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A FRAMEWORK FOR THERMAL SPRAY SHAPE DEPOSITION: THE MD* SYSTEM

Lee E. Weiss

Fritz B. Prinz

Daniel P. Siewiorek

*The Robotics Institute and
The Engineering Design Research Center
Carnegie Mellon University
Pittsburgh, PA. 15213*

Abstract

This paper presents the framework for a solid-freeform-fabrication system based on thermal spray shape deposition to build multi-material structures by incremental build-up of thin cross-sectional layers. The basis of the MD* System (recursively, Mask and Deposit) is to spray each layer using disposable masks to shape each layer. A thermal spray approach has the potential to build *dense* parts with desirable mechanical properties. Metal, ceramic, plastic, laminate, and composite structures can be deposited. Since masking enables selective deposition within a layer, complete assemblies composed of different materials can be created in a single process. For example, integrated electronic/mechanical structures are feasible.

Keywords: Thermal Spray, Net Shape Manufacture, Rapid Prototyping.

1 Background

Shape deposition processes, also known as solid freeform fabrication, build parts by incremental material build-up of thin 2-1/2 dimensional layers. A broad class of these processes build with planar cross-sections, and the growing structure is supported by solid, complementary shaped, sacrificial layers. The cross-sectional descriptions are generated by "slicing" three dimensional computer representations[1] into "slices" which may vary in thickness. Several alternative deposition materials and deposition processes are available for building the object, including selective laser sintering[2], three-dimensional printing[3], layered object manufacturing[4], Cubital's "Solider"[5]¹, and ballistic particle manufacturing[6, 7]. A principle advantage of the layered deposition approaches versus conventional CNC machining is the ease and speed which one can go from design to part fabrication without the need of part specific tooling or fixturing, and with minimal human intervention. The planning and execution effort for shape deposition is essentially independent of part complexity. Shape deposition technologies, however, cannot currently achieve the ultimate precision of CNC machining.

The material properties produced with shape deposition have also been limited, including both the range of materials which can be deposited and the resulting material densities. A shaping deposition process based on thermal spray deposition technologies (i.e., plasma, electric arc, or combustion) would have the potential to achieve superior material properties. Thermal spraying is well-established for surface coating and for some near-net shape applications. It can produce *dense* coatings with desirable mechanical properties associated with the fine grain structure produced by *rapid solidification* of atomized molten particle beams. For example, with low-pressure plasma spraying, some metals can be deposited with 99.9% density, with metallurgical bond-strength, and with 50 to 100% greater tensile strength that of wrought materials². Thermal spraying

¹Solider has similarities to 3-D Systems Stereolithography in that both are based upon photopolymerization processes. Stereolithography, however, requires explicit support structure design.

²Personal communication with Douglas Harris, APS Materials, Dayton, Ohio.

is also suitable for making composite and laminated coatings composed of metals, ceramics, and plastics.

Thermal spraying has been applied in near net shape applications by spraying onto pre-formed patterns, or substrates, to create 2-1/2 dimensional shells. These shells can be used to make custom tooling [1] or high-performance nozzles for example. It is conceivable to use thermal spraying in an shape deposition process (i.e., without a pre-formed pattern) by using a well-defined narrow-beam spray with a well-controlled deposition rate, to scan and to build each layer to the desired thickness. Such beam definition and spray control, however, are difficult to achieve with conventional spray technology. One goal of the ballistic particle manufacturing process[6, 7] is to develop "ink-jet" technologies for this purpose, however the current system is limited to wax deposition. Alternatively, we have experimented with various aperture techniques to focus arc-sprayed beams, but found these to be unreliable (i.e., the aperture quickly clogs) and inefficient (i.e., both scanning time and material waste).

As an alternative approach to narrow-beam deposition, this paper presents a masking method to accurately shape each layer. Since masking enables selective deposition within a layer, complete assemblies composed of different materials can be created in a single process. For example, integrated electronic/mechanical structures are feasible. This paper presents the framework for implementing this MD* (to recursively mask and deposit) System.

2 Masking

The basis for the MD* approach is to spray each layer using a disposable mask which has the shape of the current cross-section, analogous to using stencils for paint-spraying applications. To build each layer, one mask would be required for the primary deposition material (e.g., steel) and a second complementary shaped mask would be required for the support material. Each mask is seated upon the current top layer and removed when the new layer is completed. The issues for thermal masking are:

- How to create a uniform deposition thickness of material within the masks borders,
- Selection of a mask material for durability (i.e., to withstand that heat and abrasion of the thermal spray), be of relatively low cost, and
- How to make masks and to accurately place them.

