High volume additive manufacturing of finished production parts – a quality approach

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Abstract:

Today, additive e-Manufacturing is considered the acceptable approach to prototype and one off production parts. Progressive companies must look past the prototyping stereotypes and develop manufacturing strategies utilizing additive manufacturing equipment, processes and materials for high volume production. This paper addresses the key focus areas necessary in the success of this industry changing methodology. This paper first addresses the status of additive manufacturing in prototype and production environments. Second, it presents the main obstacles to overcome to make the cultural shift to true additive e-Manufacturing within current industries the methodologies support. Third, it describes the educational process that will be needed to inform industry leaders and academics in the adoption of additive manufacturing systems and a "design to the process" approach. Finally, it presents a case study demonstrating the above ideas and how they are being used by Rapid Quality Manufacturing, Inc. as a guide for new business development.

1. STATUS OF ADDITIVE MANUFACTURING IN PROTOTYPE AND PRODUCTION ENVIRONMENTS

1.1. Status of additive prototyping / manufacturing

Additive fabrication and prototyping of mechanical parts has been around since the late 1980's. Since the early days of Sterolithography (SLA), Fused Deposition Modeling (FDM), and Selective Laser Sintering (SLS) engineers and designers have utilized these systems for the development of prototype parts.

The industrial sectors that are using additive manufacturing worldwide can be seen in figure 1.0 below:

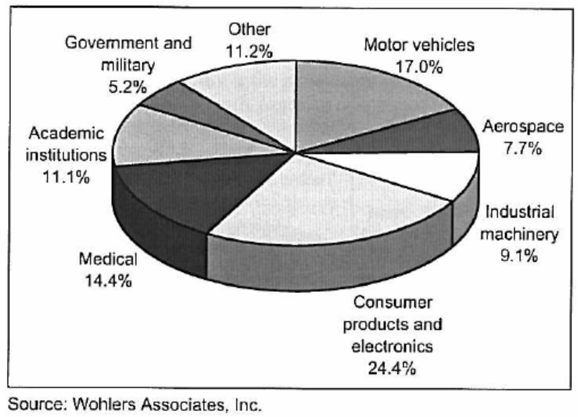

Figure 1.0 – Industries that are embracing additive manufacturing.

One finds that there is a broad use of the technology across multiple industries. Figure 2.0 shows the range of applications of additive manufactured parts across all sectors.

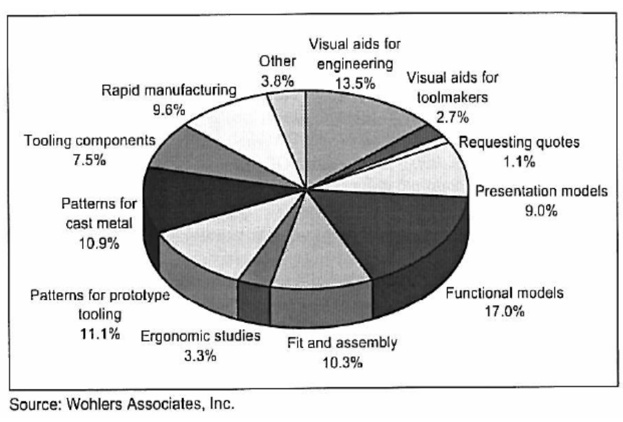

Figure 2.0 – Popular applications of additive processes.

One of the benefits of additive manufacturing has been in the tooling and pattern related areas, equating to 29.5% of all additive manufactured parts in 2005. As the additive manufacturing industry has grown, more and more service providers are using this technology for the production of finished products vs. prototypes. The term Rapid Manufacturing or Digital Manufacturing is now a standard topic among service providers within the industry. Rapid Manufacturing is defined as the direct production of finished goods from an additive manufacturing process. Rapid manufacturing has continued to grow since 2003 and represented 9.6% of the additive manufacturing market at the end of 2005.

