FEATURE

UV-Cure Military Aerospace Coatings—An Emerging Market

By Joel A. Johnson and Corey Q. Bliss

Until recently, little research and development had been performed toward developing radiation-curable coatings for military applications. Reasons for this include the relatively small size of the military coatings market, the lack of research and development (R&D) investment by Department of Defense (DoD) agencies, and the technical challenges associated with coating large objects under relatively uncontrolled environmental conditions. While most civilian coatings have been directed toward OEM applications, much of the painting done for the DoD is effectively aftermarket or refinish in nature. Over the past several years, however, the Air Force Research Laboratory (AFRL) has made an active commitment to explore the limits of where UV-cure coatings can be used for aerospace applications.

One factor in overall cost, and an important reason why AFRL is investing in UV coatings R&D, is the potential for very rapid cure.

AFRL's effort is part of a DoD trend to seek out high quality, value-added products. No longer are military coatings purchased solely on price. DoD acquisition reform over the past decade now encourages end-users to look at life cycle cost and use options with higher initial cost if they result in overall savings. This is particularly important with capital intensive assets such as aircraft where the cost of the paint is a small fraction of the complete aircraft painting expense.

UV-Cure Advantages

One factor in overall cost, and an important reason why AFRL is investing in UV coatings R&D, is the potential for very rapid cure. The traditional coating systems for aircraft consist of epoxy primers and polyurethane topcoats. Because of long cure times, these systems take 1-3 days before a painted plane is "dry-to-fly." While the coatings continue to cure for weeks, "dry-to-fly" is the point at which the coatings have enough integrity to be flown without sustaining any damage. Since painting operations are the last step in the maintenance cycle, the "dry-to-fly" requirement extends aircraft unavailability for three days. This time could be saved with faster UV-cure coatings. A quick turn around for coating repairs increases availability of both aircraft and hangars.

UV cure's potential to reduce or eliminate VOCs and HAPs is also attractive to the Air Force. This is particularly true for field locations that have stringent local VOC regulations, which currently prohibit or limit painting. An overall reduction in VOC/HAPs also helps Air Logistic Centers (ALCs) comply with the Environmental Protection Agency (EPA) regulations. Low VOC coatings would enable more Air Force painting and ensure that our nation's critical assets are continuously protected.

Application of a topcoat to a KC-135 Stratotanker engine nacelle at Oklahoma City ALC, Tinker AFB.

Current Aerospace Coatings

A typical military aircraft coating system consists of an aluminum alloy substrate (e.g., AA2024-T3, AA7075-T6) which has an inorganic chromate conversion coating applied (e.g., Alodine 1200) for corrosion protection and adhesion promotion. This is followed by application of an epoxy primer containing strontium chromate pigment for corrosion protection. Finally, a polyurethane topcoat is applied for color, gloss, weathering and barrier properties. A schematic of this multi-coating system is provided in Figure 1.

The performance of each layer of the paint system is dictated by its military specification (MIL-SPEC) requirements. The most common MIL-SPECs for the conversion coating, primer and topcoat are MIL-C-5541E, MIL-PRF-23377J, and MIL-PRF-85285D, respectively. Each is available at *www.dsp.dla.mil/* for download and review. When a coating company develops a new product, it is submitted for independent MIL-SPEC performance analysis. If the performance is acceptable it is placed on a qualified product list (QPL). DoD end users can pick the product listed on the QPL that provides the best overall value for their application. Often times, the most expensive product is chosen because it provides the best weathering and durability, thus reducing the need for additional costly painting operations in the future.

Military aerospace topcoats vary in their gloss requirements. By far, the largest market is for low gloss camouflage systems (≤9 G.U. at 85°). Gloss topcoats are utilized on training aircraft and by the Coast Guard, semi-gloss is used on aerospace ground equipment (AGE), and an ultra-low gloss is used on gunship aircraft. In addition to standard aircraft coatings, there are numerous "specialty coatings" beyond the scope of this communication, which may be applicable to UV cure.

