Robotic UV Curing for Automotive Exterior Applications

By Paul Mills

As car makers continue to look at UV-curable coatings as a future exterior paint finish, there has been a significant effort to develop coatings that meet the cosmetic and performance requirements of the customer. At the same time, many car makers have lamented that not enough effort has been put forth to develop a cost-effective and technically viable means of curing parts as large and complex as a car body. This paper describes recent developments in using robotically actuated UV lamps to cure automotive exteriors. The technical and economic benefits of this approach are described and compared to the approach of using large fixed-lamp arrays.

Introduction

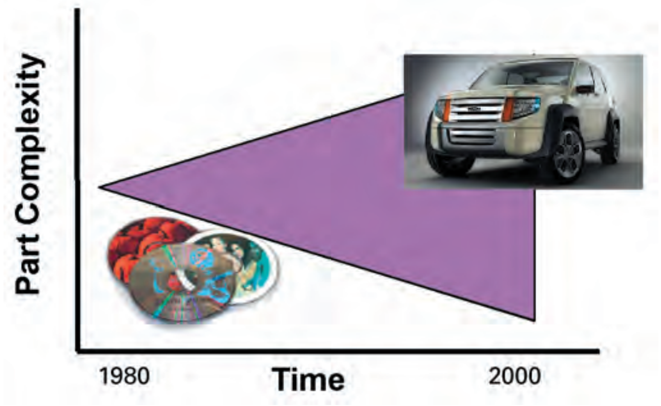
UV coatings remain attractive to car makers because of their scratch and mar resistant characteristics, rapid process speed, and the environmental friendliness of UV technology.

In describing the attributes of UV coating on their Model U concept car, Ford Motor Company observed that “Environmental concerns in manufacturing are also addressed with a new UV-cure clearcoat system developed by Akzo Nobel. Clearcoat is the topmost layer of a vehicle’s paint. It gives a vehicle its shine and protects the paint from damage. During the clearcoat cure, the Model U was exposed to ultraviolet light rather than to the high temperatures that are used traditionally. This system provides a harder finish and means the Model U will be more resistant to scratches than most cars and trucks. The process eliminates the need for a bake oven and uses less energy and solvents than traditional systems.”[1]

The UV-curing industry has evolved over the last 20 years (Figure 1) from predominantly flat, geometrically simple and symmetric applications (such as paper, floor tiles, wood panels, optical fiber and DVDs) to complex 3-D shapes (such as UV-cure composites and automotive refinish primer/surfacers). This evolution requires a fresh approach to what equipment is most appropriate and how to best cure these non-traditional parts.

FIGURE 1

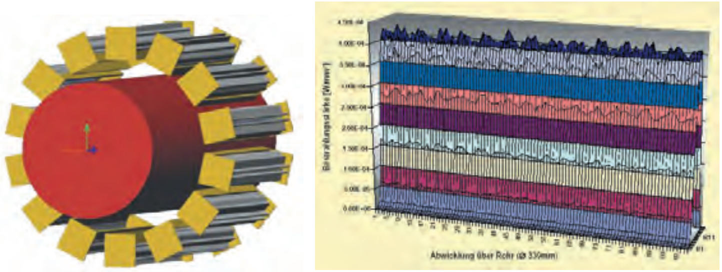
The evoloution of UV curing from simple, flat geometry to the complexity of a Model U Ford



Since a 100% UV-cure mechanism depends on each facet of the part receiving equal exposure to the UV-light source, the challenges of curing a car body are formidable.

FIGURE 2

Illustration of how a fixed-lamp array can produce relatively uniform irradiation of a curvilinear surface



Example of an arrangement of multiple fixed lamps positioned to irradiate a curvileinear part

The resulting irradiation profile. The profile is not perfectly uniform because of various factors including gaps between lamps, varying target distance along the lamp length and edge effects from each lamp.