There are many positive and exciting examples where production of finished goods are meeting customer needs and replacing historical methods of production. The choice of which parts can and should be made utilizing additive manufacturing is endless. As this new approach takes hold many parts that have been identified as complex in nature suddenly fit well into the additive manufacturing process. For service providers who deal with the aerospace and medical industries, the question is not can a part be made using additive technologies, but rather can it be made to production and quality expectations.

2. MAIN OBSTACLES TO HIGH VOLUME ADDITIVE MANUFACTURED PRODUCTION PARTS

Additive manufacturing equipment capabilities vary based on supplier, type of machine (plastics or metals) and actual materials used (17-4 stainless vs. CoCr). Speed and productivity continue to improve at an accelerated pace. Most platforms are small in scale today but as industry demand grows, technical improvements will be made to enable higher and higher volumes of production parts. The higher volume production issue does not lie in the technology but in areas surrounding the technology.

2.1. Manufacturing vs. prototyping culture

The first obstacle to overcome is the difference between a prototyping culture vs. a manufacturing culture. My thirteen-year career at Procter & Gamble allowed me the opportunity to work in the engineering, prototyping, and manufacturing functions. I had the unique opportunity to design, assemble, install start-up and qualify converting equipment across North America, Europe and Asia. Over a ten-year period I had the responsibility to make prototype products on a production converter along with running production product on a prototyping converter. Theoretically this was the same equipment, materials and processes used in both cases. The end result was successful but not optimal for business success.

Prototype products were used for new product and/or process development. The volumes of products produced were low; sometimes only a few cases at a time. The goal was to develop several iterations of products across multiple designs, batches of materials and process settings. Production products were ones that had a defined bill of material, a qualified material supply chain, quality specifications, sales plans and distribution plans. Production products were to be run on either existing manufacturing platforms or new platforms that would be installed and started up in locations around the globe. The volume of cases for a production converter would be in the hundreds of thousands of cases during a normal year.

The main barrier between these two converting methodologies was cultural in nature. Prototyping engineers and technicians were rewarded for utilizing equipment, materials and people to get the process to run. The goal was not to run efficiently but rather produce a product for customer or consumer testing. This culture would be defined as a "**make it run**" culture.

Manufacturing resources were rewarded for utilizing standard equipment across multiple converting platforms and run as many good quality cases as possible. This culture would be defined as "**make it run profitably**". This included on-going gains in efficiency, reduction of scrap, and the continual improvement of finished product quality.

Both cultures are critical to developing and distributing products that exceed customer expectations. The point of this industry comparison is that it directly relates to prototyping and production cultures that will exist within the additive manufacturing environment. For service providers to be successful in higher volume production parts there will need to be a separation of rapid prototyping functions from their rapid manufacturing functions. The two are inherently in conflict with each other.

2.2. International standards - ISO

The second obstacle will relate to the integration of additive manufacturing equipment and processes with international standards. As companies move from additive prototyping into additive manufacturing, one of the first technical barriers to success is the expectation of their customer base relating to production quality systems. For this paper we will look at one standard in particular within the aerospace industry; AS9100.

Figure 3.0 below represents the Plan-Do-Check-Act process based approach that is mandated by the AS9100 standard. The objective of this standard is to assure customer satisfaction by continually improving safe and reliable products that not only meet or exceed customer expectations but also regulatory requirements.

The AS9100 standard provides additional requirements within the aerospace industry that must be addressed when implementing an ISO 9001:2000 quality system. There are approximately 100 additional elements incorporated from the base ISO 9001:2000 quality system. Some of the elements represent a specific challenge for new additive manufacturing equipment and processes.

The following is an excerpt from an interview with Robin Byers, ISO Consultant, Pleiades International, Inc.

Curt Taylor "What are the main barriers to ISO AS9100 integration and new technologies like additive manufacturing?"