Technical Requirements

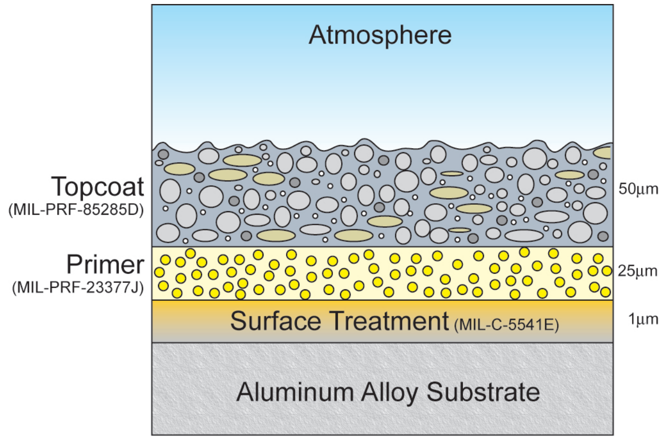
One challenge in adopting UV cure for military applications is that there are currently no MIL-SPEC requirements for this class of coating. AFRL is currently drafting a series of performance requirements based upon the current state-of-the-art. A comprehensive list for both primers and topcoats for general camouflage aircraft coatings is available by request from the authors. A selection of some of the particular challenges that are unique to UV cure will subsequently be discussed.

For primers, the greatest challenge will be to develop a coating that provides both the desired corrosion protection and adhesion. While most conventional primers today rely on chromium- (Cr^{6+}) based inhibitors, these days are numbered. The Occupational Safety and Health Administration (OSHA) has recently lowered the permissible exposure limit (PEL) for chromium by an order of magnitude, from 52 µg/L to 5 µg/L. Certain aircraft painting operations have been allowed a 25 µg/L exception, however, any new primer technologies will most likely need to be chromium free to gain acceptance. Chrome-free primer development is a challenge in itself without the added requirements of a UV-cure resin system.

Adhesion to aluminum, titanium, steel, and composite substrates is a

FIGURE 1

Cross-section of a typical military aerospace coating system that utilizes a chromate containing epoxy primer and low-gloss polyurethane topcoat



Typical aircraft corrosion often found near seams and fasteners.

critical property for aerospace primers. One major concern is that the coating may not achieve full cure at the substrate/film interface due to excessive wet film thickness, incomplete lamp exposure or shadowing. Adhesion is often disrupted with aircraft primers due to surface contamination as well. Since nearly all legacy Air Force aircraft leak hydraulic fluid to some extent, solvent-borne primers are generally used. These coatings tend to absorb the hydraulic fluid and permit suitable substrate wetting. UV-cure formulations must be robust enough to handle a certain amount of surface contamination such as this.

For topcoats, the greatest concerns are associated with achieving full cure, low gloss and acceptable exterior weathering. All military aerospace topcoats need to be opaque to provide the desired color and aesthetic properties. Obtaining consistent full cure of these opaque coatings is a challenge, particularly since most military topcoats are dark gray. Pigments that strongly absorb in ultraviolet wavelengths will need to be avoided, if possible. Very few opaque UV cure starting point formulations are available which have the baseline physical and chemical properties required by aircraft topcoats.

Most commercial UV-cure coatings are designed to achieve high-gloss or semi-gloss finishes. Little R&D has been done toward obtaining the extreme low gloss required for most military topcoats. In conventional military topcoats, low gloss is obtained through use of relatively large particle size extender pigments. When film shrinkage occurs due to solvent evaporation, these particles protrude on the surface of the film, causing an appropriate surface roughness that provides the desired gloss. The lack of significant film shrinkage in solvent-free UV-cure formulations eliminates this mode of obtaining low gloss. This may prevent the ability to develop true VOC free coatings for this application. Waterborne UV-cure formulations may be an option but present an additional set of technical challenges.

Aerospace coatings in general require high-performance resins and pigments due to their harsh service environment. Exposure to intense UV-B radiation at flight altitudes prohibits conventional industrial polyurethane coatings from being widely used due to color fading and chalking. To make matters worse, this degradation is usually accelerated with low-gloss coatings. Current aerospace grade topcoats typically utilize very stable inorganic pigments, photolytically stable resins (often fluorinated), hindered amine light stabilizers (HALS) and UV-absorber additives. Any potential UV-cure formulations would need to exhibit minimal gloss change and a color change of less than one ΔE after 3,000 hours of Xenon Arc exposure. The fact that some of the same wavelengths used to initiate cure of UV coatings are also responsible for degradation presents a significant challenge to developing a successful formulation.