Early Attempts at UV Curing of Auto Exteriors

The usual method proposed to date has been to create a tunnel containing a large number of fixed position lamps. The lamp positions are pre-set to provide uniform illumination over the entire part surface. This technique is borrowed from common industrial applications and has even been used to prepare prototype UV-coated automobiles in Europe. This technique was employed for the 2001 Team UV project that produced a small UV-coated racecar. [2]

The Team UV racecar project used many fixed lamps to cure a small UV-coated racecar.

In order to achieve the required uniform exposure, a common procedure involves positioning several radiometers on the parts complex surface and making a series of iterative trials, fine tuning the position of lamps after comparing the radiometric data after each trial run.

To reduce the time of trial-and-error, a method has recently been proposed that relies on a sophisticated computer simulation to model the exposure of many fixed position lamps needed to create uniformity. [3]

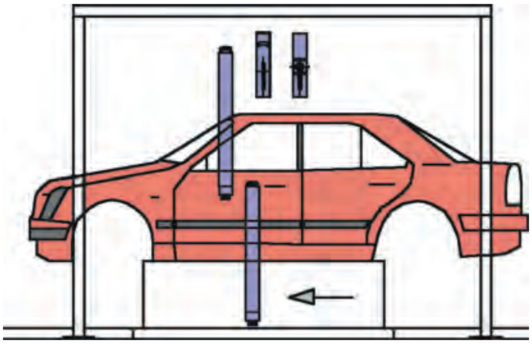
While this approach may expedite the painstaking process of empirically determining lamp position with a radiometer, the model is extremely complex and does not appear to take into account all factors, such as reflections, advance curing as the part moves into the curing tunnel and other subtle effects that are difficult to model mathematically. Since this approach "imputes" lamp positioning by considering the combined effects of "a thousand points of light" it does not provide much help if the actual measurements do not coincide with the model. The user, faced with the practical problem of what to change is back to an empirical, iterative, solution.

Limitations and Risks of Fixed Lamp Arrays

The proposal to cure auto bodies using a tunnel populated with many

FIGURE 3

Car body geometry effects uniformity of UV curing



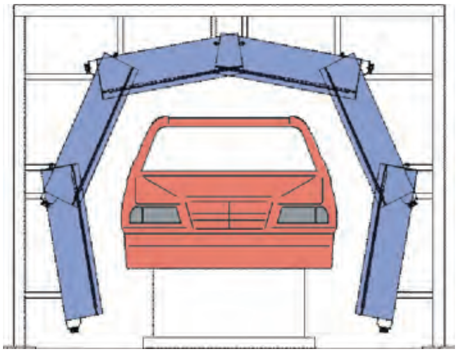
The ever changing geometry of a car body adds to the difficulty of achieving uniform irradiance with fixed lamps due to varying target distance as the part moves past the array.

lamp lifetime and UV uniformity. It also entails larger power supplies and cooling systems including water-cooled lamp modules.

It appears that a "one (lamp) size fits all" approach is not the best solution for auto bodies. Some surfaces can be treated very effectively with large lamp lengths, while others might require smaller sized lamps to accommodate rapidly changing curvatures. Having one size tool is therefore inefficient.

FIGURE 4

Larger lamp lengths can improve efficiency



Using larger lamp lengths improves the cost and logistics of the fixed lamp approach but still presents geometry problems.

fixed position lamps is attractive to the lamp supplier but fraught with practical difficulties for the car maker.

Alignment of Lamps

Since each fixed lamp has a finite, linear, footprint only a "best fit" can be hoped for on a complex curvilinear surface. The tradeoff is obvious, if the footprint of the lamp footprint is made smaller, the more fixed lamps that are required, but the better fit can be achieved.

Figure 2 illustrates IST Metz ray-tracing program illustrates how an array of fixed lamps can produce relatively uniform irradiation of a curvilinear surface.

While this method is satisfactory for parts where the target distance to the lamp is constant, using fixed lamps is made more difficult by the fact that a car body does not remain at a fixed target distance to the lamps (Figure 3). And since the entire body must pass before all lamps in the tunnel by conveyor, there can be significant variation.

This means that not only must a "best fit" be developed for any given surface of the body, but that an overall best fit must be achieved for the entire body as it is processed. Clearly this is a challenging problem.

