A Response to "TRIZ on Rapid Prototyping - a case study for technology foresight"

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WorldTech provides technology search and evaluation services for a variety of government and corporate customers and helps a select group of emerging technology companies commercialize their defense, homeland security, manufacturing, and energy technologies and sell them internationally. As part of our technology search services, I follow the development of rapid prototyping technologies very closely, visit emerging rapid prototyping companies, and meet with many of their customers. We also provide international marketing services to Optomec (http://www.optomec.com/), a manufacturer of laser deposition rapid prototyping technologies for metal parts (Laser Engineered Net Shaping) and for electronic circuits at the chip and circuit levels (Maskless Mesoscale Materials Deposition) , and for Hytec (http://www.hytecinc.com/), a manufacturer of 3D x-ray tomography systems (Flash CT) that is capable of imaging all internal and external part features with accuracies to 0.025" and generate a 3D CAD/CAM file.

The July 2003 TRIZ Journal article written by Jörg Stelzner, Carlos Palacios, and Tobias Swaton provided an excellent example of the limitations of using TRIZ (or any other design methodology) without subject matter expertise. I have used examples from our research evaluating rapid prototyping technologies and working with Optomec to provide a critique of their article and to provide illustrations of some of the design goals, challenges, and contradictions that designers of rapid prototyping technologies face.

The authors assumed that all rapid prototyping technologies follow the same design approach as stereolithography (SLA). By generalizing a large field with a dozen major approaches, each of which has multiple components for which the component problems have multiple approaches, the result was an overly simplistic analysis that ignored many of the critical developments and trends in the rapid prototyping space. Within this space, there are three major sub-markets that are currently commercially viable:

1. Concept modeling and low-end plastic rapid prototyping systems priced under $100,000.
2. Rapid prototyping systems for fabricating plastic parts priced between $250,000 and $750,000.
3. Rapid prototyping systems for fabricating metal parts priced between $500,000 and $2,000,000 (most are over $1 million).

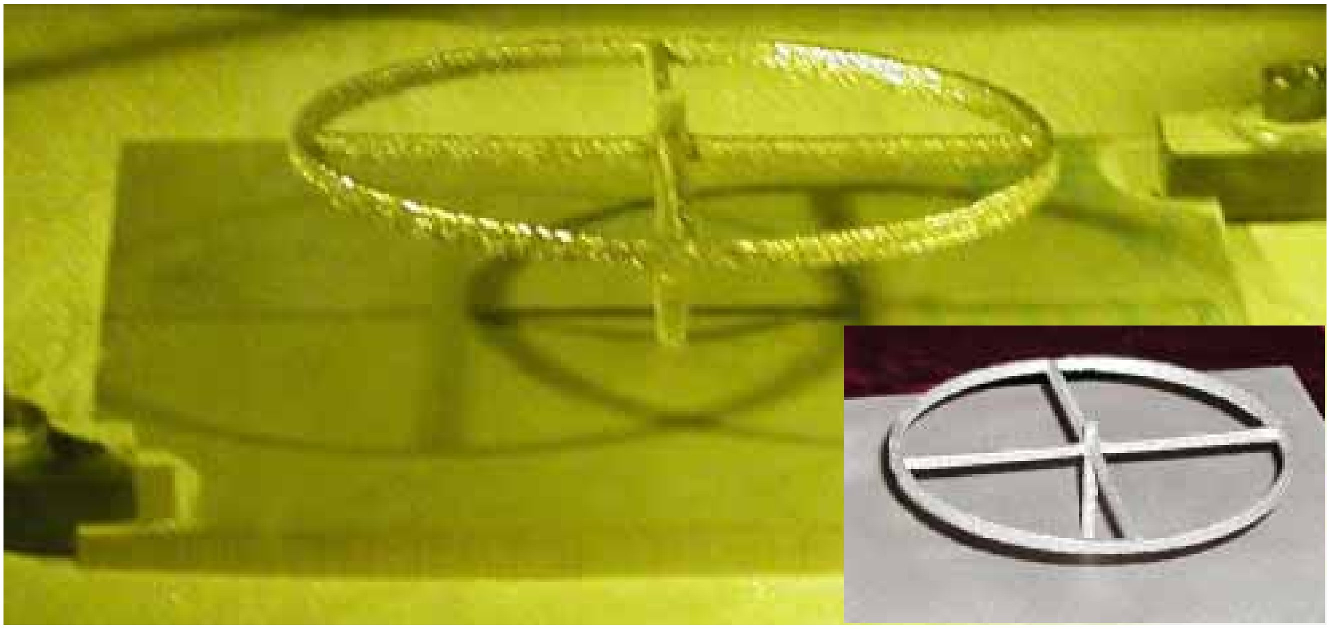
These are very different markets with different customer and technical requirements. As a result, one needs to be extremely careful about making generalizations and understand the different trends, both technological and business, in each market segment. An example is the author's claim on page eight of their article that "with the emergence of 3D printing substituting complex laser sintering machines, a trend towards more simple machines can be stated." The largest unit growth of rapid prototyping machine sales has been in the concept modeling segment for machines priced between $30,000 and $60,000. These machines offer low cost largely by sacrificing material properties with a trend towards improved. Parts made on these machines will never be used in production applications where low volumes of parts are needed or for flight critical parts on aircraft. Alternatively, parts made on 3D systems SLA and selective laser sintering (SLS) machines are flying on the International Space Station. This tradeoff is acceptable for concept modeling applications and over time may evolve such that there may not be much difference in quality between the first two market segments.