Despite these challenges, AFRL is committed to exploring the performance boundaries of this class of coating. Selected items of the proposed technical objectives which are most important are provided in Table 1. While this list is not complete, it provides some initial guidance to potential formulators. As UV-cure aerospace coatings mature, a new MIL-SPEC will be issued to detail full-performance requirements.

Implementation Requirements

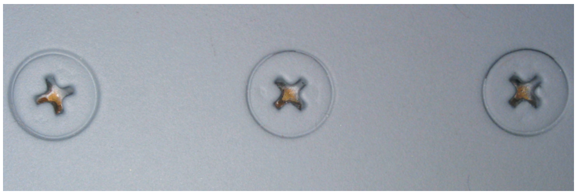
The closest civilian analogy to military aerospace coatings is the automotive refinish market. The application environment is relatively uncontrolled and the objects are large and often have complex shapes. As previously mentioned, UV-cure coatings need to adhere to a variety of substrates as well as "less than optimal" substrate conditions. In addition, the presence of countless fasteners (e.g., rivets, bolts, screws, etc.) creates a challenge to ensure that full cure is obtained at the interface between these objects and the skin. It is critical to ensure that these items are fully protected because they are the most corrosion prone areas of the aircraft outer mold line. This is because paint films with inadequate flexibility tend to crack at the fastener-skin interface and the use of dissimilar metals is a source of galvanic corrosion. To further complicate matters, the uneven surface caused by fasteners

A stripped C-5 Galaxy waiting to be fully repainted. It is extremely difficult to completely remove all of the existing coating and prepare the substrate to a pristine condition prior to repainting.

TABLE 1

Select UV cure aerospace coating performance requirements

Coating	Property	Test Conditions	Objective	Threshold
Primer	Pretreatment	Cleaned AA 2024-T3 & AA 7075-T6 substrates	No pretreatment required or compatibility with non-chromated pretreatment	Compatibility with approved chromated pretreatment
Primer	Pigment	Primer must be non-chrome	0 wt% Pb, Cr, Cd	< 0.06 wt% Pb; < 0.01 wt% Cr & Cd
Primer	Dry-to-Topcoat	Allow topcoat application without sacrifice in performance	< 10 minutes after lamp exposure	< 1 hour after application
Topcoat	Wet Edge	15 minutes between coats	No streaks, tiger stripes or other visual irregularities	Slight gloss difference
Topcoat	Color (ASTM D2244)	Fed. Std. 595 Color 36173	ΔE <1 from standard	ΔE <1 from standard
Topcoat	Gloss (ASTM D523)	Applies to low gloss camo	< 3 G.U. @ 60° < 5 G.U. @ 85°	< 5 G.U. @ 60° < 9 G.U. @ 85°
Topcoat	Opacity (ASTM 2805)	Applies to low gloss camo	Contrast ratio >.99	Contrast ratio >.95
System	Application	>60°F and <90°F >30% RH and <90%RH	Brush, roller or spray application	Only capable of spray application
System	UV Cure	>60°F and <90°F >30% RH and <90%RH	UV-A lamps for both primer and topcoat	Use of same lamp system for both primer and topcoat
System	Dry-to-Fly	Obtain proper adhesion, hardness, and water resistance	Prime and topcoat a 200 sq. ft. area under 2 hours	Prime and topcoat a 200 sq. ft. area under 6 hours
System	Chemical Resistance (ASTM D5402)	Fully cured coatings under ambient change, or cracking conditions	No significant loss of material, swelling, hardness hardness change, or cracking	No significant loss of material, swelling,
System	Low Temp Flex (ASTM D522)	Fully cured complete coating system at -51°C with 2" diameter rod	No signs of cracking or loss of adhesion in the bend area	No signs of cracking or loss of adhesion in the bend area
System	Xenon Arc (ASTM G-155)	Fully cured complete coating system	ΔE and change in gloss of less than 1 after 3,000 hrs. of exposure	ΔE and change in gloss ofless than 1 after 2,000 hrs. of exposure
System	Salt Fog (ASTM B 117)	Fully cured complete coating system	After 3,000 hours of exposure, the coating shall have no discoloration, blisters and undercutting	After 2,000 hours of exposure, shall have no scribe discoloration, blisters and undercutting
System	Filiform Corrosion Resistance (ASTM D2803)	Primer with untinted gloss white topcoat (color FED-STD-595 color 17925)	No filiform corrosion extending beyond 2.00 mm, and majority of filaments less than 1.00 mm after 1,008 hrs.	No filiform corrosion extending beyond 6.35 mm, and majority of filaments less than 3.18 mm after 1,008 hrs.