Assuming such a fit can be achieved for a given body configuration, it will be necessary to derive an entirely different arrangement for another body style—making setup an enormous undertaking. Some users have expressed concern over how to cure components that face away from the lamps such as the inside of mirror housings, underside of tire wells and bumper fascias.

A "gut-check" in considering whether the idea of fixed lamp curing of a coating makes sense is to ask whether it would make sense to apply this same coating using a similar arrangement of fixed applicators.

Capital cost

The use of multiple lamps carries a financial burden due to redundancy and inefficiency. Typically each lamp requires its own power source, cooling apparatus, mounting fixture, controls, etc. One way to mitigate this problem is to use individual lamps with as large a radiant footprint as practical (Figure 4). This approach is only possible with electrode (or arc) lamp technology since microwave UV lamps are currently restricted to 10" or less in footprint. But using larger arc lamps reduces the

System Maintenance and SPC Considerations

Another undesirable aspect of using a large array of lamps is the challenge of maintaining and monitoring a large number of discrete devices. What is the proper procedure when a single lamp degrades or fails due to aging? If a new lamp is installed on an ad hoc basis each time then there will eventually be varying intensity levels among the irradiators in the array. By analogy, what should a car owner do when the first spark plug wears to the point of replacement—replace the entire set or just the deficient plug?

Another question is raised on whether to individually monitor the output of each lamp module. It is possible for a single lamp to fail and potentially go unnoticed—producing parts, which may not have adequate cure. Of course, the technology exists to monitor and even close-loop control lamp modules to maintain consistent output, but the cost of such monitoring and control for very large arrays of lamps may be expensive.

As was touched on previously, lamp maintenance will necessarily disturb the position of lamps, which must be put right again. It has been suggested that the lamps could be mounted on small, motorized micro-positioners, but again the control and capital cost of implementing this on large arrays may not be practicable.

Robotic UV Curing

For many years numerous attempts to use robots to manipulate UV lamps have been attempted with varying success. As pointed out by one lamp supplier "there are issues that need to be considered when using a robot. First, the lamps must be sufficiently robust to withstand the acceleration and de-acceleration swings of the robot arm and, the lamp must be able to operate efficiently and reliably in a variety of different positions...Finally, the robot must be programmed to ensure that it delivers the correct UV energy to all parts." [4]

The Daimler-Chrysler UV Technology Center in Ulm, Germany, tests robotic cure.

Recent investigations by Daimler-Chrysler into the use of robotic curing for automotive coatings have correctly identified significant challenges related to the process cure window, noting that "if UV technology is to be transferred to the production process of a vehicle painting line, then one should be able to calculate the hardening lines and the movements of the hardening movements. Simulation tools are needed for this purpose." [5]

In 2004, a group of companies formed the North American Automotive UV Consortium to develop these and other missing tools and techniques to advance robotic UV curing. The group initially developed a "roadmap" to guide the team's development efforts:

- Development of UV sources suitable for robotic use
- Characterization of the output of these sources (i.e. the radiant "footprint")
- Development of offline programming simulation tools for light path programming
- Development of tools and techniques for online validation of simulations
- Cure test studies with coating suppliers
- Collaboration with carmakers on pilot and production scale programs

Development of Robotic UV Sources

Many of the existing UV sources are not ideal for robotic applications. They are too complex, too unstable, too heavy, or require too many interconnections to be mounted on a fast-moving robot arm.

A compact arc lamp source was developed for robotic applications by IST Metz GmbH. This unit weighs approximately 18 pounds, which makes it suitable for use on a wide range of industrial robots with capacities in the <10 Kg (22 pounds) range, keeping the cost of the robot to a minimum while offering a broad selection of units to choose from.

