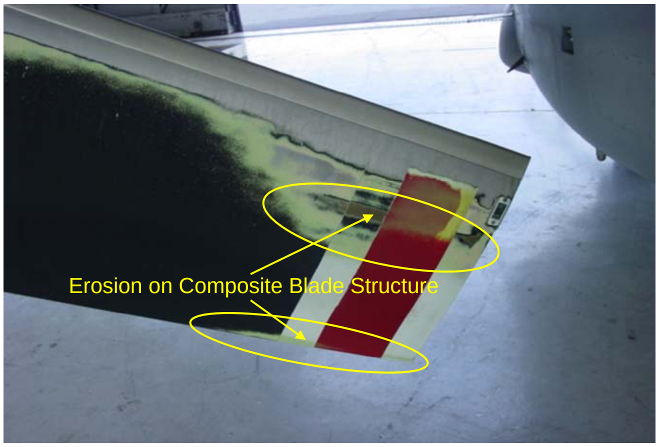


Fig. 1. Erosion damage on a V-22 blade.

To alleviate the maintenance costs, a number of research efforts have investigated alternative abrasion strip materials to identify new structures or coatings that are more resistant to erosion damage. Any system to be considered for application to a rotor blade must not only provide enhanced sand and rain erosion protection, but must also be compatible with the large strains that rotor blades experience. Additionally, they must be compatible with ice protection and lightning strike protection systems. An obvious protection mechanism for rotor blades is to coat the surface with a material that is harder than the impacting sand particles, which are primarily composed of silica. Ceramic hard coatings offer the hardness needed for erosion protection, but their inability to accommodate the strains seen in rotor blades has prohibited their use to date.

Considerable recent effort has focused on the development of polyurethane-based elastomeric spray coatings for erosion protection. Upon impact, sand particles bounce off the polymeric material with little damage to the material. As a general rule, elastomeric materials do not perform as well in rain erosion. This is particularly true for adhesively bonded tapes, which tend to fail at the bond interface. Unfilled polymers have very low thermal and electrical conductivities, limiting the performance of underlying ice protection and lightning strike protection systems.

As damage is accumulated from raindrop, sand particle, and pebble impacts, repair of the erosion protection system is desirable. The development of a thermally conductive polymeric spray coating that is rain erosion resistant and repairable is a highly attractive solution, as the coating may be

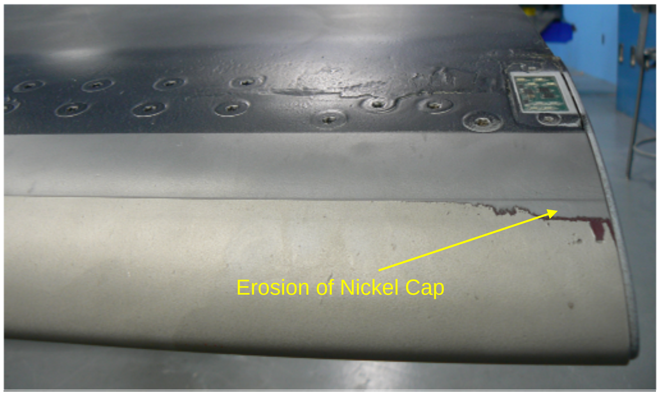


Fig. 2. Erosion damage on a V-22 blade nickel cap.

readily applied to both composite and metallic structures; while thermal conductivity of the coating material enables ice protection for the rotor blades where embedded heaters are used in the leading edge area.

Hontek Corporation has developed a polyurethane-based spray coating for rotor blade erosion protection. At a nominal 0.020 inch thickness, this spray coating is similar to tape systems which are often used in the field for erosion protection. When the tape systems fail, they must be removed and replaced, an arduous and time-consuming task. Hontek has developed on-aircraft repair procedures for this coating system, allowing for rapid repair times and minimized aircraft downtime.

The coating system is composed of three components: primer, basecoat, and topcoat. Hontek has developed different repair techniques, depending on the extent of damage. A topcoat-only repair process may be used if the black topcoat has been penetrated, exposing the basecoat. A more thorough repair process has been developed for damage that extends to the primer or underlying structure.