The ideality of moving towards virtual modeling might be valid for Z Corp's process that make a 3D part from a starch powder, but it totally ignores the primary market for most rapid prototyping machines -- making low volume functional prototypes, tools, and finished parts. Even then, it makes the assumption that an expensive virtual simulation would eliminate the need to touch, feel, and demonstrate a prototype design. This ideality is suspect for any focus group or customer interview applications of concept modeling rapid who need to have a physical object. It also makes the assumption that virtual simulation tools are widely available and cost effective – a contradiction. Likewise, Altshuller's principle #27: An inexpensive short-life object instead of an expensive durable one applies here. The marginal cost of printing one part is low, generally several hundred dollars. There are almost 600 service bureaus in 41 countries who will build parts for customers from a 3D CAD file using one or more of over a dozen types of rapid prototyping machines (See http://home.att.net/~castleisland/sb_ci.htm for a directory of service bureaus). As a result, one does not have to purchase their own $30,000+ machine. Although virtual reality technologies are a potential substitute, these technologies remain very expensive and difficult to use.

A better choice of ideality for the design of rapid prototyping machines would be to make finished parts with material properties comparable to or better than the book properties, to not require any support structures, and to do all of this at or below the cost of making the same item using traditional processes. For example, Optomec's laser engineered net shaping (LENS) technology has material properties comparable to or better than book properties, is cost competitive with traditional machining for some aerospace and tooling applications, and does not require support structures (See Figure 1). However, the technology still has a lot of room for improvement for both its speed and surface finishes. Even then, the challenge for generating an exact part is more of a problem with powder production than the LENS technology -- put simply, there are no economic supplies of metal powders under 36 micron at this time; the technologies to make smaller powders remain in the lab and have not been scaled up. This is an excellent TRIZ example of how the solution may come from a different area of technology. Alternatively, one could combine additive rapid prototyping processes with traditional subtractive processes. One future development path for LENS would be to either develop new control software to allow the system to use the laser to finish the part or to manipulate the existing control software (e.g. create a "recipe" where no powder is fed to the machine and the laser settings are calibrated to optimally remove material of a specific alloy) to achieve the same goal. However, aside from potential patent infringement issues, the most cost effective approach may simply be to use a separate existing machine to provide the final processing step.

The requirement of support structures is an example of where Optomec has achieved a rapid prototyping technology breakthrough. LENS is capable of building overhanging structures without supports because the metal material provides the support. The forming process uses a laser to melt a spot on the substrate, adds powder to that point, melts the powder, and cools the new layer in a fraction of a second. Gravity has no impact on the forming process – this is why NASA is evaluating LENS as a rapid prototyping and repair technology for future use on the space station or on a mission to Mars.

Figure 1: Patent-Pending LENS Geometry Breakthrough - 90 Degree overhang in 2 ½ axis deposition with no support structures. Note that the wheel post is still attached to the substrate.



Source: Optomec

Effective applications of technology forecasting require the examination the different technology paths and the various markets and applications for each path. I have identified thirteen major approaches to rapid prototyping technologies and the companies associated with each of these approaches:

1. Stereolithography (3D Systems, CMET, Denken, Meiko, Unirapid, Autostrade)
2. 3D Printing of Starch Powders (Z Corp)
3. 3D Printing (Ink Jet) of Plastics (3D Systems, Solidscape, SDI, Object
4. Fused Deposition Modeling Process extruding heated plastic (Stratasys, Beijing Yinhua)
5. 3D Printing of Metal Powders (Extrude Hone)
6. Selective Laser Sintering (3D Systems, EOS)
7. Laser Forming (Optomec, POM, Aeromet, MCP)
8. Maskless Mesoscale Materials Deposition of metals, oxides, ceramics, composites, biologic materials, and plastics (Optomec)
9. Electron Beam Melting (Arcam)
10. Bonding of Sheet Materials (Helisys (LOM), Schroff Development, Toyoda Machine Works, Kira)
11. Laser Cladding using steel wire feed (Roders)
12. Spray Metal Tooling (Ford Motor Company, Idaho National Engineering and Environmental Lab, 3D Systems)
13. Rapid Casting Technologies (MCP)

