Heat-Resistant UV-Curable Clearcoat for Aircraft Exteriors

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Abstract

We are assessing the feasibility of developing and implementing a heat-resistant UV-curable clear paint, or clearcoat, for use on the aircraft exterior. The clearcoat would protect underlying paint from discoloration experienced in service, thus improving its appearance and engineering performance. Non-pigmented urethane-based sample submissions were tested to our requirements for finish quality and engineering performance, with results approaching those of qualified thermally-cured exterior urethanes. Pathways were identified for development and deployment of the clearcoat in production. Heat-soak testing of several rounds of clearcoat formulations from two suppliers showed substantially improved heat resistance compared to a thermally-cured clearcoat used as a control.

Summary: Potential opportunities were identified for using very-fast-curing exterior aircraft paints for the purpose of reducing paint process cycle time and improving finish quality and durability for the airline customer. We determined that significant benefit would be realized with ultraviolet-curable (UV-curable) pigmented and clear paints, when applied to areas requiring special-purpose coatings and when these coatings would impose unacceptable delays to the process flow unless their cure time was very short.

An example of such an application is an identified need for heat-resistant coatings for exhaust vent areas, which is the subject of this article. A list of engineering and appearance requirements for this heat-resistant coating was generated, including the level of heat resistance deemed to be necessary to justify its use. These requirements are based on those for presently qualified exterior paints and include additional requirements specific to this special application.

Two formulators were identified who had the resources and motivation to develop UV-curable clearcoats for aircraft exterior use. To facilitate the development process a close collaboration was set up between these formulators, their raw material suppliers and the UV-cure equipment suppliers. A gated development path leading ultimately to use of the UV-curable clearcoat in production was established. At each development step the business case for proceeding to the next phase is assessed before continuing to the next.

We recently completed testing of clearcoat formulas from these two suppliers that have undergone several rounds of testing, reformulation and retesting. The latest formulations are close to satisfying the basic engineering requirements, with only minor adjustments required to fully satisfy these requirements. Efforts by the formulators to enhance the heat resistance of these formulas have resulted in a substantial improvement over the thermally-cured clearcoat tested as a control.

The problem to be addressed: Heat-induced discoloration of paint near utility exhaust vents. The clearcoats under development in this work have been evaluated for their ability to mitigate yellowing of the thermally-cured urethane paints applied to the exterior downstream of small exhaust vents on the underside of the airplane. Fig. 1 is a schematic depiction of an exhaust vent and the region downstream most affected by heat. These paints are exposed to temperatures as high as 150C (300F) for extended periods in service. Over a period of months severe discoloration (yellowing and browning) has been observed to occur. Applying an overcoating with the appropriate formulation would limit access of atmospheric oxygen to this paint, thus slowing the yellowing process. The clearcoat must have a very fast cure to minimize paint process flow impact due to addition of steps for masking, application and cure of the clearcoat, hence the emphasis on UV-cured formulations.

The total area needing protection is relatively small (<5 sq m or <50 sq ft) so it is anticipated that off-the-shelf curing systems designed for automotive aftermarket decoration may be adaptable to this application. At least one such system has been made available with explosion-proof upgrades to meet NFPA Article 500, Class I, Div 1 fire codes (required in our paint shops).

Why UV cure? Drivers for using UV-curable exterior aircraft paints: The best opportunity for paint process flow time reduction is in the curing step. While the fastest thermally-curable formulas require hours reach a "dry-to-mask" condition, UV-curable paints achieve full cure in seconds. Moreover, they are ready for flight at that point, while the thermally-cured paint still requires further cure to be ready for flight. Additionally, since UV cure can be accomplished without heating the paint hangar, other work can progress while paint is curing, unlike the case for thermally-cured paint. UV-curable paints have the added benefit of helping reduce emissions of volatile organic compounds (VOCs), since they are typically formulated with up to 100% solids. (In a "100% solids" paint formulation, all of the paint material that reaches the part remains behind to dry, with no evaporative loss. This includes the reactive diluent in UV-curable formulations.)

