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Using Measurement Science to Drive Design Guide Development for Additive Manufacturing

It is clear that for the US Army to utilize Additive Manufacturing (AM), concise design guides must be developed.

Successful design guides, such as the AWS D1.1 for Welding, require measurement science in the areas of machine parameters and feedback, surface preparation, filler metal composition and joint configurations.

Thus, for Additive Manufacturing, it is our position that measurement sciences are needed in the areas of:

> Part Support Protocol, Powder Properties (Composition, Size, Morphology), Build Environment (Temperature, Atmosphere, Sensor Feedback), Recoater Blades (Type, Amount of Wear), Build Plate (Material), Part Positioning, Part Removal, Beam Focus, Filters (Amount of clogging), Final Part Dimensions & Roughness (and the correlation to the original 3-D model), Machine Software & Design Software.

Once the part is produced with a known set of parameters, the challenge is to define the mechanical & metallurgical properties to be measured and ensure part-to-part and machine-to-machine consistency.

In developing a design guide, many of the items listed above merely need to be recorded so that lessons can be learned for future builds (i.e., Part support protocol, build plate material, part positioning, design software used). Other items need to be measured in a more quantifiable way that NIST may already have experience with (i.e., Final dimensions and roughness, amount of clogging on the filters, amount of wear on the recoater blade). Finally, new sensors need to be developed/enhanced to provide real-time feedback on the build environment and the beam focus to ensure consistent part quality.

Thus, a combination of generally accepted practices, standard measurement techniques and sensor development is needed to ensure the continued improvement of additive manufacturing. With improvements to AM, the industry and government will finally achieve a provisional design guide at the very least.

Maas and Blacker, The Ex One Company, LLC

Input provided by Dan Maas and Jesse Blacker
The Ex One Company, LLC. November 16, 2012

1. What are the key measurement science barriers that prevent innovation in metal-based AM?

   Dynamic Measurements and Control:
   - In-process, real-time sensing and control
   - Real-time model-based feed-forward control
   - Transient changes in process characteristics with real-time dynamic feedback
   - Process mapping – both for control and for process learning

   Scale:
   - Nano/micro/millimeter AM for metals and metal/ceramics
   - Large scale (measured in meters) AM machines and equipment

   Material Composition (not just metals):
   - Functionally gradient materials, metal matrix composites, ceramic / metal mixtures
   - Embedded nano-particle / nano-fiber structures

   Environmental Impact:
   - Temperature, humidity and dew point
   - Re-use, recycle, ratios of virgin to re-used
   - Thermal cycling, oxidation, atmospheres

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

   Atomic-scale to meso-scale modeling and simulations:
   - An integrated modeling platform addressing atomistic-informed meso-scale modeling has applications for functionally gradient materials, ceramic / metal interface structures, metal matrix composites, etc.
     - "Atomistic-informed meso-scale modeling: Interfaces and their interactions with defects influence a wide range of behaviors from crystal reorientation, slip, twinning, boundary sliding, migration, phase stability, etc. Little of this can be predicted by treating only one type of defect/interface interaction alone. Models are packed with information. For one model to 'inform' another means that the transfer of knowledge of dominant mechanisms, phenomena, or physical properties, at the lower scale measurably transforms the way in which the higher scale is modeled and/or performs. In this regard, scientific expertise has to be exercised to determine what atomic scale information is useful and applicable to the rate conditions applied at the meso-scale." Irene J. Beyerlein, Office of Science, U.S. Department of Energy.
     - NIST has already started the Materials Genome Initiative (MGI) to develop a materials innovation infrastructure.

3. Some comments / suggestions for near-term consideration regarding the current Artifact Standard.

- Provide guidelines for the inspection methodology
    - Example: should the artifact sit upon 3 spheres to establish a plane?
    - Example: explain the purpose of the steps/incline/ramp
- Use the artifact to produce specimens for mechanical property testing
    - Provide guidelines for compression, tensile, fatigue, impact, etc.
- Consider several size artifacts for micro and meter size AM build boxes

Shane Collins, growit3d

Note: Included in this article is background information on powder bed fusion. The chart at the end lists what I believe are the necessary parameters that need to be measured and monitored for powder bed fusion. Standardization, measurement, and monitoring of these parameters are necessary for a robust powder bed fusion process.
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Laser and Electron Beam PBF

By Shane Collins

Powder bed fusion (PBF) is the ASTM accepted term for an additive manufacturing process where a point heat source selectively fuses or melts a region of a powder bed. In the United States, the metal powder bed fusion processes are know by the trade names SLM® and DMLS® for the laser beam process and EBM® for the electron beam processes. Curiously, there are no machines that perform the PBF process manufactured in the United States. That fact not withstanding, PBF has become a popular method of creating high value medical and aerospace prototype components as well as production components in safety critical applications. This article compares the electron beam and laser beam technology while taking a look at the practical aspects of the two systems for future PBF process development.

My first home computer was a 386 PC clone running windows 3.1. For the time it was pretty fast and had enough power to run my wife's CAD program, CADKEY. What made it fast for the time was the upgraded video bus from the normal ISA to the faster VESA local bus that moved data from the microprocessor back and forth to the video card. It was fast enough to run a 2D CAD program, but displaying video on the CRT was not possible. That was what TVs were for.

About that same time in my professional career I was involved in the digital imaging revolution that paved the way for image processing, calibrated measurements and digital image archiving. However, before digital cameras existed, digital imaging involved the acquisition of video signals where NTSC or PAL video was captured with a computer board called a frame grabber. The frame grabbers for the aforementioned 386 PC cost $12,000 to $20,000 because of buffering circuitry necessary for displaying the video on the computer's CRT. With the introduction of the 486 and the PCI bus the data transfer rate was significantly improved and uncompressed video signals were easily transferred to the video card for display on the CRT. The cost of the frame grabbers plunged to a few hundred dollars while the image capture quality greatly improved. The 486 PC computer with the speed of the PCI bus facilitated a revolution in video image capture and digital image analysis.