One method of producing a uniform distribution is to use a multiplicity of appropriately spaced spray sources with Gaussian distributions. Material deposition from conventional thermal spray sources, such as arc or plasma torches, typically *approximate* Gaussian distributions. It can be shown empirically that the summation of one dimensional Gaussian distributions, each with a standard deviation of σ and which are spaced apart by 1.5σ , or less, produces an approximately uniform distribution between the peaks of the first and last source. The summation of two-dimensional symmetric Gaussians (i.e., the idealized distribution from a spray source) produces approximately uniform distributions, of decreasing magnitudes, in all planes parallel to the plane defined by the peaks of the first and last source. Thus, a uniform distribution may be achieved by spraying multiple passes with a single source, as shown in Figure 1, such that; all passes are spaced by 1.5σ , and the bounds of the spray source extend beyond the mask opening. Alternatively a uniform distribution can be achieved using a set of equally spaced sources and spraying in a single pass.

Real spray sources, however, do not produce ideal Gaussian distributions due to torch asymmetries, imperfect mass-flow control, and gas turbulence. In addition, any inaccuracies of motion control of the spray torch relative to the substrate (i.e., speed, orthogonality, stand-off, and trajectory) will create further deviations from a uniform distribution. One alternative is to reduce the distance between spray passes to less than 1.5σ which, however, also results in thicker layers. In the limit as the spray distance between passes approaches zero, the deposited distribution approaches a uniform distribution, independent of the spray

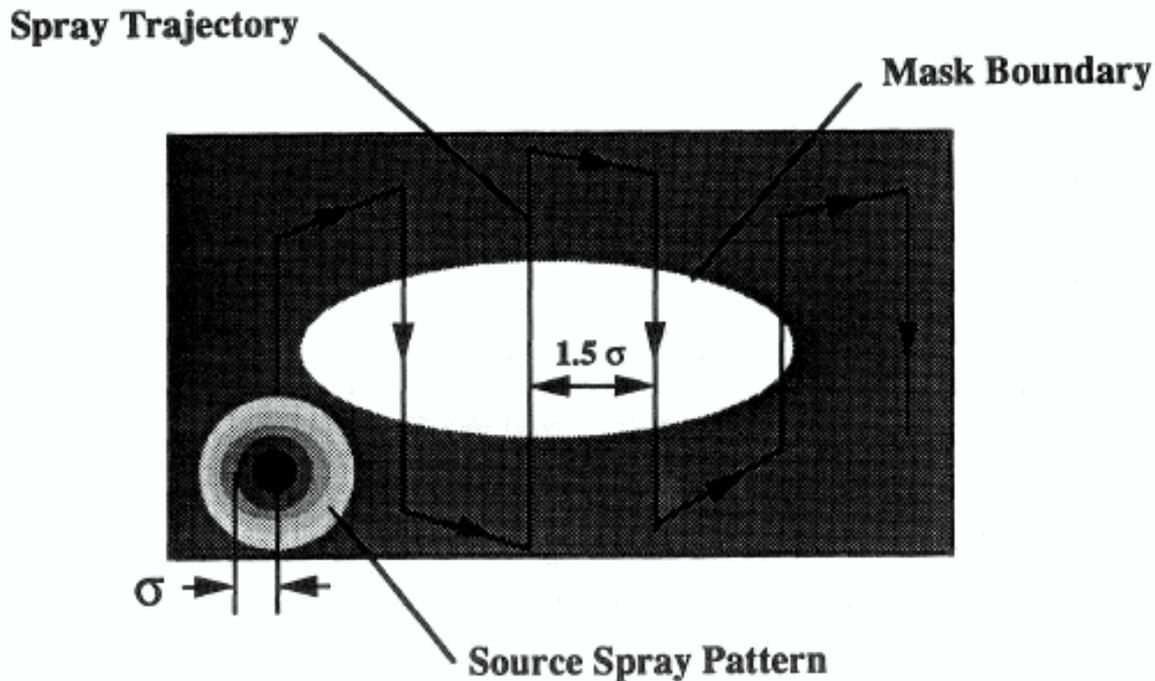


Figure 1: Spray trajectory.

distribution shape. Material deposition rates can be reduced by using high-speed translational servo stages (e.g. 2 ft/sec) to move the thermal sources relative to the substrate and by minimizing powder feed mass flow into a thermal source (e.g., powder feed rate into plasma torch).