EFFECTS OF HONTEK COATING ON BLADE PERFORMANCE

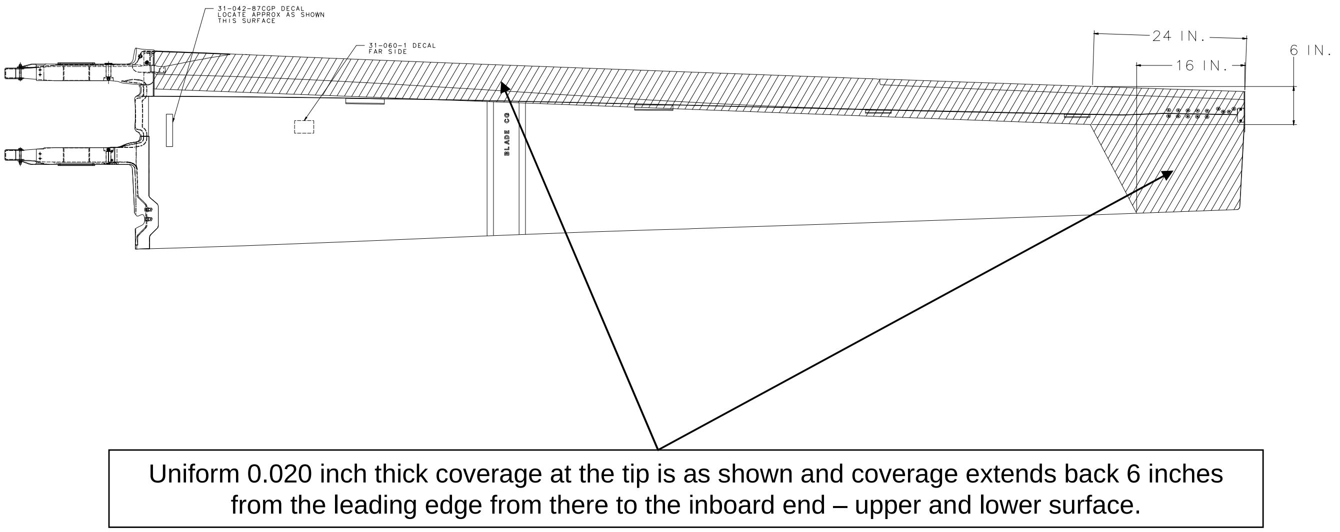
Based on the performance of the Hontek coating performance in the Black Hawk field trial and the erosion damage seen on V-22 rotor blades, NAVAIR, Hontek, and Bell initiated an effort to evaluate the coating for V-22 proprotor blades. The evaluation was defined to effects of the coating over the existing V-22 blade structure. This is to say that no change in the blade structure would be considered to minimize requalification costs.

In addition to erosion protection, the study evaluated the effect of the coating on blade performance. The metallic abrasion strip serves functions other than just erosion protection. While expanded copper mesh is often embedded on the surface of the composite body skin for lightning strike protection, the abrasion strip serves as the primary electrical pathway to dissipate lightning strike energy. Additionally, the metallic abrasion strip serves as a thermal pathway to transfer heat from embedded heater blankets to the blade leading edge surface for ice protection. While the Hontek coating has fillers for increased conductivity, the starting conductivity of the unfilled polyurethane is so low that the filled Hontek material still acts as an insulator. While the conductivity of the Hontek material is greater than for the unfilled material, it remains roughly an order of magnitude lower than the titanium used in the abrasion strip. Application of the coating over the abrasion strip adds a thermally and electrically insulating layer that needs to be evaluated for the ice and lightning strike protection systems in the as-designed V-22 blade structure.

To perform studies of the effects of the Hontek coating on the V-22 blade, an initial coating pattern was determined based on the location of erosion damage seen in use. Based on the Black Hawk experience, a uniform 0.020 inch coating thickness was considered for the entire coating area. A schematic of this baseline coating pattern is shown in Fig. 3. All analyses were performed with this coating pattern.