Robin Byers "Probably the greatest barrier is the 7.5.1.3 requirement to control and validate the production equipment, tools and programs prior to production. Many companies fail to properly validate and determine the true capability of the processes."

Curt Taylor "What are the biggest areas to overcome within the standard relating to additive manufacturing / production?"

SAE AS9100 Revision B

The model of a process-based quality management system shown in Figure 1 illustrates the process linkages presented in clauses 4 to 8. This illustration shows that customers play a significant role in defining requirements as inputs. Monitoring of customer satisfaction requires the evaluation of information relating to customer perception as to whether the organization has met the customer requirements. The model shown in Figure 1 covers all the requirements of this International Standard, but does not show processes at a detailed level.

NOTE: In addition, the methodology known as "Plan-Do-Check-Act" (PDCA) can be applied to all processes. PDCA can be briefly described as follows.

Plan: establish the objectives and processes necessary to deliver results in accordance with customer requirements and the organization's policies.

Do: implement the processes.

Check: monitor and measure processes and product against policies, objectives and requirements for the product and report the results.

Act: take actions to continually improve process performance.

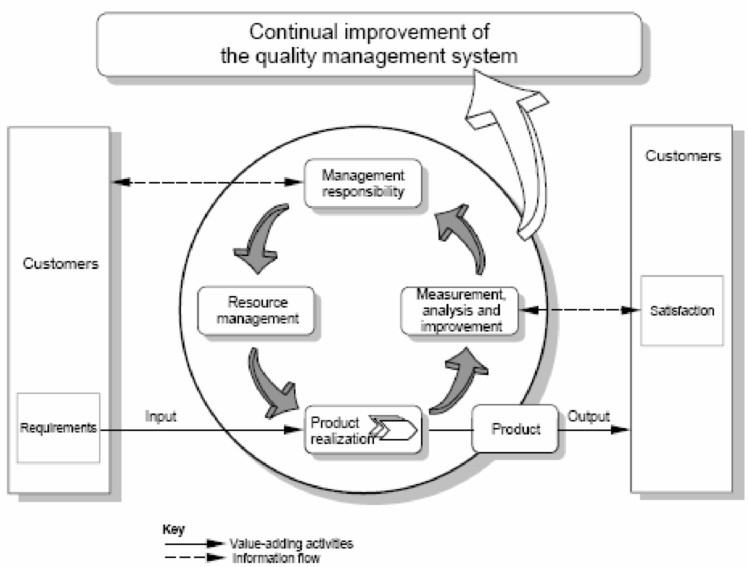

FIGURE 1 - Model of a Process-Based Quality Management System

Figure 3.0 – Model of a process-based quality management system

Robin Byers "The most important barrier to overcome is the development of an effective document control system that encompasses total control of internal and external documents. The complete system also would properly track the interactions of the documented systems to assure long-term compliance and stability. Clearly section 4.3 Configuration Management and the associated ISO 10007 will be a challenge with new technologies like additive manufacturing equipment and processes."

Curt Taylor "What is the best approach for additive manufacturing entrepreneurs to take when adapting AS9100 to their start-ups?"

Robin Byers "All too often companies create systems and methods that provide little or no return-on-investment. They simply create and implement systems based on their interpretation, training and focus on the standard vs. creating and implementing a system that focuses on what is best for the business while using the standard as a foundational guide. They must change the focus more to their business, and less to the standard. Once they have properly created their business system, using the standard as a guide, they will comply with the standard."

The end result is that new companies looking to take additive manufacturing technologies to the obvious next level of production will have their work cut out for them. The next section of this paper identifies some, but not all of, the production system work that additive manufacturing companies will have to address prior to high volume production of parts.

