Automated Fabrication of Ceramic Components from Tape-Cast Ceramic

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ABSTRACT

This paper describes a machine and process for automated fabrication of functional 3-D laminated engineering components, ceramics in the present example. A laser cuts successive layers of a part derived from a CAD model description out of unfired tape-cast ceramic sheets vacuum-clamped to an x-y sled. A material-handling robot uses a selective-area gripper to extract only the desired part outlines from the surrounding waste material, then stacks the slices to build the part. This system design enables rapid manufacture of functional engineering components with arbitrarily complex internal and external geometries from virtually any material available in sheet form.

I. Introduction

This paper describes the results of our investigation of a machine and process for automated fabrication of laminated engineering components. The purpose of our system is to enable custom manufacturing of functional 3-D components with arbitrarily complex internal and external geometries.

We examined four key areas: testing a novel means of manipulating individual laminae of arbitrary shapes; determining the achievable precision of robotically-assembled laminated components; determining the dimensional tolerance achievable by precompensating for part shrinkage that will occur during post-processing; and testing the mechanical strength of ceramic parts so produced. The first two are described here; structural performance and materials processing issues are presented in a separate publication within these proceedings [1].

System Overview

The CAM-LEM approach is illustrated in Fig. 1. A part originates from a computer description, which is analyzed to decompose the part into boundary contours of thin slices. These individual slices are laser cut from “green” sheet stock per the computed contours. The resulting part-slice regions are extracted from the sheet stock and stacked to assemble a physical 3-D realization of the original CAD description. The assembly operation includes a "tacking," procedure that fixes the position of each sheet relative to the pre-existing stack. After assembly, the layers are

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"laminated" by warm isostatic pressing (or other suitable method) to achieve intimate interlayer contact, promoting high-integrity bonding in the subsequent sintering operation. The laminated "green" object is then fired (with an optimized heating schedule) to densify the object and fuse the layers (and particles within the layers) into a monolithic structure. The result is a 3-D part which exhibits not only correct geometric form, but functional structural behavior as well.

As in all Rapid-Prototyping or Solid-Freeform-Fabrication systems, temporary support structures are required when forming surface contributions with downward-pointing surface normals (e.g., cantilevers, "ceilings," "stalactites," etc.). The CAM-LEM process uses "fugitive" materials for support of green assemblies. Fugitive materials are laser cut from sheet stock, generating shapes complementary to respective desired part cross sections. Fugitive materials and engineering materials are cut alternately, enabling construction of layered assemblies of solid blocks with spatially-varying material properties. During postprocessing (firing), the fugitive material burns out and the engineering material fuses into a structural solid.

The results described here were obtained using an experimental system developed at Case Western Reserve University. Components of the system include: a Coherent Model 42 50-Watt CO_2 laser; a NEAT 100mm by 100mm travel x-y sled; a four-axis Seiko XY-2000 robot; a Sun SparcStation IPC host computer; a VME-based multiprocessor system for real-time control; a variety of pneumatic actuators and controls; and an aluminum-framed Plexiglas safety enclosure. We integrated these elements into a system suitable for performing our feasibility evaluation experiments.

Figure 2 is a photograph of a variety of materials cut with the experimental system. The part outline shown is a standard mechanical-test part, which we used for strength testing of ceramic assemblies. This photograph also illustrates the extensibility of CAM-LEM to a wide variety of material choices. The materials shown are, from left to right: paper, tape-cast alumina, cardboard, iron-nickel powder in a BASF binder, Plexiglas, and Styrofoam. While these materials will utilize different bonding techniques, the CAM-LEM software and machine design apply universally.

Figure 3 illustrates the precision and complexity manageable with the CAM-LEM approach. The object shown is comprised of 307 layers of paper. The source CAD file (generated by Laser Design, Inc., using a 3-D laser scan) originated in "STL" form--the de-facto standard for rapid prototyping [2]. CAM-LEM, Inc.'s software successfully translated the file into slices and contours, and the experimental CAM-LEM system generated each slice; assembly was performed manually.