When doing patent searches, one has to be careful to cover all of the different directions and fields whose developments impact the technology one is evaluating. For example, LENS is benefiting from developments in Maskless Mesoscale Materials Deposition (eventually the two technologies may merge such that one uses LENS to build a metal part and M^3D to embed sensors and electronics into the metal part), material science, nano powder technologies, and laser physics.

Annual revenues are not a proxy for the profitability of a technology. Many emerging technology firms generate most of their revenues from DoD, DARPA, NASA, NIST, and/or NiH, research contracts (e.g. Optomec, Hytec, Aeromet). Roders and Extrude Hone generate over 95% of their revenues from the sale of non rapid prototyping, subtractive-process machine tools. MCP generates most of their revenues from their materials business (again non-rapid prototyping). For rapid prototyping, I would want to know three numbers for each vendor: the number of machines sold, the price, and the number of employees. Machines sold times average price per machine provides an approximate measure of actual revenues from rapid prototyping machine sales. Terry Wohler's $390 annual state of the industry report is the best source for this data. I would also want to have some sense of the production costs, but this requires a detailed understanding of each technology, significant probing of component suppliers, some analyst work, and a few guesses. Employee counts and the size of the company's facilities (either in square feet or their capabilities) can give some sense of overhead.

I would characterize the rapid prototyping industry to be mature for technologies that form plastic parts and in the early growth phase for technologies that form metal parts. None of the metal rapid prototyping technologies are profitable at this time or have achieved annual machine sales volumes that are large enough to achieve any production economies of scale. Some of the plastic rapid prototyping technologies have been profitable in the past but have been profitable in the past two years. 3D Systems, the largest public rapid prototyping company and the dominant player for rapid prototyping of plastic parts, has not generated any net profits over the past seven years, has not been profitable any two years in a row, and lost over $17 million in 2001 and 2003. Again, the Wohler's Report and SEC filings for the few publicly-traded companies are the best source of data. The three best tradeshows and conferences for learning about rapid prototyping technologies, seeing machines, and handling samples are 1) the Society of Manufacturing Engineer's annual Rapid Prototyping Conference, 2) the annual DoD Mantech conference (DoD clearance required), and 3) the IMTS show held every other year.