Requirements for a UV-curable heat-resistant exterior clearcoat: A number of requirements must be satisfied in order to achieve the most benefit from use of a UV-curable heat-resistant exterior clearcoat. Together they present a significant formulation and process-integration challenge similar to that faced by the automotive industry, but with several added challenges unique to commercial airplane finishing. There is also the heat-resistance requirement for the clearcoat presently under development.

The requirements include:

- *Spray properties close to thermally-curable paints*. For optimum finish quality and shop-friendliness, the paint must have a spraying viscosity similar to that of thermally curable formulas, and similar "leveling" power (ability to form a smooth film) and resistance to runs and sags. The closer the spray behavior is to conventional paint, the faster the learning curve will be for the painters, and reworks will be minimized. A typical approach is to formulate the paint with high room-temperature viscosity, then heat the paint to lower the viscosity to a sprayable range. Leveling and sag resistance are then controlled by the rate of viscosity recovery as the paint film cools on the surface.

- *"Hang time" requirement:* The room-temperature viscosity must be high enough to support a film about 0.002" in thickness (for adequate protection of underlying paint), applied in a single coat on a vertical surface, for a period long enough to allow time to return to the wet film with the curing lamps. Use of thixotrope additives is typically needed to extend the "hang time" to an acceptable length while retaining good leveling. Without these additives the paint would either (1) continue to "level" slowly, finally developing sags after an interval typically too short to allow time to return with the cure system, or (2) level incompletely, leaving an unacceptably rough, "orange-peely" finish.

- *Cure process requirements:* Equipment complexity, weight, cost and power consumption must be minimized. Ozone generation must be minimized or prevented to obtain the maximum environmental benefit. The equipment must be safe to use, portable and lightweight enough to operate on a movable paint platform or cart. The paint must be sensitive enough, and the UV intensity high enough, to enable a sufficiently high coverage rate of the cure lamps over the painted surface to maximize the flow-time savings and offset the higher equipment costs associated with UV cure. There is also a fire-safety requirement calling for explosion-proof (NFPA Article 500, Class-I, Div-1) operation to enable curing in the paint hangar. These factors tend to favor a one-bulb, UV-A cure system, that is either intrinsically safe or can be enclosed in a positive-pressure inert-gas envelope.

- *Overspray cure requirement:* Since it is impossible to channel 100% of overspray droplets into the paint hangar air exhaust, every surface of the hangar eventually gets coated with a fine layer of overspray droplets. This is not a problem with thermally-cured paints; the droplets merely harden where they land. With UV-curable paint the overspray droplets will remain wet indefinitely, which is clearly unacceptable. A secondary cure process ("dual-cure") is the typical approach, where the overspray droplets eventually harden enough via a secondary cure mechanism to minimize safety concerns (typically within 12 to 24 hr). This secondary mechanism does not require UV exposure, and can proceed in the dark.

- *Engineering and appearance requirements:* In addition to the above the paint formula must satisfy all the engineering and appearance requirements established for thermally-cured paint. Table 1 lists the engineering and appearance properties we used as a predictor of successfully passing the entire qualification-test and appearance test batteries. Table 2 illustrates the progress made toward satisfying these requirements in "stop-light" format (green = passing, red = failing, yellow = marginally passing—needs some final adjustment.

- *Heat –resistance requirements:* Finally, the paint formula must also be resistant to yellowing, and slow the yellowing process in underlying paint, to a degree that justifies the time and expense of adding an extra coat of paint. This requirement has proven to be especially challenging, and although substantial progress has been made toward this goal we cannot anticipate the degree to which the discoloration can ultimately be mitigated. Because of this we have set the requirement as "best available performance". This indefinite level will be assessed to determine the business case for implementing the clearcoat as a heat-resistant coating.

