RESEARCH

A Rapid Tool Manufacturing System Based on Stereolithography and Thermal Spraying*

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This paper describes a system for rapid tool manufacturing based on the integration of stereolithography and thermal spraying. With stereolithography apparatus (SLA), plastic prototype models are built directly from liquid photopolymers by laser scanning. Thermal spraying is then used to incrementally deposit metal onto the SLA models to build the tool. A broad range of tooling can be fabricated including injection molds, forming dies, and EDM electrodes. The system integrates SLA and thermal spraying into a CAD/CAM environment which includes robotic spray capability, and computer-aided process planning. Information flows efficiently from design through fabrication by incorporating a common geometric modeling system for part and process representations. Our goal is to demonstrate that automating and integrating these processes, within a unified modeling environment, can significantly improve productivity through rapid fabrication and also reduce costs. We are building a system testbed for an injection mold tooling paradigm.

INTRODUCTION

The capability to manufacture a wide variety of quality products in a timely and cost-effective response to market requirements is a key to global competitiveness. The opportunities for improving manufacturing technology range across the entire spectrum of industries, materials, and manufacturing techniques. There is no single technological innovation which, by itself, will significantly improve productivity; rather it is a systems issue which involves rethinking many manufacturing activities. One such activity is the manufacture of tooling (i.e., design, prototype, and fabrication) such as dies and molds required for the high-volume production methods that generate most of our manufactured products. Tooling manufacture is typically an expensive and time-consuming process. The reasons lie not only in the fabrication costs and time constraints imposed by conventional machining methods, but also in the organizational framework. In most organizations, different groups employ different processes to design and manufacture tools and products, and the expertise in tool design and product design reside in different groups, impeding communications between them. The representational and physical models used in design, prototyping, and manufacturing are often incompatible with one another, so that transitions between the stages are time-consuming and error-prone. Products often make several complete cycles through design, prototyping, and fabrication before reaching production. Thus, new product development or product modification implies a series of iterative changes for both product manufacturers and toolmakers. For all these reasons, a rapid and smooth transition from product concept to production remains a challenge.

This paper describes the development of a unified CAD/CAM tool manufacturing system to address this challenge for an injection molding paradigm. In this system, both prototyping and tooling fabrication are based upon compatible shaping deposition processes, while the underlying geometric and process models share a common representational scheme. Our goal is to demonstrate that automating and integrating these processes can significantly improve productivity through greater design flexibility, rapid fabrication, and reduce cost.

Shaping deposition processes build three-dimensional shapes by incremental material buildup of thin layers, and can make geometrically complex parts with little difficulty. These processes include selective laser sintering [1], laminated object manufacturing [2], ballistic powder metallurgy [3], three-dimensional printing [4], stereolithography, and near-net thermal spraying. Our system incorporates the commercially available technologies: stereolithography apparatus (SLA) and arc spray equipment. Stereolithography[1] is a new process which creates plastic prototype models directly from a vat of liquid photocurable polymer by selectively solidifying it with a scanning laser beam. In arc spraying, metal wire is melted in an electric arc, atomized, and sprayed onto a substrate surface. On contact, the sprayed material solidifies and forms a surface coating. Spray coatings can be built up by depositing multiple fused layers which, when separated from the substrate, form a free-standing shell with the shape of the substrate surface. By mounting the shell in a frame and backing it up with appropriate materials, a broad range of tooling can

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[1] Stereolithography has been commercialized by 3D Systems, Inc. (Valencia, CA).

be fabricated including injection molds, forming dies, and EDM electrodes. For example, the cavities of injection molds can be fabricated by direct deposition of metal onto plastic SLA models of the desired part and backing the framed shell with epoxy resins. Relative to conventional machining methods, the sprayed metal tooling approach has the potential to more quickly and less expensively produce tools, particularly for those parts with complex shapes or large dimensions. Thus, with stereolithography, an initial part shape or prototype is quickly created. Thermal spraying is then used to make tools based on the part shapes produced by stereolithography.

The potential effect of combining thermal spraying with stereolithography to build tooling is enhanced by integrating and automating these processes within a unified CAD/CAM environment. The goal of integration is to reduce the number of iterative cycles through design, prototyping, and fabrication. CAD-based evaluation and modification tools can operate on design models to help the designer create manufacturable designs on the basis of requirements and limitations of the downstream processes. For example, there are certain shape features in thermally sprayed parts which are difficult to spray. The system should identify these features so that the designer may modify them before reaching the fabrication stage. Another example is to automatically critique ejectability by analyzing whether there is sufficient draft for part ejection from an injection mold. If drafts are not sufficient, the system should identify this geometric problem and bring it to the designer's attention.

Another step in the CAD/CAM approach is to automate the thermal spray process with robotics. Tooling manufacture by thermal spraying is currently a labor-intensive artform. Shifting emphasis to robotic spraying, driven by an off-line trajectory and process planner, will improve tooling quality by achieving consistent and predictable performance of the sprayed metal shell.

