Robot-Assisted Shape Deposition Manufacturing

K. Hartmann, R. Krishnan, R. Merz, G. Neplotnik,
F.B. Prinz, L. Schultz, M. Terk and L.E. Weiss

The Robotics Institute and
The Engineering Design Research Center
Carnegie Mellon University

Abstract

Solid Freeform Fabrication and Shape Deposition are rapid manufacturing processes which build parts by incremental material deposition and fusion of cross-sectional layers. In this paper, several thermal deposition processes are described for directly fabricating prototype metal shapes using robotically manipulated material deposition systems. A robotic palletizing/part transfer system is also described which integrates multiple deposition and shaping processes into a single facility for rapidly manufacturing functional shapes.

Introduction

To successfully compete in today's global markets requires the rapid product development and manufacture of new designs to respond to changing market demands. Success requires several innovative manufacturing processes. For one example, computer-aided-design and computer-aided-manufacturing (CAD/CAM) systems are required which can quickly produce physical objects directly from CAD models. Rapid fabrication is useful for such manufacturing tasks as prototyping, low-volume parts production, and for producing the custom tooling required for high-volume production. Successful automation can reduce fabrication times by efficiently using CAD data and by minimizing human intervention.

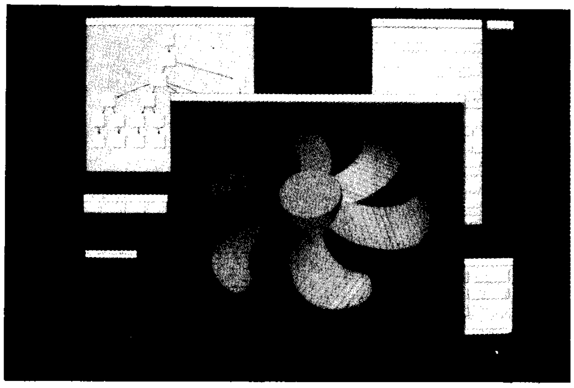
Conventional CAD/CAM systems have relied on computer-numerically-controlled (CNC) machinery to help build new shapes. Despite efforts to automate CNC operations, typical lead times can be long and consequently parts are expensive. There are several fundamental technical limitations which account for such delays. It is difficult to plan cutting trajectories for complex geometries. Part-specific fixturing must be selected and often manufactured. Part-specific cutting processes and tools must be selected (i.e., mills, lathes, drills, EDM, etc.). And, some geometries are difficult if not impossible to build. Ultimately, a skilled machinist is needed to operate the equipment. Although progress has been made toward autonomous planning and execution of CNC operations, significant human intervention is still required.

New approaches to shape fabrication are required which do not impose the constraints of conventional CNC equipment. Solid freeform fabrication processes[1,2] such as stereolithography, selective laser sintering, and 3D printing, are one such set of emerging technologies which address the challenge of rapid fabrication. In contrast to CNC machining for forming shapes, solid freeform fabrication (SFF) processes simplify process planning and execution by decomposing 3-D geometries into layered 2-D representations and eliminating the need for part-specific tooling and fixturing. These processes build parts by incremental material deposition and fusion of planar cross-sectional layers supported by sacrificial material. Support structures eliminate the need for custom fixturing and permit undercut features to be built up. The planning and execution of SFF processes is independent of the part geometry and therefore relatively quick. Part designers can even operate the equipment.

Commercially available SFF processes have been used primarily for those rapid prototyping applications for which plastic, wax and ceramic models and patterns are sufficient. They currently cannot *directly* fabricate metal shapes which have superior material properties, good surface appearance and accurate dimensions required for many applications such as the rapid manufacture of production tooling. They can be used *indirectly* by first quickly creating plastic or wax patterns and ceramic shells from which metal shapes can be cast, however additional machining operations may then be required.

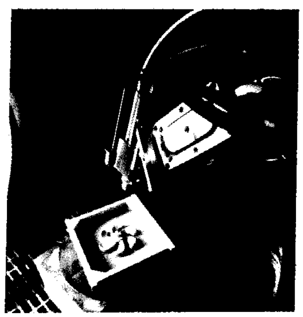
The Robotics Institute and The Engineering Design Research Center of Carnegie Mellon University (CMU) have been investigating SFF based upon thermal deposition processes as a way to *directly* build metal shapes. Thermal deposition processes, which include thermal spraying (i.e., arc and plasma) and welding, deposit molten metal and can produce materials with excellent mechanical properties. Robotic manipulation of the thermal deposition torches and robotic parts transfer in a multi-process facility have played important roles in implementing automated systems. This paper describes three such systems developed at CMU. The first system uses stereolithography patterns and thermal spraying for building metal-faced prototype injection mold tools. Another system, called MD*, builds prototype metal shapes directly in layers without the need for preform patterns. The most recent system, called Shape Deposition Manufacturing, is a new fabrication paradigm which uses robotics to integrate SFF and conventional processes into a single system to create functional parts.