2.3. Manufacturing processes / production methodologies

The third obstacle to higher volume production parts deals with process and production methodologies. Additive manufacturing technologies consist of a variety of processes that flow together in the production of quality products. Repeatability within the system will be critical to ensure customer satisfaction on-going. The process with additive manufacturing will consist of materials, machines, methods and the human factor. Each of these areas will first need detailed definition of all inputs and outputs for each style of equipment that is used within an additive manufacturing company. Materials will need to be managed including inventory, batch and lot verification along with certifications and internal quality sampling. Machines will need definition of critical operating parameters including SPC methods used to ensure they are operating within specification. Methods will have to be developed and optimized to ensure that individuals are using best-in-class procedures. The human factor will include training and the development of competitive intelligence for each style of machine used in the production environment.

From the interview in section 2.2 above we found that the first priority with AS9100 relating to additive manufacturing will be section 7.5.1.3 - control of production equipment. In reviewing figure 4.0 below, you can see how the standard references historical methods of production to include CNC and programs relating to such equipment.

7.5.1.3 Control of Production Equipment, Tools and Numerical Control (NC) Machine Programs: Production equipment, tools and programs shall be validated prior to use and maintained and inspected periodically according to documented procedures. Validation prior to production use shall include verification of the first article produced to the design data/specification.

Figure 4.0 – Section 7.5.1.3 of ISO AS9100 standard

Additive manufacturing service providers to the aerospace industry will be required to develop new methods of validation based on the equipment they are using. This will require a strong manufacturing relationship between equipment developer and service providers. Identifying process, material and control parameters will be critical. Additive manufacturing service providers will initially validate their process internally in an attempt to meet the mandate of the standard. Those that work hand in hand with equipment developers in this process will have a much better chance of ensuring the validity of the final product.

The second priority that was discussed in the interview in section 2.2 related to configuration management. For the world of digital manufacturing, solid models are modified through several stages of the process and it will be critical to have a solid ERP system for version management. Materialise is beginning beta testing on one such application called Magics e-RP. As you can see in Figure 5.0 below, the approach that Materialise is taking is to integrate Magics e-RP into a company's current ERP system in an effort to support a digital production environment. The objective of the application is to create a planning system for the rapid prototyping and manufacturing industry, provide a technical framework for automating productions and helping work preparation and configuration management.

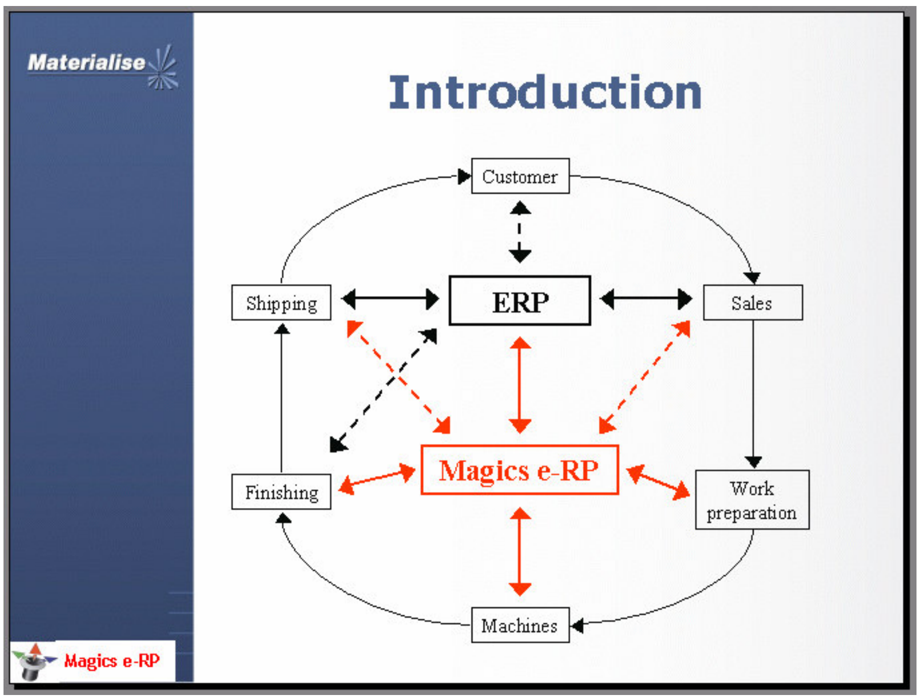

Figure 5.0 – Slide from Magics e-RP presentation

As you can see from Figure 6.0 below Magics e-RP takes additive manufacturing production planning to the next level by providing visualization techniques and customized data tables of variables key to managing a higher volume production environment.