Aerodynamic, Dynamics and Load Effects

The 0.020 inch coating thickness required for erosion protection, thicker than typical paint systems, adds a measurable weight and profile change to the rotor blade. If the entire



Uniform 0.020 inch thick coverage at the tip is as shown and coverage extends back 6 inches from the leading edge from there to the inboard end – upper and lower surface.

Fig. 3. Baseline Hontek coating pattern.

V-22 blade surface were coated with the 0.020 inch thick coating, it was estimated to add 14.5 pounds (6.58 kg) per blade (or 87 lb [39.5 kg] per aircraft.) By reducing the coating location to the pattern defined in Fig. 3, the estimated weight increase would be reduced to 4.5 lb (2.04 kg) per blade (or 27 lb [12.25 kg] per aircraft.) As the coating is applied to the external surface of the blade, it changes the surface profile, potentially affecting aerodynamic performance in hover and forward flight. The addition of material, especially at the tip end of the blade, affects the mass and mass distribution of the rotor blade, thereby affecting air loads, pitch change, frequency response, and stresses on the hub structures. While little aerodynamic, dynamic, or load change was expected, the analysis was performed to verify these expectations.

In the development of the V-22, Bell-Boeing developed aerodynamic models to evaluate designs using computational fluid dynamic (CFD) tools. To evaluate the aerodynamic effects of the Hontek coating, Bell modified an existing model of the V-22 blade to add the 0.020 inch coating thickness to areas defined in the coating pattern. In the stations near the outboard tip, this coating altered the external profile of both the leading and trailing edges. CFD analysis showed minimal aerodynamic effects that were negligible within the manufacturing variation of the blade.

Since the baseline coating pattern was estimated to add 4.5 pounds per blade, a modeling effort was initiated to evaluate the effects of the coating to ensure that there would be minimal effects to blade dynamic tuning, mass balance, and loads. Rotor fan plots showed no significant change in the rotor tuning of a coated blade when compared to the baseline blade construction. Mass balance of the blade, especially chordwise mass balance near the outboard tip, was affected by the application of the coating.

Evaluation of the mass balance against the baseline blade construction showed that it still met blade criteria. Follow-on analysis showed that a coated blade still met blade flutter and whirl flutter criteria. Additionally, the coating showed no significant change to rotor loads.

Effects on Ice Protection System

With the ability to operate in airplane mode at altitudes up to 24,000 feet, the V-22 is designed to operate at full mission capability in icing conditions, ice fog, and hoarfrost up to moderate intensities down to –20°C (–4°F) ambient temperature. Through several winters of testing in Nova Scotia, the V-22 ice protection system was qualified. This system prevents ice buildup on the wing, rotor blades, and other critical areas. Early in the evaluation phase of the Hontek coating for blade erosion protection, it was identified that the application of the Hontek coating could not be allowed to negate the work that had been performed to qualify the ice protection system.

To prevent ice buildup on the rotor blades in icing conditions, the blades are designed with thermal blankets embedded under the leading edge abrasion strip. Each blade has an anti-ice parting strip at the leading edge. Immediately aft of the parting strip on both the upper and lower blade surfaces, the blade is divided spanwise into multiple deice zones. Based on the measured outside air temperature, these deice zones are designed to turn on and off for specified periods of time to melt and shed any accumulated ice. The addition of a thermally insulating coating to the blade surface raised several concerns. The primary concern was that the coating would hinder heat transfer to the surface, preventing the heating needed to drive ice melting and shedding. A secondary concern was that the insulating coating might retain the heat in the blade structure, potentially causing thermal degradation of the composite structure. Since the validation and qualification of the ice protection system was lengthy and costly, Bell initiated a modeling effort to evaluate the effects of the coating on the deicing performance.

In the initial modeling effort, Bell built thermal models of the blade structure at different blade station locations. Initial efforts with 2-D LEWICE software led to only partial success, as there were a number of instances where the analyses would not converge. An effort to perform the modeling with SINDA/G software proved more successful.