It is the objective of CAM-LEM, Inc. to create a commercial system capable of fabricating objects with the precision and complexity exemplified by Fig. 3. Such a system should be fully automatic, and capable of constructing objects from a variety of engineering materials. Assemblies so constructed will be transformable into fused solids, where the integrity of inter-laminar bonding rivals that of the bulk material properties themselves.

II. Results

CAM-LEM, Inc. in cooperation with CWRU investigated several key technological issues enabling the realization of such a system. The machine-design issues of achieving the demanding material handling and the precision automatic layered assembly, are described here.

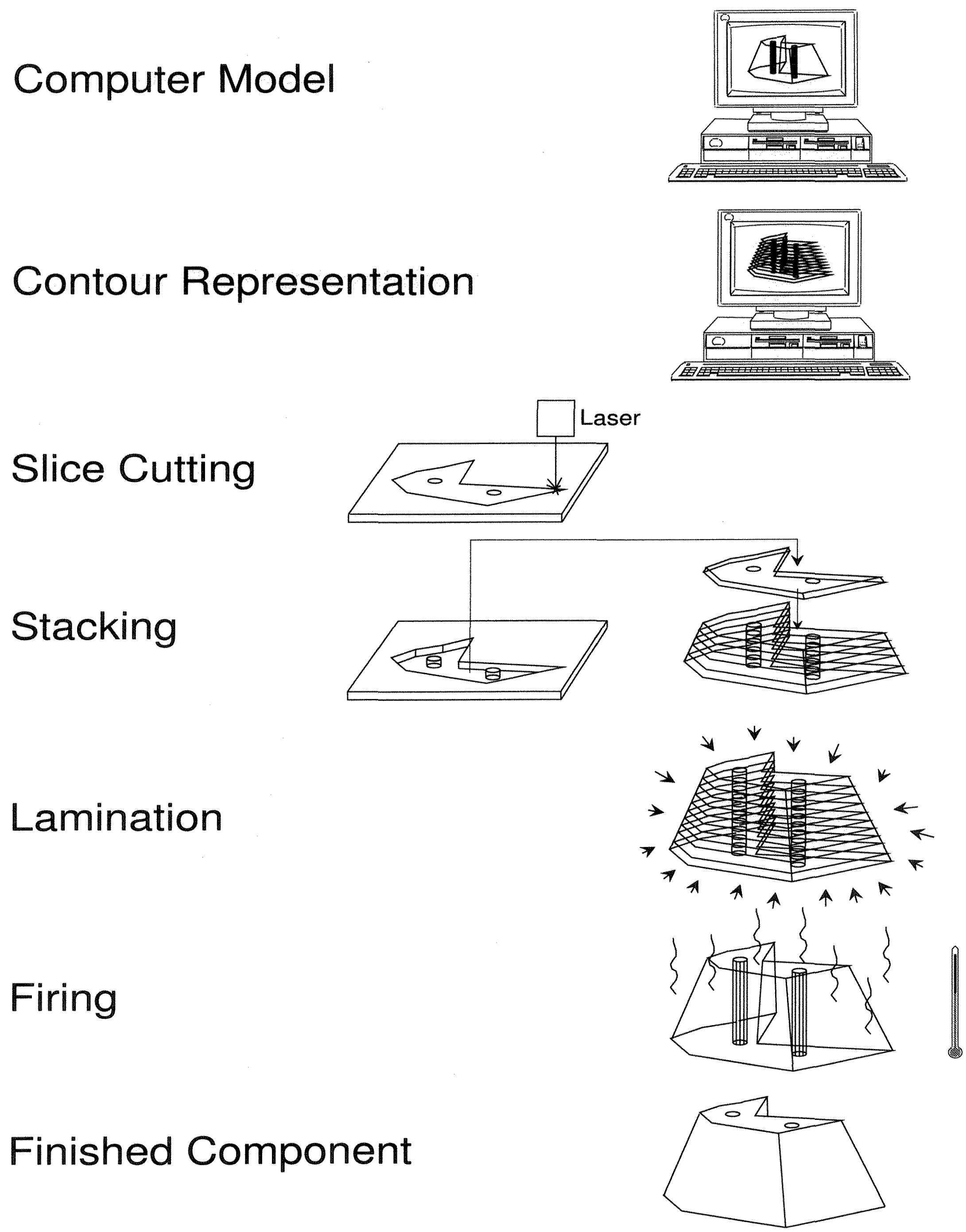

Figure 1: The CAM-LEM Process

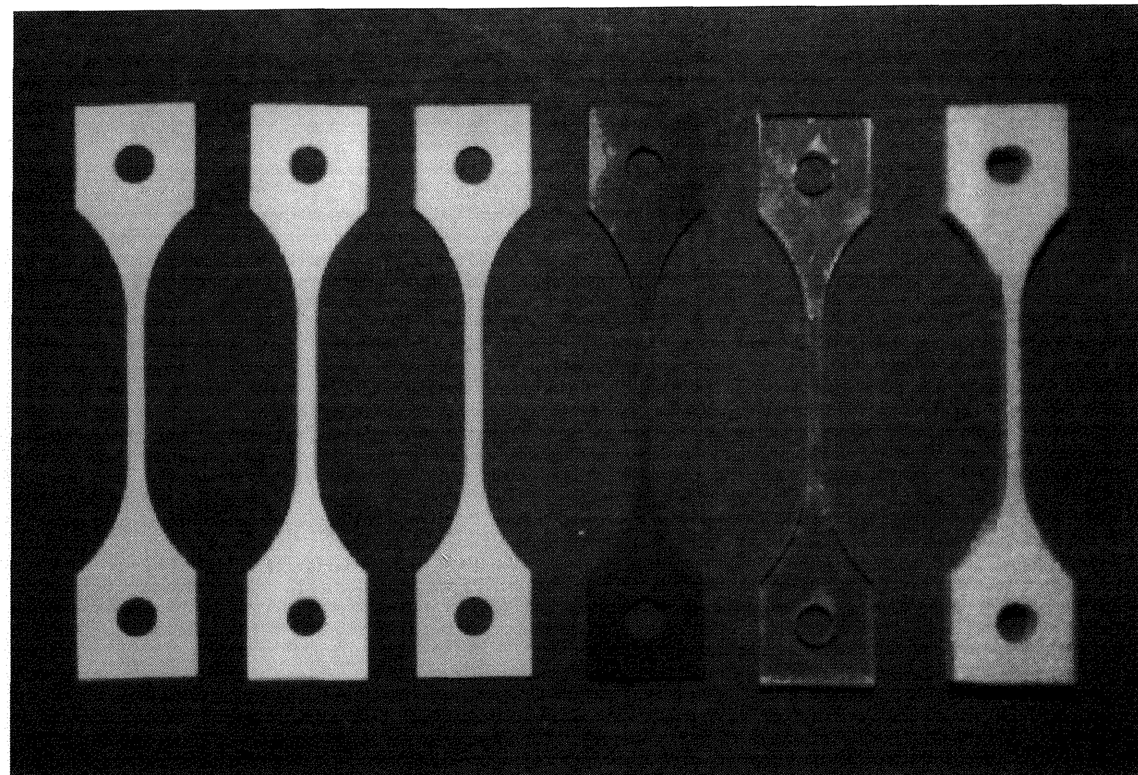

Figure 2: Example materials cut with experimental CAM-LEM system.