Another alternative is to use a machining operation to mill or grind layers, at critical elevations of the build process, to achieve the desired accuracy. The ramifications of incorporating machining operations, however, present some difficult engineering challenges. In particular, interlayer bonding of sprayed materials is both mechanical and metallurgical in nature. Both types of bonding contribute to interlayer adhesion. The ability to achieve mechanical bonding is diminished when a surface is machined to a smooth finish. Therefore, additional grit blasting or surface roughening may be required after machining.

After the primary material is sprayed and its mask removed, the next step is to mask-off the primary material with a complementary mask and then spray the support material. The support material is discussed in a following section. Regarding the selection of the masking material, preliminary experimentation has demonstrated that pressure sensitive labeling paper satisfies the aforementioned requirements for electric arc spraying. For example, 420 stainless steel does not adhere to the paper and a sharp, accurate border of steel is produced at the boundary of the mask and deposited metal. Due to the high velocity and turbulence of the thermal jet stream, it is necessary that the paper have an adhesive backing so that it adheres to the current top layer and so that small mask features are not blown about. A laser-based cutting approach for mask making is described in a following section.

3 Support Material

The primary function of the support layers in shape deposition processes is to provide surfaces upon which any undercuts of the growing part shape can be built. In thermal spray processes, the sprayed material also requires a surface, or substrate, to which it can adhere. As the sprayed molten material (i.e., metal, plastic, or ceramic) impinges upon the substrate, it solidifies and cools causing residual stress to accumulate, layer by layer, in the deposited material. The stress field can cause shape distortion and may ultimately

lead to delamination of the deposited material from the underlying substrate. Residual stress is particularly problematic for materials with a high elastic modulus such as steel. Using a spray process which keeps the substrate and the growing part at an elevated temperature can overcome some of these problems, but present additional process control challenges of their own.

Thus in a thermal spray shape deposition process, the support material should also serve as a substrate which should be able to:

- Withstand the elevated temperature and abrasive action of sprayed molten material, and
- Act as a surface to which sprayed material will adhere (e.g., such that steel will not delaminate from it due to residual stress) and later “release” the part when it is completed.

Low melting point tin/bismuth alloys satisfy these requirements for arc sprayed steel and have been used successfully in our labs to make pre-formed patterns for making sprayed steel dies[8]. The sprayed steel bonds locally to the tin/bismuth by superficially melting and abrading a very thin layer of the low melt alloy. This creates an “anchor pattern” to facilitate coating adhesion. The alloy may then be melted away when the part is completed. For example, Cerrocast³ has a melting point of approximately 280° F. The sprayed steel adheres to the Cerrocast surface and is “clamped” to the pattern surface. The clamping action is critical since sprayed metal, in particular steel, has a tendency to warp and peel away from the substrate surface due to residual stress. This clamping action counters this tendency. The steel must be deposited at a low rate such that the temperature of the Cerrocast does not raise above its melting point. In addition, since Cerrocast has a much higher coefficient of thermal expansion than steel, it is desirable to keep its temperature low to avoid shape distortion and delamination from the steel.

4 Residual Stress

It is possible to deposit material with thermal spraying in a virtually stress-free state by maintaining the substrate/part at an elevated temperature (i.e., above $\sim .65 T_m$) during spraying. Unfortunately, Cerrocast will melt at these elevated temperatures if steel is being deposited. Annealing the finished part is unacceptable since shape distortion would have already occurred. A method is therefore required to relieve the residual stress during the building process.

Residual stress results, in part, from long range internal stress fields by accumulating monopolar dislocation configurations in certain areas of the material. Removing monopolar dislocations through bipolar dislocation structures can reduce internal stress build-ups. There are several options for stress-relieving, including selective induction heating, shot-peening, and vibratory stress-relief. Induction heating would have the problem of melting surrounding Cerrocast. However, it may be possible to re-deposit and to re-level the melted portions. On the other hand, shot-peening and vibratory stress-relief would not have the associated heating problems. Both processes impart a compressive load to the the sprayed material which counters the tensile load produced by the residual stress. While the ability to uniformly relieve stress is difficult to achieve with three-dimensional geometries, the planar geometry of this layered approach significantly simplifies the problem.