Finally, the level of integration and the number of different models in this CAD/CAM system requires geometric representations that can be abstracted at several levels and that can be manipulated over several dimensions. Rather than use several different modeling environments customized for the demands of each subsystem, the models in our framework for design, analysis, and fabrication share a single common *unifying* geometric representation implemented in the software modeling system NOODLES. With this approach, model manipulation capability is robust and models need not be transformed between subsystems.

The system which we are developing represents a significant departure in tool manufacturing compared with conventional methodologies. The majority of ongoing research [5, 6] focuses on automating numerical control (NC) fabrication by removing material from metal blanks. Manufacturing a broad class of complex geometries is difficult without extensive programmer and operator intervention, so that NC fabrication remains expensive and relatively time-consuming. In addition, the fabrication of prototype parts has remained disjoint from the processes to fabricate the production part. In contrast, geometric complexity is not an issue with SLA, so that complex metal shapes can be fabricated by direct metal deposition onto the SLA models. Also, tooling fabrication builds directly upon the prototyping process. Such process compatibility and system integration will facilitate a continuous transition from design to prototyping to mass production within a single manufacturing enterprise.

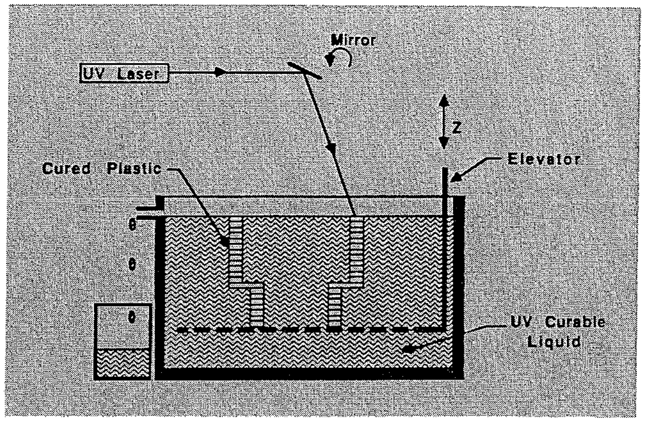

FIG. 1. Stereolithography apparatus

This paper describes the system framework and the components which have currently been developed, and is organized as follows: First, the stereolithography and sprayed tooling processes are reviewed. The procedures for spraying SLA model patterns to build injection mold tooling are then described. A case study for manufacturing a geometrically complex plastic turbine-blade design using these processes is presented. The limitations of the sprayed tooling method are identified, and some potential solutions are suggested. A framework for planning robotic spraying is then presented. The robotic spray testbed facility is currently being built, including a robot with a coordinated positioning worktable, and a computer controlled arc spray system. Next, the geometric representation NOODLES and its applications to CAD/CAM modeling and process planning are described.

STEREOLITHOGRAPHY

Stereolithography is a process which quickly makes plastic prototypes of arbitrary geometric complexity directly from the computer models of the parts. The stereolithography apparatus (SLA) does not require experienced model makers, and the machine runs unattended once the building operation is started. It is relatively straightforward for the designer to program and run the SLA.

SLA is the product of 3D Systems, Inc. of Valencia, CA. Their system (Fig. 1) is composed of a vat of photosensitive liquid polymer, an x–y scanning ultraviolet laser beam with a 0.25 mm (0.01 in.) beam diameter, a z-axis elevator in the vat. The laser light is focused on the liquid's surface and cures the polymer, making solid forms wherever the light has scanned. The depth of cure is dosage-dependent. The physical object to be created, as described by a boundary representation model,[2] is first "sliced" into thin cross-sectional layers along the z-axis. For each slice, the laser's trajectory is dictated by the cross sections boundary and by the bounded region.

The elevator platform is initially positioned at the surface of the liquid. As the laser draws a cross section in the x–y plane, a solid layer is formed on the elevator platform. The

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[2] In the 3D Systems device, this is a triangulated, planar surface PHIGS B-Rep.