Fast forward to 2004 and a similar revolution can be seen in the field of metal laser sintering with the introduction of the solid state Yb doped fiber laser that replaced the ubiquitous CO2 lasers. The advantages of the fiber laser over the gas laser were low cost of ownership, better absorption due to the emission wavelength, continuous wave nature of the beam, and fine focus capability of 100µ and lower beam diameter. This intensity produced 25kW/mm^2 and allowed for 20µ powder layers to be completely melted several layers deep on each pass of the laser beam. The development and introduction of the fiber laser was an enabling technology for metal laser sintering and will be discussed in more detail, but first a look at the early years.

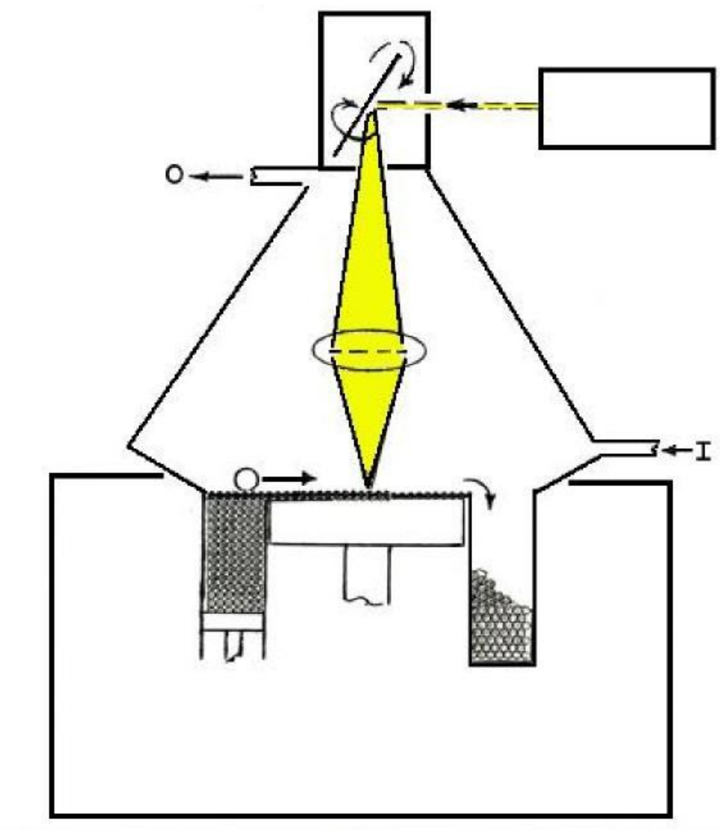
Laser beam PBF systems have their roots in the 1990s from technology developed and commercialized by the Fraunhofer Institute, Trumph, EOS, Concept Laser and Fockel and Schwartz, all from Germany. These early systems used gas or disk lasers and processed primarily bronze based composite materials. One of the first fully dense alloy (55% Au-28.5% Ag) systems was introduced by Bego at the 2003 IDS conference as a solution for making dental copings for porcelain fused to metal restorations. Shortly after the 2003 IDS, EOS and Sirona Medical Systems were working in a cooperation to commercialize the manufacture of fully dense CoCr dental materials using laser beam PBF. Due to the high cost of gold powder becoming entrapped inside the machines, it would be many years later that sealed machines would make gold alloy processing feasible, whereas lower cost CoCr (ASTM F75) processing found many applications in general industry and led to other alloy processing, including 316L and 17-4 stainless steels.

About the same time that laser beam PBF systems adopted the fiber laser and started processing true ISO and ASTM alloys, Arcam from Sweden was processing fully dense titanium components in their electron beam based PBF system. Although internal tests proved it possible to process most electrically conductive metal powders, Arcam concentrated on titanium, particularly Ti 6Al-4V.
Both the laser and electron beam systems have nearly a decade in manufacturing and marketing commercial systems. Today, there are about a half dozen companies selling laser beam based PBF machines with a world wide installed base of nearly 900 systems. Arcam is the only commercial electron beam based PBF system with an installed base of 100 systems world wide. So, in about the same amount of time there are multiple manufacturers of laser beam based systems with an installed base nearly 9 times greater than electron beam bases systems.

Having more manufacturers and significantly more machines installed, one might draw the conclusion that laser beam based systems are superior to electron beam based systems. If this is the case, what is it about laser beam based systems that make them highly accepted and what is it that makes electron beam based systems less prevalent? Although this article is not meant to be a feature by feature comparison, the fundamentals presented help to explain the current status.

Laser Beam System Overview

As previously discussed the laser beam based PBF systems use a fiber laser as the fusion heat source. The two manufacturers that supply fiber lasers to the laser beam PBF machine manufacturers are U.K. based SPI which was founded in 2003 and acquired by Trumph in 2008, and Oxford, MA, IPG who boast sales of more than 40,000 fiber lasers since 1990. The engines that power the laser beam PBF systems are supplied by competent companies that also supply lasers for laser drilling, laser ablation, laser cutting, laser marking, and laser cladding where PBF is a small percentage of their overall business.



Optical diagram of laser beam PBF system

Next to the heat source, the most important component of the laser beam PBF systems are the beam deflection optics that provide the scanning capability for selectively melting areas of the powder bed. With scan speeds up to 15 m/s, the scanning mirror must be fast, accurate and reliable. Most of the laser based PBF machine manufacturers use scanning optics from Scanlab of Germany. Scanlab manufactures a wide variety of 2D and 3D scanning systems for OEM applications including micro-machining, DNA Sequencing, laser cutting and additive manufacturing. Again, as in the fiber laser business, the PBF component of Scanlab's sales is small in comparison to the total market for these devices.