Close up view of painted fastener heads. Coatings must be capable of fully protecting the fastener as well as the interface between the fastener and skin to help reduce galvanic induced corrosion.

raises the potential for shadowing. While it is possible to develop dual cure formulations that permit "dark cure," the introduction of 2-K mixing and pot-life restrictions removes many of the potential advantages of a UV-cure system over conventional systems.

Any coatings developed for aircraft applications will need to be inherently resistant to oxygen inhibition of cure. While the automotive refinish market can accommodate a small amount of surface inhibition by physically removing uncured resin, the size of aircraft would prohibit this type of remediation. "Touch time" by personnel adds significant cost and slows the operational throughput. The use of thiol-ene based chemistry, which is not oxygen inhibited, may offer a significant advantage to formulation of UV-cure aerospace coatings.

Wet-film thickness control will be critical to the success of any UV-cure formulation. Conventional coatings allow greater flexibility in film thickness variability, which allows painters to use HVLP spray guns and their application expertise to achieve the target film thicknesses. With UV cure, a thick wet film that prevents adequate cure at the substrate-film interface can potentially cause adhesion failures. This phenomenon is especially sensitive for opaque coatings. A solution to this problem may reside in the use of robotic application methods to precisely control wet-film thickness.

One disadvantage of UV cure is the additional requirement of lamp equipment. Fortunately, there is a wide variety of different styles, bulbs, and power outputs from which to choose. Nevertheless, if a UV-cure primer and topcoat are to be used together, the same lamp equipment and bulbs need to be applicable to each to streamline logistics. UV-A spectral output is preferred due to the reduced occupational safety requirements compared to shorter wavelength alternatives. Stand-off distance and exposure time are critical to ensure full cure, and here is another opportunity for robotics to reduce technical risk. There are currently no restrictions on the type of lamps that can potentially be utilized, particularly since it is imperative to match the lamp with the coating formulations of interest.

Air Force Strategy

The AFRL near-term strategy for UV-cure aerospace coatings is to target coatings for small area repairs applied at field locations where regular maintenance is performed. The small sizes facilitate hand-held lamps and allow thorough surface preparation to be performed. It offers an excellent opportunity to demonstrate the performance of UV-cure formulations with relatively low risk. The next logical step will be to target off-aircraft parts (e.g., control surfaces) and AGE using a robotic application and cure mechanism. The relatively flat surfaces on many off-aircraft parts are an excellent fit to demonstrate robotic capability and the applicability to larger area objects. Furthermore, the application environment is well controlled and proper substrate preparation is easier to achieve.

Application of a topcoat to an F-117A Nighthawk.

A long-term goal is to eventually paint the outer mold line (that is, the entire outer surface) of aircraft at ALCs with UV-cure coatings. Obviously this is a significant challenge and represents a paradigm shift in the way aircraft are painted. Starting with small area repair and parts offers an opportunity to learn many lessons on the road toward this goal. A full cost-benefit analysis of UV curing an entire aircraft is tentatively scheduled to be performed over the next year based on current state-of-the-art materials and processes.

Summary

Certainly, the adoption of UV-cure coatings for military aerospace application has technical and implementation risks. However, the potential for ultra-fast curing and significantly reduced VOCs has convinced AFRL to make a serious investment in the technology. While coating a full aircraft using UV-cure technology is years away, a demonstration of UV-cure technology for repair and parts should be achievable in the near future. This will facilitate the development of higher performance UV-cure coatings and further define requirements of a potential MIL-SPEC for this exciting class of coatings. Successful results could benefit other commercial sectors as well, including aerospace OEMs and industrial equipment manufacturers.

—Joel A. Johnson and Corey Q. Bliss are employed at the Air Force Research Laboratory, Wright Patterson Air Force Base, Dayton, Ohio.