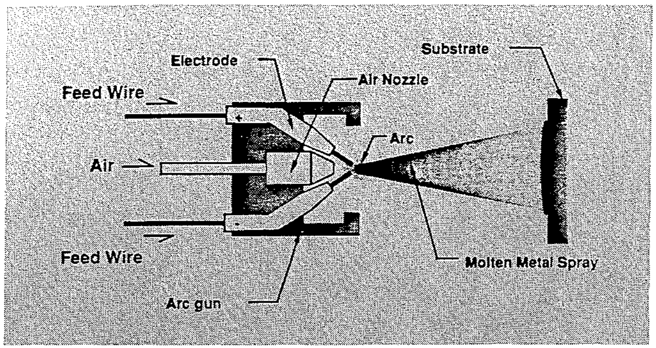

FIG. 2. Electric arc spraying

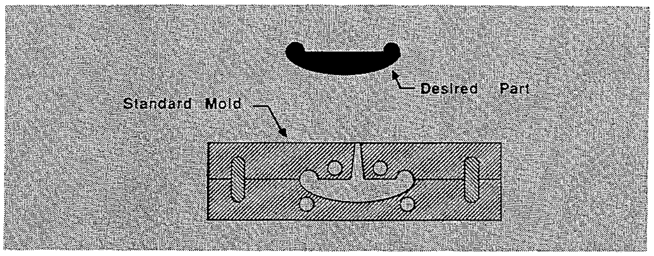

FIG. 3. Conventional mold

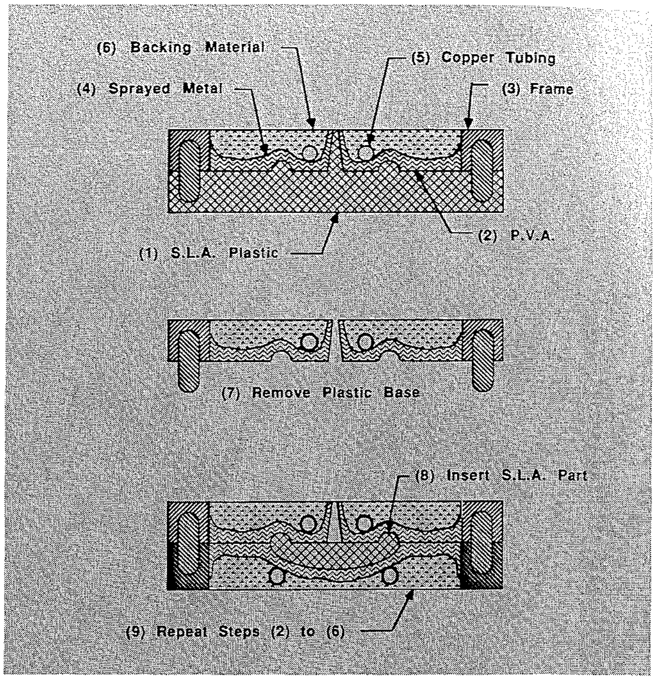

FIG. 4. Sprayed tool process

platform is lowered and then the next layer is drawn in the same way and adheres to the previous layer. The layers are typically between 0.13 and 0.5 mm (0.005 and 0.020 in.) thick. A three-dimensional plastic object thus grows in the vat, starting at the object's bottom and building to the top.

To save time, the SLA laser does not fully cure each cross section. Rather, the laser cures the boundary of a section, and then cures an internal structure, or honeycomb, that traps the uncured fluid. Top and bottom surfaces, on the other hand, are fully cured. These surfaces are cured by commanding the laser to draw the whole surface with overlapping lines; the result of this operation is called skin-fill. Final curing under separate ultraviolet lights solidifies the complete part. One of our goals is to enhance the SLA process by creating efficient slicing and vector generation algorithms which operate directly within the unifying geometric modeller NOODLES. An algorithm for this operation is described later. The current accuracy of SLA parts is of the order of 0.25 mm (0.010 in.), while surface texture is dependent on the building orientation. Additional postprocessing, such as carefully sanding and grinding the part, is therefore required for making accurate and smooth models. Since stereolithography is so new, we expect rapid improvements as the equipment and resins evolve with broadening commercial competition.

There is an engineering cost to preparing a part design for SLA construction. Support structures are added to the part to hold it together while it is being built, the part must be oriented in the vat for best surface quality and fastest build time, and SLA process parameters must be planned. One example of the latter is the choice of layer thicknesses in the part; they do not have to be constant throughout the part, and their choice has a first-order effect on the accuracy, the surface quality, and the build time of the part.

SPRAYED TOOLING

Tooling can be fabricated with arc spraying upon appropriate substrate patterns. Examples which demonstrate this process for fabricating injection molds using SLA patterns are described below and compared with conventional pattern-making techniques. The combination of stereolithography with thermal spraying provides a tooling fabrication process which builds directly upon prototype models. These models are rapidly produced and the ability to modify them for spraying applications is straightforward.

The concept of sprayed metal tooling has been in existence for decades [7]. Current commercial technology uses electric arc spraying. The arc spray process (Fig. 2) uses two spools of metal wire which are fed to a spray gun where the wire tips form consumable electrodes. A high current is passed through the electrodes creating an arc which melts the wire tips. The molten particles are atomized by a high pressure air jet directed at the arc and are accelerated in the air stream. These particles strike the surface where they flatten out and quickly solidify.

A conventional machined injection mold is shown in cross section in Fig. 3. The holes represent cooling/heating channels, and the injection geometry is that of a simple sprue gate. Alternatively, the fabrication steps for building a sprayed mold using SLA patterns are depicted in Fig. 4.

The steps are:

- **STEP 1:** Build SLA pattern used to make one mold half. This pattern is the complement of the interior of this mold half. In this example, the mold pattern includes the partial part shape, a parting plane, and sprue gate.
- **STEP 2:** Apply a water-soluble release agent onto the plastic pattern, such as polyvinyl alcohol (PVA), to facilitate separation of metal from plastic.
- **STEP 3:** Place a metal frame onto the pattern.
- **STEP 4:** Spray metal onto the pattern and around inside edge of frame. Alloyed zinc compositions are used for this particular process because of their relatively low re-