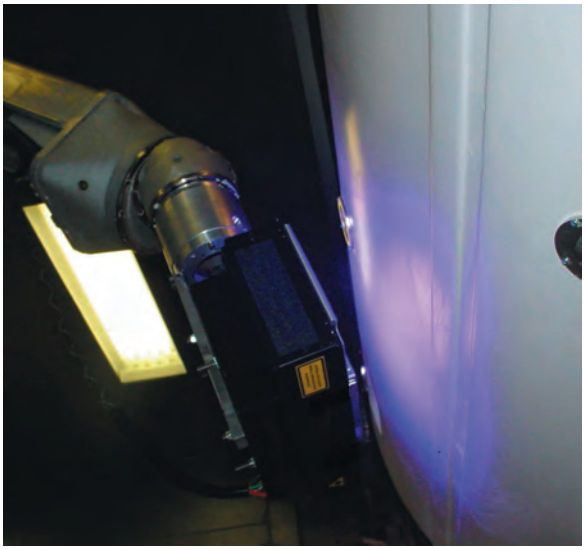
The lamp contains few electronic components, which are susceptible to damage or variation during rapid acceleration. A shutter is provided for both the safety of the operators and to provide full powder to the part within a few milliseconds of electronic shutter triggering, thus allowing the car body to be in position before beginning exposure to UV energy.

A minimum of hoses and electrical connections makes mounting of the lamp to the robot simple and keeps interconnections from becoming accidentally twisted or entangled during lamp articulation.

A second source was used for testing consisting of a UV LED array provided by Phoseon Technology. While the UV output of the LED array is somewhat lower than traditional arc lamp sources (maximum of approximately 2W/cm2), UV LED technology is rapidly developing. The advantages of the LED array are its extremely long lifetime (>30,000 lamp hours), the instant on/off capability of the device (2 ms from off to full power), and the array emits no direct heat to the target. The output of the array is a narrow bandwidth falling from 385-405 nm. One advantage of robotic manipulation of the UV LED array is that extremely close (~1.0") target distances can be maintained which provides higher average peak irradiance than could be achieved with fixed positioning of UV LED arrays. The results obtained in lab trials are very encouraging.

Characterization of the UV Source

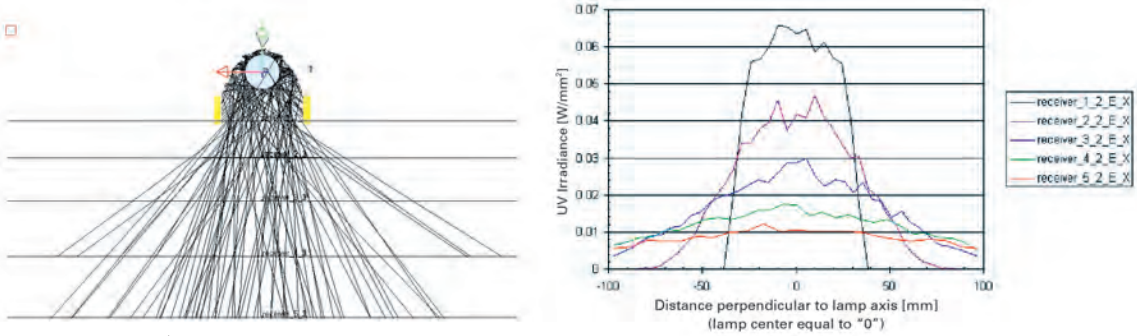
The radiant energy profile of the UV-arc lamp source was "mapped" to accurately determine the footprint of the lamp. This footprint allows a UV



UV LED source used in robot testing provides excellent promise.

FIGURE 5

Orientation and target distance of the lamp is mapped for offline robot simulation

