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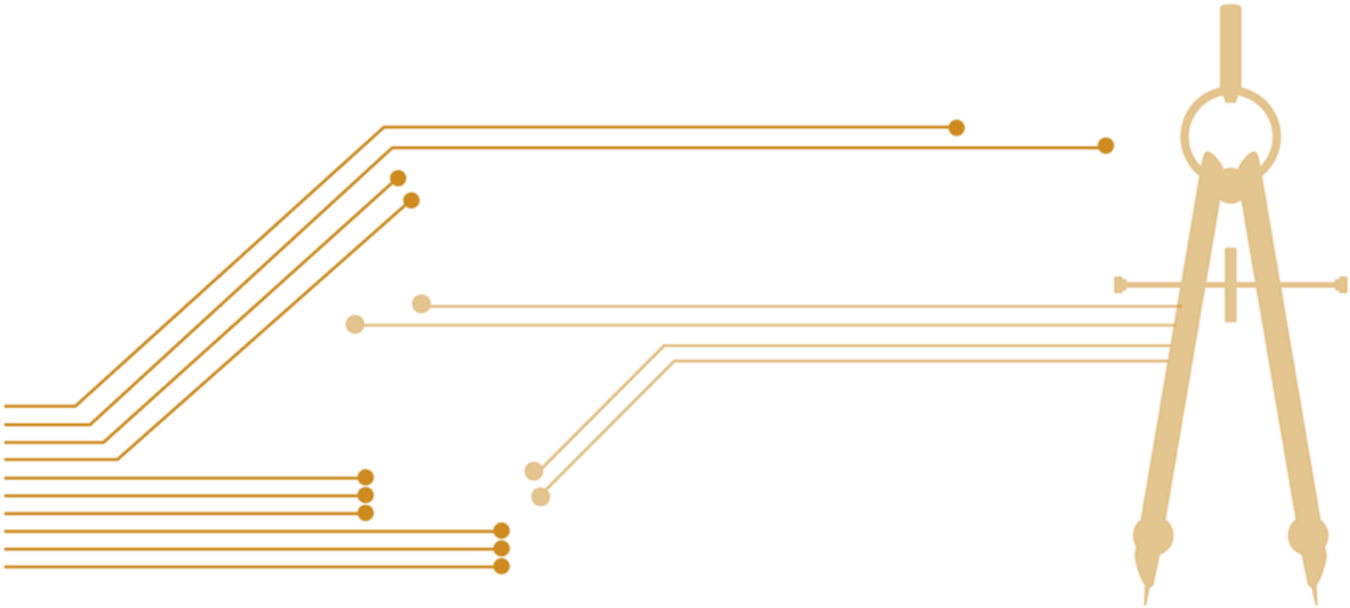

3D Printing Standards and Verification Services

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Abstract

The adoption of 3D printing, also commonly referred to as additive manufacturing, is occurring at a very rapid pace with a further projected growth of 45% compounded annual growth rate (CAGR) over the coming years. An important aspect of the widespread acceptance of industrial 3D printing has been an industry-wide focus on improving quality, reliability and repeatability of 3D printed parts. Industry stakeholders, including printer manufacturers and industrial end users of parts, have identified further quality assurance through internationally established standards, verification, and certification as essential to spur even more rapid technology adoption and implementation.

In this paper we begin by presenting the basics of 3D printing technology and then turn to explore the unique challenges that 3D printing poses with respect to ensuring the production of high quality parts. Additionally, we present an overview of the current stakeholders for 3D printed parts' quality standards and verification mechanisms. Lastly, we examine the current trends to lower costs for quality assurance of the burgeoning 3D printed parts market, which include systemic aggregation of quality assurance programs and new low cost measurement technologies.

Introduction: 3-D Printing Verification

Twenty years ago, 3D printing, also commonly referred to as additive manufacturing, was perceived as a futuristic technology; a novelty whose promise was decades away and though intriguing left too many gaps with respect to conventional manufacturing to be considered for widespread use. In the decades since, through refinement of techniques and the identification of new technologies, 3D printing has advanced significantly to the point that the incorporation of 3D-printed parts in high end industrial components is rapidly becoming commonplace.

Industrial adoption of 3D-printed parts is occurring at a very rapid pace with a further projected growth of 45% compounded annual growth rate (CAGR) over the coming years. An important aspect of this widespread acceptance has been an industry-wide focus on improving such parts' quality, reliability and repeatability. Industry stakeholders, including printer manufacturers and industrial end users of parts, have identified further quality assurance through internationally established standards, verification, and certification as essential to spur even more rapid technology adoption and implementation.

