Benchmarking of Rapid Prototyping Systems - Beginning to Set Standards

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Abstract

Many rapid prototyping (RP) technologies are available today and more are being developed around the world. The absence of benchmarking standards in the RP industry has led manufacturers to use their own standards and make claims about superior performance. The need for testing standards is already felt; standardization will become imperative in the near future. The present work aims to lay the groundwork for the development of standards to measure various performance factors. Issues such as appearance and finish are studied qualitatively; the test part and some findings are presented. Issues such as repeatability, warpage, curl, creep, shrinkage and tensile strength are proposed to be studied quantitatively; test parts designed for studying these are described. Benchmarking standards will help users choose proper systems for their applications and help operators in monitoring machine performance, enabling better control over part building.

1. Introduction

Today's various rapid prototyping (RP) systems have significant differences with respect to their operation and the materials they use. Experimental evidence shows that there are different factors which determine the geometries that build better on each process, the speed of building, the finish and strength of the parts and the accuracy and functionality of the parts. The materials that offer advantages in certain applications may not be suitable for others. The results are also influenced by the expertise of the operators. The effect of some of these factors is known and that of others is not. Figure 1 shows a few of the factors which affect part characteristics.

First time buyers and users often do not understand which system suits their requirements best. Even machine operators usually possess knowledge about one process only. How can a first time user, or a person with limited experience, go about choosing the process that is best suited for his/her requirements? To answer the many questions a potential buyer/user faces, the obvious course of action would be to compare the various processes by studying data on their performance. However, there are no benchmarking standards in the RP industry at the present time.

This paper will address the establishing of systematic benchmarking procedures which may be used to generate useful data on some important material and process characteristics of RP systems.

Qualitative issues such as appearance, form and feel will be important to users with `touch-feel' applications such as design reviews and marketing campaigns. The test part designed to study these will be described here. Some observations about test parts built with four RP technologies, namely, stereolithography (SL), selective laser sintering (SLS), laminated object manufacturing (LOM) and fused deposition modeling (FDM), will be presented.

In investment casting and functional testing, for example, the dimensional accuracy, build defects such as curl and warpage, and the strength of the parts will be important. Test parts have been designed for measuring repeatability, curl, warpage, creep, shrinkage and tensile strength. Detailed measurement plans for collecting useful data are still being developed; the design and results of these experiments will be presented at a later date.

It is important to stress that both the qualitative and quantitative results will indicate the combined capability of each process and the corresponding material, together with the skill of the operator(s). The long term goal of this project is to be able to understand the effects of process_related, material_related and operator_related factors and develop a methodology to study them separately.

2. Previous Benchmarking Studies

An extensive survey of literature, combined with information from manufacturers, users and service bureaus turned up three benchmarking studies whose results have been published. Only two companies, 3D Systems Inc. and DTM Corporation, publish/furnish information on their test parts. These companies use completely different parts for measuring dimensional accuracy. 3D Systems is the only company to have designed tests for studying different part and process characteristics.

Chrysler's Jeep and Truck Engineering conducted a benchmark study [2] in order to decide which system to invest in. A finely detailed speedometer adaptor 1.5"x1.5"x3" in size, shown in Figure 2, was built on six different systems; 3D Systems' SLA 250 and SLA 500, DTM Corporation's SLS 2000, Helisys' LOM 1015, Cubital's Solider 5000 and Stratasys' 3D Modeller. Since Chrysler owned only the SLA 250, they sent the part's STL file to all the manufacturers. For Chrysler, system speed and cost were the most important factors and were studied in detail. Cost was detailed under material, operation, pre and post processing, depreciation and maintenance. The time study included pre-processing, build and post-processing time on each system. Accuracy was not studied in detail, parts were simply measured to ensure that they were within specifications. Nor did Chrysler study the strength or surface finish of the parts.