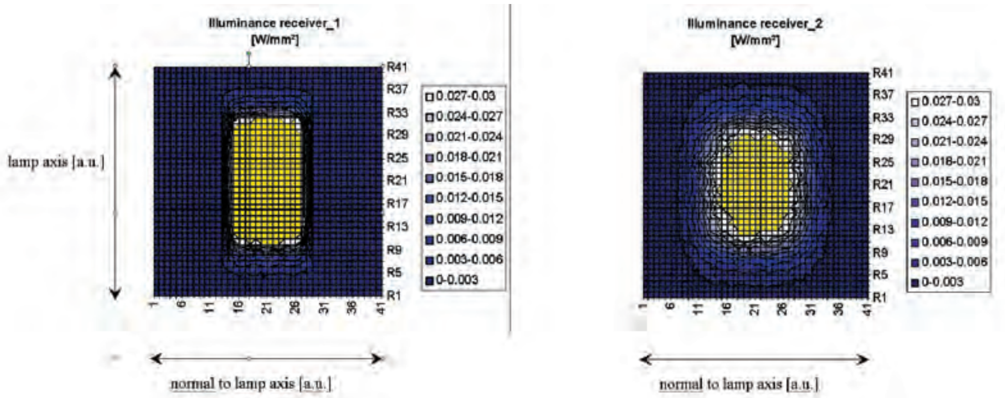


Ray tracing of the robot lamp. Note that the reflector is optimized to provide uniformity at typical target distances.

Profile of the robot lamps output at various distances from the center of the lamp axis.

FIGURE 6

Contour maps of the UV lamp output



Contour "maps" of the UV lamp output aid in the development of curing simulations. The output can be modeled into a robot tool for path programming.

robot "tool" to be created for the offline simulation software (Figure 5).

A model of the lamp output can be described quantitatively in the x, y and z axes (Figure 6). Thus, the proper orientation and target distance of the lamp can be used in the robot offline simulation. Proper rotation of the lamp can also be programmed so that the lamp is kept normal to the tangent of the surface at all times—a capability that is not possible without articulation of the lamp.

Development of Offline Simulation Tools

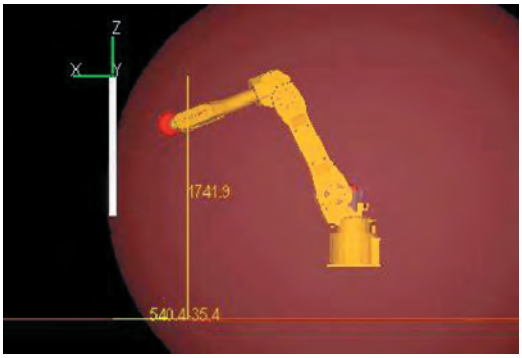
An ongoing effort of the consortium is the development of simulation software for offline light path development and analysis. This will permit car makers to develop and fine tune curing paths without interrupting production.

Modeling the UV lamp tool allows for programming paths with proper overlaps to minimize potential "striping" of the part while achieving maximum uniformity in the fastest production cycle time (Figure 7).

The program also includes the ability to track the conveyor in real time. This allows paths that minimize the effects of "mapping" or pre-curing of coating due to advanced exposure to UV light.

FIGURE 7

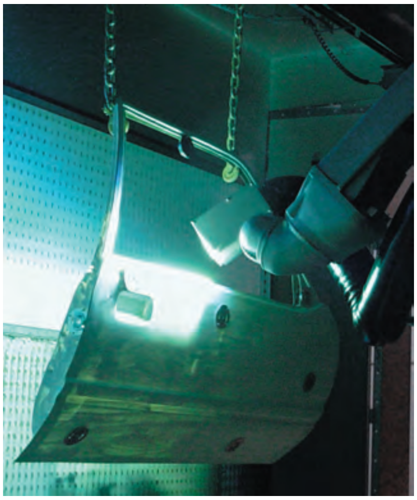
Offline simulation software



Development of the offline UV simulation software is a continuing effort to reduce setup time.

Online UV Trials

A number of online trials have been conducted at the Fanuc Robotics facility in Toledo, OH. The goal of these trials was to evaluate the performance of the UV source, accuracy of the model, and to evaluate the effects of robot arm speed, conveyor speed, part presentation and other variables.



Online robotic UV testing beginning with an automotive door panel outfitted with 10 sensors to measure peak irradiance and energy density as the part is moved through the booth.

Radiometric data was collected using a novel device (3DCURE™) supplied by EIT Incorporated. The multi-sensor data acquisition unit allowed the consortium to collect UV data from various locations on a complex surface. Sensors were embedded into locations that were predicted to be difficult to cure with fixed lamps.

The robot program was then fine-tuned to achieve uniform peak irradiance on an automotive door panel moving at a line speed of 12 FPM. Once uniform peak irradiance was established, robot variables were tuned to achieve equal UV dose. Power output of the lamp was kept constant for all testing. The unit is capable of producing 500W/in at full power.