In summary, these are just some of the main barriers to be overcome as additive manufacturing companies continue to evolve the way finished production parts are produced in the future.

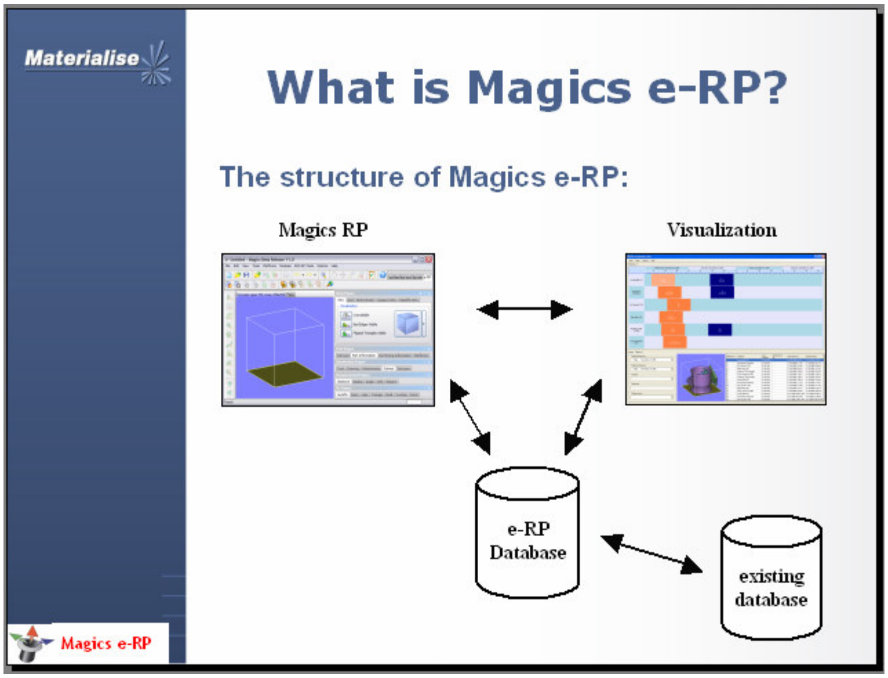

Figure 6.0 – Slide from Magics e-RP presentation

3. EDUCATIONAL PROCESS

3.1. Designing to the process

Each additive methodology has its individual challenges for how builds are set-up, produced and post processed. For instance, EOS has defined specific design parameters for Direct Metal Laser Sintering (DMLS). These "rules of thumb" are valuable for engineers and designers prior to solid models being finalized and used for finished part production.

Examples of DMLS areas of concern relate to the following:

1) Overall volume of part
2) Part overhangs
3) Hole placement and size
4) Final machining allowances
5) Overall data quality of the files used (STL, IGES, STEP)

Each service provider over time will develop competitive intelligence relating to more complex geometries. Examples of areas where competitive intelligence will play a major part in designing to the process will be:

1) Support structure design and application
2) Machining support services for post build processes (wire EDM, stress relieving, hole drilling, extrude honing, heat treating, polishing, etc.)

3.2. Educating customers

Over the past three years Morris Technologies (www.morristech.com) has worked closely with new and repeat customers using the DMLS process for tooling, prototypes and finished products. This collaboration between customer design and real life production of parts has generated a key knowledge base for MTI's customers. At the same time new customers benefit from these learnings in several ways early on in the process.