1050-4729/94 $03.00 © 1994 IEEE

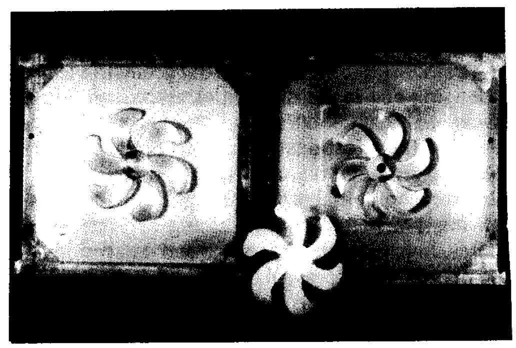


a. CAD model of fan blade.

b. Pattern built using stereolithography apparatus (SLA).



c. Robot spraying SLA pattern.



d. Resulting metal-faced injection mold tool.

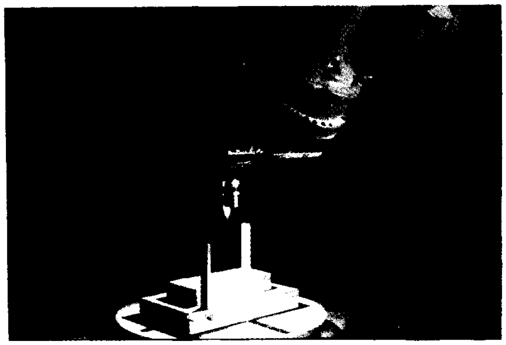
Figure 1. Sprayed metal-faced tooling process.

Sprayed Metal-Faced Tooling

Stereolithography was the first commercialized SFF process and addressed the need for rapid fabrication of plastic prototypes. It creates acrylic and epoxy models directly from a vat of liquid photocurable polymer by selectively solidifying it with a scanning laser beam (Figure 1a. and 1b.). The part is built on an elevator platform which is lowered into the liquid vat. As the laser draws a cross section in the x-y plane, a solid layer is formed on the elevator platform. The platform is lowered and then the next layer is drawn in the same way and adheres to the previous layer. A three-dimensional plastic object thus grows in the vat, starting at the object's bottom and building to the top.

SLA parts can be used as patterns for building thermally sprayed metal-faced tools, such as injection molds, from which engineering plastics parts can be produced (see Figure 1c. and 1d.)[3]. The sprayed tooling approach uses an arc spraying process in which metal wire is melted in an electric arc, atomized, and sprayed onto a plastic pattern surface. On contact, the sprayed material solidifies and forms a surface coating. Thick spray coatings (e.g., ~1mm) are built up by depositing multiple fused layers which, when separated from the pattern, form a free-standing shell with the shape of the pattern surface. By mounting the shell in a frame and backing it up with epoxy resins, an injection mold tool can be fabricated.

Spraying is a tedious task. For example it takes about two hours to spray each side of the tool in Figure 1c. Spraying also requires operator skill to achieve good results. For example, it is important to maintain proper torch stand-off (i.e., distance between torch and pattern) and to account for the effects of surface geometry on effective deposition rates (e.g., effective deposition rates are lower in concave regions due to turbulence). Therefore, the need to accurately execute spray paths based on process knowledge and pattern geometry and to consistently repeat operations makes a robotic spray approach essential in the rapid tool manufacturing domain. Manually teaching the robot, however, is tedious and error prone. Spray paths can be derived off-line from CAD models of the pattern[3]. A grid based approach in which the robot follows the surface normal along a grid projected on the pattern is straight-



a. Robot spraying shape

b. Finished Part

Figure 2. MD Star process.

forward to implement. However, there are problems achieving a uniform deposition because of the effects of surface geometry. A feature based approach which derives spray trajectories using extracted 3D geometric features is challenging due to the difficulties associated with three dimensional feature extraction. The general problem of extracting form features from CAD models is difficult based on the combinatorial nature of most proposed feature recognition algorithms. Significant progress has been made recently in recognizing certain classes of features. In particular, protrusions and depressions which are important for spray planning can be recognized in surface or solid models as recently reported.[4,5]. The integration of part and manipulator geometry together with motion and process planning for welding and spraying has been addressed in the Navy's PAWS project[6].