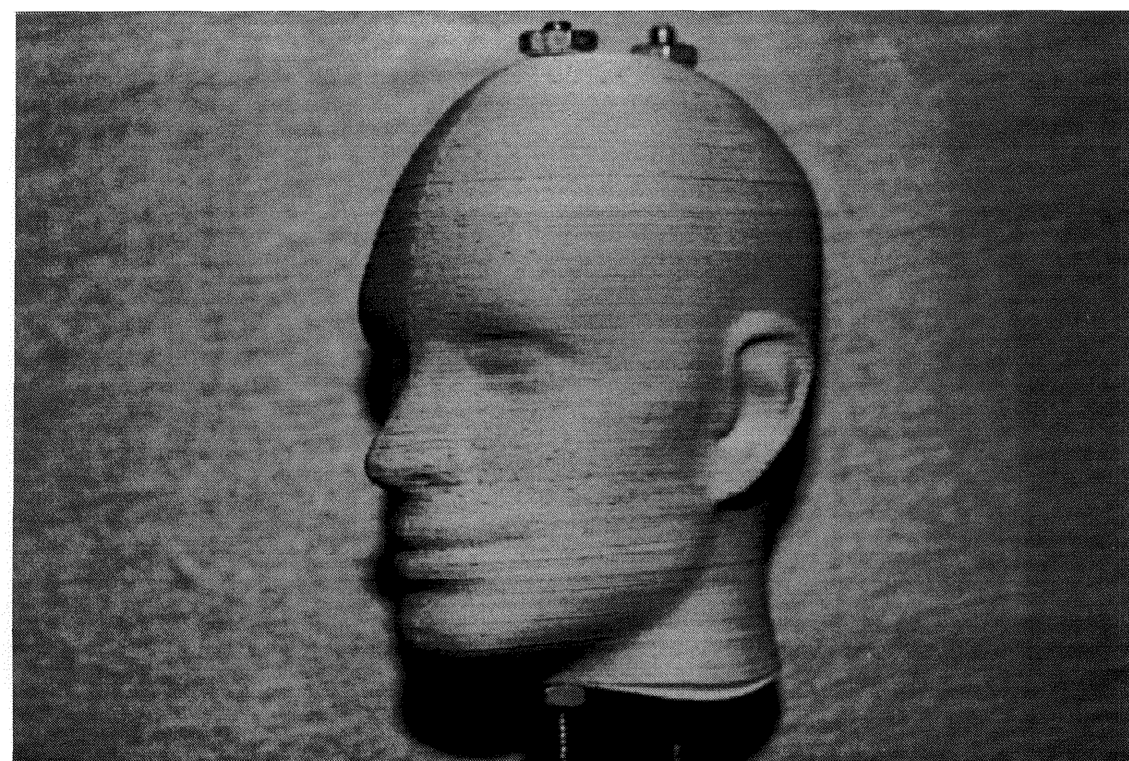

Figure 3: Example 307-layer CAM-LEM Part

Material Handling

Under the CAM-LEM technique, applied to ceramics, cross-sectional shapes of individual laminae are cut from sheet material, robotically assembled and tacked into 3-D objects, laminated into structurally-sound green (unfired) solids, and sintered to densify the ceramic particles into a monolithic body. Cutting desired regions from individual sheets offers prospective advantages over techniques which cut, deposit or fuse material directly on top of a subassembly. These techniques include stereolithography [3], selective laser sintering [4], three dimensional printing [5], and laminated object manufacturing [6]. By cutting laminae individually, the geometric formation process is fully decoupled from the material processing steps, in sharp contrast to most existing SFF techniques, thus obviating compromises in either operation. Conceptually, the CAM-LEM approach is most similar to the Helysis system of "Laminated Object Manufacturing" (LOM) [6], in which laminated objects are formed from stacks of laser-cut sheet material. The primary difference between LOM and CAM-LEM is that the LOM system stacks sheets first, then cuts outlines, whereas CAM-LEM cuts first then stacks. Due to this difference, the CAM-LEM system more readily accommodates internal voids and multiple materials, but at the expense of more demanding material handling. In particular, the CAM-LEM approach introduces the additional complexity of extracting desired cross-sectional regions after cutting them from continuous sheets. To solve this problem, we have developed a novel selective-area gripper, capable of extracting geometrically complex regions of material from the cutting plane.