5 Material Densification

A primary goal for developing this thermal spray fabrication process is to achieve superior material properties which are not directly attainable with other currently available shape deposition approaches. A critical

³Such alloys are manufactured by Cerro Metals Products Co. and sold under the trademark Cerro.

material feature for producing functional parts is that the deposited materials, in particular metals, should be dense.

Close to full densification may be achieved with 2-wire electric arc and air-sprayed plasma technologies (i.e., in the range of 1% to 5%), which is still excellent compared with powered material approaches which, at best, can achieve 74% packing density. In general, plasma spray coatings are superior to arc spray coatings, and close to 100% densification can be achieved with high-velocity oxy-fuel (HVOF) spray technology part. The challenge for using HVOF would be to identify support structure and masking materials which could withstand the highly abrasive action of HVOF, and also to maintain consistent deposition control of the HVOF torch. Tougher masking materials (e.g., plastics) and harder support materials (e.g., tin/bismuth alloys with high oxide content) may be required.

Additionally, the flat-top geometry of the growing object's shape would permit the use of material consolidation by hot-pressing at intermediate stages of the building process. A hot press could be incorporated into the system to compact the material to 100% densification, while maintaining the superior properties of rapid solidification processing. The pressing would be done after every few layers are deposited to minimize the diffusion distance between voids and the material surface.

6 System Configuration

An example configuration for implementing an MD* system[9] is depicted in Figure 2. This particular configuration could be used to build an integrated electronic/mechanical package as described in the next section. The system consists of several cells and the workpiece is carried from cell to cell by a set of precision, high-speed x-y-z translational stages. The first cell is a mask making station where masking material, such as pressure sensitive paper, is feed out on rolls and cut with a CO_2 laser[9]. The second cell consists of the thermal spray sources. A suction device (not shown) would be included here to remove each mask. The last two cells, integrated circuit feeder and milling head, are application specific and are described in the next section. The entire system could be housed in a low-pressure vacuum chamber, to maximize sprayed particles kinetic energy and thus bond strength, or in an inert gas chamber to control oxide formation. Such housings will be quite expensive however. One compromise may be to use shrouds, placed on the spray torches and positioned just above the flat substrate tops, for containing shielding gases and for preventing entrainment with surrounding air. This approach would be less expensive at the cost of poorer material properties.

7 Examples

To demonstrate the MD* concept, a prototype zinc turbine blade was fabricated, as is shown in Figure 3, with a semi-automated system consisting of a CO_2 laser cutting station and an arc-spray robot. The masks were manually transferred on a fixturing plate to the robot and placed on top of the growing part with the aid of alignment pins. Layers were sprayed to approximately .005 inch thickness and the turbine blade was built along an axis with minimum height to minimize overall build time. In a fully automated system it is anticipated that .001 inch layers can be achieved.

The MD* process would also be capable of creating multi-material structures since masking enables selective material deposition within a layer. For example, this process could create both small and large structures simultaneously such as arrays of miniature strain-gages, thermocouples, and capacitive switches built inside of structural elements. Sprayed features as small as .004 inches have been demonstrated in our lab. With an MD* process, the fabrication and assembly of complete electronic/mechanical structures, such as computer packages, can be integrated into a single process. Components such as heat pipes, EMI shields, and conductors can be sprayed in place while other discrete components such as chips, external connectors, and batteries can be embedded in the growing structure (Figure 4).