The primary benefits are:

1) Questioning why the part may be or may not be a good fit for the technology in a way that educates customers vs. challenging their current approach.
2) Explaining to the customer how the process benefits them vs. their current methodology. For example, based on customer priorities the finished part may be a good fit for prototyping but may not be better than current methodologies used today for production.
3) Where possible when a part does fit the additive manufacturing arena and can provide both a cost and schedule advantage, new design freedoms are released. Parts can be produced using the new additive manufacturing methodology while at the same time allowing engineers and designers future opportunities for version management (i.e. part 12345 revisions A, B, and C).

4. RAPID QUALITY MANUFACTURING, INC. CASE STUDY

4.1. A new company is born

Over the last three years Morris Technologies, Inc. has grown to be the industry leading service provider for Direct Metal Laser Sintering (DMLS). Morris Technologies purchased the first Electro Optical Systems (www.eos.info) M-250 series machine during the first quarter of 2003. This was the first M-250 machine in North America and fit nicely into the prototype offerings that Morris Technologies had at the time to include SLA, Urethanes, CNC Machining, and Injection Molding services. As with most DMLS service providers at that time, rapid tooling was the focus.

When EOS released the new M-270 series DMLS machine Morris Technologies was one of the first companies to begin utilizing the added benefits of this new machine that includes higher laser resolution, speed and material offerings. Morris Technologies has built a strong relationship with EOS and has been instrumental in the development of beta materials to include CoCr (Cobalt Chromium).

The added benefits of the M-270 system lead Morris Technologies into a new world of direct part production across multiple industries to include aerospace, medical, computer and electronics, automotive and consumer goods. Initially customer requests were directly related to prototype parts with unique geometries and small volumes. Once customers started realizing the improvements that could be achieved in cost and schedule vs. other current methods of production the obvious question was presented: "What if we wanted to ramp up into annual production volumes?"

During the summer of 2006, Morris Technologies realized the need for a production supply chain relating to DMLS. It would be the obvious evolution to the previous three years of work with rapid prototyping using DMLS. Rapid Quality Manufacturing, Inc. was born. Rapid Quality Manufacturing, Inc.'s goal would be simple: Create a new company solely focused on additive manufacturing of production quality parts using best-in-class practices.

4.2. Case study

Over the past ten months Rapid Quality Manufacturing, Inc. (RQM) has been developing the necessary business model to support higher volume production of additive manufactured parts. The company was incorporated in March 2007 and began operation in April 2007. The goal is simple: Where specific product lines of production quality parts can be produced more economically than current methods, RQM will develop the infrastructure necessary to support multiple industries toward best-in-class additive manufacturing standards.

Currently Morris Technologies, Inc. and Rapid Quality Manufacturing, Inc. are working with key customers on product lines that can and will fit a successful model of DMLS production. We are working closely with EOS in this effort and look forward to breaking down barriers to enable true high volume additive manufacturing of finished production parts.

RQM will initially focus on many of the barriers mentioned in this paper. These focus areas will include the following:

1) Utilizing an integrated process approach to SAE AS9100:B aerospace and ISO 13485 medical certifications.
2) Equipment and process validation to include all necessary support equipment and vendors. This will include Materials, Methods, Machines and Human processes.
3) Become a primary site for Magics e-RP software integration.
4) Work in collaboration with Morris Technologies, Inc. customers to identify best fit production product designs as they move from the prototyping stage of product development.
5) Continue to be an active leader within the industry by driving additive manufacturing concepts and methodologies.

In summary, the additive manufacturing industry is still in the early phases of development. The goal will be to capture learnings, grow additive manufacturing businesses and provide a new manufacturing platform for customers and end users. The production environment will require a new approach to ensure all quality expectations are met or exceeded. If successful, this will allow customers and end users that require complex parts the design freedoms to improve product costs, efficiencies and effectiveness today and into the future.

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