Quality assurance companies have created departments focused specifically on the 3D printing market. Moreover, several national and international consortia and government agencies have embarked on multi-year programs to define worldwide standards to ensure the quality of 3D printed parts. At the culmination of these programs, the consortium expects to make a worldwide presentation of detailed standards regarding the qualification and processing of materials, as well as new testing guidelines.

But the path to the full implementation of such standards is not a clear one. Based on the potential explosion in scale of new printing devices, printable materials, and printing applications, we anticipate a gap in the capability of the industry to enforce the new standards and continue to develop additional characterization methods in order to keep pace. With respect to the sheer size of the new market, we project that quality assurance aggregators will streamline testing and certification costs in the 3D printing industry as they have demonstrated in the conventional manufacturing space. With respect to new materials and characterization technologies, we predict that new technical solutions such as low cost dimensional measurement will be developed and proliferate through the marketplace.

I. The State of 3D Printing Technology

Thousands of 3D printers are available in the market today, and just about every other week a new model of 3D printer is introduced. The price of these printers ranges from a few hundred dollars at the entry-level, to the level of "sky-is-the-limit" (high-end, special size/materials). Printer manufacturers, software developers, service providers, and 3D printing users are rushing to the marketplace with new business models created daily. Some of the most important developments are highlighted in the following sections.

1.Types of 3D Printing Technologies

1.1.Materials and Printer types

A wide range of materials is available for 3D printing material. The most commonly used materials are the following:

Polylactic Acid (PLA): Easy for printing. Plant-derived and biodegradable. Available for various color and rigidness levels.

Nylon: Slippery and slightly pliable. Good for parts requiring low friction. Some take on dyes well, and can be particularly strong.

Acrylonitrile butadiene stryrene (ABS): The most common 3D printingplastics. Strong. Available in a variety of colors. Unpleasant odor during printing.

Stainless Steel: Typically infused with bronze. Cheapest form of metal printing. Very strong and suitable for significantly large objects.

Titanium Alloys: Powders are sintered together by laser to produce metal parts.

Similar to the wide range of materials available, there are a wide variety of printing technologies. In combination, the field of 3D printing has become diverse and interesting. The following are a few of the most successful current 3D printing technologies:

Selective Laser Sintering (SLS): Computer-controlled laser pulses down on the platform, tracing a cross-section of the object onto tiny particles of plastic, ceramic or glass. The laser heats the powder either to just below boiling point (sintering) or above boiling point (melting), which fuses the particles together into a solid form.

Fused Deposition Modeling (FDM): 3D prototypes are created by heating and extruding a filament of plastic material. The extrusion nozzle moves over the build platform, "drawing" a cross section of an object onto the platform. When this thin layer of plastic cools and hardens, it immediately binds to the layer beneath it. Once a layer is completed, the base is lowered slightly, making way to add the next layer of plastic.

PolyJet: Works by jetting photopolymer materials in ultra-thin layers (16μm) onto a build tray until the part is completed. Each photopolymer layer is cured by UV light immediately after it is jetted.

Stereolithography (SLA): Method based on the hardening of successive layers of fluid resin using UV rays or lasers. After each layer is fused, the perforated platform is lowered very slightly and another slice is traced out and hardened by the UV / laser. This process is repeated until a complete object has been printed.

1.2. Challenges with 3D printing materials

Despite the rapid advancement, 3D printing materials still face the following challenges:

Strength: 3D printed parts are not as strong as traditionally-manufactured parts. Their layer-by-layer technique of manufacturing is both their biggest strength and their greatest weakness. Metal printing very often uses powder metals, which contain oxides, which not only make the metal rust more easily, but also act like holes in Swiss cheese which weaken the final products.

Surface finish: 3-D printed objects generally have matte finish with rough layer lines all over. Although we can post-process parts to make the object's surface smooth, this generally involves labor and/or additional chemicals, and loses detail and tolerance on parts.

Energy inefficiency: According to research done by Loughborough University, melting or fusing 3D printing materials consumes about 50 to 100 times more electrical energy than injection molding, casting or machining in order to make an item of the same weight.

Reliance on plastics: Environmental movements in recent history have attempted to reduce reliance on plastics, from grocery bags to water bottles, and replace them with ones that can be made from recycled materials . The most popular—and cheapest—3D printers use plastic filament. If 3D printing becomes industrialized, disposal of this by-product will become a new environmental issue.

Safety concerns: 3D printer poses a serious health risk when used inside the home. The printers emit particles in great numbers and can cause serious health-related issues.

In particular, there are additional challenges for 3D printing metal materials. A clear example of this is the higher temperature level required to print metal objects, which in turn translates to even higher energy consumption and a higher manufacturing cost for 3D-printed products.