The final significant optical element is the correction lens that ensures the beam is round as it traverses the build platform and keeps the beam velocity proportional to the angular velocity of the scanning mirror. Most of the systems use the f-Theta lens design with anti-reflection coatings to help prevent damaging laser reflections back into the laser. There are a number of f-Theta lens manufacturers that sell off the shelf solutions as well as custom OEM applications. However, there appears to be a limit to the intensity of laser power that is possible when employing the f-Theta lens design. Somewhere in the 300W laser power range the f-Theta lens heats up and causes optical distortions as the lens changes temperature. In order to overcome this shortcoming and to meet the increased power needs of laser based PBF systems, Scanlab recently introduced varioSCAN focusing units that dynamically vary the focal length in conjunction with the scanning mirrors. With the varioSCAN units installed, f-Theta lenses are no longer needed and this optical layout supports 1 kW laser power as well as multiple laser inputs for increased scan speeds or multiple laser power modes. Another recent development with the scanning optics is the linear beam intensity profile. Unlike the typical Gaussian distribution beam profile where the beam intensity decreases from the beam center to the outside circumference, it is now possible to have a nearly equalized beam intensity across the entire profile. This has a profound affect on the overlap of the hatch spacing necessary to ensure fully melted surfaces. It is like the difference in mowing your lawn with a lawnmower having a blade that is all the same distance above the ground, versus mowing your lawn with a lawn mower where the blade curves up at the wheels. In the latter example it would be necessary to overlap your rows quite a bit to cut the grass all the same length, whereas in the former example the wheels only have to be overlapped to achieve the same length. The equalized beam intensity profile has the potential to improve surface finish, decrease scan time and reduce subsurface porosity when fully implemented.

To summarize the laser based PBF systems, the lasers and scanning optics are supplied by companies that manufacture many times more ship-sets than what are used for laser based PBF machines. This means the heart of the systems can be acquired with off the shelf items and to some degree the development of laser based PBF technology is paced by IPG, SPI and Scanlab. To be sure there is much more work to integrate the optics, electronics and electro-mechanical bits, not to mention the man-years in process development, but it is more execution rather than development.

Electron Beam System Overview

Powerful electron beams used for welding have their roots back in the late 1950s from the German physicist, Karl-Heinz Steingerwald. Today, two of the oldest electron beam welding machine manufacturers claim to have combined machine installations of over 1800 systems world wide. The main benefit to the electron beam over the laser beam in welding is in the higher beam energy density without affects due to reflectivity.

Arcam adapted the electron beam technology for freeform fabrication in 1997 with sights on building net shape plastic injection mold tooling using steel alloy powders. By 2003 Arcam had 4 electron beam PBF machines in house and another 4 machines at external installations. After a few years working with steel powders, Arcam turned their focus to titanium alloys and that remains their most widely usedalloy today, both internally and at user installations. Arcam currently supplies machines, materials and parameters for Ti CP, Ti 6Al-4V, Ti 6Al-4V ELI, and CoCr (ASTM F75), but electron beam PBF machine users have successfully processed many more alloys including high nickel and intermetallic compounds.

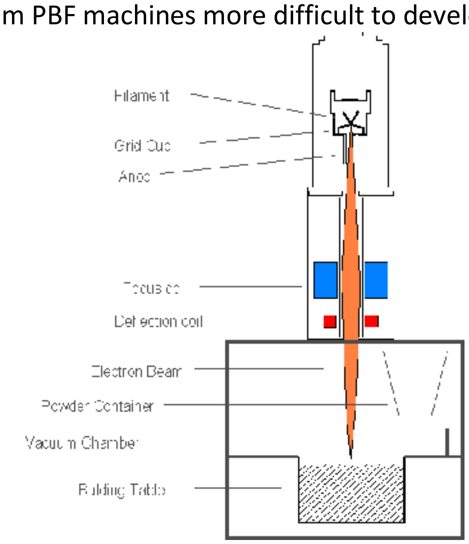
In the electron beam PBF system the electrons are generated from the filament and attracted toward a positively charged anode where a beam is formed. The focusing coil produces a converging, Gaussian beam and the deflection coil directs the scanning of the beam. The focusing and deflection coils are the electronic counterparts of the scanning and f-Theta optics of the laser beam systems. Since there are no moving parts in the electron beam PBF system, the scan speed can approach 3000m/sec (compared to 15m/sec with lasers) with usable beam power in the several kW range.

The physics of the electron beam interaction with the powder bed is complex. In addition to the kinetic energy from the electrons irradiating the surface, there are four other forces at play that have been modeled by Christian Eschey (Technische Universitaet Muenchen): pulse transmission, hermodynamics, electrostatics and electrodynamics. These forces can create unwanted consequences during the electron beam PBF process and are dependent on the powder morphology and chemical composition due to different electrical resistance from powder particle to powder particle. One such unwanted consequence is the powder’s propensity to disperse upon contact by the electron beam. Powder dispersion, aka “smoke” usually results in a total build failure.

As a means of mitigating the powder dispersion failure, Arcam learned to partially sinter the powder layer prior to selective melting. This caused the powder layer to adhere to the previous layer and also to itself, thus preventing powder dispersion. The elegant solution for the heat needed for sintering the powder came directly from the electron beam which was possible due to the high beam energy and fast scan speed.

Whether it was intentional or not the need to sinter the powder prior to selective melting meant the powder bed had to be heated to very high temperatures, approaching 650°C to 700°C for titanium and up to 1100°C for intermetallic compounds. This created a difficult operating environment for electro-mechanical components in the build chamber, but it had advantageous affects compared to a cold process on component microstructure and was self-annealing, which reduced the requirement for unwanted support contacts.

The electron beam PBF machines require a vacuum in the build chamber in order to have a focused beam. The added complexity from the vacuum pumps, chamber reinforcement and seals necessary to maintain $1X10^{-4}$ mbar vacuum add a level of machine integration difficulty not required for the laser based PBF systems. In addition to the vacuum requirement, the electron beam interaction with the powder makes the electron beam PBF machines more difficult to develop and optimize.



Electron Beam PBF diagram

Comparison between laser and electron beam PBF

Visual inspection of as built components made on the electron beam PBF machines shows a much rougher surface finish and less accuracy to the CAD model than components made with laser beam PBF machines. This is due to coarser powder, thicker layers and a larger melt pool in the electron beam PBF machines. There is nothing inherent with the electron beam technology that would prevent the same or better surface finish for the electron beam based system. It has been the historical implementation of the technology for freeform fabrication that created this disparity, specifically the trade off between build speed for surface finish.

However, surface finish alone is not a sufficient reason that in the same amount of time there are 9 times more laser beam based PBF systems installed as there are electron beam based PBF systems. Some of the difference can be attributed to the higher cost of the electron beam based machines and the marketing efforts of multiple laser beam machines, but the underlying advantage of the current state-of-the-art laser beam based PBF systems is higher levels of successful first-time component builds. This supports the job shop prototype business model, while having to build a component several times in order to dial-in the build parameters for success is relegated to the production business model. To date we are seeing more demand for prototype components than demand for production components and while the ratio of prototype to production components will likely shift to production in the coming years, much of the process development and certification work is currently being done on the laser beam systems.