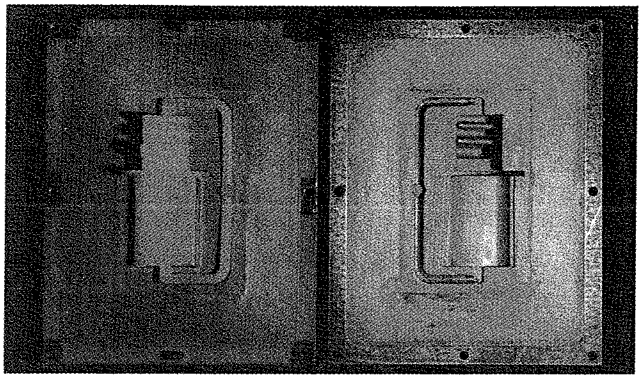

FIG. 5. **Sprayed turbine blade mold**

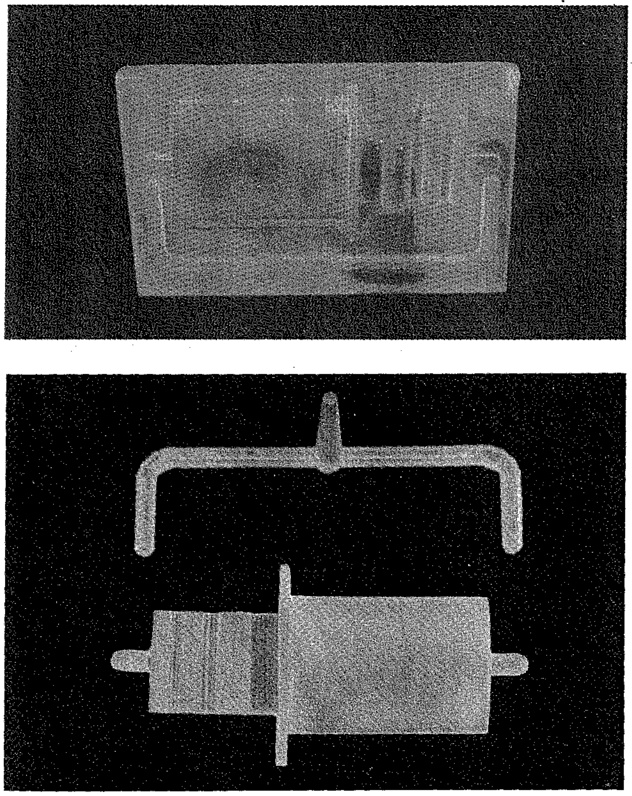

FIG. 6. **SLA mold patterns: (A) pattern for first mold half; (B) inserts for second mold half.**

sidual stress. Sprayed shell thicknesses are typically on the order of 2–7 mm. Fine pattern details are accurately replicated by this spray process.

- **STEP 5:** Lay in place copper tubing for heating and cooling channels for the injection mold process. Additional injection mold components, such as prefabricated ejector pin assemblies (not shown), can be added in STEP 1 and sprayed in place in STEP 4.
- **STEP 6:** Pour in a backing material to support the metal shell. Typical backing materials include epoxy mixed with aluminum shot.
- **STEP 7:** Separate the substrate pattern from the mold half. This is aided by dissolving the PVA in water. This completes the fabrication of the first mold half.

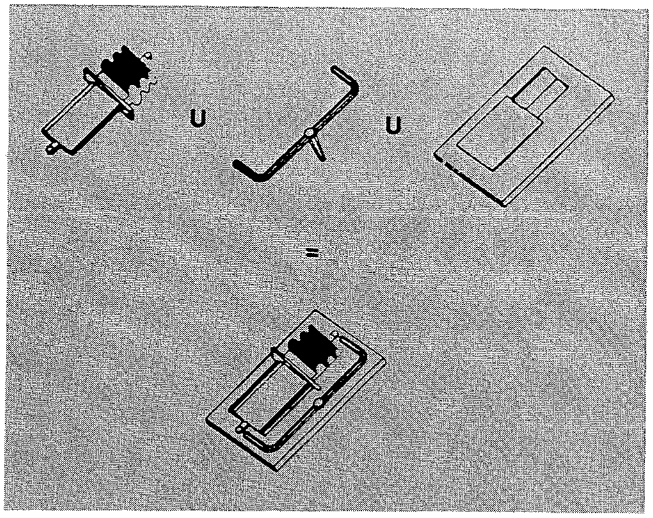

FIG. 7. **Model of SLA pattern**

- **STEP 8:** With SLA, build a model of the whole part to be molded, including runners and gates, and insert the model into the first mold half. This forms the pattern for spraying the second mold half.
- **STEP 9:** The second mold half is completed by repeating STEPS 2–7.

The mold fabrication is completed by removing the SLA insert.

Using these steps, we have fabricated the injection mold in Fig. 5 for making a polyethylene turbine blade. This example is interesting because of this shape's complexity and useful since molded plastic blades can be used for making castings for metal blades. This tool also includes a nonplanar parting surface and a complex runner system. The fabrication of this tool requires three SLA mold patterns, shown in Fig. 6 which can be built simultaneously in the vat. The first pattern in Fig. 6 is sprayed to make the first half of the mold. In contrast to the planar parting surface in the first example, the blade mold requires a nonplanar parting surface to permit ejection of the molded blade from the tool. To create this pattern, the computer models of the blade and runner are embedded into the parting plane model in Fig. 7 using simple union operators. Another major advantage of using SLA to create spray patterns is demonstrated by this nonplanar parting plane example. Conventionally, the first mold half can be prepared by partially embedding a complete prototype model of the part into, say, melted paraffin. The paraffin then cools to form a planar parting surface around the remaining partial part shape. With this approach it is difficult to sculpt nonplanar surfaces. Other approaches which build up parting planes with sheet-wax, clay, or plaster are tedious and difficult. Machining complex patterns is time-consuming and expensive. With SLA it is straightforward and relatively quick to build complex patterns, with nonplanar parting surfaces, and include the runner system in these models.