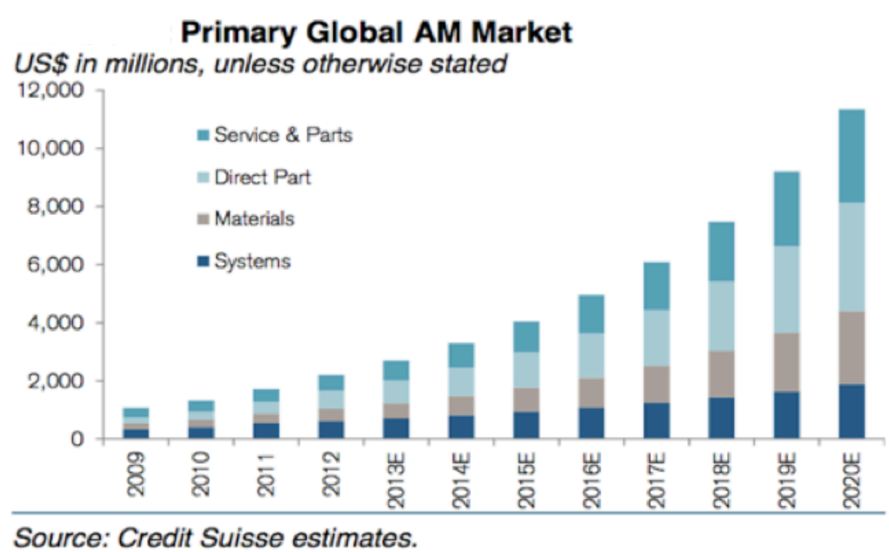

Figure 1: 3d Printing Market Forecast by Segments

2. 3D Printing Business Models

2.1 Major market trends

Industry analysts predict tremendous growth opportunities in the 3D printing business for the next few years. The trend is consistent across all 3D printing segments and regions, as indicated by Figure 1 and Figure 2.

2.2 Industrial 3-D Printing

Industrial 3-D printers generally have larger print throughput capacities, top-notch resolution and use significantly durable printing materials.

2.2.1 Major companies moving into industrial 3D Printing

Up to now, 3-D printing has been most useful in creating prototypes. But from the automotive to the electronics and toy industries, 3D printers will increasingly produce critical parts and finished products. For example, Bentley is one company that has already demonstrated the feasibility of using 3D printing for small, complex parts. Motorcyclists and bikers will also be able to order their own customized helmets that are printed to fit their individual head size and structure.

2.2.2 Why companies will choose industrial 3-D Printing

Industrial 3D printers are superior to consumer-grade 3D printers for manufacturing fully-functioning quality prototypes. As mentioned before, the best industrial 3D printers have large print capacities, top-notch resolution and use extremely durable materials. These printers make manufacturing a much simpler process for individual users and companies.

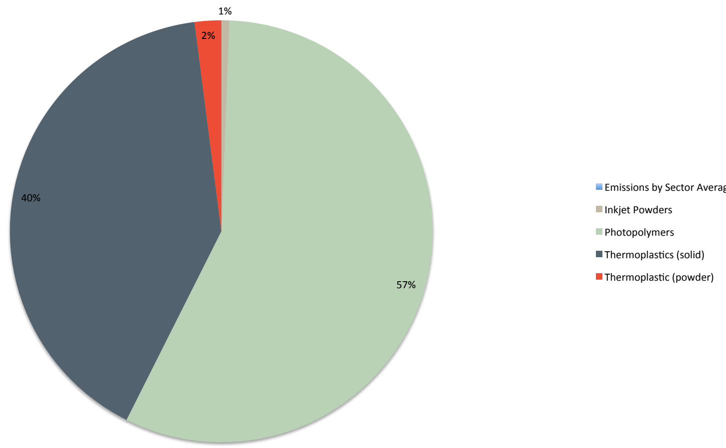

Figure 2: The Current Breakdown of 3D Printing Materials Market

2.3 3-D Printers for small business and Home Use

Everyone who is looking at how 3-D printing affects small business and home users feels pretty certain it is going to have a large impact. However, the magnitude of disruption is uncertain. For now, early-adopting small business owners tend to use 3D printing for prototyping, creating replacement and intricate parts, and for making customized gifts. The barrier to more widespread use of the printers is not cost—the cheapest 3D printers will drop from $1,000 to $100 within the next few years—but technical know-how.