The models of the blade structure without the Hontek coating were built at different locations where there were existing flight test data from the Nova Scotia testing. The models were correlated to the flight test data at an outside air temperature of –10°F (–23.3°C) to ensure model integrity. With the validation of the models for the as-built blade structure, the extra coating layer was applied to the thermal model. The coating was defined to have a nominal coating thickness of 0.020 inch. The analyses for the different blade stations were rerun at the ambient temperature –10°F (–23.3°C) to determine the impact of the coating on the transfer of heat from the thermal blankets to the iced blade surface. To ensure that there was margin to allow for variations in the thicknesses of the different structures in the blade design, a minimum peak surface temperature of 45°F (7.2°C) was required after heat was applied at the embedded heater location. If the surface temperature did not achieve 45°F (7.2°C), it was determined that the erosion coating had degraded the ability of the blade to melt and shed accumulated ice. After the analyses of the heat transfer to the blade surface were performed, additional analyses were performed to ensure that the coating did not retain the heat in the blade structure, causing it to rise to levels where the composite structure might be degraded. A schematic of this process is shown in Fig. 4.

The modeling effort produced several results. The SINDA/G software successfully matched the instrumented test results at various locations along the blade at –10°F and 12°F (–23.3°C and –11.1°C) outside air temperatures. The addition of the Hontek coating did not hinder the blade surface from reaching this required minimum 45°F (7.2°C) temperature, except in one inboard deice zone. Since erosion damage is less severe on the inboard section of rotor blades, it was proposed that a reduced Hontek coating thickness might prevent the reduced erosion while retaining ice protection. A follow-on analysis was performed to determine if a reduced coating thickness of 0.010 inch, half the nominal coating thickness, might enhance the ice protection. The analysis showed that this would have little impact for ice protection relative to the full 0.020 inch thickness.

The thermal modeling did show a delay in the surface reaching maximum temperature. This delay offers the potential that the accumulated ice might shed differently off a Hontek coated surface when compared to a standard bare blade. If the melting were delayed, there is an increased possibility that the ice would not completely shed and might run back and refreeze on the trailing edge of the blade, where there are no heaters. Finally, analysis of the internal blade temperatures showed that there was sufficient margin to prevent any thermal degradation to the internal composite blade structure.

Based on the full range of results, the thermal analyses suggested that the coating pattern should be modified as shown in Fig. 5 to remove the coating from an inboard deice zone where there was insufficient margin in the peak surface temperature to retain confidence in the ice protection system.

A follow-on testing of instrumented blades with the Hontek coating was proposed for several reasons. All of the thermal analyses assumed that the blade surface would retain a uniform smooth surface. Erosion damage might roughen the Hontek coating to the extent that mechanical adhesion of the ice to the roughened Hontek coating might hinder ice shedding even when the blade surface had reached a temperature sufficient to initiate melting. Also, the delay in the heat transfer to the blade surface might generate a runback refreeze condition on the blades. Due to the cost to perform such a test on instrumented blades, the team decided to proceed with the modified coating pattern and delay this test until after a field trial had been performed to validate the benefit of the Hontek coating on V-22 blade life.