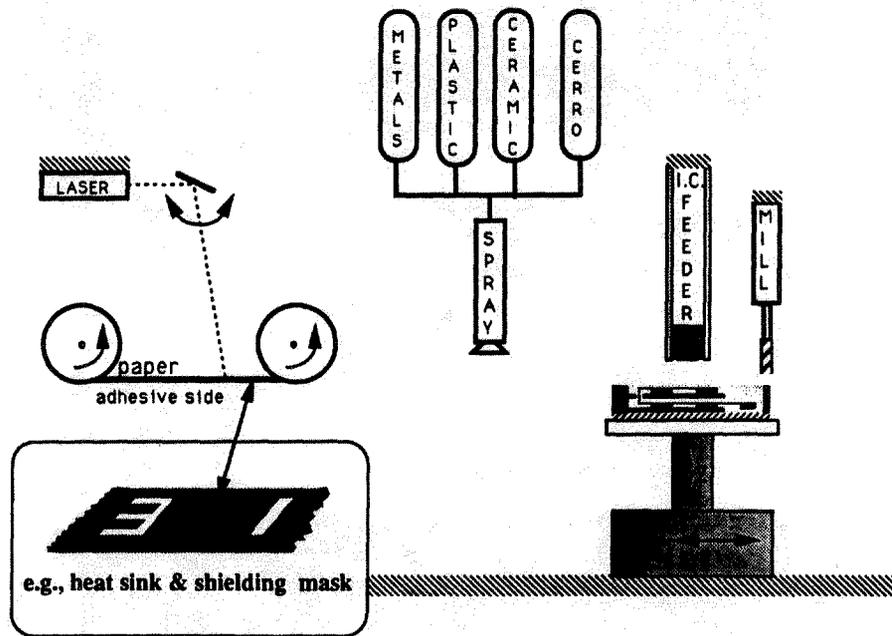


Figure 2: MD* System Configuration.

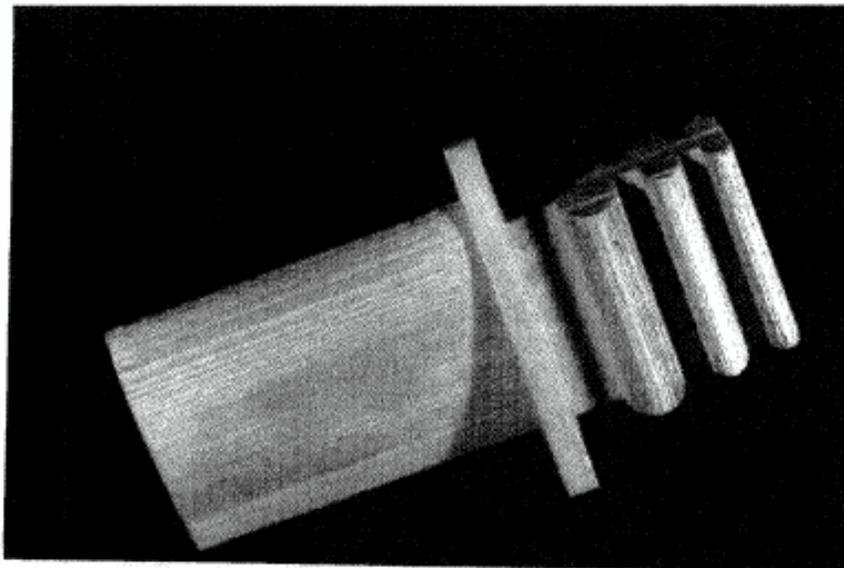


Figure 3: Prototype turbine blade fabricated with MD*.

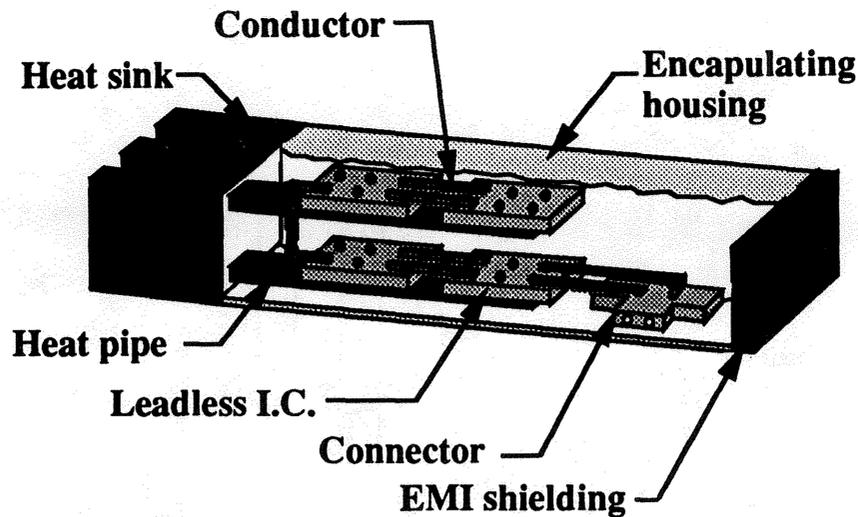


Figure 4: Integrated electronic/mechanical package.