Another contributor to the success of the laser beam based PBF machines is in the ability to routinely process many different alloys including maraging steel, high nickel super alloys, 316L, 17-4 and 15-5 stainless steel, CoCrMo and aluminum to name the most popular. Because of the complexity of the electron beam interaction with the powder surface and the need for high temperature processing, optimization of build parameters is tedious and time consuming on the electron beam PBF machines. A build failure entails a several hour cool down time followed by a lengthy restart process. Compare that to a build failure on a laser based PBF machine, where the operator immediately opens the chamber door, pounds down a high spot, for example, closes the chamber door, and restarts the build with modified parameters. The iterative process is much faster and allows a higher degree of experimentation by general users. On the electron beam PBF machine side, sophisticated modeling that accounts for feedstock particle size, shape and composition along with electron beam dynamics needs to be developed to qualify interesting alloys.

Conclusion

Intellectual property rights and patents held by Arcam could help to explain why there is only one electron beam PBF machine manufacturer. However, one only needs to look at the litigation in the laser beam PBF market along with the various distribution agreements that have emerged to understand this is not the whole story. Usually, when markets are viable, competition finds a path around, and forward. The primary reasons why there are multiple laser beam based PBF machine manufacturers are: ease of acquiring off the shelf components to manufacture the machines, ability to process in a cold build chamber, relative ease of qualifying new materials, and demand for components made from the process. Having said that, the technology that has the most upside in terms of additive manufacturing of metals in a powder bed is the electron beam process. This is due to the electronic control of the beam diameter and deflection that can scan so fast it appears to have multiple beams hitting the surface at once. As long as the scanning optics in a laser based system have mass, it won’t be possible to meet the scan speed or beam dynamics of the electron beam system.

Other than beam dynamics, features that create the total PBF solution can be implemented with either electron beam or laser beam systems. Both types of processes can have vacuum, can have heated powder beds, can have thin or thick layers, can be scaled up or down for component size (electron beams have an advantage for sub micron spot sizes), and can utilize different powder morphology and composition (laser beams have an advantage on non-conductive powders). In fact, we are already starting to see thicker layers to speed up processing on laser based machines as the 400W and now 1kW lasers are available from IPG and SPI. We find vacuum pumps installed on a laser based machine from at least one machine manufacturer, and the surface finish on electron beam based PBF components has improved significantly with the introduction of thinner layers and multi-beam contour scanning. In short, we are witnessing a convergence of the two technologies.

As the two PBF technologies converge, there is a need for measurement and control of the process fundamentals in order to produce safety critical components. Here is a comprehensive list of those parameters.

Feedstock	Measurement	EB PBF	LB PBF	
	Powder Flow	H	H	S, I, MP
	Chemical Composition	H	H	S, I, MP
	Particle Size	H	H	S, I, MP
	O_2	H	L-H	MP
	Spread Coherence	H	H	
Power Density at Part Bed	Beam Diameter	H	H	
	Beam Profile	H	H	
	Consistency A	H	H	
	Consistency T	H	H	
Process	Melt Pool	H	H	
	Hatch Space	H	H	
	Contour Space	L-H	L-H	
Part Bed Temp	Build Platform	H	H	
	Top Layer	H	L-H	
Machine	Z axis movement	H	H	
	Recoater Contamination	H	H	
	Build Atmosphere	H	H	
	Gas Flow	L	H	
Component	Mechanical Properties	H	H	
	Porosity	H	H	
	Microstructure	H	H	
	Surface Finish	H		
	Internal Stress	L	H-L	
	Dimensions	H	H	
	Remaining Powder	H	H	

Requirement H=High, L=Low

S= Supplier

I- Incoming Inspection

MP- Required in Manufacturing Plan

A= Part Bed Area

T- Build Time

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1. What are the key measurement science barriers that prevent innovation in metal-based AM?
   - **Quantify the dimensioning and tolerancing capabilities of an AM machine**. AM parts can be used for functional models and for fit and assembly, thus it is important to quantify the dimensioning and tolerancing capabilities of an AM machine. This capability may be complex due to possible shrinkage issues in the AM build process. In some AM processes, shrinkage may be a function of the part geometry.
   - **Comprehensive material specifications and standards for each AM process**. Without these specifications and standards, engineers will not consider AM as a method of manufacturing.
   - **Measurement of material properties at high temperatures**. Some metal AM processes build metals in high temperature that is above the melting point of the metal. In order to fully understand these processes and predict the resulting microstructure, the material properties at elevated temperatures are needed. The measurement of these properties is expensive. Since each material is different, a lot of effort is needed.
   - **Measurement of the key process parameters at high temperatures**. In some metal AM processes, measurement of the key process parameters at extreme environment, such as high temperature, may be needed to ensure quality and reliability of the parts.

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?
   - **Open-architecture controllers and reconfigurable machine modules for integrated processes**. Just like CNC machining centers, AM machines need to take advantage of the open-architecture controllers and machine modularity so that more innovative processes can be created.
   - **Creation of comprehensive material specifications and database**. Research and development is needed to find the material properties at elevated temperatures. This should also include the mixing of materials in high temperatures for applications in functionally graded material (FGM).
   - **Better understanding of the processing-structure-property relationships of materials**. It will involve physics based modeling and accurate measurement of the key parameters involved in the process. This will help establish the ability to accurately fabricate complicated shapes with a minimum number of experiments.
   - **In-process measurement and feedback control to help improve reliability, repeatability, and uniformity across machines**. Nondestructive evaluation technology should be developed to enable early defect detection which is important.
   - **Machine qualification standards to ensure part-to-part consistency**. The standards will include all areas such as material input, preparation, processing, and post-processing if applicable.
   - **Repair qualification standards**. If a part or product can be repaired and reused for its initial product function, not only will the material waste and amount of landfill be reduced, but also energy and matter consumption during manufacture will be reduced because existing components are utilized. However, some companies have a need for parts that require repair or replacement frequently, but without a robust qualification process, repair may not be an option such as in the aerospace industry. The lack of standards in repair impedes its use for parts remanufacturing.