We have successfully tested cutting and manipulating various materials including paper, cardboard, Coors Ceramics tape-cast ceramic, CWRU tape-cast ceramic, plastics, and tape of powdered metals. Our tests have shown that the gripping operations are virtually independent of the type of material used. We used identical functions, procedures, and parameters in picking up and stacking both the paper and ceramic tape, for example.

The design of the cutting surface is important for obtaining high-quality cuts. Initially, a smooth aluminum cutting surface was used. However, parts cut on this surface exhibited poor edge quality (possibly due to reflections of the laser from the aluminum surface). Further, polymeric binder material vaporized by the laser would recondense on the cutting surface, further roughening the cut edges, and often causing the desired part to adhere to the table and/or to the waste material. In addition, parts placed loosely on the cutting surface were displaced by the laser's air-jet flow. (The air-jet flow is necessary to protect the lens of the laser, and to help eject debris from the laser cuts, thus improving edge finish.)

To prevent part displacement during cutting, the cutting surface plate was punctured with an array of holes, and a vacuum suction was applied to clamp the sheet material to the cutting surface. This approach prevented part slippage but exacerbated the recondensation and adhesion problem. Alternative surfaces of wire mesh, wire cloth, acrylic plates, ceramic mesh, and others were tested. In these cases, rough surfaces provided too little vacuum clamping force and smooth surfaces had problems with material condensation and adhesion.

The most successful cutting surface tested thus far consists of an aluminum "honeycomb" material commonly used in aerospace applications requiring strong, lightweight structures. This material provided good vacuum clamping and little material condensation and adhesion. The honeycomb cutting table structure provides a sufficiently high density of support for small part feature sizes. It also provides adequate ventilation beneath the laser cutting surface for debris released through laser cutting since the cell wall thickness is smaller than the laser beam diameter. Prior tests showed that the laser does not cut aluminum at the power levels required to cut slice materials, and that few materials tested thus far adhere to aluminum. This combination of factors results in a strong, robust, and reliable solution to the cutting table design. A ceramic grid cutting surface with which we had some success can be seen in Figs. 4 and 6.

Figure 4 is a photograph documenting the success of our selective-area gripper. On the left side of this photo, a top view of the robot's gripper is visible, as well as the outline of a complex part cut from alumina tape, extracted, and stacked by the robot. The part shown is actually a 2-layer assembly, stacked with high precision. On the right side of the photograph is the x-y sled's cutting surface. Alumina tape stock was placed on this surface, laser cut, and the desired part area was extracted by the gripper. The complement of the desired part shape can be seen clearly, including the small circular cutouts, which were left behind by the gripper when the desired area was extracted.