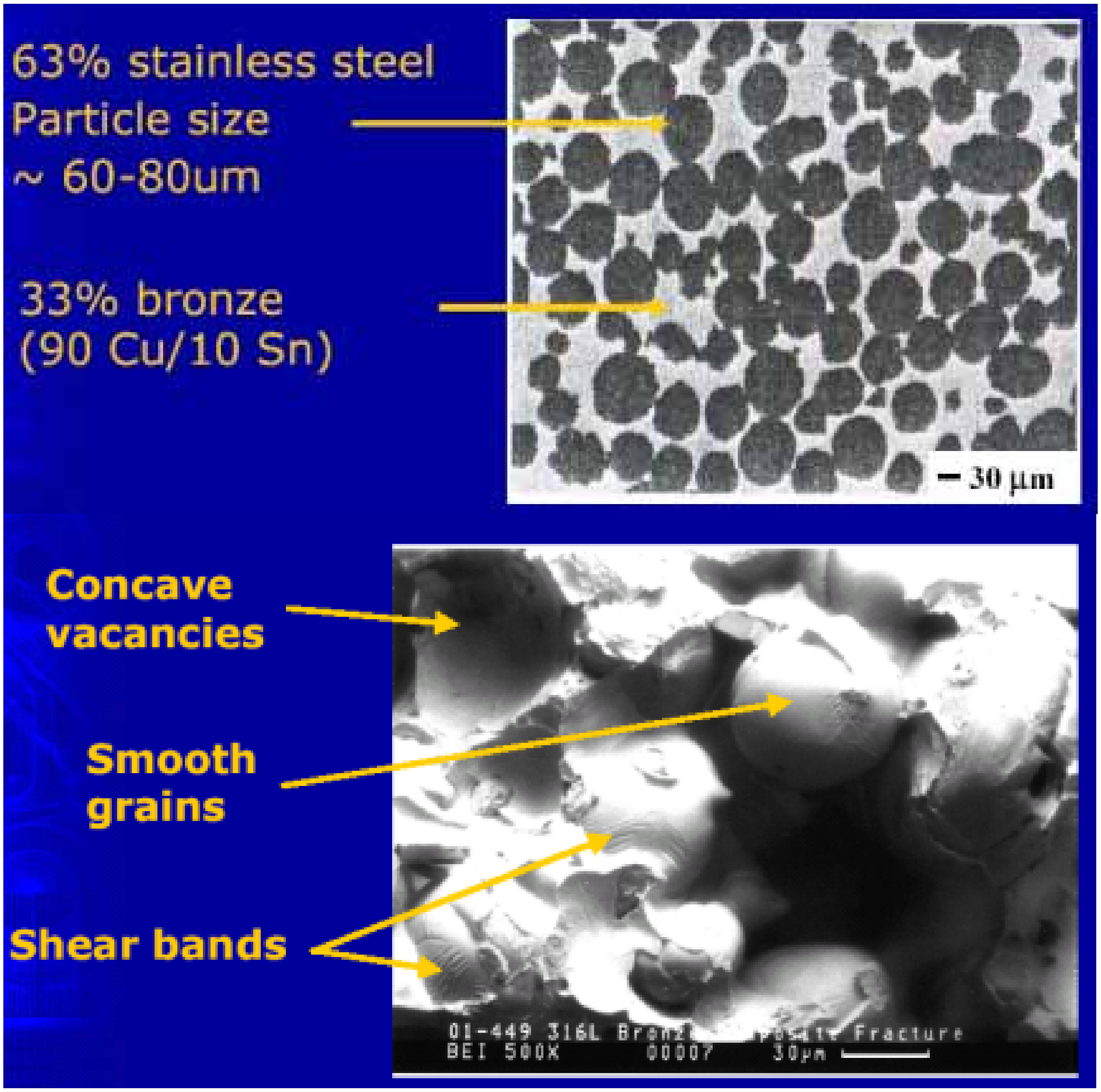
As the authors cite in their paper, process speed (generally measured in cubic inches of material deposited per hour), material properties (including strength), and accuracy are the three primary measures of performance indicators. Accuracy is more important for plastic rapid prototyping processes, while material properties and speed are more important for metal rapid prototyping processes. This is largely due to the fact that metal parts can easily be finished using traditional manufacturing process such as EDM, milling, turning, grinding, or abrasive flow while these processes may not apply or be practical for plastic parts. In addition, material properties for metal parts outweigh process speed in the cases where the process can create exotic custom material properties that are not possible using other processes – e.g. significantly smaller grain structures, columnar grain growth through layers, gradient materials, or hollow structures in super hard or aerospace alloys.

Note that the choice of different materials creates significant design problems for RP system designers. Temperature is a major problem. There is an inherent contradiction between material properties and temperature. To achieve material properties for metals comparable to or better than book values, one must reach melt temperatures that range between 1218° F (aluminum) and 6,170° F (Tungsten). Most steel and nickel alloys melt at about 2750° F while titanium melts at 3272° F. High temperatures have significant energy and safety costs. However, if one operates at lower temperatures, the process will use less energy and may be safer (even sintering steel at 1600° F can cause very bad burns if mishandled) but the tradeoff is degraded material properties.

For example, the 3D printing is a simple process, but the material properties for metal parts are extremely poor. Z-Corp only makes concept prototypes that crumble to starch dust if one drops it. Extrude Hone's 3D printing technology uses an ink jet style device to lay down powdered metal and a binding glue to create a "green" part. This green part is then sintered at approximately 1600° F in a heat treating oven for 12 to 24 hours. The sintering process burns away the glue and creates a part that is very porous. Finally, the part is infiltrated (e.g. dipped) in a vat of melted bronze. The result is a part that is approximately 63% stainless steel, 33% bronze, and 4% air.

Figure 2 shows a photomicrograph of a sample formed using this process. Note the 60 to 80 micron grain sizes and very rough surfaces. This part will have very poor corrosion resistance properties and would never be certified for any aircraft engine or flight critical part. The laser sintering processes provide similar results, but use a laser to melt plastic binders that are mixed with the powdered metal. Note that the version of selective laser sintering that makes plastic parts provides excellent material properties -- good enough that some are being used on the space station.

Figure 2: Photomicrographs of Stainless Steel



Source: Rhonda L. Anderson, "Rapid Manufacturing of Metal Matrix Composite Materials Using Three Using Three-Dimensional Printing", Defense Manufacturing Conference, December 4, 2002, Dallas, Texas.