While the sprayed tooling approach is attractive for several applications, it has several limitations. Geometry is limited since spraying is a line-of-sight operation (i.e., you cannot spray into deep holes). It is difficult to maintain accuracy since several processes are involved. The resulting tool represents a composite structure of a thin metal shell typically backed up by non metallic materials. Fatigue and thermal stresses may cause delamination of the metal shell from its backing material thus limiting the the tool life time. To address these problems a thermal spray SFF process, which is described below, was developed.

MD*

MD* (for recursive mask and deposit) is a thermal spray deposition SFF process which directly builds three-dimensional multi-material structures of arbitrary geometric complexity[7]. Parts are manufactured by successively spraying cross-sectional layers, where each layer may contain several different materials. The basis for this approach is to spray each layer using a disposable mask, which has the shape of the current cross-section, to shape each layer. Masks can be produced from paper rolls with a CO_2 laser. Each layer is typically .005 inches thick. For each material in a layer, a disposable mask is made that exposes the area where that material occurs. The mask is placed upon the top layer of the growing part shape and a robotically manipulated thermal spray gun traverses the areas exposed by the mask. A sacrificial low melting support material is similarly deposited.

A semi-automated MD* system has been implemented to demonstrate the feasibility of this approach. The system consists of two separate cells including a laser mask cutting cell and a robotic thermal spray cell. Masks are manually transferred between cells. The mask cutting cell incorporates a 22 watt CO_2 laser focused to a .004 inch spot size. The laser beam is guided by a set of servo-controlled, galvanometric mirrors. The CAD tools used to automatically "slice" objects into cross-sections and to generate the laser beam trajectories to cut each cross-section are described in (8). The thermal spray cell, in Figure 2, incorporates a GMF S-700 robot which manipulates a 2-wire electric arc torch.

Robot motion control, which is described in detail in (9), addresses the issue of maximizing the uniformity of the deposited material; that is, how to best spray flat layers. The strategy for spraying includes a calibration procedure to orient the spray torch so as to maximize the symmetry of the deposited material when the torch is not in motion.

While the MD* approach incorporates a versatile material deposition process, it has several limitations which are also common to other SFF processes. First, they exhibit a stair-step surface texture, and parts must typically be sanded and polished. Second, in any SFF approach in which material deposition involves thermal bonding residual stress builds up due unavoidable temperature gradients [10]. This can lead to warpage and

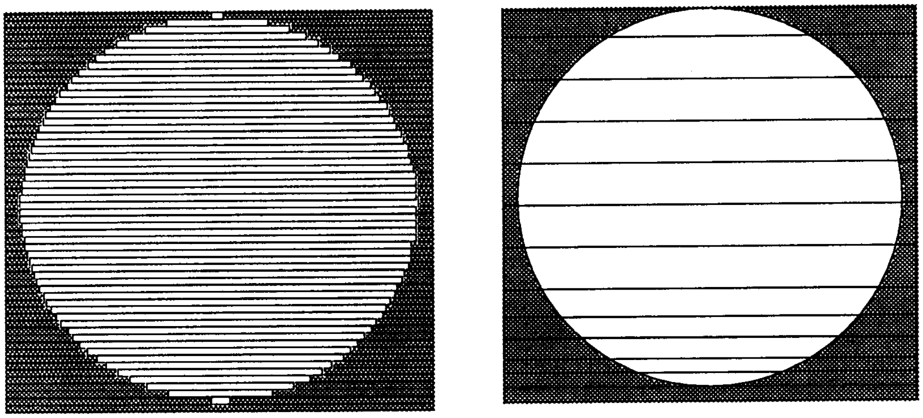


Figure 3. Conventional solid freeform fabrication versus shape deposition.

delamination. Finally, it is difficult to achieve the accuracy, precision, and resolution which can be achieved with CNC machining.

Shape Deposition

In our experience, no single SFF or conventional manufacturing process will satisfy all the requirements for rapidly and directly creating functional metal parts such as custom production tooling. To address this problem are developing a system which combines the benefits of SFF (i.e., quickly planned, independent of geometry), CNC milling (i.e., accuracy and precision with good surface quality), thermal spraying (i.e., combined deposition and sintering, with controlled heat transfer), and welding (i.e., superior material properties and high deposition rate).