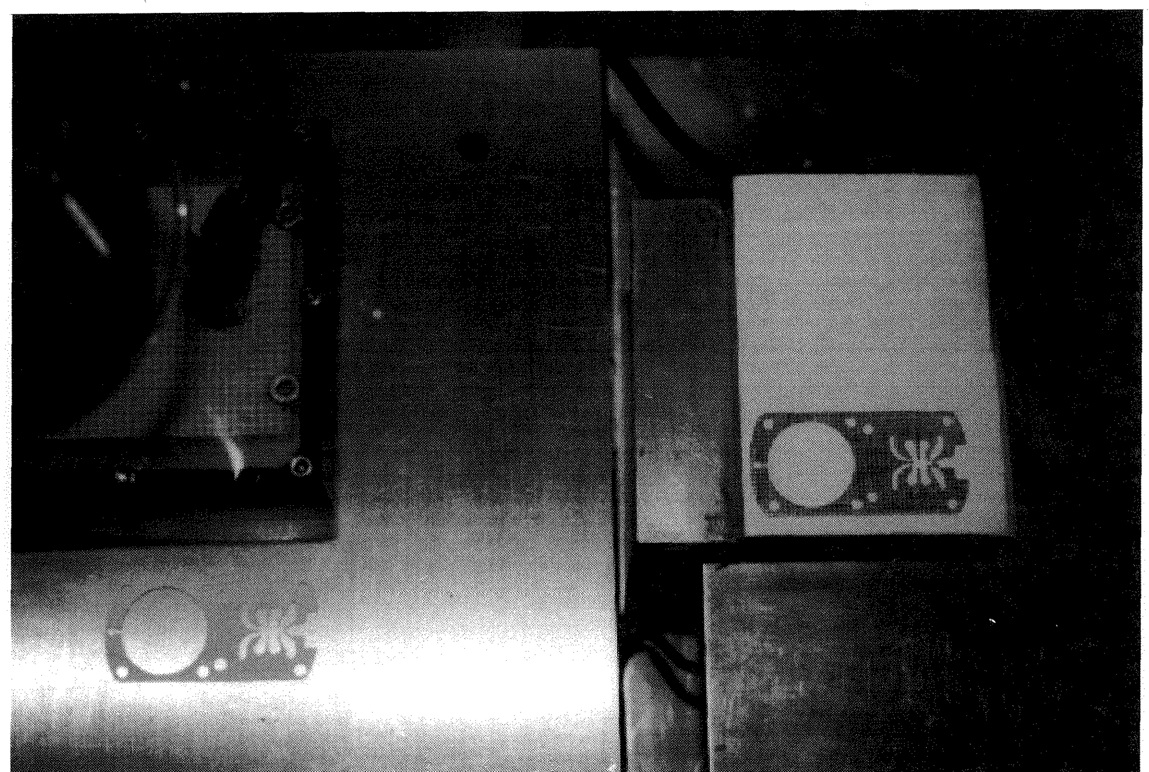

Figure 4: Selective-area extraction of complex shape.

Assembly Precision Evaluation

A second key feasibility evaluation was to determine the achievable precision of robotically-assembled laminated components. To quantify possible inaccuracies due to part slippage during gripper manipulation, we devised an automated test.

The computer commanded the robot to repeatedly pick up a ceramic specimen (a z-motion), translate the part approximately the distance required to perform assembly (a y-motion), then return the specimen to its original position (reverse y and z motions) and release the part on the table. This sequence of operations simulates what happens in an actual cutting and stacking operation. The dog-bone shape employed for this test, later used for strength-test experiments, offered sufficient geometric complexity (curved edges, both wide and narrow sections, and internal cutouts) to comprise a realistically challenging evaluation. Part position and orientation were computed by calculating the part centroid and orientation from images acquired by a CCD camera mounted above the release position of the part. After each manipulation cycle, the position of the part and its angle relative to the camera were recorded to determine placement repeatability.