In 1994, Chrysler sent the same part to RP manufacturers worldwide [4]. The formula for cost comparison was updated but the objective to assist users or purchasers of RP equipment in selecting the fastest and/or cheapest system remained the same. The study concluded that there are no set rules to choose any one RP system over others. It is recommended that each company review factors like end use of models, urgency of turn around time, availability of capital and trained personnel and location of equipment before selecting any technology.

Aubin [3] documents a study of RP technologies from all over the world. The report lists system, maintenance and training costs, build volumes and expected accuracies. Technical capabilities of available systems were characterized and technologies under development were reviewed. A benchmark study was carried out using the Intelligent Manufacturing Systems (IMS) part shown in Figure 3. 4 parts were sought from each company, fabricated from an STL file. The participants were allowed to build a maximum of 6 parts and present the best 4, indicating how many they had built. However, information on the measurements obtained from the parts is proprietary and is not available. The comparison of the pre-processing, building and post-processing times indicates that the processes studied compare differently in these areas.

Van Putte [1] describes a study conducted by Eastman Kodak to study the capability of five RP processes to faithfully reproduce features on a test part. The part, shown in Figure 4, was originally designed to see how various computer-aided design (CAD) / computer-aided manufacturing (CAM) packages could design, alter, analyze and machine typical Kodak components.

Part drawings were made on Pro-Engineer and Aries. The STL files were sent to the service bureaus of five companies: 3D Systems, DTM, Cubital, DuPont and Helisys. The parts were measured using a coordinate measuring machine (CMM), vernier calipers and an optical comparitor. Sixteen X-Y and four Z measurements were taken on each part.

Subtracting the CAD dimensions from the measured ones gave a set of data for each part. Using a statistical software package, the data was analyzed in 2 sets, one for the X-Y plane and the other for the Z-plane, to determine the capability of each process to replicate the original CAD model. A shrinkage correction factor was applied by changing the limits for the capability analysis in such a way as to maximize the performance of each part. A `WAR-PAGE' chart designed by Cubital was used to subjectively assign a warpage value to the base of each part by comparing it to the lines on the chart.

Van Putte himself voices many concerns about the study. Only one part was built by each process. The test part design consisted of features important to Kodak and may have been more favorable to some processes than to others. The same software was not used to generate part drawings. All these factors limit the usefulness of the results to other users who are looking for benchmarking data.

While the Chrysler and Kodak studies are interesting, they are primarily of use only to themselves and the data is of little use to other users of these RP systems whose typical parts may be significantly different, as also the factors critical to their applications. The objective of the present study is to fill this gap by designing experiments which can be used to systematically compare RP systems.

A group of European companies has also conducted a benchmark study [8]. A test part containing thin walls, tapers, slots, holes and free form surfaces was designed and built by 12 vendors. The results are available but have not been reviewed by the authors at this time.

3. Qualitative Issues

A simple test part (shown in Figure 5) which contains only cylinders, cones and prismatic boxes, was designed. Each part has four cylinders, tilted at 0, 30, 60 and 90 degrees from the vertical axis. These were used to study the effect of tilting features. A stepped cone with four sections of different cone angles was used to study stair-stepping. The prismatic boxes were used to study straightness and parallelism of edges and warpage of flat surfaces.

Parts were built with 6 materials on the 4 systems mentioned in section 1. A study of the parts and processes, combined with technical discussions with machine operators [5,6,7], provided an insight into various pre-processing, building and post-processing issues. Such understanding is essential in developing benchmarking standards.

3.1 Pre-Processing Issues

Part building is affected by the inherent errors in converting data from a CAD file to a format acceptable by an RP system. Any benchmarking process will have to ensure that the same CAD software and file format are used. However, this still does not rule out differences in interpretation of the accepted format by the system software.

Build layouts for this study were created as assemblies on Aries by using multiple copies of the test part. This created a concatenation of STL files for each assembly, which the SLS and LOM software found hard to read [6]. Also, in one instance, the FDM software read one cylinder as being separate from the rest of the test part, in spite of the cylinder being `unioned' to the base of the part [6]. Subsequently, the part built without problems.