Another advantage of the robotic technique is that the target distance to the part can be set and maintained at the optimum distance for the reflector design. For many lamp units, especially those using elliptical reflectors designed to focus to a line, the focal lengths are relatively close (typically around 2" from the face of the lamp). This means that the lamp must be operated out-of-focus (in what some refer to as the “far field”). While this is common practice it is also inefficient as the power falls off rapidly in the far field.

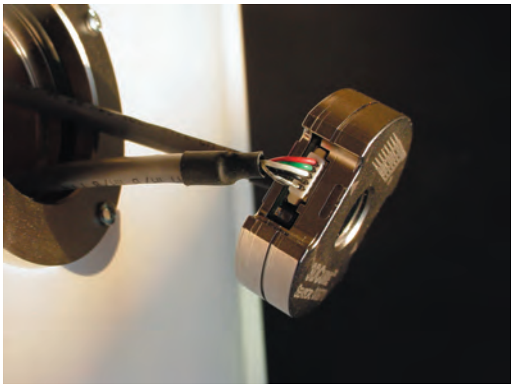
Figure 8 shows the process of fine tuning the light path for consistent peak irradiance during one of the earliest line trials. The total time to tune the system so that peak irradiance is kept within a narrow range is estimated to be less than one hour.

Preliminary Results

Of the six-steps outlined in the roadmap developed by the consortium, solid progress with encouraging results have been obtained from efforts on the first four steps.

Technical Discussion

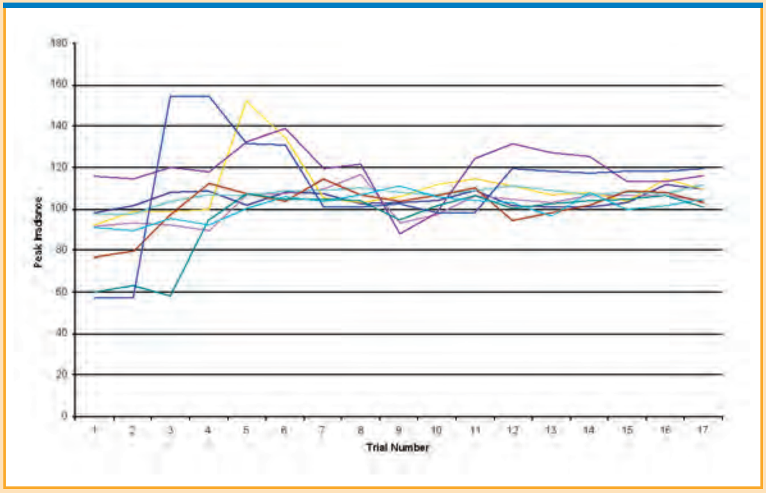
1. The UV lamp designed for robotic use is a successful development. The unit is lightweight and agile and therefore posed no obvious problems in use. The shutter system was an important safety feature for frequent trials.
2. Several improvements will be implemented in the next generation of lamp design. There were also several ideas for improvement in how to integrate the lamp unit to the robot.
3. Offline programming work is underway and already yielding positive results. Lab trials identified



Close up view of one of the UV sensors implanted on the test surface and connected to a data acquisition module.

FIGURE 8

Robotic UV testing—path tuning



many features, which can be added to the programming.

4. Online data collection using the 3DCURE™ unit was successful in allowing the team to rapidly develop paths that yielded uniform peak irradiance and energy density. Several improvements to the data collection system are being implemented to make higher speed data collection easier.
5. The radiometric data indicates that sufficient peak irradiance and dose can be achieved with the line speed (12 FPM) and robot arm speed (600 mm/sec) that were used during the trials to affect proper cure of commercial formulations. (Based on baseline cure data provided by coating formulators). This opens the doors to steps 5 and 6 of the roadmap that will involve curing of coatings at production cycle times.