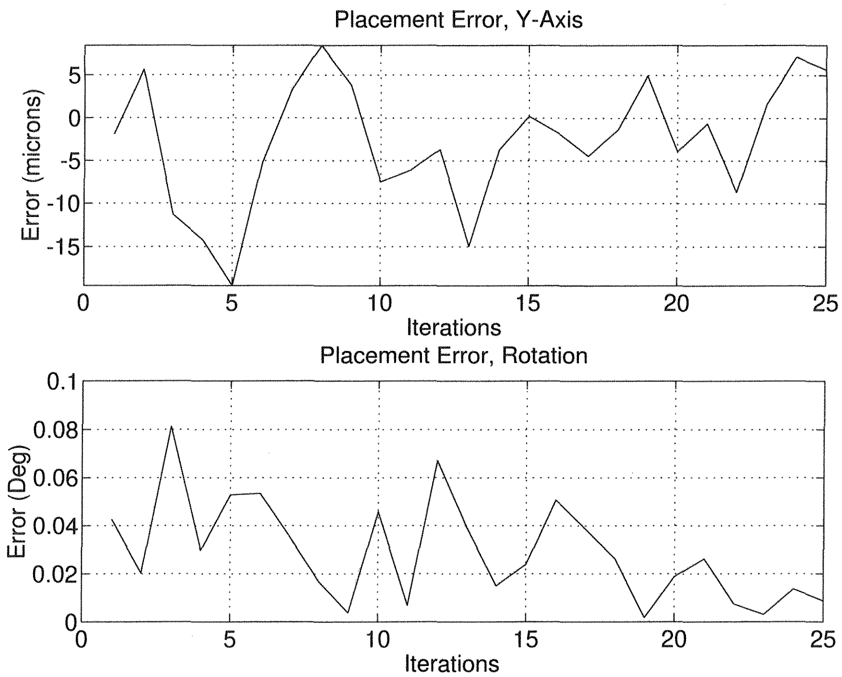

Figure 5: Part placement error during selective-area gripper handling

Figure 5 shows the results of 25 iterations of the test of part placement. The plots show the change in position of the part centroid location and part orientation between each iteration. The standard deviation of the readings for y and the angle were 7.2 microns and 0.021 degrees, respectively. A 0.021 degree rotation about the center of the part results in a displacement of the outer edge of the test specimen by 14 microns.

From these results we conclude that our selective area gripper is capable of moving part slices with high repeatability. In fact, handling errors are within the resolution limit of the Seiko XY-2000 robot, so these measurements only establish a conservative upper bound on the achievable precision.

Further tests were performed on a robotically-stacked rectangular assembly, shown in Fig. 6. Each square cross section, 24mm on a side, was laser cut from Coors alumina tape, lifted by the gripper, and stacked onto the assembly. The assembly shown includes 25 layers of 610mm-thick tape. While the edge roughness of robotically-stacked assemblies has not yet been formally quantified, we subjectively conclude that the stacking accuracy exhibited in our experiments demonstrates excellent assembly precision.

III. Conclusion

We have demonstrated the ability of the CAM-LEM system to create complex parts from industry-standard STL files. Complex paper models exhibit precision comparable to other SFF methods. We have also shown how the CAM-LEM process can utilize other sheet materials, such as ceramic tape, to create engineering components with structural properties rivaling the bulk material properties themselves. The cut-then-stack approach facilitates the formation of interior voids and channels without the need to remove waste manually. Further, fugitive material added to the assembly can support cantilevered structures. Further work will investigate the ability of a 5-axis cutting system to cut edge tangents to optimize build time and surface finish by using thicker material layers. We conclude that a CAM-LEM Solid Freeform Fabrication system is feasible and are pursuing development of a fully-functional prototype.

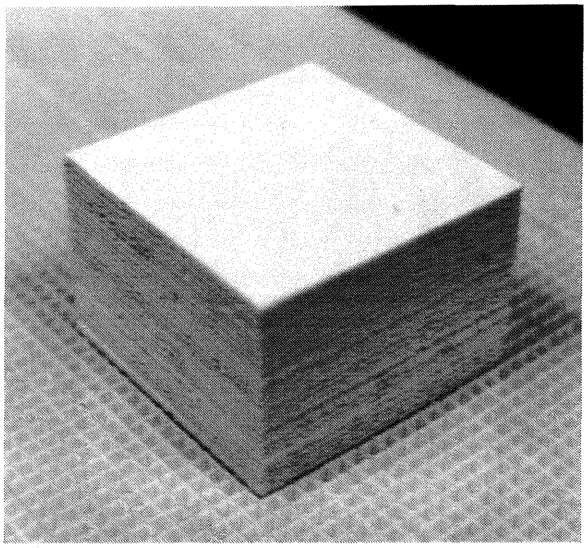

Figure 6: Cut and Robotically Stacked Squares

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