An important finding is that while the STL format was accepted by all the systems used in the study, the method of constructing the drawing file on a CAD system was found to affect part building on the LOM process. The LOM process is different from the other processes in that it builds parts by cutting away excess material while the others build parts by adding or fusing material where required. The software on the LOM machine recognizes different entities in an STL file and cuts them separately from the sheets of paper. Therefore, on the test part, the cylinders were separated from the base since they were drawn separately and `unioned' into the base. This would not have happened if the drawing had been constructed by subtracting geometry from a block; the test part would then have been treated as one entity [6,7].

Constructing the part drawing with the LOM process in mind will solve this problem but we can only speculate whether the laser on the SL and SLS machines will cure parts differently, based on whether two features were drawn as separate entities or constructed out of one block. If some areas are cured/sintered twice over, parts may be affected in ways not yet known.

3.2 Part Building Issues

Aesthetics: The SL parts (5154, Weave) looked the best, except for `swirls' on some inclined cylinders. The SLS (polycarbonate), FDM (wax), SLS (nylon), SL (5180, Quickcast) and LOM parts rank in order on the basis of appearance. Laser scoring and cross-hatching are causes for the LOM parts to rank low.

Geometric features: All 4 processes appear capable of building cylinders at different angles. The results can be expected to be different if hollow cylinders are built, especially with thin walls.

Stair_stepping was not a problem on any of the cones on any machine. However, only the SLA built all cone tips well. All other processes built some parts where the sharp point was not achieved. Edges were sharpest on LOM parts, followed by SL (5154, Weave), SL (5180, Quickcast), SLS (nylon), FDM (wax) and SLS (polycarbonate) parts.

Material issues: Problems exist with materials on all 4 systems. Building nylon parts on the SLS process requires very tight temperature control [6]. Temperatures even slightly higher than the recommended value harden the loose nylon powder which becomes difficult to remove, affecting appearance and accuracy. In some areas on the test parts, the nylon was so hard that it could not be removed even by sand blasting. A smaller build volume is also recommended for nylon parts [6].

With the LOM process, delamination occurs between layers on some parts. Variation in paper quality, specifically coating inconsistency, is suspected to be the one of the causes for this [7].

The new resin (5180), used on the SLA, has higher surface tension than the old ones. Layers finer than 0.006" are hard to build in styles other than Quickcast. It also increases build time because there is a `pre-dip' delay between layers while the previous layer cures.

While building nylon parts on the FDM process, the nozzle leaves fine "fuzzes" on parts. This can be controlled by using recommended nozzle sizes and velocities, but the problem is still more evident than with investment casting wax [5].

Operation issues: While all four technologies permit build interruption, none of them continue a build successfully after a long delay. Unexpected interruptions occurred on the LOM and SLS machines. A paper jam stopped the build on the former while exhaustion of the nitrogen supply from the supply cylinder was the cause on the latter. An improved paper transport mechanism will help reduce operator monitoring for the LOM process. For large builds on the SLS process, a continuous supply of nitrogen from a plant, as opposed to using a cylinder, may become necessary.

Build time: Although the present study did not involve comparison of build times, some factors which limit process speed are highlighted for interest. The FDM process took the longest time for building a set of parts. Faster builds can be achieved by increasing the space between successive nozzle paths, which determines how densely the material is laid out. However, the mechanical traverse of the nozzle is always slower than the scanning speed of a laser using a set of mirrors. On the LOM process, even though a laser is used, it traverses mechanically, again limiting build speed. Also, since excess material has to be removed after the build is complete, cross-hatching has to be carried out over the entire block. For small parts, a significant portion of build time will be spent on this.

Build failures: In the first set of parts built on the SLS machine with polycarbonate, many of the inclined cylinders and some of the horizontal cylinders broke loose. Some cylinders were also broken into dissimilar sections, appearing to indicate that the sintering had failed to hold material together in those sections. In a subsequent build, parts built with the same material were intact. The cause for the failure is not known.