Progress to date: We have tested clearcoat formulations from two suppliers that went through several cycles of test, reformulate and retest. At present we have obtained substantial reduction in discoloration for the UV-curable clearcoat applied to the control color coat, compared to the thermally-cured control clearcoat applied to this same color coat. These clearcoat formulations are also passing the application and engineering test requirements, with only minor adjustments needed to move to the full qualification-test battery. However, it is not clear if we are yet observing any lessening of discoloration of the underlying paint. In the coming months we expect to test several new formulations that we hope will show further improvement.

In the heat-soak tests, aluminum test coupons were coated with the standard thermally-cured paint stack-up (conversion coating, primer and pigmented urethane), then coated and cured with either thermally-cured or UV-curable clearcoat. Color and gloss measurements were obtained before exposure and at several times during exposure to look for trends. Panels were exposed to a range of temperatures ranging from room temperature to 150C (300F). The color values were used to obtain delta-E as a function of soak time and temperature.

Fig. 2 shows the observed behavior of delta-E (hence discoloration) at a soak duration of 60 days, over the range of soak temperature studied. In each plot delta-E is plotted against soak temperature. The three plots show a thermally-cured white paint (color coat) without clearcoat (dark blue), the same paint with the best-performing thermally-cured clearcoat (light blue) and with the best-performing UV-curable clearcoats (red and violet) from the two suppliers.

After 60 days' soak, insignificant discoloration was seen at the room-temperature "control" soak and at 70C (160F), which is near the maximum temperature experienced away from the hot-exhaust vents. Significant discoloration was seen for all paint combinations tested at 120C (250F) and 150C (300F); these temperatures were chosen to simulate the conditions near the hot-exhaust vents. Over the soak temperature range studied a consistent improvement is seen for the UV-cured clearcoats over the thermal clearcoat, although neither UV-curable clearcoat showed any clear evidence of mitigation of discoloration of the underlying pigmented paint. The substantial scale of the improvement (about 50% for the best-performing formulation) gives us hope that we can at least match the performance of the white paint with a "basecoat-clearcoat" system.

These results, taken together, are very promising, given that after a long period of development we are at the point where we could qualify one or both of these UV-curable formulations to the applicable exterior specifications for use as a general-use fast-cure clearcoat.

UV-curable paint development at Boeing—a gated process: The development process followed the flow as depicted in Fig. 3. It is a series of development phases connected by gates; at each gate the test results are assessed and a business case analysis performed to support the decision to proceed to the next phase. The development phases are as follows:

- *Identifying formulators:* We began the development process by canvassing the industry for formulators who either had an off-the-shelf product with potential for meeting our requirements, or who had the resources and interest in developing a clearcoat for us. We identified two formulators who began the process of formulating and submitting liquid and cured samples for us to test. While we work with these formulators we are continuing to check for additional sources with either an off-the-shelf product or the potential for developing a product meeting our requirements.

- *Iterative screen-testing of submissions:* To expedite the test process a battery of screen tests is employed that is a subset of the full qualification-test battery included in the paint specification. The test battery is listed in Table 1. The first five properties are tested only on samples applied and cured in our lab. They give us an overall idea of the spray and cure properties, and hence the application suitability of the formula. All samples are tested for the remaining properties listed. All of the remaining properties except for heat resistance give us a preview of the general engineering performance as an exterior paint.

  There follows several iterative cycles of testing, reporting of results to the formulators and submission of reworked formulations, until we test formulations that are close to satisfying the screen-test requirements. As anticipated, the greatest challenges have been in achieving adequate surface and through-cure with a single bulb, and resistance to yellowing during accelerated weathering. Results to date, however, suggest ways to meet these requirements through adjustments to the paint formula and to the cure process.

- *Qualification testing and incorporation into the specification:* Once we obtain a formula satisfying the screen-test requirements it will be sent through the entire qualification test battery. We anticipate several more iterative cycles of testing and re-submission as adjustments to the photoinitiator package, thixotropes and other additives, as well as residual adjustments to reactive diluent and oligomer components).