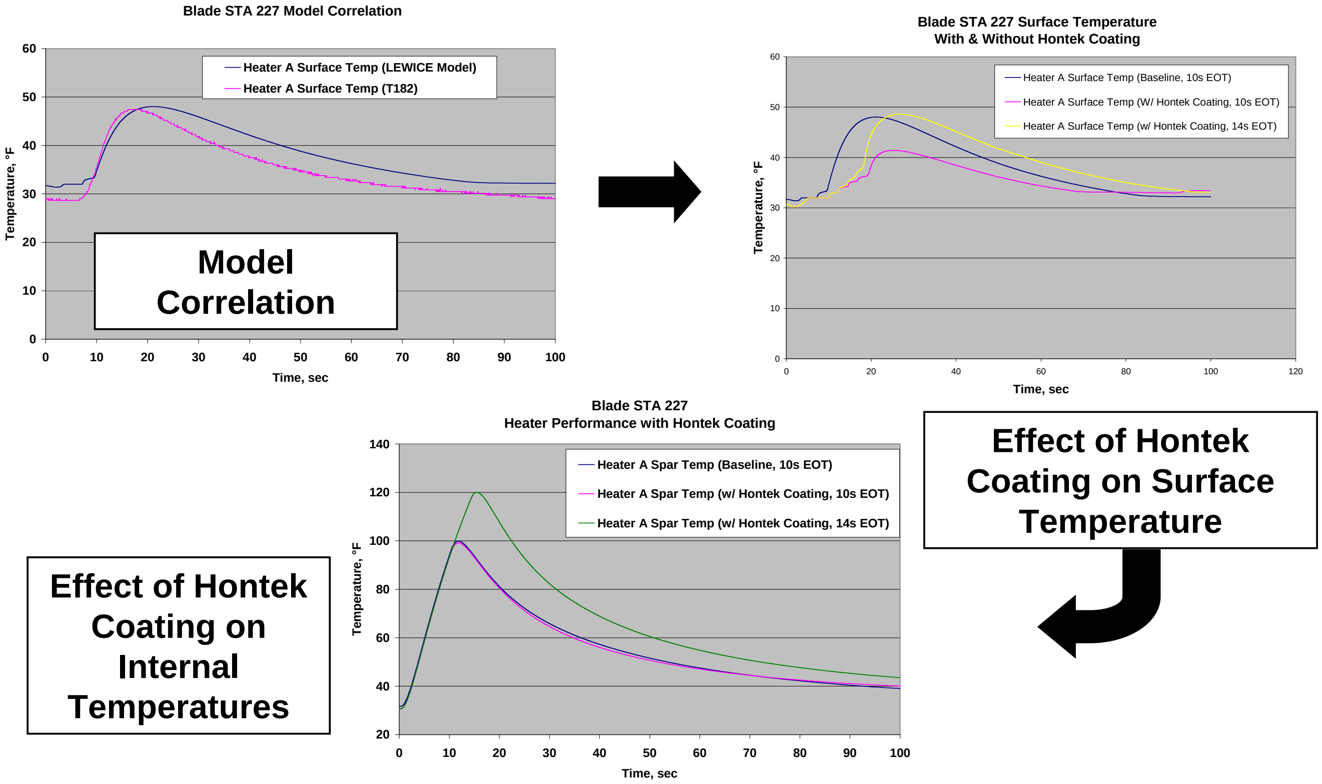
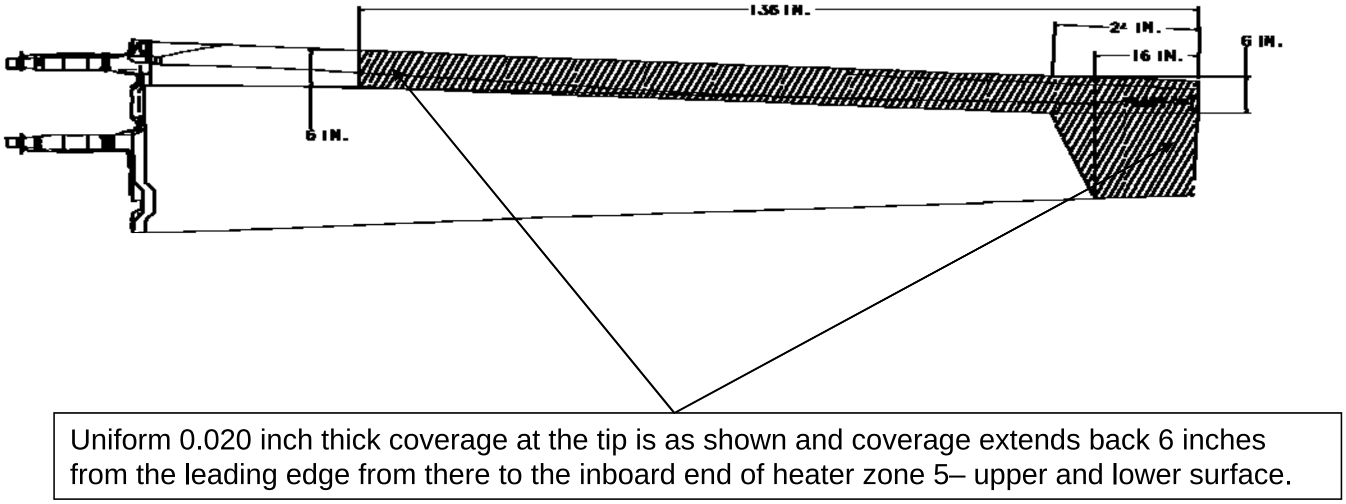


Fig. 4. Thermal analysis procedure for ice protection analysis.