- **Updated AM software research and development**. AM processes can potentially produce very innovative materials that cannot be made before, thus updated AM software to support such capability should be researched and developed. For example, functionally graded material (FGM) may be characterized by the variation in composition and structure gradually over volume, resulting in corresponding changes in the properties of the material. The current standard CAD models do not have such capability.
- **Technologies to improve dimensional accuracy and surface finish**. All techniques to improve accuracy of AM processes, either in-processing or post-processing, are needed to widen the applications and the market for AM processes.

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Measurement Barriers in the Implementation of Metals Additive Manufacturing for Military Aircraft Repair and Maintenance

Additive manufacturing (AM) of metals (e.g., titanium, nickel, aluminum) has many potential benefits in numerous industries, particularly in the field of aerospace engineering. Titanium alloys (i.e., Ti-6Al-4V) are of specific interest because their high cost could be mitigated by AM's low "buy-to-fly" ratio. Of particular interest to NAVAIR Jacksonville (FRCSE) is implementing direct digital manufacturing (DDM) to produce parts for legacy aircraft from drawings or reverse engineering when replacements parts are no longer commercially available. Additionally, DDM could be implemented during aircraft maintenance and repair to improve operational availability and cost savings by avoiding long lead times associated with obtaining one-off-repairable parts (OOR) from traditional manufacturing methods.[1]

However, there are still many measurement science barriers that prevent innovation in metal-based AM and aspects that must be further evaluated prior to extensive implementation in industries seeking to adopt AM, such as the aerospace industry. Primarily, a database of the mechanical properties of materials produced by AM must be established. Characteristics (e.g., fracture toughness, yield strength, etc) from material produced by AM must be compared with the current Metallic Materials Properties Development and Standardization (MMPDS) data for the same alloy produced by a traditional method. As parts produced by AM are anisotropic and vary by fabrication method, careful consideration must be made in measuring and reporting mechanical property values.[2] A clear understanding of the mechanical properties of parts produced by AM prior to industrial (e.g., aerospace) applications is critical. However, the AM parts do not necessarily have to match or exceed the mechanical properties of parts made by traditional manufacturing because as long as the mechanical properties are known and are reproducible the part may still be engineered to specification. For example, if ultimate tensile strength of a material is reported in the MMPDS as 100 ksi from a traditional manufacturing method but the ultimate tensile strength for the AM part is measured at 80 ksi, a structural engineer can perform a static strength and/or fatigue analysis to determine acceptability or make alterations in the design such that the new material is still usable for a particular application. However, without a clear understanding of the mechanical properties of metallic material produced by AM, it is not known which industrial applications are realistic. Documented databases of mechanical properties and the establishment of industry specifications and standards for parts produced by AM are crucial.

Furthermore, advancements in measurement science must address necessary parameters for parts qualification, such as statistical reproducibility in AM for process control. Many industries seeking to adopt AM will require the ability to reproducibly manufacture drop-in replacement parts or parts from novel designs. (i.e., Military applications of metal alloy AM may utilize new and improved designs, as well as the ability to rapidly manufacture and reverse engineer drop-in replacement parts for numerous platforms to ensure operational availability.) Therefore, the ability to rapidly qualify parts is of key importance. Understanding, measuring, and controlling inter-part, inter-machine variation and reproducibility for the implementation of repeatable and predictable processes during part manufacturing will be one key aspect of rapid qualification needed for the implementation of AM in military aircraft repair and maintenance, as well as in other industries requiring process control. Further R&D is required in this area to accelerate innovations in metal-based AM.

Finally, predictive modeling and simulation tools will be an important aspect of innovative structural design using AM. A benefit of AM is design flexibility and alleviation from some traditional manufacturing constraints. However, in order for design freedom to be fully realized, predictive modeling and simulation tools are required that can calculate mechanical properties in relation to structural variables (e.g., geometry, payload, etc). Physics based models are also needed to predict microstructure, properties, and defects during the AM process.[1]

References:

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2. Ian Gibson, David W. Rosen, and Brent Stucker. *Additive Manufacturing Technologies.* 2010, Springer Science + Business Media, LLC, New York, NY.

Patton, Cossette, Tackett, and Cox, ASTM F-42 Educational Working Group

Ken Patton, Principal Investigator, RapidTech
Dr. Imelda Cossette, Principal Investigator of MatEd
Ed Tackett, Director, RapidTech
Frank Cox, Director, MatEd

Additive Manufacturing Competencies

With ASTM's establishment of Standard F-42, an Educational Working Group (EWG) was established to develop core competencies for emerging student technicians working in the field of Additive Manufacturing. This effort is funded by a National Science Foundation grant instrument to Edmonds Community College (MatEd, the National Resource Center for Material Science) in partnership with RapidTech (National Center for Additive Manufacturing). The Goal of the grant is to develop Student Core and Professional Competencies supporting the developed global standards for Additive Manufacturing and to disseminate those competencies to the Nation's educational community for inclusion in technician education and Engineering programs, helping to insure that manufacturing technicians and Engineers are prepared to enter the workforce with the knowledge and skills necessary to work in the manufacturing environments of tomorrow.

As the Task Force develops the various standards, they are supplied to the EWG for transformation into core and professional competencies with the STEM area identified with each.

RapidTech and MatEd synthesize the standards into core and professional competencies, which are then distributed, to the EWG as a whole to make recommendations for edit. The final results are then shared with the Executive Committee of ASTM F-42, which is chaired by Bret Stucker.

The "Student Core and Professional Competencies" is a living document that is modified each time a standard is approved or modified. The results are then disseminated nationally to the educational community for inclusion in their manufacturing technician and engineering instructional programs.
Ken Patton, Principal Investigator of RapidTech, chairs the educational working group with membership of over 25 educational and industry leaders in Additive Manufacturing. Those members include Ed Tackett, Director of RapidTech, Dr. Imelda Cossette, Principal Investigator of MatEd and Frank Cox of MatEd, Tim Gornet and Dr. Bret Stucker of U. of Louisville, Dr. David Rosen of Georgia Tech, and many other leaders of Additive Manufacturing Education. It should be noted that industry also participates on the EWG and provides excellent guidance in the development of Student Core and Professional Competencies.