- *Concurrent cure-system development:* Concurrent to formulating the paint we evaluated several approaches to the cure process. To obtain adequate through cure in the least exposure time and with the lowest UV intensity, the oligomeric resin, reactive diluent and photoinitiator package all need to be optimized for the intensity and spectral output of the curing lamp system. For the formulas presently under development we identified an optimal UVA intensity range and dosage range for obtaining through-cure with maximized coverage rate (i.e. minimized cure time) for the paint formulas being developed.

  To satisfy our safety and process-engineering requirements we are focusing on a one-bulb UVA process. We adopted conventional UV lamp technology due to its technical maturity. While LED-based curing would be ideal for our application, and is well-established for curing printing-ink films, it still lacks technical maturity at the performance levels required to cure paint films at the coverage rates we require. This technology is developing rapidly, and we will be testing formulations cured by this technology.

  Delivery of the UV to the painted surface could be accomplished either by (1) UV lamp fixtures installed throughout the hangar and surrounding the airplane (including floor units for the underside) or (2) by scanning a lamp system over the surface. The former scheme, while conceptually simple (just throw a switch to effect the cure) and fast (all painted areas exposed simultaneously), was rejected as prohibitively costly and unsafe due to stray UV radiation. Also, since the hangar would be off-limits during cure, no simultaneous operations could proceed. Thus we adopted the idea of scanning the UV lamps over the painted surface, as is done in the automotive industry. In our case the lamp array is moving, not the painted surface. Thus the actual effective cure time would be the time required to "paint" the surface with the required dosage per unit area of UV. This overall cure time is dependent not only on UV intensity and paint sensitivity but also on the time required to set up and maneuver the cure lamps over the entire painted surface.

- *Scale-up to curing large test substrates:* When we obtain a qualifiable paint formula and associated cure process at the lab-bench scale, the next step is to scale up to a lab system capable of curing large substrates in a manner simulating the "push-broom" coverage process expected on the airplane.

- *Application and cure on simulated airplane sections:* The next development phase is scale-up to a production-prototype cure system that is explosion-proof and capable of operation on a paint platform or mobile cart on the floor. This prototype will be evaluated in simulations of representative aircraft-painting scenarios, and any residual issues with cure system or paints addressed. Scrapped fuselage skin panels, similar in size to the area to be painted in production, will be used for these trials, which will be conducted in the paint hangar with the painters who would be painting customer airplanes.

- *Production trials on customer airplanes:* Finally, if all continues to proceed nominally we will move to a net-configuration cure system and production trials on customer airplanes chosen in the same manner as for any new coating or marking system.

As each phase of development is completed we will conduct a business-case study for proceeding to the next step. Presently we are assessing the best path for qualification testing. Once one or more paints pass the qualification-test battery we will revisit the business case to determine whether it makes sense to go to an initial implementation. The follow-on development phases (large-scale lab testing, painter trials and production trials) will then be planned accordingly. Conceivably at any point the business case may not close, at which point the results will be documented for possible re-evaluation in the future, as technology improves and the business needs change.

However, even in the event of a decision to terminate the effort, we anticipate that the unique application and cure testing resources put in place for the development effort can be utilized in other ways. An example of this would be to provide testing services in support of contract research and development work assigned to our labs.

A collaborative effort: As described above, development of a successful UV-curable paint formula must be dovetailed with the development of a curing system for it. To facilitate this process both paint formulators are working closely with a cure-system developer and raw-material suppliers as well as with the end user. Meetings between the various stakeholders are held to manage the development process; in particular to ensure that resources and expertise are most effectively deployed.

Conclusions: There is still significant development to be done to achieve the objective of a UV-curable clearcoat that confers useful protection from heat-induced discoloration. Even if we do not achieve useful heat protection, the clearcoat formulas developed in this work may find use as specialty coatings elsewhere on the airplane. More applications may be possible if pigmented versions can be developed in follow-on work.