Cost Model Development—Robotic vs. Fixed Lamp Systems

The North American Automotive UV Consortium has developed an interactive cost model that provides comparative capital and operating cost data needed by manufacturers. A summary of cost model results for replacing variable power, 600W/in lamps with a similar output robotic curing cell is shown in Figure 9.

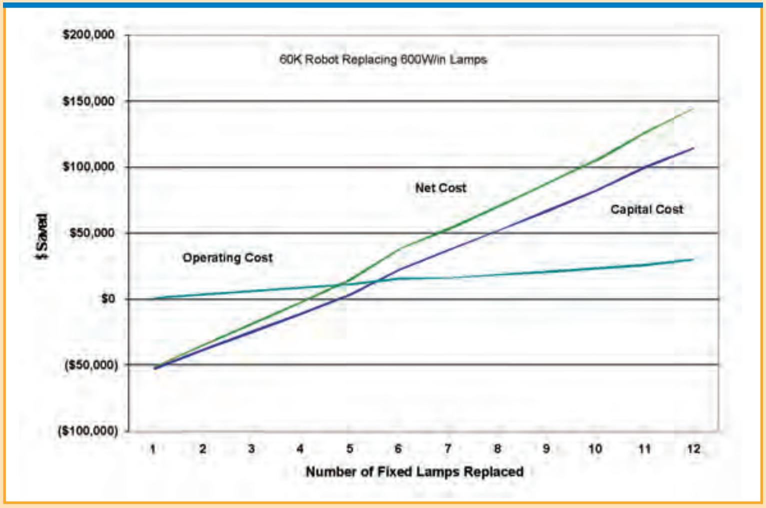
The results presented here are for a simplified model where capital cost is based on list costs of all equipment under study, published energy consumption and replacement parts costs. The model does not attempt to quantify "soft costs" involved in equipment setup times, floor space consumption, downtime, etc., which appear to favor a robotic approach. The capital cost comparison is sensitive to the cost of the robot, since this is a relatively expensive component. The following comparison anticipates a $60K robot and associated hardware needed for integration. The model is also sensitive to the cost of fixed lamps. The comparison in Figure 9 was computed using microwave powered 10" lamps rated at 600W/in with variable power supplies since the literature suggests that variable power may be necessary to achieve the required uniformity and to provide various monitoring features.

While numerous scenarios have been evaluated, a few trends are already clear.

First, the operating cost of a single robot lamp is always less expensive than a multi-lamp array. This is due to the lower parts replacement requirements and the lower energy consumption.

FIGURE 9

Cost model for replacement of 600W/in lamps with similar robotic curing cell



Second, the capital cost of eliminating fixed lamps with a robotic cure system is higher until a threshold number of fixed lamps are replaced. In the model presented here, the robotic system has a lower capital cost once an array of five or more fixed lamps are replaced. If more exotic equipment is anticipated (such as lamp monitoring or micro positioners for fixed lamps) then the robotic system may offer capital savings compared to even smaller arrays. Conversely, if exotic robotic equipment is installed, it may make the robotic system more costly to install.

Future Development

While good progress has been made leading to several improvements in the tools and technology for robotic UV curing, there is a still a steep development curve to be tackled.

1. Continued refinement of the UV lamps sources including UV LED developments.
2. Improvements in the offline simulation software to include subtle variable observed in online trials so that offline simulation and real world cure experience are related as closely as possible.
3. Improved data acquisition tools will allow more accurate programming and measuring of UV irradiation to further define the process window.
4. Refinements to the first four steps of the six-step roadmap will lead to future expansion of the testing to include actual curing of coated parts under simulated production conditions (e.g. cycle time).
5. One outcome of the work to date has been the formation of a new company (UV Robotics LLC) that will specialize in the integration of UV lamps, robots and other process equipment and controls for end-use applications.
6. The North American Automotive UV Consortium anticipates expanding its membership to include coating suppliers and Tier One and OEM automotive partners.

While the goal of this work is to provide car makers with a set of tools that enable use of UV coatings, the work clearly has implications for the Tier One producers and other industrial processes. Commercialization of these tools is expected shortly. ◗

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—Paul Mills is director of the North American Automotive UV Consortium, Strongville, Ohio.