Skill and Knowledge methodology
The underlying methodology behind the Core and Professional competences is that each individual competency can be defined as either a skill or knowledge. A knowledge based competency is well suited for distance education while a skill competency is more tactile in nature requiring a practicum and would not be generally suitable for distance education but is suitable for a hybrid educational model.

Science Technology Math & Engineering
Each individual competency is categorized by the major STEM category. This allows educators to measure STEM competency can be defined

For more information please visit: www.rapidtech.org or www.materialseducation.org

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Process Metrology for Metal-Based Additive Manufacturing

1. What are the key measurement science barriers that prevent innovation in metal-based AM?

For metal-based additive manufacturing (AM) processes, the key measurement science barriers include process variable measurements (i.e., **Process Metrology**), e.g., temperatures and metal molten pool sizes and evolutions during the process. Meaningful, Accurate and reliable process variable data offers detailed, insightful information to understand the process physics, to monitor the process characteristics and performance, and the part quality and consistency. Moreover, process variable measurements often serve as necessity to validate the process modeling/simulations, which are also for fundamental process understanding, a key to enhance process performance and part quality.

From literature, for virtually every manufacturing process, Process Metrology (process variable measurements) was widely studied and considered necessary for process advancements. However, process metrology has not been seriously addressed in metal-based AM technologies including selective laser sintering/melting and electron beam melting, etc. In literature, there is very limited data of process variable measurements of metal-based AM in the public domain.

It is understandable that the process metrology in metal-base AM is very challenging because of extreme high temperatures, temperature gradients, complex material states (solid/liquid), and some with unique environments such as vacuum. Further, limited accessibility to the process chamber adds additional challenge to integrate instruments.

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

Current sensor technologies including infrared imagers, high-speed cameras seem to have the capability for process variable measurements in AM, for example, the desired temperatures ranges, spatial and temporal resolutions, etc.

Some of the most important areas where R&D is needed may include:

(1) How to integrate sensors with an AM machine? How to be flexible for different machine platforms (same of different process principles)?

(2) How to process the vast amount of data? How to interpret the data correctly? How to use sensors and data analysis to obtain meaningful results?

The other areas of importance too for R&D in AM process metrology, with benefits in process advancements and part improvements, may include:

(3) How to apply acquired/analyzed sensor data for process modeling and simulation validations?

(4) How to correlate acquired/analyzed sensor data with AM part properties from other measurements?

Jyoti Mazumder, University of Michigan at Ann Arbor

Metal based additive manufacturing is almost two decades old and primarily includes two broad types: 1) Powder Bed such as Selective Laser Sintering(SLS)and 2) Pneumatic powder delivery such as Direct Metal Deposition(DMD). Powder bed has the advantage of support materials and can prototype complicated part relatively easily, but deposition rate, and work envelop is limited. Deposition of multiple materials is also a challenge. For DMD high deposition rate, work envelop, multiple material deposition, repair and reconfiguration of real components are advantages but surface roughness increases with high deposition rate.

Presently both processes are evaluated post mortem. In order to promote broad use of additive manufacturing(AM) online measurement and control techniques are needed. Moreover, to further enhance the AM technology and realize the full potential of AM for fabrication of Meta---materials with properties not normally observed in mother nature, complicated on line measurement of composition and phase transformation are needed. In order to achieve close near net shape dimension, measurement techniques have to be non--- contact and fast(~ms). Some of the critical needs for measurement are listed below.

1) Future measurement and standards for metal--basedAM

Measurement techniques for AM need to be **in situ**, not post mortem, to control the process to achieve desired dimension, structure and properties. Some of the Urgent needs for measurements are:

i) Deposition layer thickness for micron level accuracy
ii) Surface roughness with micron level accuracy
iii) Composition of the deposited layer
iv) Phase transformation during the deposition and solidification process.
v) Detection of defects such as cracks, porosity, undercut/underfill, residual stress and distortion.
vi) Develop the feedback control utilizing the above mentioned measurement techniques to produce the desired properties.

2) ***Measurement Science Barriers, challenges and gaps preventing broader use***

Major scientific barriers and challenges are:

i) *Lack of the materials and process data* base which are universally acceptable. AM produced materials properties are highly dependent on the process parameters. Therefore, drawing any scientific conclusion from the literature data becomes extremely difficult.

Suggested Solution: develop a group of dimensionless numbers so that data can be extrapolated for different conditions(Ref: T Chande and J Mazumder, Metallurgical Transactions B, Vol. 14B, 181---190, 1983.) This is a practice widely accepted in scientific and engineering communities. For example Reynolds's number for flow, Biot's number for heat transfer etc.. With a single number we will be able to describe the process and properties connection.

ii) *Detection defects resolved within milliseconds* or travel time to cross one heat source beam diameter.

Suggested Solution: Fast data acquisition for non ---contact measurement techniques (e.g. Reflective topography[U.S. Patent #5,446,549], Spectroscopic characterization [Real time Cr measurement using optical emission spectroscopy during direct metal deposition process, *IEEE Sensors Journal*, (vol 12(5) pp958 -964, May2012]) with fast feature extraction using machine learning algorithm.

iii) Deploying measured data for process control

iv) Integrated simulation and measurement techniques for fabrication of "Designed Materials" with unique properties.

3) ASTM 42 priorities

i) All the constituent parameters for energy source(e.g. Laser, Electron Beam) need to standardized. Some of it already exists

ii) All the constituent parameters for the powder and raw stocks need to standardized

iii) AM fabricated materials characterization for certification process need to be standardized.

4) R&D needs

R&D needs are described in the "*Suggested solution*" next to the scientific barriers

Tom Campbell, Virginia Tech University

1. What are the key measurement science barriers that prevent innovation in metal-based AM?
   - Powder consistency (shape, properties, agglomerates, etc.)
   - Closed-loop metrology capability within Additive Manufacturing systems (temperature, pressure, raw materials remaining, etc.)
   - Post-build measurements (certifications, calibrations, etc.)