Uniform 0.020 inch thick coverage at the tip is as shown and coverage extends back 6 inches from the leading edge from there to the inboard end of heater zone 5– upper and lower surface.

Fig. 5. Hontek coating pattern revised for ice protection.

Effects on Lightning Strike Protection

One final concern remained to be addressed before V-22 blades could be coated with the Hontek system for a field trial in an erosive environment. Both the baseline and revised coating patterns defined a constant 0.020 inch coating thickness over the entire area to be coated. This area included a coating over both the metal abrasion strip near the leading edge as well as a coating over the composite body near the outboard tip. The application of this thick coating on the metallic abrasion strip isolates any lightning strike from the intended primary conductive path. Additionally, in the outboard tip area, the 0.020 inch thick coating would be applied over the expanded copper mesh that was built into the blade skin for lightning strike protection. There was anecdotal evidence from previous testing that a thick electrically insulating coating might enhance damage of a composite structure from a lightning strike. While the test data was not available, the 0.020 inch thick Hontek coating had been previously qualified on composite structure of the Black Hawk blades. A validation test for V-22 structure was performed by applying the coating, as defined in Fig. 5, to a V-22 blade and subjecting the blade to a lightning strike to determine the direct effects. A single Zone 1A high current (200 kA) test was applied to a high voltage puncture location on the composite blade body near the tip. The test currents punctured through the upper and lower blade skin. Additional damage occurred along the leading edge and at mid-blade. The damage was extensive enough to require a redesign of the coating pattern over the composite body.

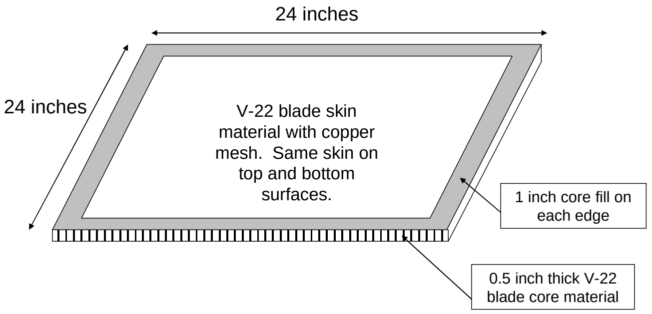


Fig. 6. Lightning strike panel sketch.

Anecdotal evidence had suggested that a reduced coating thickness would minimize the amount of damage from a high-current lightning strike. To determine the appropriate coating thickness, a number of composite sandwich panels were manufactured, coated with different Hontek coating thicknesses and subjected to Zone 1A high-current strikes. The 24 inch × 24 inch flat panels, as shown in Fig. 6, were manufactured of the same materials as found in the V-22 blade structure. This included the application of the expanded copper mesh to the composite skins.

The panels were coated with the Hontek coating in a range of thicknesses from 0.005 inch up to 0.020 inch, the thickness of the coating on the previously performed lightning strike test on the full V-22 blade. In addition to the Hontek-coated panels, a control panel, consisting of the standard Bell topcoat, typically 0.005-0.007 inch thick, was added to the test matrix as a reference. Additionally, since many rotorcraft fly with tape applied to blades for erosion protection, an extreme case was manufactured. This extreme case consisted of the standard Bell topcoat, typically 0.005–0.007 inch thick, with 0.020 inch thick tape applied on top of the Bell topcoat. The panels were subjected to Zone 1A high-current strikes and the subsequent damage area was determined. Figure 7 shows the range of damaged area, outlined in white, on several tested panels. The damage consisted of skin-to-core disbonds and crushed core.