The first build with the Quickcast style (resin 5180) also failed unexplainably. Fine strands of material were found all over the parts, completely covering them with 'fuzz'. All features were stretched in the Z direction; the parts were 1.5 to 2 times taller than their actual size. The next build was good, though no parameters were changed.

3.3 Post-Processing Issues

All RP processes have recommended procedures which are followed before part building is truly complete. In addition, operators develop their own skills and techniques from experience. To some extent, post-processing is dictated by the end use of the part. Parts for design reviews may be smoothed and painted, Quickcast parts meant for investment casting are carefully drained of uncured resin, and so on. Operator skills influence final part accuracy and finish to varying degrees on different systems. This influence is highest on the LOM parts.

Removing excess material from the LOM parts is difficult where geometries are intricate. Special tools are not available. Operators use suitable wood working tools. Not knowing the exact geometry can make cleanup even harder, with the danger of accidentally breaking part features being very high for delicate sections. When features are broken, they can be glued back on with wood glue but the effect of this glue on dimensions, especially in the Z direction, needs to be studied. The process is best suited for large, simple parts.

FDM parts require little or no processing. Fine strands of material, which may appear on some parts, can be blown away with an ordinary hair dryer [5]. SLS parts rank second in ease of post_processing, the most difficulty is encountered with cleaning hardened nylon. SLA parts usually require more time than FDM and SLS parts since post_processing involves support removal, draining of uncured resin, curing in an oven and cleaning with chemicals.

4. Quantitative Issues

The factor of greatest interest to this study is repeatability. Repeatability is really a machine issue; two supposedly identical machines, though theoretically of the same capabilities, will still have their differences. It is important for users to understand how consistently a particular machine will build a part when built at different times, platform locations, orientations, by different operators using different materials. It is reasonable to expect variations as mechanical parts wear on the machines. By following a standardized test procedure, it is possible to monitor a machine's capabilities and make adjustments wherever possible to obtain builds that are known to be within the machine's capabilities. A benchmarking procedure will be developed in this light using the test part which was used for the qualitative study described in section 3.

Other factors of interest include build defects such as curl and warpage, material strength (tensile), and part deterioration over time (creep, shrinkage).

Warpage is defined as the out of plane deviation of flat surfaces. The test part is, once again, the one described in section 3. A CMM can be used to measure the coordinates at many points on the top surface of each prismatic box. By fitting a plane through these points, the deviations found at the inspected sections can be used to calculate warpage.

For determining tensile strength, it is proposed that ASTM standard 638-72 flat tensile test bars be built and tested.

Curling is the deformation that occurs in parts with geometries such as cantilever lengths and is due to internal stresses which develop during part building. Creep is defined as the dimensional change that occurs over time due to molecular changes and gravity, that is, the weight of the part. Two types of shrinkage can be studied, linear and bulk shrinkage. Linear shrinkage is defined as the change in part dimensions over time. Bulk shrinkage is defined as the change in volume of a part over time. Test parts and procedures to verify performance of RP systems on these factors will be developed.

