SUPERFINISHING OF PRINTED METALLIC PARTS FOR HIGH PERFORMANCE NAVAL SYSTEMS

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MAJOR GOALS

The goal of this Defense University Research Instrumentation Grant is to establish an infrastructure at Penn State University to enable research and education in the area of superfinishing processes; with a special focus on additively manufactured parts used for high performance naval systems. The objectives of the project are to:

- Purchase and install machine tools and acquire the necessary training to execute superfinishing processes related to: 1) rigid, abrasive media machining, 2) viscous, abrasive media machining (e.g. abrasive flow machining), and 3) electro-chemical machining
- Initiate fundamental research into the engineering science of these processes and to conduct engineering development to expand their capability
- Initiate research projects focused on the use of these superfinishing processes for refining the topographies of metal components printed using powder bed fusion processes and directed energy deposition processes and of specific interest to the U.S. Navy
- Integrate the processes into the undergraduate and graduate engineering curriculum

ACCOMPLISHED

Over the course of this project, the Superfinishing Laboratory has been established at Penn State, strategic partnerships with entities within the university and with Extrude Hone have been established, graduate student research has been initiated, and the laboratory has been used to support on-going Navy projects. Each of these is discussed next.

<u>Superfinishing Laboratory</u>

The Superfinishing Laboratory has been established at the Penn State University Park campus in room 112 Leonhard Building. It is managed by the Dept. of Industrial & Manufacturing Engineering (IME). The first eight months of the project (March 1, 2018 – October 1, 2018) were spent assessing available technologies, negotiating with vendors, and getting approval from the Navy to alter purchases initially proposed for the purpose getting greater value and increased capability. Equipment installation began February 2, 2019 and was finished on September 5, 2019 with the installation of a replacement filter press for the ECM.

The finishing technologies that were acquired are:

- Walther Trowal TT-45 Centrifugal Disk Finishing Machine
- Walther Trowal MV-21 Multi-Vibe Bowl Finishing Machine
- Extrude Hone Vector 150 Abrasive Flow Machine
- Extrude Hone CoolPulse 1000 Electro-Chemical Machine

These technologies were chosen based on the following criteria:

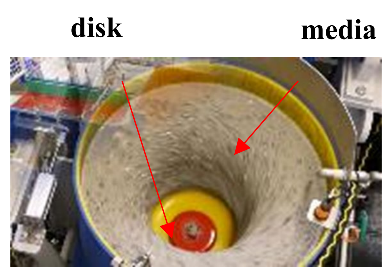
- Demonstrated commercial applications of processing metallic, additively manufactured (AM) parts
- Demonstrated capability of smoothing a HIP'd, metallic AM surface from a roughness of R_a 24 μm to R_a 0.2 μm or less, the latter value being the prescribed surface finish for an ASTM E66 fatigue test
- Demonstrated complementary capability of processing routine AM part geometries
- Potential for increased capability with R & D to accommodate difficult to machine AM part geometries

The TT-45 is illustrated in Fig. 1a. It is a technology that is primarily used to smooth open surfaces and open edges accessible to free flowing, rigid abrasive media. An example part shape that is routinely processed in the TT 45 is illustrated in Fig. 1b.

The media and free tumbling parts are displaced and energized by a rotating disk at the bottom of the bowl (see Fig. 1c and 1d). The abrasion rate and asymptotic finish that occurs locally on a surface is directly affected by the pressure the media exerts on the surface as it slides past it in combination with the media velocity. This in turn is heavily influenced by the wheel velocity, the grit shape, grit size, and grit composition of the media, and the flow rate of the soap-water solution that is injected into the bowl. Examples of media are provided in Fig. 1e. A typical matrix material is clay, plastic, or a natural material such as walnut shell or corn cobb. A typical grit is aluminum oxide or silicon carbide.

a)

b)



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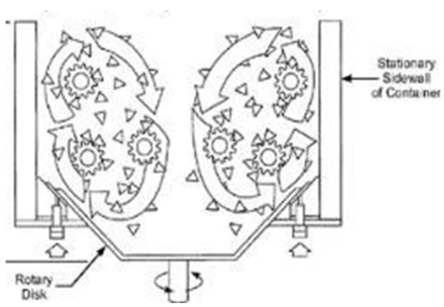


d)

e)

Figure 1. TT 45 Centrifugal Disk Finisher: a) TT 45 in Penn State Lab; b) open surfaced parts typically machined*; c) disk and media in motion*; d) part and media tumbling action; e) rigid media; *courtesy of Walther Trowal

The MV 21 is illustrated in Fig. 2a. It is a technology that is used to smooth surfaces and edges that are accessible to rigid abrasive media (Fig.2b) that is in both motion and under pressure. An example part shape that has been processed using the MV -21 is illustrated in Fig. 2c. The abrasive action that is used to smooth surfaces is similar to that used for the TT-45. However, in this case, the parts are anchored to the bottom of the bowl with a simple fixture (Fig 2d). The bowl rests on a suspension. The relative motion between the media and parts is energized by the rigid body vibration of the bowl, which is driven directionally by three motors as shown in Fig. 2e. Media pressure and velocity are directly proportional to the amplitude of vibration of the bowl. Media flow direction is controlled by motor orientation.