The panels with the thinnest coating showed the least damage. The panel with the 0.020 inch thick Hontek coating and the panel with the Bell topcoat and 0.020 inch tape showed the most damage. In the case of the latter panel, this damage extends to the edges, where only the clamping pressure during testing resisted further skin disbonding. The damage area was found to be related to the coating thickness. Figure 8 shows the relationship between coating thickness and damage area.

Based on these results, the coating pattern was modified to apply the full 0.020 inch thick Hontek coating over the metal abrasion strip. A reduced coating thickness, not to exceed 0.008 inch, was deemed to be appropriate for lightning strike protection over the composite body. This revised coating pattern is shown in Fig. 9. These results were validated on a final lightning strike test on a full V-22 blade that was coated per the design in Fig. 9 and subjected to a high current strike. This test on a full blade produced minimal damage, as predicted by the panel testing.

FIELD TRIAL STATUS

In parallel with the various analysis and testing efforts to determine the effects of the Hontek coating on V-22 blades, Bell and Hontek developed processes to repeatably and reliably apply the Hontek coating to V-22 blades in the appropriate locations and thicknesses as defined in Fig. 9. These processes included masking sequences to apply the Hontek primer, basecoat, and topcoat to the appropriate areas at the appropriate thickness. The coating is applied by spraying a number of layers on the unmasked surfaces. The buildup of this thick coating is different from standard primer and topcoat systems, which are relatively thin. The Hontek coating

Bell Topcoat
(0.005-0.007 inch thick)

Hontek
0.006 inch thick

Hontek 0.020 inch thick
(same as Full Blade Test)

Bell Topcoat + 0.020 inch thick
tape

Fig. 7. Lightning strike panels tested with different coating thicknesses.

requires unique controls to ensure that the coating is applied with a uniform thickness on a blade structure with many contours. After numerous trials, including the coating of the two blades used for lighting strike testing, Bell and Hontek developed mask and spray processes for the controlled application of the coating to V-22 blade surfaces. The culmination of this effort was the application of the Hontek coating to three blades for a field trial. These three blades, and the team that accomplished the coating, are shown in Fig. 10.

The field trial is the culmination of the effort to evaluate the Hontek coating for V-22 blades. The field trial provides evidence of the true life extension that the coating adds to the blades. Additionally, it allows maintainers the training that is needed to perform periodic repairs using the topcoat-only and full-coating repair kits that Hontek has developed to support the Black Hawks flying with the Hontek coating.