2. What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?
   - Measure effects of aging (e.g., oxidation) of raw materials on process repeatability
   - Full life cycle measurement capabilities must be put in place to ensure consistent and usable metals products (see (1) above)
   - Funding increases from NIST, NSF, DOE, etc., to pay for metals measurements research in universities and corporate entities

Vito Gervasi, Milwaukee School of Engineering
Director R&D, RP-Research
1025 N. Broadway
Milwaukee, WI
https://www.msoe.edu/academics/research_centers/rpc/

1) What are the key measurement science barriers that prevent innovation in metal-based AM?

a) Detection and characterization of inconsistencies and defects at a reasonable resolution within each layer (and perhaps some number of layers combined) of AM parts.

b) Detecting and predicting final geometry relative to CAD intent, real-time and/or at build completion.

c) High-resolution metallurgical inspection of quality of metallic AM component using NDA methods on a layer-by-layer basis.

d) Measurement and detection of "grown-in" stress within the component.

e) For Bi-metallic FGM's the properties of the interphase are important to measure and characterize.

f) Highly complex components are difficult to test and evaluate (i.e. a complex optimized cellular structure). Also, statistically, with build history known, the load capabilities of an optimized cellular structure could be predicted.

g) Non-destructive detection and measurement of anisotropic properties.

h) Monitoring and controlling grain size and direction is critical for some AM metal applications.

i) For some AM parts, due to variable density, there is some challenge associated with specifying where the part begins/ends. For example, intentional or unintentional porosity needs to be detected and characterized for some applications. Now, with "variable density steel" available part inspection presents many new challenges not prevalent in wrought or cast materials. Each density region may need to be handled as a separate material.

Note 1: Defects are often created in AM components due to the layer-wise build method of metallic parts. The defects occurring within a layer or between layers of AM components are sealed in by subsequent layers. One method/opportunity of detection may be real-time layer-by-layer quality inspection and image analysis for components. This information should be archived and tied to the specific part throughout its life cycle.

Note 2: The AM community needs to be able to statistically predict the behavior of a component during its intended use (especially in critical applications such as aerospace or medicine).

Note 3: Scanning during AM part growth has huge potential of detecting potentially high-risk parts before they are placed in service. This tracking combines with statistics can reduce the risk and liability of using AM-metal components.

2) What are the most important areas where R&D is needed—particularly in measurement and standards—to overcome these barriers and to accelerate innovation in metal-based AM?

a) Challenges abound:

i) Tools for real-time scanning and evaluation of AM parts during or after being grown.

ii) Software tools to data-mine the enormous amounts of data from scans and imaging.

iii) Harsh environment inspection. Inspection during builds will be challenging due to atm and temperatures. Optics will become metalized under vacuum or could become clouded depending on the process. Protective measures or robust scanners are needed.

iv) Development of a standard or benchmark tool(s) to easily assess a range of capabilities of a process will be key and software to help designers recognize what is and isn't possible will also be beneficial. There are direction dependent opportunities/challenges which should not be ignored.

v) Two phase materials present unique and strategically critical opportunities and challenges. The ability to use combinations of materials (intermingled in some manner) to realize the best properties of both materials in one component has great potential. These high performance materials will require advanced inspection methods to verify the CAD intent was realized and to ensure material density and metallurgy is maintained within spec throughout.

Constance J.S. Philips, NCMS
Sr. Program Manager
RARE Parts Collaborative Program
Ann Arbor, MI
www.ncms.org

Production and Use of Standard Parts and Our Lessons-learned Thus Far

The collaborative AM program at NCMS has been on-going for 21 years, and for at least a decade we have used a standard part for assessment of AM machine-material capability. Historically, this part was only an assessment tool for a user's determination of his machine's feature building capabilities using differing materials. The User's knowledge was then used is his operations and in his AM part design or part redesign for AM. Our part design evolved over several years of trying other test part designs coming primarily from machine OEMs and was designed to be particularly challenging to any AM system. NASA Marshall Space Flight Center, Ken Cooper specifically, designed the **NASA Benchmark Part** to contain features encountered frequently in our work with DoD maintenance and repair depots and the challenges of legacy part replacement. We shared the stl file with several others over the years including NIST most recently.

While our original use of the NASA Benchmark Part was to better understand the feature building capabilities and limitations of the various AM machines and materials we use, we view the NASA Benchmark Part as potentially useful in generating a feature database eventually yielding Design Allowables. We are currently in the beginning stages of building parts with this hypothesis in mind. Before embarking on this adventure, we inquired of NIST if there was an overarching protocol in use in the conducting of such a study. NIST staff shared with us the files associated with the building and measurement of their Standard Part under study. Thus far in our study we find it necessary to establish a well-defined set of protocols and are only learning now to what degree their definition is needed.

Control Needs:

Build Documentation Protocol

In an attempt to be able to attribute feature attributes and measurements to a process and to a specific material used, we anticipated that documentation of the build process would be needed. Our first attempt at specifying a build documentation sheet and the first article built and submitted for measurement revealed immediately the need for additional controls to be specified. Additional facets of the build needing definition and control are surely to emerge as we proceed. The latest Build Documentation Sheet is attached as Exhibit 1. You will note that the level of fidelity of data is low without having process monitoring and feedback available as an intrinsic part of the build processes.

Feature Measurement and Documentation Protocols

Anticipating that the measurement of specific features against the CAD file will be another learning process and will require additional protocols, our study is not placing the responsibility for these measurements and reporting on the Parts' builders at this time. It is our desire to utilize a third party having diverse measurement expertise, perhaps NIST itself, to devise a measurement protocol for the diverse set of features contained in the NASA Benchmark Part by actually applying the best measurement instrumentation available, measuring the features in each of our test articles, and then define a protocol for the recording of that data. These combined protocols would then be available for use in future Part builds and provide the needed control to minimize the variations introduced into data via the measurement devices themselves and establish basic rules for measurement documentation.

A picture of the NASA Benchmark Part CAD rendition is attached as Exhibit 2.

Call for a Set of National standard Protocols

We believe if these NASA Benchmark Part protocols or protocols such as these were developed via an organization with the capabilities of NIST, we could realize a set of national standard protocols for the conducting of Part and feature studies in the future. We need to have the ability to replicate any such study. We believe basic tenets must be defined before embarking upon costly process, materials, and Part research and development. As users of these AM technologies, we want the best data possible, with the highest degree of reliability and repeatability as possible within this constantly emerging AM landscape. Having a nationally adopted set of protocols would facilitate and contribute to not only eventual definition of Design Allowables but also to the advancements developed by AM OEMs for machines, process controllers, operating systems, software, materials, inspection and process monitoring systems.