2.4 Printing Services

Instead of owning a 3D printer and self-printing objects, there are advantages to outsourcing 3D printing services instead. In addition to lowering the cost, these service providers take the hassle out of setting up, testing, and operating a 3-D printer by providing:

Design: Concept to 3D modeling
Manufacture: Quality, Volume and Materials
Sales of printers and supplies
Equipment Service and Consulting
Marketplace for 3D printing products

Providers of such services include: Shapeways, i.Materialise, Ponoko, RedEye, Sculpteo. The advantages and disadvantages for 3-D printing outsourcing to an external provider are the following:

Advantages
- Cost of owning 3D printers
- Design Services: for customers without CAD experience
- Quality: Special printer capabilities
- Volume: Larger quantities
- Materials: Special materials

Disadvantages
- Iterations can be slow and expensive

II. Methods of 3D printing standards and verification

All the major stakeholders in 3D printing commerce recognize the need for well-defined standards, verification and certification mechanisms. Printer and material manufacturers seek to differentiate their products based on their ability to print high-quality parts. These manufacturers research and report on the capabilities of their printers and materials. However, the definition of "high quality" must be universally defined and accepted by the industry. National and international quality consortia and government agencies have traditionally held the role of defining objective, repeatable, and enforceable standards in the manufacturing industry as a whole. These consortia are, generally speaking, public-private organizations that convene to define common standards for materials, materials testing, and dimensional analysis.

1. Role of consortia

1.1 Major Consortia Players

The types of consortia and government agencies associated with 3D printing standards and verification can be loosely grouped into two categories. Firstly, there is a traditional manufacturing standard-and-testing consortia as well as government agencies that have created subgroups to specifically address the unique challenges of 3D printing. Secondly, there are 3D printing industry and printing users consortia.

The foremost of the traditional manufacturing standards consortia to establish standards in additive manufacturing is the American Society of Testing and Materials (ASTM) which formed a technical committee (ASTM F42) for additive manufacturing in 2009. ASTM F42 convenes bi-annually with participation of approximately 70 of its 215 members. The organization lists its scope as "The promotion of knowledge, stimulation of research and implementation of technology through the development of standards for additive manufacturing technologies." Moreover, it states that the work of the organization "will be coordinated with other ASTM technical committees and other national and international organizations having mutual or related interests."

ASTM's international counterpart, the International Organization for Standards (ISO) also established a technical committee (TC261) for additive manufacturing in 2011. Nineteen participating countries are currently listed as ISO TC 261 members. The scope of the technical committee is defined as "Standardization in the field of Additive Manufacturing (AM) concerning their processes, terms and definitions, process chains (Hard- and Software), test procedures, quality parameters, supply agreements and all kind of fundamentals." In November of 2013, ISO and ASTM published a joint plan to unify ASTM and ISO additive manufacturing standards. ASTM's analysis of the structure of required standards is presented in Figure 3.

Other major consortia with committees and activities related to additive manufacturing include the American Society of Mechanical Engineers (ASME), the Society of Materials Engineering (SME), the Society of Automotive Engineers (SAE), and the American Society of Precision Engineering (ASPE).

Consortia specializing in the development of the 3D printing industry as a whole as well as those including standards as a primary focus include the Additive Manufacturing Users' Group (AMUG), America Makes (The National Additive Manufacturing Innovation Institute), and the Additive Manufacturing Consortium (AMC), and a European consortium, the Support Action for Standardization in Additive Manufacturing (SASAM).

1.2 Details of when Agencies will Release Standards

Two U.S. governmental organizations worth noting for establishing 3D printing verification standards