The steps for fabricating such a package are illustrated in Figure 5:

1. Deposit first n layers upon a suitable substrate (e.g. Cerrocast). The first n layers form sections of the heat sink, housing, EMI shielding, and Cerrocast support. (For example, if layer deposition thickness is .005" and the height of the deposited structure is .1", then $n=20$ layers.) Separate masks are required for each material for each layer. To assure good mechanical adhesion between adjacent materials within a layer, the layer borders may be staggered as shown in the insert.
2. Build heat pipe, while continuing to deposit heat sink, housing, and EMI shield.
3. Continue to deposit the primary material as well as the sacrificial material, such as wax or Cerrocast, which is used to reserve space for the discrete components.
4. Mill out the sacrificial material to make spaces for the ICs and external connectors.
5. Insert ICs and connector into package.
6. Deposit conductors and continue building heat sink, etc.
7. Build up the multi-layer interconnect conductor(s) and continue building heat sinks, etc..
8. Repeat previous steps to fabricate additional component layers.
9. Remove the substrate/Cerrocast using localized heating or with machining.

Such integrated electronic/mechanical packages would have several advantages. They should exhibit high reliability due to the elimination of discrete board interconnects, the intimate and absolute mechanical couplings (e.g. the encapsulated connections to ICs should withstand high-G forces), and the elimination of a final assembly process. There should be efficient thermal management since thermal conduits with arbitrarily complex shapes can be fabricated for the specific application and package geometry. Very dense packaging systems could be fabricated since discrete mechanical interconnects and boards are eliminated. Arbitrarily shaped packages can be fabricated to fit nonstandard volumes and to accommodate the stringent space allocation problems associated with, for example, aerospace and automotive structures. And there should be excellent corrosion resistance due to total encapsulation.

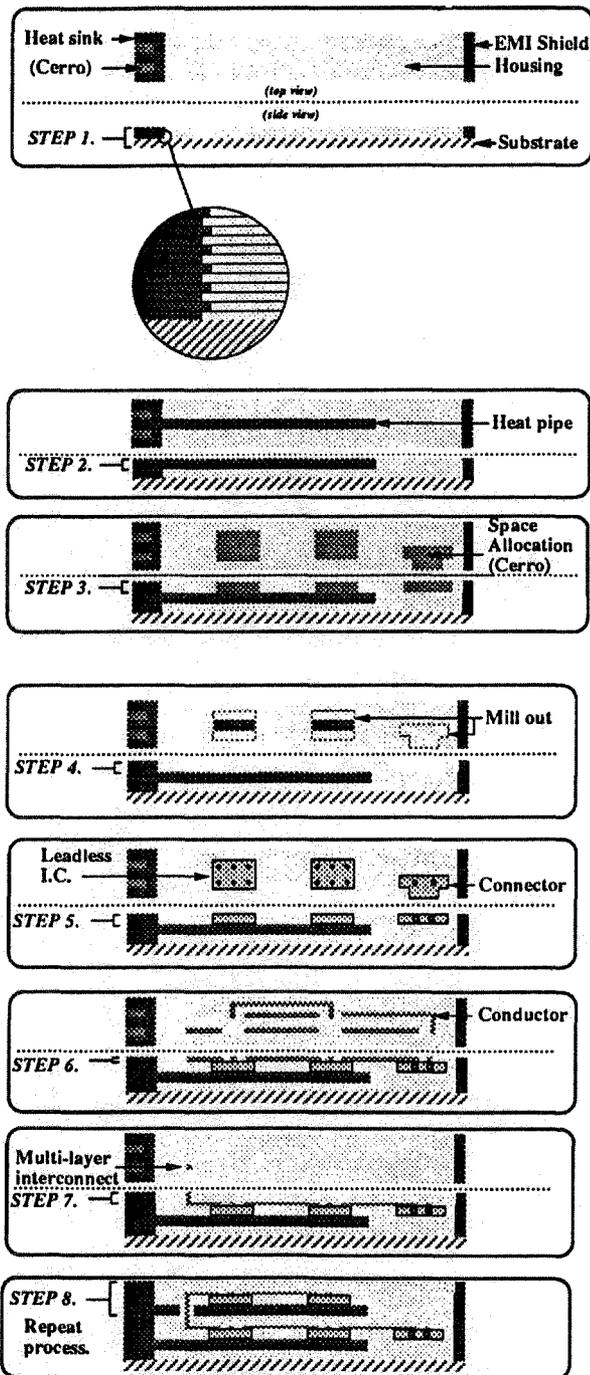


Figure 5: Fabrication Steps

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