Exhibit 1

Commercial Technologies for Maintenance Activities (CTMA)

ncms
An NCMS/DoD Partnership

RARE Parts Program

Benchmark Part Build Sheet

Submit with Part to:
C. Philips
NCMS
3025 Boardwalk Dr.
Ann Arbor, MI 48108

PART NO.______________ NASA Benchmark Part ☐ or NIST Test Artifact ☐

CALIBRATE MACHINE PER OEM INSTRUCTIONS PRIOR TO STARTING BUILD[1]

Company ID:______________________________

Build Address:______________________________

Date of Build:______________ Build Location Coordinates[2]:______________

Process:______________________________

Machine model:______________________________

Material specification & source of supply:______________________________

____

Parameter settings:______________________________

Special settings, eg. pre-heated chamber, pre-heated material, etc.:______________

____

Support structure software used:______________________________

Nozzle size:______________________________

Laser type & power:______________________________

Laser spot size:______________________________

E-beam current:______________ E-beam spot size:______________

Total lapse build time:______________________________

Note any build interruptions, issues experienced, etc.:______________

____

Note any other factors that may have influenced the build outcome:______________

____

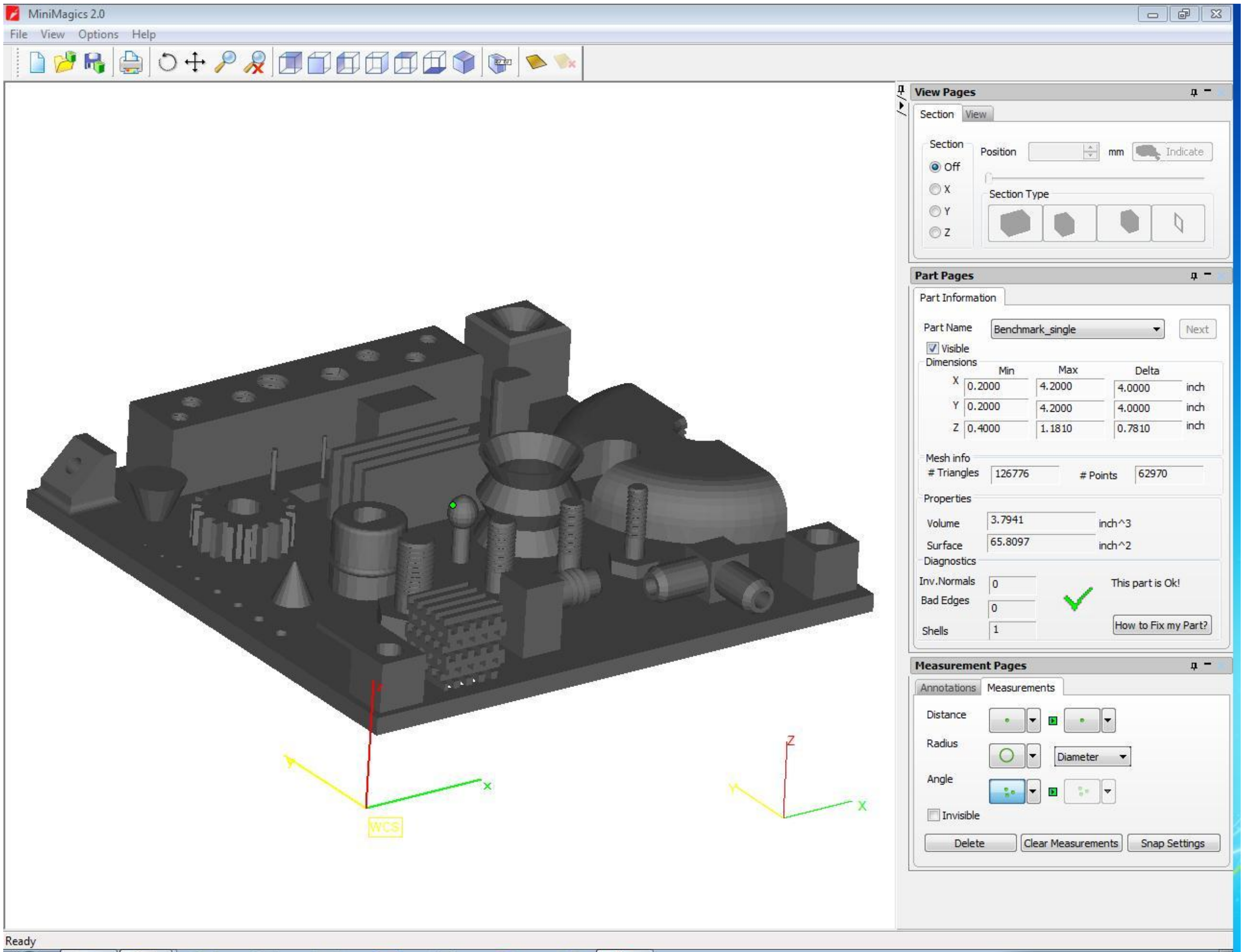
Hand-mark Company ID and PART NO. on part bottom, this build sheet is to accompany each Benchmark Part. Retain a copy for your records.

Signed by:______________ Part built by:______________

[1] Per OEM instructions per material if so specified.

[2] Per ASTM F2921-11e2 Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies

Exhibit 2


MiniMagics 2.0
File View Options Help
View Pages
Section View
Section
Off
X
Y
Z
Position
mm
Indicate
Section Type
Part Pages
Part Information
Part Name
Benchmark_single
Next
Visible
Dimensions
Min Max Delta
X 0.2000 4.2000 4.0000 inch
Y 0.2000 4.2000 4.0000 inch
Z 0.4000 1.1810 0.7810 inch
Mesh info
Triangles 126776
Points 62970
Properties
Volume 3.7941 inch^3
Surface 65.8097 inch^2
Diagnostics
Inv.Normals 0
Bad Edges 0
Shells 1
This part is Ok!
How to Fix my Part?
Measurement Pages
Annotations Measurements
Distance
Radius
Diameter
Angle
Invisible
Delete
Clear Measurements
Snap Settings
WCS
Ready