Once the first half of the mold is completed, the initial pattern is removed and SLA models of the blade with tab gates and the runner with the injection sprue gate are inserted into the mold cavities. The process is then repeated to build the second mold half.

Limitations

It has been estimated [7–9] that there can be an order of magnitude reduction in both the cost and time for producing injection mold tooling by thermal spraying in comparison with conventional machining methods. Similar savings could also be realized for manufacturing other types of tooling such as forming dies or EDM electrodes. The question arises: Why hasn't the use of sprayed metal tooling proliferated considering these potential savings? There are several reasons:

- **Zinc for Prototypes and Small Batch Applications:** Alloyed zinc is the only metal, as reported in the literature, to be commercially successful in the fabrication of sprayed tooling using the aforementioned steps. More involved spray processes for steel deposition have been described [10], and there are reports that a handful of shops have built sprayed steel tools.

  During the spraying process, molten metal is sprayed onto previously solidified layers of the shell. Residual stress is created in the shell by the shrinkage of the metal as it solidifies. This stress is intensified by the temperature gradient between cooler layers and the freshly deposited hot layer. The net effect of the residual stress is to limit the maximum thickness of the shell. The effect manifests itself when the shell peels away from the substrate as new layers are applied. Steel, stainless steel, and many other alloys demonstrate this problem; zinc, on the other hand, can be sprayed to significant thicknesses. There is no clear prediction of this behavior for layered spraying processes in the literature.

  Zinc-based tools are relatively soft and are used primarily in prototyping and low-batch production applications. Prototype tooling is used to make parts for marketing and customer evaluation and for preliminary part testing. Prototype tools are also used to evaluate a tool design (e.g., to assess gate locations in the runner system) before committing that design to a machined steel tool. Beyond prototype tools, the sprayed tool process should be extended to fabricating steel tools for production quality tooling.
- **Difficulty in Making Patterns:** The time and cost of making complex patterns with conventional machining is roughly the same as directly machining a tool. Thus, the benefits of sprayed tooling, including its speed and relatively low cost, are lost with conventional patternmaking techniques. Improved pattern-making abilities, such as provided for by SLA, should be pursued.
- **Poor Process Control:** The sprayed tool process is currently limited to manual spraying by a skilled technician who must adjust process parameters such as arc voltage, wire feed rate, and air pressure, as well as control the gun motion relative to the substrate. Errors in the technician's judgment, operator fatigue, and poor spray technique yield poor quality tooling. The difficulties in quality control are accentuated when spraying large shapes which may take days to spray. Further, a systematic study of spray parameters in relation to the structural quality of sprayed metal shells for tooling applications has not been reported in the literature. Therefore, methods and strategies to achieve consistent and predictable process performance must be developed.
- **Shapes That Are Hard To Spray:** The spray gun should ideally be aimed so that the trajectories of the atomized metal particles are close to the substrate's surface normals. This assures maximal splattering of the molten particles. Some part designs have geometric features which make it difficult to satisfy this condition. Particles which strike the surface tangentially (e.g., greater than about 45° from the normal) do not sufficiently splatter, resulting in either poor adhesion, increased porosity, or overspray. For example spraying concave surfaces with small aspect ratios (e.g., holes with small diameter-to-depth ratios) is difficult, if not impossible, since particles tend to strike the steep sidewalls at acute angles and bounce off into the hole. Therefore, alternative strategies and technologies should be investigated to extend the scope of geometries which can be effectively sprayed.

Several areas of research should be investigated to address these issues. We have identified and demonstrated the use of SLA for rapidly fabricating the complex mold patterns. Another element is to incorporate robotic spraying, driven by an off-line path planner which uses knowledge of metal spraying. The use of robotic automation has several ramifications. It will facilitate process control by its consistent and tireless performance and it can be easily integrated with sensory feedback (e.g., temperature measurement) for additional on-line control. We believe that the ability to reliably spray steel will require such tight process control. Complex shapes need tightly controlled spray trajectories. Robotic spraying will facilitate these trajectories. Off-line trajectory planning based on design models will not require tedious "teach by showing" operations, while the incorporation of process models to formulate spray strategies will improve spray performance compared to manual operation. This paper presents a framework for the robotic spray planning system.

For "hard-to-spray shapes" there are a number of possible directions to pursue. While the accurate aiming capability of robotic spraying will be helpful, the ability to spray concave shapes with small aspect ratios (e.g., small deep holes) is still limited by the divergence of particles from the spray gun and the limitation of spraying along the line of sight. The use of continuous detonation spray guns which have highly focused spray beams should be investigated for this application.