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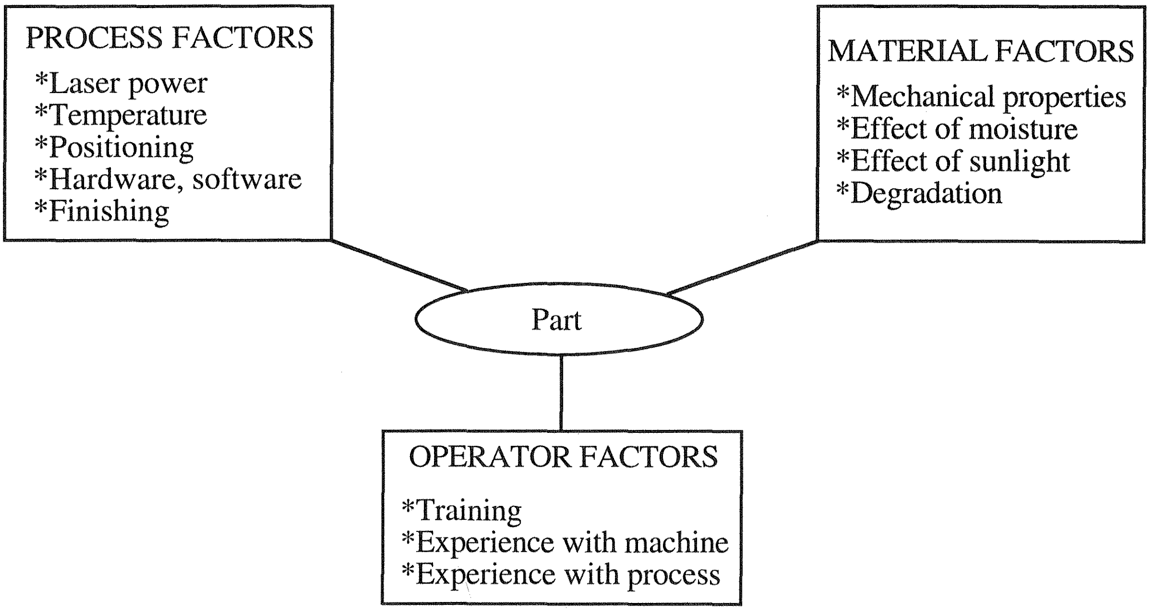