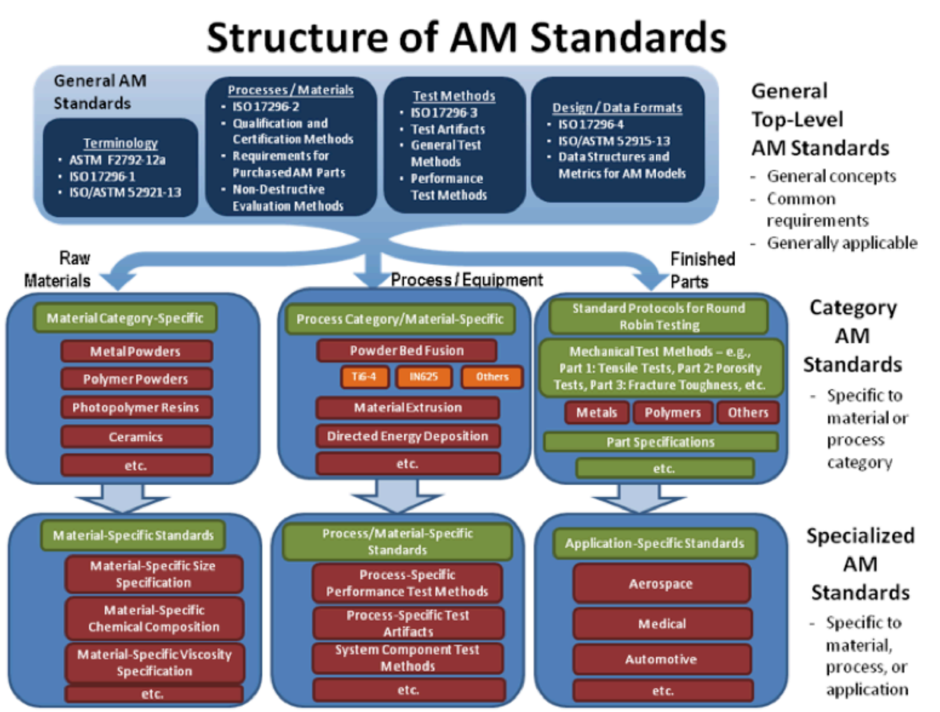

Figure 3: Structure of AM Standards

and techniques include the National Institute of Standards and Testing (NIST), and Oak Ridge National Laboratory (ORNL). A sample test artifact is shown in Figure 4. NIST's Measurement Science Roadmap is presented in Figure 5.

The ORNL contribution to additive manufacturing as a whole is broader in scope than that of NIST. ORNL has partnered with America Makes and AMC to host additive manufacturing conferences and has also participated in projects to demonstrate advanced 3D printing techniques, such as printing a Shelby Cobra for the Detroit Auto Show in January of 2015. With respect to additive manufacturing verification, ORNL has a specialized metrology initiative using neutron characterization techniques to measure geometric tolerances and map residual stress in 3D printed components.

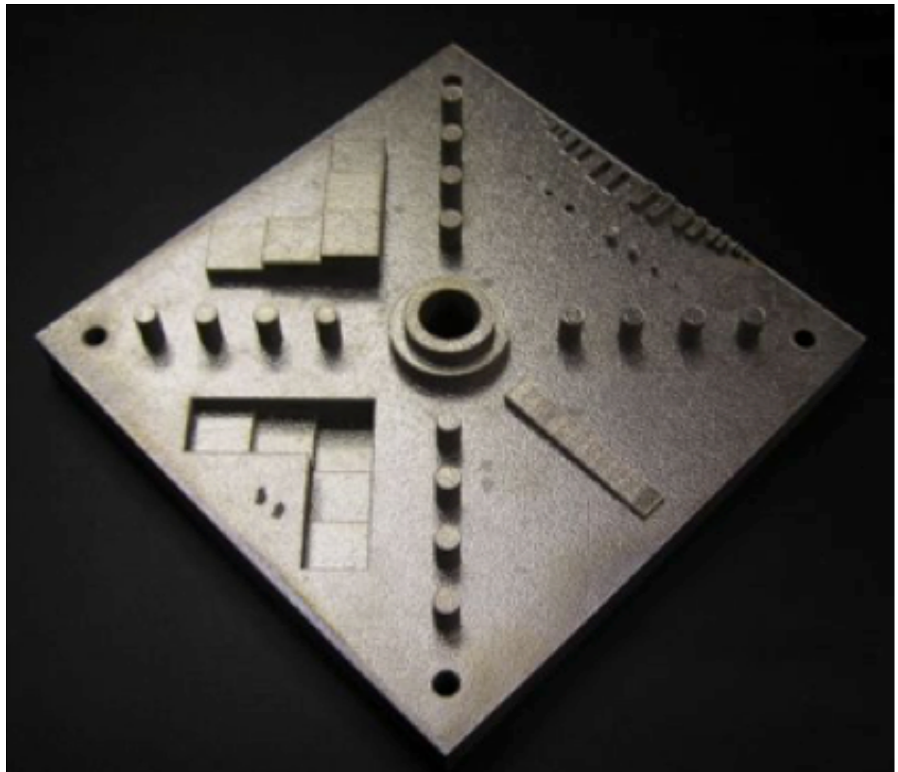

Figure 4: NIST Test Artifact

1.3 Role of Non-profits and Universities

Several universities have research programs in additive manufacturing which include elements of 3D printing verification. Some notable examples include an America Makes sponsored project involving North Carolina State University, Iowa State University and several corporate sponsors "to create a system that will be able to produce a mechanical product to final geometric specification".