Ultimately the design system should account for "hard to spray shapes" by having up-to-date knowledge of the spray capabilities. Such a system should give feedback to the part designer about the manufacturing process ramifications of part geometry prior to the fabrication stage. Our system will build upon ongoing research at Carnegie Mellon on design for manufacturing [11] to provide such feedback.

ROBOTIC SPRAYING

The need to execute accurately spray paths based on process knowledge and to repeat consistently operations makes a robotic system essential in the rapid tool manufacturing domain. Arc spraying robots currently provide repeatability in surface coating applications [12, 13]. However, the spray paths are manually generated with a teach pendant for all but the simplest of part geometries. Automated and intelligent decision-making capabilities, using design models and process knowledge for off-line path generation, are absent from these systems.

Automated thermal spraying requires the scheduling of the arc spray parameters and the selection of the robot path. These parameters include: arc voltage, wire feed rate, atomiz-

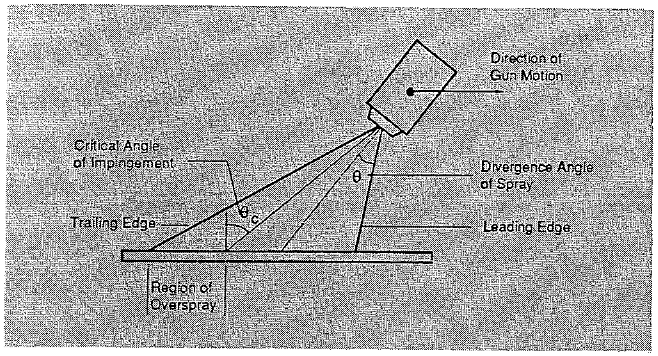

FIG. 8. Overspray

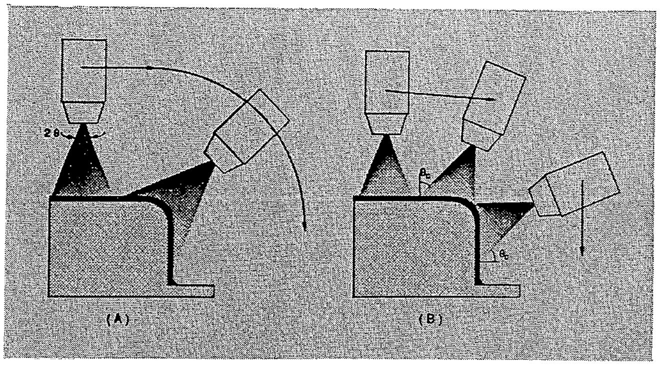

FIG. 9. Spray paths

ing gas pressure, atomizing gas type, wire diameter, and nozzle geometry. Many of these parameters are directly affected by the type of material being sprayed. Because the number of parameters is high, an experimental testbed is crucial to study systematically how these parameters affect shell quality. Some insight into this problem may be gained from published statistical methods for tuning the thermal spray process parameters to produce optimal thin surface coatings [14].

Although arc parameters directly affect the sprayed shell quality [15], the path of the gun is of equal importance. Robot paths must be found that traverse the substrate to deposit a uniform layer even when the substrate presents geometric features that make spraying difficult.

For example, consider overspray as shown in Fig. 8. Particle trajectories should align with the surface normals to assure maximal splattering of the molten particles. As the angle of impingement increases, that is, as the angle between the particle trajectory and the surface normal increase, the shell quality degrades. After some critical impingement angle θ_c, the particles bounce off the surface as wasted overspray or become entrapped in the shell reducing its strength. Although θ_c is a function of the spray parameters, $\theta_c = 45°$ has been used as a rule-of-thumb [16]. The amount of overspray generated is therefore dependent upon the gun orientation relative to the part surface. The following examples illustrate how this information can be accounted for in planning.

For a simple planning algorithm, the spray path is defined by a grid on the surface of the substrate. In this algorithm, the spray gun is oriented normal to the surface and follows each line of the grid with a constant standoff distance. This strategy is referred to as the surface-normal tracking strategy. To analyze the overspray performance of this strategy, consider the convex corner of the cross section shown in Fig. 9 (A). θ is defined as the spray divergence angle. There is no overspray so long as all of the spray hits a flat surface, the gun axis is perpendicular to the flat surface, and $\theta \leq \theta_c$. However, this strategy produces overspray on both the vertical and horizontal surfaces as the gun negotiates the corner.

An alternative two-step strategy (Fig. 9B) eliminates overspray for this example. As the gun approaches the corner, it is oriented so that the trailing edge of the spray cone makes an incident angle of θ_c. As the leading edge starts traversing the curved surface, its incident angle increases and spraying is stopped when it becomes θ_c. At this time both the leading and the trailing edges make incident angles of θ_c so that there is no overspray on any surface. The gun is then reoriented so that the leading edge makes an incident angle of θ_c with the vertical surface, and repositioned so that the trailing edge makes an incident angle of θ_c with the curved surface. Spraying is restarted from this position and proceeds down the vertical surface.

These two strategies demonstrate spray planning for a simplified two-dimensional case. In practice, strategies will have to be synthesized which account for the interaction of the spray cone with three-dimensional and more complex shapes, and which address a range of spray performance requirements. However, these examples demonstrate one important result. The first strategy only considers geometry, while the second strategy also considers process limitations; the framework of considering both geometry and process resulted in a superior strategy.