Figure 1. Factors Affecting Performance of RP Systems

Figure 2. Chrysler Benchmark Part

Figure 3. The IMS Benchmark Part

Figure 4. The Kodak Benchmark Part

Figure 5. Part for Qualitative Study

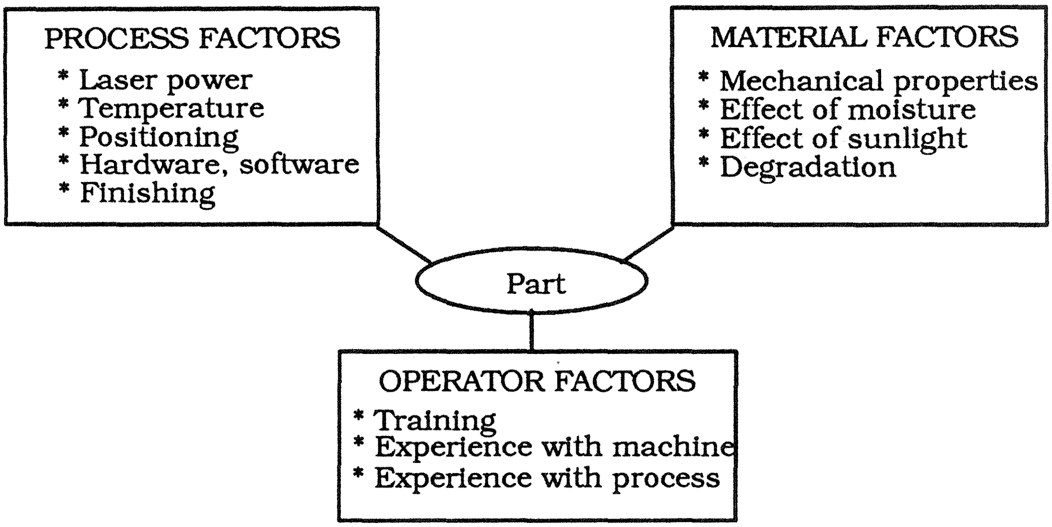

Figure 1. Factors Affecting Performance of RP Systems

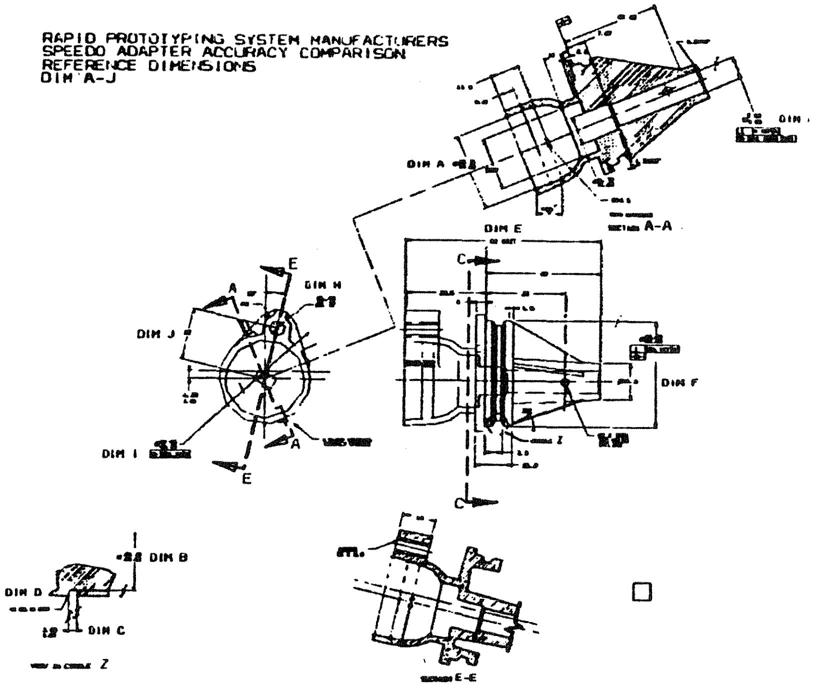

Figure 2. Chrysler Benchmark Part

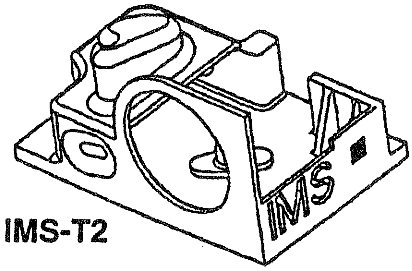

Figure 3. The IMS Benchmark Part

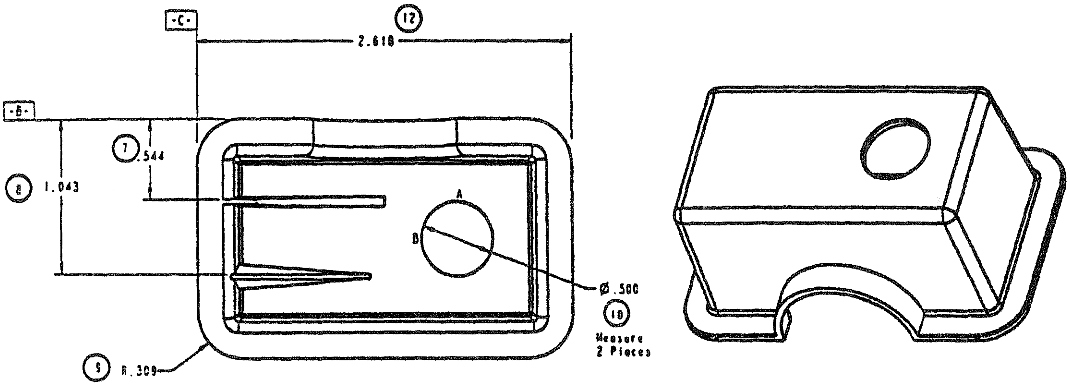

Figure 4. The Kodak Benchmark Part

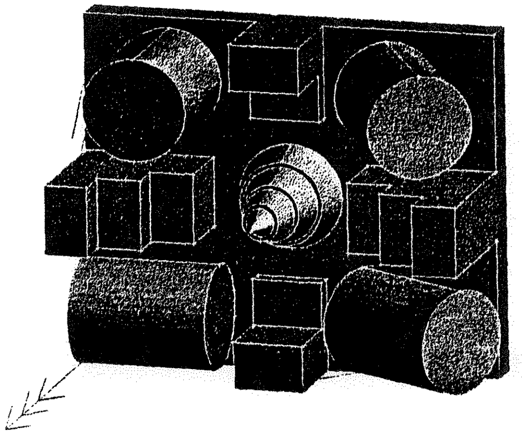

Figure 5. Part for Qualitative Study