Another university based effort is the

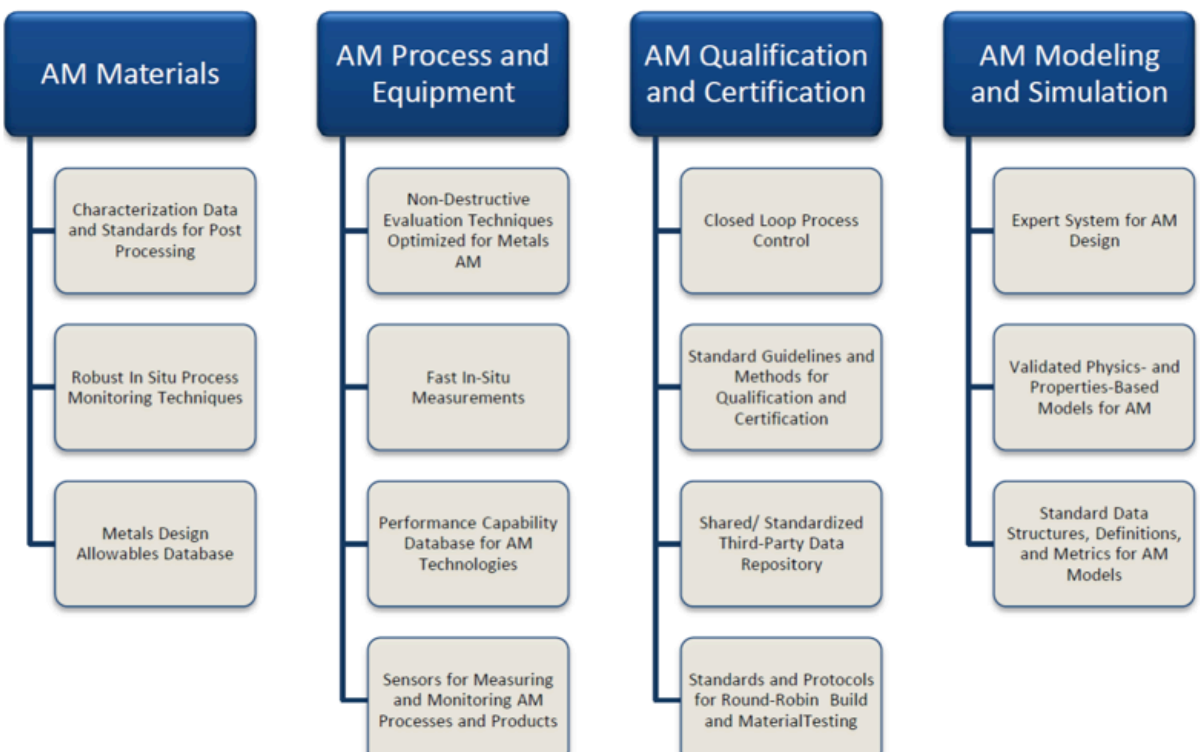

Figure 5: NIST Measurement Science Roadmap Manufacturing Report

Rapid Prototype Consortium (RPC) of the Milwaukee School of Engineering (MSOE). The MSOE also partners with America Makes and SME to offer a certificate in Additive Manufacturing through which practitioners can become certified by passing an exam on the collective "body of knowledge" of additive manufacturing.

There are also other emerging programs in 3D-printing user certification; for example, NYU's School of Professional Studies offers certificate programs in 3D Modeling and Printing, as well as 3D Design and Fabrication.

2. Role of Manufacturers in standards and verification

2.1 Manufacturers Internal Quality

While 3D printer manufacturers and service providers are certainly highly active participants in the previously mentioned consortia, they also seek to define and differentiate their product offerings based on their ability to print high quality parts on a more fundamental level. For example, Stratasys, a leader in Fused Deposition Modeling (FDM) of thermoplastics, has published a white paper available for download on their website entitled "The Accuracy Myth" authored by Bonnie Meyer (Figure 6), addressing a quality emphasis on dimensional accuracy and repeatability. The purpose of the white paper is to establish the long term dimensional stability of FDM printed parts manufactured on a Stratasys printer while assuring the end user of the capability of Stratasys materials and printers.

2.2 Manufacturers Partnerships

Major 3D printer manufacturers have also embarked on partnerships with their industrial customers. One notable example is the partnership between EOS GmBH, the industry leader in printer manufacturing for laser sintering of metal alloys, and MTU Aero Engines, a German aerospace engine manufacturer. In January of 2015, EOS and MTU announced their plans to integrate an MTU-developed metrology technology described as "Optical Tomography" on EOS systems to monitor laser energy and material sintering properties in real time to help ensure material quality and integrity.

3. Ranking and Crowdsourced Quality

At the lower end of the 3D printing quality and service spectrum are efforts of printing services to crowdsource quality control through user assessment and feedback. An example of this method is the design ranking feature of the Shapeways 3D printing service. Regulation of quality with respect to design integrity is done by labeling product designs as "Never Printed Before", "First to Try"", "Below 50% - Not Printable", "50-80% - First To Try", and "80% and above". One may make note of the fact that a design can be rated as "Product" quality despite the one in five chance that it might not print.

3.1 User-Generated Quality Standards

Another example of crowdsourced quality includes a user-generated database in the "3D Printing Tests" section on MarkerBot's Thingverse website. Through this database, users generate and share their own quality test structures and describe in detail the parameters employed to print the object. In the representative sample in Figure 6 the user updated a test printing file and a picture of the final result as well as detailed instructions regarding the machine printing speed used. The purpose of this test fixture is to demonstrate the finish and resolution of the MakerBot Ultimaker 2 as a function of printing speed and temperature.