This strategy is to first slice the CAD model of the shape to be fabricated into layers while maintaining the corresponding outer surface geometry information. (Layer thickness will vary depending on the part geometry.) Each layer consists of primary material(s) (i.e., the material forming the part being created) and complementary shaped sacrificial support structure material which is removed when the entire part is completed. Each layer is deposited as a near-net shape using thermal deposition including spraying and/or welding. The layer is then shaped with a 5-axis CNC milling machine to net shape before proceeding with the next layer. Shape deposition eliminates the stair-step surface appearance common to conventional SFF prototyping technologies, as shown in Figure 3. In addition, each layer is shot-peened to control internal stress buildup[11].

An automated testbed facility (in Figure 4) has been implemented, and a CAD-based process planner/controller has been developed for investigating the Shape Deposition manufacturing paradigm. This testbed configuration consists of four processing stations; CNC milling, thermal deposition, shot-peening, and cleaning(not shown) The growing parts are built on pallets which are transferred from station-to-station using a robotic palletizing system. Each station has a pallet receiver mechanism. The part transfer robot places the pallet on the receiver which locates and clamps the pallet in place.

The thermal deposition station incorporates several deposition sources. The station consists of an acoustic chamber (for noise abatement and dust containment), an air handling system (for dust filtration and collection) and a robotic deposition system. The deposition robot is equipped with a tool changing wrist and is able to acquire one of several deposition torches which are mounted to a docking mechanism(Figure 5). The current sources include arc and plasma spraying, and MIG and TIG welding. To deposit material, the robot picks up the appropriate torch and manipulates it over the growing shape. The feedstock mechanisms and power supplies for these sources are located upon a mezzanine above the acoustic chamber, and the pallet is moved into the chamber through a trap door.

The shaping station is a 5-axis, high-speed CNC machine with an 21-head tool changer mechanism. The hydraulically-actuated receiver used in this station

Figure 4. Testbed MD* facility at Carnegie Mellon University.

Figure 5. Thermal spray robot.

is able to repeatedly locate the pallet within approximately 0.0002 inches. When cutting fluids are used to mill a part, the pallet is then transferred to a cleaning station to remove residuals. The shot peening station, which uses a conventional pressurized media delivery system, also incorporates grit-blasting capabilities for surface preparation prior to conventional spraying operations.

A CAD planning and control system has been developed for the MD* process to automatically determine the manufacturing steps necessary to build the part, to generate the code required to run the cell and to execute the commands on the individual stations. The process planner first takes a CAD model of the part and adaptively slices it into layers of varying thickness based upon both geometric and material criteria. Each layer is then further subdivided into smaller, single material 'compacts' which must be deposited in sequence in order to form any undercut features. In the next step, a strategy is chosen to manufacture each compact. Each available strategy contains a basic sequence of operations based upon spraying, welding, cutting, shot peening and grit blasting. For each operation in a strategy, certain applicability criteria can be specified so that specific operations will only be used depending upon attributes such as the material of the compact, thickness of the layer, total thickness of the part up to the current layer, etc. In the final step, the trajectories are calculated for the robotic deposition and CNC cutting operations. The strategy and trajectory planning modules are linked to a database containing all the material and process dependent data.

A master program containing the commands necessary to control the palletizing system and to download and execute the trajectories on the individual stations is then generated and downloaded to a SUN 3-160 Workstation which serves as the main control computer of the manufacturing cell. This program is made up of a set of 5 simple commands for downloading, running and deleting a program or trajectory on a certain cell, and putting the pallet into or retrieving it from a certain cell. For example a segment of a typical program follows:

PLACE_PART SPRAY; *place pallet into spray booth*
PUT_FILE mds7 SPRAY; *download trajectory file 'mds7' to spray robot controller*
RUN_FILE mds7 SPRAY; *execute spraying operation*
DELETE_FILE mds7 SPRAY;
PICK_PART SPRAY; *get pallet from spray booth*
PLACE_PART CNC; *place pallet into CNC machine*
RUN_FILE part7_1_Plane CNC; *plane surface*
RUN_FILE part7_1_2d10 CNC; *contour shape*
PICK_PART CNC; *get pallet from CNC machine*

The milling machine, the spray robot and the transport robot use the standard controllers supplied with this equipment for trajectory and I/O control. They are connected to the main computer via RS-232 or internet interfaces. The process parameters (e.g., plasma power, cutting speeds, etc.) are specified in the trajectory files which are downloaded from the main controller. Digital I/O on each of these controllers is used for safety interlocks, for checking device status, and for switching devices on and off.