For comparison, Figure 3 shows a photomicrograph of a H13 tool steel part fabricated using LENS. The grain size averages 3 microns, compared to a handbook standard of 27 microns. By manipulating the 13 LENS process parameters (laser output power, material spectral absorbtivity, laser spot diameter, laser spot transition speed, powder mass flow rate, draw sequence, substrate material, substrate temperature, background oxygen level, thermal “cycle time”, layer thickness, particle size distribution, and hatch separation), one can create different process "recipes" that can create versions of the same material with ten different part properties (volumetric build rate, yield strength, ultimate strength, elongation to break, fatigue limit, hardness, surface finish, grain size, porosity of material, and dimensional accuracy). The LENS process is capable of forming or repairing parts from virtually any metal that can be investment cast. Optomec has developed "recipes" to process over eighty steel, tool steel, stainless steel, titanium, nickel, cobalt, tungsten, aluminum, copper, metal matrix composite, and other materials and is regularly adding new materials to the list.

Figure 3: LENS can make H13 steel parts with 3 micron grain structures

Source: Optomec

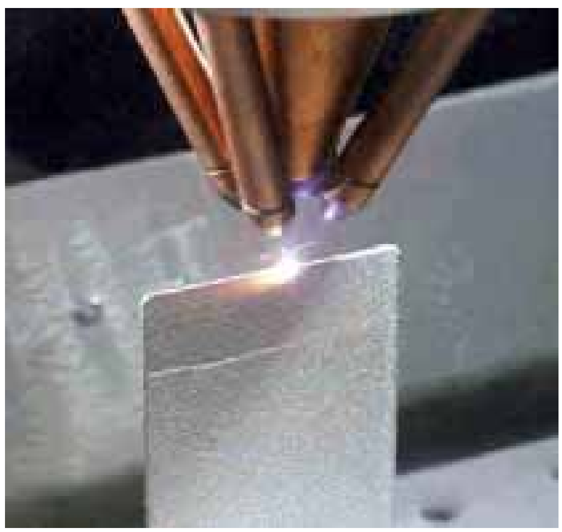
Frequently, there are contradictions between process parameters. For example, one can create extremely small grain structures to provide 30% to 45% better corrosion resistance, but at the price of slower speeds. LENS is currently going through the flight testing and certification processes for use in aircraft engine and structural part applications. Although this is a long process that will take several years, ultimately LENS is expected to successfully pass all of the military and FAA certification requirements.

Likewise, the Arcam Electron Beam Melting produces H13 parts with material properties comparable to or better than handbook standards. Arcam claims that one cannot differentiate between their H13 samples and H13 billets purchased from traditional metal suppliers. I have visually inspected both Optomec and Arcam H13 samples and found the Arcam results to be to be comparable to that of LENS.

One should note that there are frequently multiple approaches to solving the component designs such as how the process feeds the raw material. In Figure 1 in their paper, the authors mislabeled the 3D System's stereolithography process as "Rapid Prototyping" and use it as a general description of all rapid prototyping technologies when it is one of over a dozen approaches. Likewise, they make the same error in Figure 3 of their paper. This figure does demonstrate one of the approaches to feeding material -- the resin or powder sweep approach. Arcam's electron beam melting approach is very similar except their process uses powdered H13 tool steel, operates in a vacuum, uses a much more powerful electron beam instead of a low power laser, and generates temperatures in excess of 3,000° F compared to under 300° F for stereolithography. Another approach is to use a thin plastic (FDM) or metal (Roders) wire. Other examples include the various ink jet or 3D printing approaches, rolling layers of paper, wood, or metal, and even a patented approach using magnetic forces to sweep steel powder over a magnetized substrate before using a laser to sinter or melt the powder to form the next layer.

Optomec's LENS process uses four inert-gas pressurized powder feeders that surround the laser (see Figure 4) and spray spherical powdered metals, typically 36 to 150 microns in diameter but some nano powder coatings have been used. This design provides geometric flexibility (LENS systems can have seven axis – 3 axis table, 2 axis laser wrist, 2 axis tilt / rotary stage) that enables repair applications and allows hybrid approaches where one only laser forms value-added features instead of being forced to entirely fabricated the part using the RP process (e.g. Arcam). It also allow the fabrication of parts with gradient materials where the materials gradually change from layer-to-layer. Example applications include the creation of copper heat sinks within steel parts or creating gradient Molybdenum coating layers with a 1 mm H13 to Molybdenum transition layer and 1 mm of Molybdenum to make tool last as much as five times longer while eliminating some material science bonding and thermal problems that would occur without the gradient material transition layer.

Figure 4: LENS Laser Head Heats Substrate While Powder Is Delivered Through Four Pressurized Nozzles



Source: Optomec