III. Market Opportunities

1.Established Quality Companies

Currently there are companies and non-profit organizations which offer standard compliance auditing and

Width Nominal (3.000", 76.2 mm)	Apr-2008 Actual	Aug-2011 Actual	Change over time
Sample 1	2.997"	2.997"	0.000" (0.00 mm)
Sample 2	3.001"	3.000"	-0.001" (0.03 mm)
Sample 3	2.999"	2.998"	-0.001" (0.03 mm)
Average	2.999"	2.998"	-0.001" (0.03 mm)

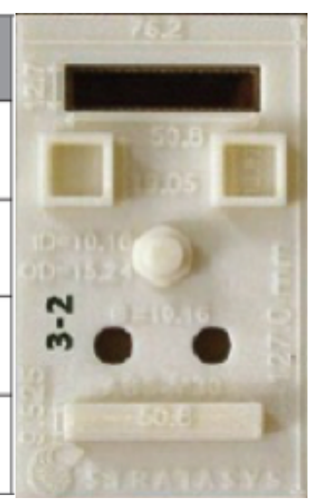

Figure 6: "The Accuracy Myth" by Bonnie Meyer

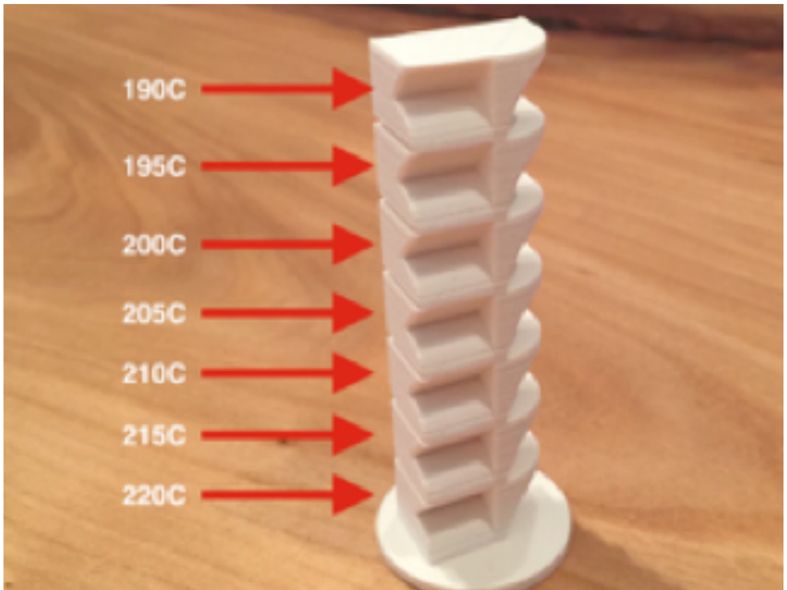

Figure 7: MakerBot Ultimaker 2, Temperature Torture Calibration Test by Bjorn

safety certification, and coordinate standards across multiple OEMs. Such companies include the Underwriter's Laboratory (UL), Sigma Labs, Intertek, American Association for Laboratory Accreditation (A2AL), and the Performance Review Institute (PRI).

For example, UL provides product review, compliance services and certification in the additive manufacturing (3D printing) space. This services include addressing equipment and materials compliance, as well as providing printed parts and product validation for the medical, automotive, building materials, jewelry, household products, and electronics industries.

An emerging trend is the consolidation of partnerships at the high-end 3D printing space, where there is a price premium and requirement for quality, which ultimately validates the need for the services outlined above. For example, GE awarded $500,000 to Sigma Labs, which announced the PrintRite3D software/hardware system in 2012 to ensure higher quality 3D printing of metal parts for critical applications. Another example is EOS partners, partnering with MTU, whose Optical Tomography (OT) augments the monitoring capabilities by using multiple sensors to verify system status, and camera based OT technology to control the exposure processes. Those in turn ensure the material quality and finish.

1.2 Role of Quality aggregators – web based market efficiencies

Outside the high-end 3D printing market where quality standards must be met, another emerging trend is the emergence of web based aggregators which reduce qualification costs while maintaining quality standards. Such aggregators include the Interlink program by Intertek , Net-inspect, and PRI's Nadcap and MedAccred programs. These service providers act as clearinghouses to link certified parts manufactures to commercial-end customers. This type of service could easily extend to encompass 3D printed parts. For example, MedAccred, destined for medical application parts, could include a 3-D printed knee replacement component.

1.3 Software Verification and certification by S/W vendors

Effective software algorithms reduce 3D printing time and waste, such as comparison of 3D geometric data and validation of translated models. The typical considerations include: (a) correctly define printer boundary conditions and nozzle diameter of the 3D printer, (b) manually define additional needed features, such as support structures to properly construct the printed parts, (c) define the position of normal vectors of the meshes in the .stl file, and (d) ensure that the 3D surface should be closed. In addition, the software algorithm should be able to highlight the problem area for the users and suggest corrective action.