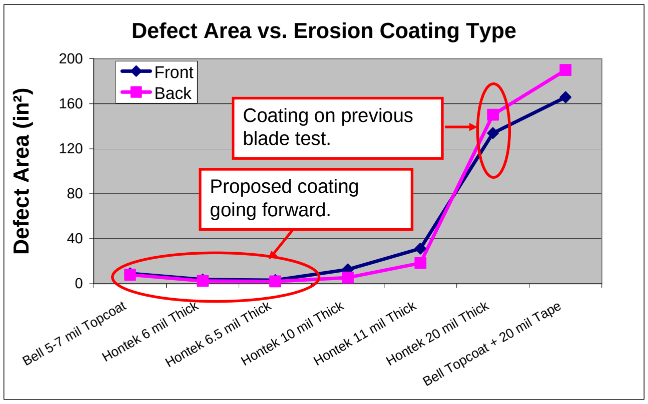


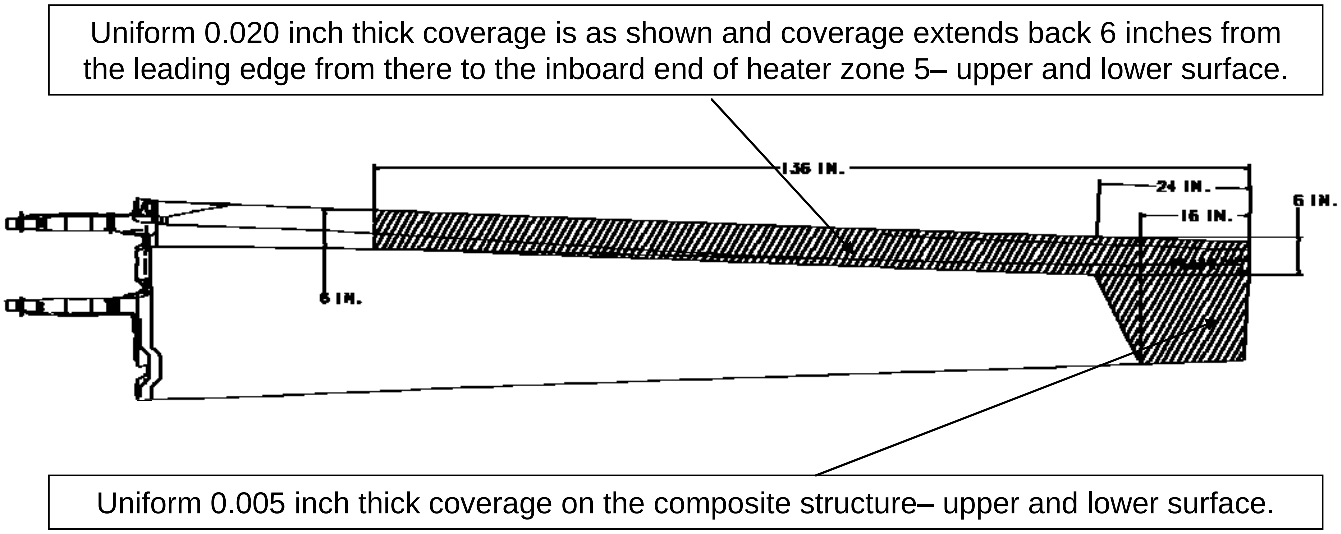
Fig. 8. Lightning strike damage as a function of coating thickness.

Since the V-22 has three blades on each of its two rotors, a set of six blades is needed per aircraft. Due to the additional weight of the coating on the blade, each rotor requires that all the blades be either bare or Hontek-coated for balance. An aircraft may fly with one rotor containing bare blades and the other rotor containing Hontek-coated blades. For the field trial, it was determined that three blades would receive the Hontek coating. Flying with one rotor bare and one rotor containing Hontek-coated blades allows direct measurement of the accumulated damage on each set of blades during the field trial. Correlation may then be done to determine the benefit of the coating.

At the current time, the final details of the field trial are ongoing. The plan is to install the three Hontek-coated blades on a V-22 aircraft flying in a desert location in the continental United States. Periodic evaluations will be performed to identify any damaged areas requiring repair and to document the expected reduction in erosion damage on the coated blades. Finally, the field trial will determine if the repair intervals that were determined for the Black Hawk are applicable to the V-22.

CONCLUSIONS

Through a systematic study, the application of the Hontek coating has been evaluated in an effort to reduce erosion damage on V-22 proprotor blades. Through a series of analyses and tests, this study has determined the effects of the proposed coating in the aerodynamics, dynamics, ice protection, and lightning strike protection of the V-22 blade design. This thorough investigation has shown little effect on the aerodynamics and dynamics. During the study, the coating application pattern on the blade structure has been modified to accommodate concerns with ice protection and


Uniform 0.020 inch thick coverage is as shown and coverage extends back 6 inches from the leading edge from there to the inboard end of heater zone 5– upper and lower surface.

Uniform 0.005 inch thick coverage on the composite structure– upper and lower surface.

Fig. 9. Hontek coating pattern revised for lightning strike protection.

lightning strike protection as thermal modeling of the ice protection system and lightning strike testing of a coated blade has shown the potential for degradation of these protective systems in the blade design.

The study has culminated in the application of the Hontek coating to three V-22 blades for a field trial in a desert environment to document the life extension that the coating offers to V-22 blades. At the current time, three blades have been coated and the final details of the field trial are in progress.

Fig. 10. Hontek-coated field trial blades and the team that produced them.

ACKNOWLEDGMENTS

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