Robot paths must be found to traverse the workpiece given these process limitations. The basis of one approach to this problem is a planner based on geometry features, such as the corner feature of the example. A feature-based strategy uses extracted features to recognize spray problem areas, and then uses successful strategies, predetermined for each feature, to generate a robot path plan. The capability to define and extract three-dimensional features is being developed within the NOODLES environment [17]. One goal of our research is to identify a useful set of features for spray planning and to develop effective spray strategies for them.

The discovery of a good path for the spray torch is critical to successful robotic spraying. Equally critical is the translation of the torch's path into a complete, reachable, and smooth robot trajectory. It is simple to create trajectories that are unreachable by the robot. A second difficulty coming from off-line generated paths is the problem of creating paths that result in smooth robot motion. The tool manufacturing system will build upon robot path optimization research at Carnegie Mellon [18]. This work addresses both the reachability and path smoothness challenges.

NOODLES MODELING

The representational requirements for modeling systems, including the levels of abstraction, the nature of the analyses, and the geometric manipulations, vary with the context of the model's use. In CAD/CAM applications, the models for design, analysis, and evaluation, and fabrication are quite different for each subsystem. In typical systems numerous modeling environments are incorporated to satisfy the requirements of each subsystem. An approach which incorporates several different modeling environments has several drawbacks. First, it is error-prone and inefficient since models must be transformed between each separate environment. Second, nonuniform data structures make the software difficult to manage.

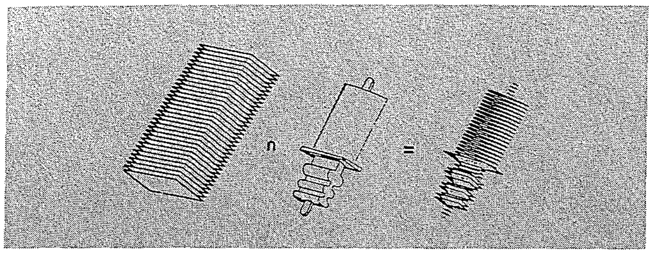

FIG. 10. Slicing with NOODLES.

Finally, it is not easily extendible to new system applications which may require a mixture of the attributes of different environments. We feel the key to successful integration is to provide a modeling environment in which design models, description of prototype models, and manufacturing methods are uniformly treated. To address this issue, our manufacturing system is built upon a geometric modeling environment, NOODLES [19], where subsystem models share a common representational and manipulation scheme.

The following examples demonstrate some of the diverse modeling requirements for this CAD-based manufacturing system:

- The user designing a part should be allowed to select the appropriate modeling description paradigm depending upon the immediate need. For example, designs, at times, can best be synthesized using constructive solid geometry, or building solids up from sets of surfaces, while, at others, sweeping lower-dimensional elements, such as curves and surfaces, into solid representations produce more satisfactory results.
- The SLA process planner must convert solid models into an ordered set of $2\frac{1}{2}$ D cross sections (i.e., cross sections with an associated depth or thickness) and span these cross sections with appropriate drawing vectors. This operation inherently involves working simultaneously in several dimensions since one generates planes from solid models, and then vectors, or line segments, from the planes.
- The robotic spray planner operates with yet other abstractions. Grids are projected onto the object's shell to produce surface patches which are analyzed for spraying action. In turn, the spraying actions are modeled as curvilinear paths which sweep the relevant portions of the tool geometry into volumes for interference testing. At this level, assessing the interference is not constrained to be intersections between solids, but also intersections between surfaces and surfaces, or surfaces and solids.
- Features are the most complex level of abstraction for this system. The spray planning system, for example, needs to extract convex corner features from the geometric descriptions in order to aim properly the spray to avoid overspray.

Geometric modeling can be performed at various levels, such as wire-frame, surface, or solid modeling. The previous examples suggest that all levels are required in the system. Although solid modeling approaches have the richest information, the representation of lower level elements such as lines and surfaces is not explicit. Furthermore, operations provided within solid modeling approaches do not apply when nonsolid elements are used. The ideal geometric modeling system should uniformly represent and operate on nonhomogeneous (i.e., mixed dimensions) elements such as vertices, lines, surfaces, and solids. NOODLES offers an environment where nonhomogeneous elements are uniformly represented and permits Boolean operations between elements of any dimensionality.