For users who don't want to use professional 3D software, .stl files can be downloaded from a 3D database, such as Thingiverse, GrabCAD, Ponoko or Nervous System. Those designs can then be customized using a WebGL-based 3D modeling tool. For in-browser 3D modeling environments, controllers such as "Leonar3Do" by Leopoly, can help the user navigate and work in a 3D virtual reality space.

When the 3D model is finished, it can be verified before printing using Netfabb for mesh repair function, Willlt3DPrint, or Blender. After verification, the model is sliced to generate a G-code which defines the tool path for the extruder head of the 3D printer firmware. Codes for the 3D printer head movements follow a NIST G-code standard.

2. Emerging Tech opportunities

2.1 3-D Scanning and Imaging

3D scanners analyze a real-world object to collect data and then construct 3D models, using optical technologies, tomography scanning, contact mode or non-contact mode scanning. A coordinate measuring machine (CCM) is an example of a high precision contact mode scanner, frequently used in manufacturing. Non-contact active scanners emit radiation or light, ultrasound, or X-rays. For example, a 3D laser scanner is an active scanner using laser light to probe the subject using the time-of-flight laser range. A triangulation-based 3D laser scanner shines a laser on the subject, and exploits a camera to look for the location of the laser dot. Conoscopic holography measures distance by using the polarization property of the converging light cone that reflects from an object.

Additional 3D scanning techniques include computed tomography (CT), which generates a large series of 2D X-ray images. It produces a discrete 3D volumetric representation and corresponding 3D surface.

2.2 Lower cost coordinate measurements

Low cost digital metrology is becoming available which will enable a wider usage of 3D printing. Examples include the iSense 3D Scanner for Apple's iPAD and Mac products, RealSense 3D Camera for Intel's tablets/phones, and HP Sprout computers.

The iSense 3D scanner is integrated with companies such as Cubify.com to accompany their 3D printers. Those 3D scans can be uploaded directly for 3D printing either at home or through cloud printing. Intel's RealSense is an integrated 3D camera which tracks points of a moving object to form 3D images. The scan can then be saved and shared digitally, or printed with the use of 3D printer. HP's Sprout Computer uses DLP Projector technology and Intel's RealSense 3D camera to capture a 2D or 3D object.

2.3 Lower cost materials characterization

The steps of the 3D printing process involve thermal treatment in order to connect extruded printing materials between and within layers. Such thermal treatment modifies the material properties, which can lead to enhanced or reduced reliability of the parts or products. The reliability SPEC is based on specific applications. Since the process flow is different from "subtractive manufacturing", the requirement of specification needs to be studied in detail when those 3D printed parts are used for critical applications, such as high performance mechanical applications or medical devices.

For example, when a printed part is used in a highly mechanically stressful application, the tensile and fatigue behaviors must be studied. Often parts for those applications are made of alloys, whose material phases can easily be modified during thermal processes, and need to be analyzed using X-ray diffraction or Cross-section electron microscopies to control and ensure the end-product reliability.

Those material analysis instruments are expensive and not available to most of the machinery part manufacturers. Thus, as commercial applications continue to grow, we envision an increasing need of such high-end qualification services. This can lead to additional aggregation to reduce the characterization cost, and opens the possibility for the generation of new business models and partnerships.

2.4 Self-verification and reporting service

Web-based 3D printing services, such as "crowdsourced reviews and ranking", provide useful resources for user communities regarding the designs, printers, and material selection, as well as information about ranks designers and companies providing general 3D printing services.

For example, Shapeways is an internet-based market place of 3D printing services and reviews (http://www.shapeways.com/). Other similar web based marketplace and review forums include Ponoko (http://www.shapeways.com/), Sculpteo (http://www.sculpteo.com/en/), and iMaterialise (http://i.materialise.com/).

Additionally, for the medium to low-end 3D printing applications where quantitative validation and certification are not required, those "crowdsourced reviews and ranking" websites are effective alternatives for product validation.

Conclusion

The 3D printing market is rapidly expanding and gaining widespread acceptance for industrial applications. Ensuring the manufacturing of high quality, highly repeatable parts through standards and verification is an essential element for speeding the further adoption of the new technology. Multiple stakeholders are currently addressing the needs for quality assurance with expected completion of the most detailed and stringent international quality standards due in 2018. In the meantime, new technologies may emerge that will require further characterization. Also, due to the high cost of existing characterization techniques and the potential scale of the new market, improvements are needed to reduce the cost of quality assurance programs as well as create new lower cost characterization methods.

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