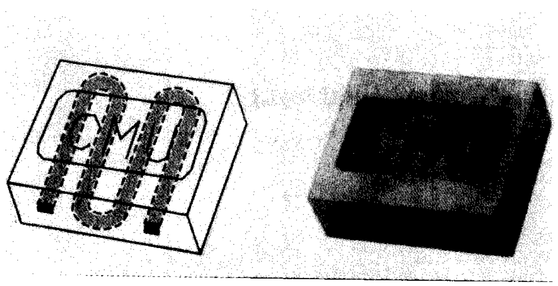


Figure 6. A Completed Part

A typical part built with the MD* process is shown in Figure 6 on the left. It is a steel die with an internal cooling channel. The serpentine shaped cooling channel, which is also depicted on the right of the figure cannot be built with conventional milling operations alone.

Discussion

Building our shape deposition manufacturing facility around robots has several advantages over a dedicated and customized facility. In particular the robotic palletizing/transfer system allows several parts to be built at a single time thus increasing through-put. For example one part can be milled while another is being deposited. It is also straight-forward to explore a variety of different processes and add new ones. While the current system has a payload of approximately 100 Kg. and size of approximately 300 mm x 300 mm x 300 mm, bigger parts could be made by scaling up the individual processing stations.

The implementation of this type of system, however, was complicated by a lack of standardization amongst the equipment manufactures. Currently the transport robot uses INFORM, the spray robot uses Karel and the mill uses standard G-code programming. A standardized protocol for specifying trajectories and programs on CNC and robotic equipment would be a great benefit.

Bibliography

[1] Bourell, D.L., Beaman, J.J., Marcus, H.L. and Barlow, J.W., Solid Freeform Fabrication An Advanced Manufacturing Approach, *Proceedings of Solid Freeform Fabrication Symposium*, The University of Texas at Austin, Texas, August 6-8, 1990, 1-7.

[2] Marcus H.L. and Bourell, D.L., "Solid Freeform Fabrication," *Advanced Materials & Processes*, 144(3) Sept. (1993) 28-35.

[3] Weiss, L. E., et. al., "A Rapid Tool Manufacturing System Based On Stereolithography and Thermal Spraying", ASME's Manufacturing Review, March, 1990.

[4] Hall, M.A., et.al., Feature Abstraction in Knowledge-based Critique of Designs, *Issues in Design/Manufacture Integration*, A. Sharon (ed.), ASME Winter Annual Meeting, Dallas, TX, V. 29, 94-101.

[5] Gadh, R. and Prinz, F.B., Recognition of Geometric forms using the differential depth filter, *Computer-Aided Design*, November, 1992, 24(11), 583-598.

[6]- Hemmerle, J.S., Terk, M., Gürsöz, E.L., Prinz, F.B., Doyle, T., Next Generation Manufacturing Task Planner for Robotic Arc Welding, *ISA Transactions*, 1(2), 1992, 97-113.

[7] Weiss, L.E., Prinz, F.B., Adams, D.A. and Siewiorek, D.P., Thermal Spray Shape Deposition, *ASM Journal of Thermal Spray Technology*, 1(3), Sept. (1992) 231-237.

[8] Merz, R., Weiss, L. and Prinz, F.B., "Planning Mask Cutting For Thermal Spray Shape Deposition," EDRC 24-73-91

[9] Fasching, M.M., Prinz, F.B. and Weiss, L.E., "Planning Robotic Trajectories For Thermal Spray Shape Deposition," *ASMJournal of Thermal Spray Technology*, 2(1), March (1993) 45-50.

[10] Amon, C, Beuth, J., Kirchner, H., Merz, R., Prinz, F., Schmaltz, K. and Weiss, L., "Material Issues in Layered Forming," Solid Freeform Fabrication An Advanced Manufacturing Approach, *Proceedings of Solid Freeform Fabrication Symposium*, The University of Texas at Austin, Texas, August 1993.

[11] K.I'Anson, et. al., Use of the Shot Peening process for Surface Modification of Thermal Sprayed Coatings, *Proceedings of the ASM Fourth Nat'l. Thermal Spray Conference*, Pittsburgh, PA., May 4-10, 1991, pp 138-145.