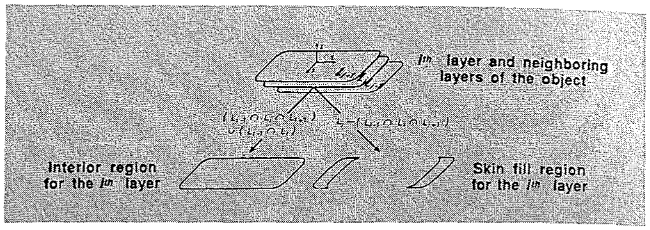

FIG. 11. Locating skin-fills and interiors with NOODLES

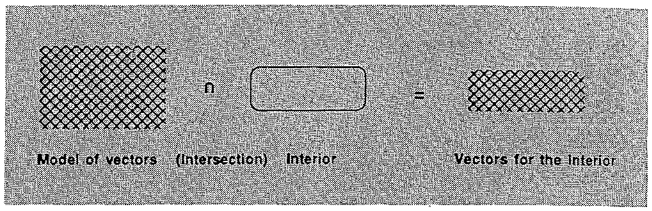

FIG. 12. Vector generation with NOODLES

One example which uses nonhomogeneous representations is the planning of the layered shape deposition processes. The first step is to obtain the cross sections of the object. These sections are obtained from the Boolean intersection between the object and a stack of planar faces that are appropriately spaced. Figure 10 shows that the result of this nonregular operation is a collection of cross sections. Identification of the interior and skin-fill areas for SLA applications can also be achieved with set operations. The intersection between the projections of contiguous cross sections identifies the interior area; the differences between these cross sections produce the skin-fill areas (Fig. 11). Finally, the vectors to be scanned by the laser are obtained by intersecting appropriate grids with the portions of the cross section. For example, as shown in Fig. 12, the interior area of a cross section is intersected with a cross hatch grid. The object boundaries for the laser are quickly found from the perimeters of the cross sections. Similarly, the grids for robotic path planning are defined by the perimeters of the intersection of the surface boundary of the object with two perpendicular sets of stacks of planar faces.

A feature extraction algorithm is also being developed which automatically recognizes form features of objects represented in NOODLES [17]. This algorithm uses a graph grammar to describe and recognize shape features, based on an augmented topology of the modeled objects which contain these features. The NOODLES representation provides the information for construction of the augmented topology graphs. These graphs constitute the search space for the recognition of the subgraphs which correspond to the features. In injection molding, features like ribs and bosses are recognized in this manner [20]. Once a feature is recognized by mapping the descriptive subgraph into the object graph, various regimes in the subgraph are also identified with their counterparts in the surface model. The relevant attributes for a feature can thus be evaluated by referring to the actual representation. For instance, the draft angle attributes of the rib features in an injection molded part is very relevant for assessing ejectability.

When a rib is recognized by identifying certain surfaces on the object with the opposing sides of the rib, the draft angle can be computed using the geometric information in the model.

FUTURE WORK

The extension of this system to superior prototype tools and production-quality tooling will require further research and development into steel-based sprayed tools. High-volume production-quality manufacturing and prototype tools used for high impact loading applications, such as stamping, require steel tooling. This requires not only the capability to spray steel shells, but also to develop complementary backing materials. These materials must have matching coefficients of thermal expansion with steel, and have sufficient ruggedness and strength. This backing requirement may be extremely difficult to achieve for mass production tools requiring tens of thousands of loading cycles and high impact resistance. An incremental approach would be to first develop backing materials for *low-batch* production steel tools. Such tools would have several advantages:

1. Die designs first prototyped in zinc-based alloys, including those conventionally machined from Kirksite, often do not adequately predict the performance of their machined steel counterparts. Surface frictional and thermal characteristics differ for these materials. The machined steel dies must then be further iterated to achieve acceptable performance. This process is costly and time-consuming. Sprayed steel prototype tools would more accurately predict the performance of machined steel tools and would reduce the number of redesign/refabrication iterations.
2. If sprayed steel tools could be made *on-demand* and inexpensively and also be able to withstand thousands of cycles, then multiple tools could be produced as needed for use in production. This gives the advantage of quicker response to market demands.

Our initial experimentation shows that 420 stainless steel, for example, can be deposited onto SLA parts without distorting the plastic. However, the process for steel is less forgiving than for zinc. Therefore, robotic spraying seems to be critical to *reliably* and *consistently* spray steel. One significant challenge for steel spraying will be to find a release agent which meets the needs of withstanding the heat of the molten metal, of being strong enough to hold the sprayed metal in the presence of considerable stress, and of releasing after spraying. Release agents, currently proprietary, exist which begin to satisfy these requirements.

Another approach to fabricating production quality tooling is to use electric discharge machining (EDM) to form high-quality steel dies. The EDM process can be enhanced for forming complex shapes by first manufacturing the EDM electrodes using the SLA/thermal spray system concept; this reduces the costs and time to produce the electrodes. Multiple electrodes are typically required for roughing and then for fine detail and each can quickly be made with spraying. The roughing die can be an SLA made part, thinly coated with copper. The process for the final electrode would include: Build an SLA die pattern of the complement of the desired EDM shape, add a frame, spray the die pattern with copper, insert electrode conductor wire, and finally back up the copper shell.

CONCLUSION

This paper presents a framework for a rapid tool manufacturing system based upon the integration of stereolithography and thermal spraying. These processes are particularly well suited for building complex shapes. The basic fabrication processes have been demonstrated experimentally, the system issues have been identified, and our current research directions have been outlined including automated spraying and geometric modeling. A testbed is being built within this framework. We feel that a testbed based on stereolithography and thermal spraying integrated in a unifying CAD/CAM environment will help prove the promise of timely and cost-effective tool manufacture.

The ultimate goal of our research will be to develop a system capable of quickly manufacturing sprayed steel tooling in a cost-effective fashion.

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