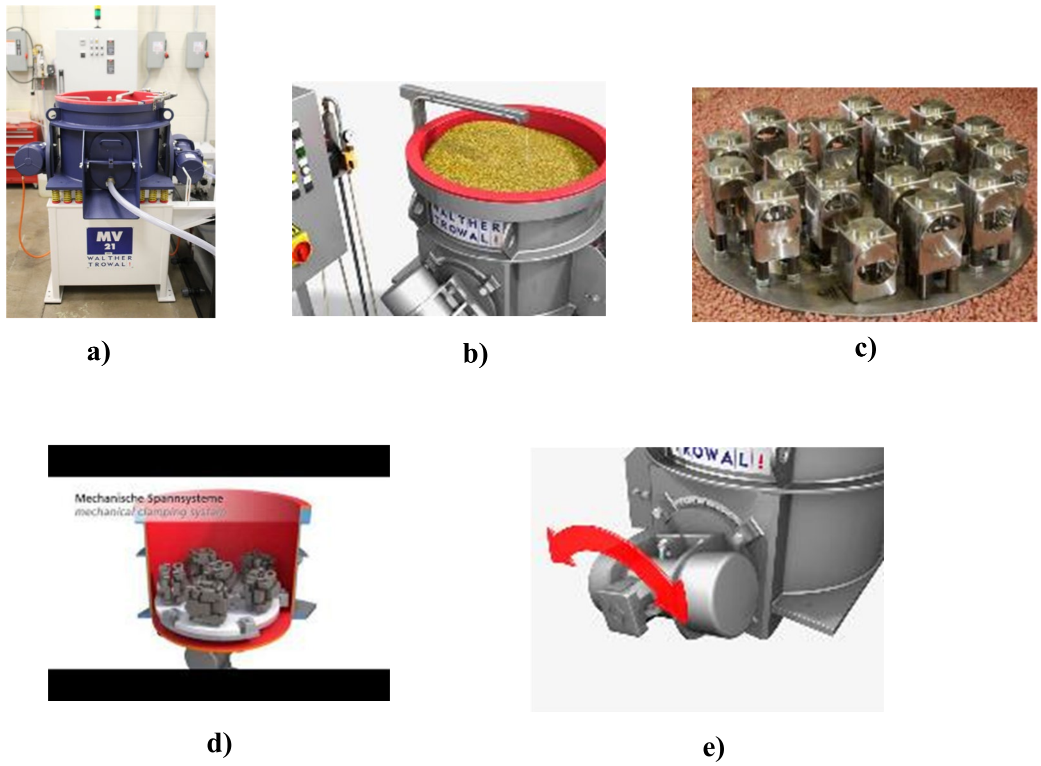


Figure 2. MV 21 Multi-Vibe Bowl Finisher: a) MV 21 in Penn State Lab; b) tumbling media in bowl*; c) parts typically machined*; d) parts fixtured to bowl bottom*; e) motor with adjustable orientation* ; * courtesy of Walther Trowal

This machine uses the same type of media as the TT-45. However, the abrasion rate is substantially slower because it does not impart the same degree of kinetic energy into the media. But the machine can force the media to do work in a greater variety of directions. This allows the machine to process surfaces in large blind cavities, internal passages, as well as external open surfaces. It should also be noted that an inventory of rigid media was purchased from Walther Trowal to run both machines. This media was selected on its applicability to processing printed metallic parts made of titanium based alloys, nickel based alloys, stainless steel alloys, aluminum alloys, and nickel-aluminum bronze. It was selected on the basis of being able to take a metallic surface from R_a 24 µm to R_a 0.2 µm or less.

The Vector 150 is illustrated in Fig. 3a. It is a technology that is primarily used to smooth surfaces and edges that are accessible to free flowing, viscous, abrasive media (Fig. 3b). An example part shape that is routinely processed in the Vector 150 is illustrated in Fig. 3c.

The media is energized and displaced by two reciprocating pistons in the machine (Fig. 3d). The media is routed to the surfaces of the part by a dedicated fixture, which is positioned between the two piston bores. For most applications, the fixture consists of two halves which encapsulate and hold the part as well as route the media.

The polymer carrier in the media is a derivative of silicone rubber. Different carriers are formulated to achieve viscosities ranging from that of motor oil to stiff putty. The grit content within a media is also varied by chemical composition (diamond, boron nitride, silicon carbide, aluminum oxide), grit size, and grit mass percentage. Through a partnership arrangement with Extrude Hone, the complete inventory of media (some 10,000 varieties) are available for research at Penn State.

Similar to the other technologies, the abrasion rate and asymptotic finish that occurs locally on a surface is directly affected by the pressure the grit exerts on the surface as it slides and tumbles past it in combination with the grit velocity. This is controlled by the media pressure via the pistons, the carrier viscosity, and the grit size. It is also heavily influenced by the path the media must travel through, because the media loses pressure with increased travel distance and sudden changes in flow cross section.

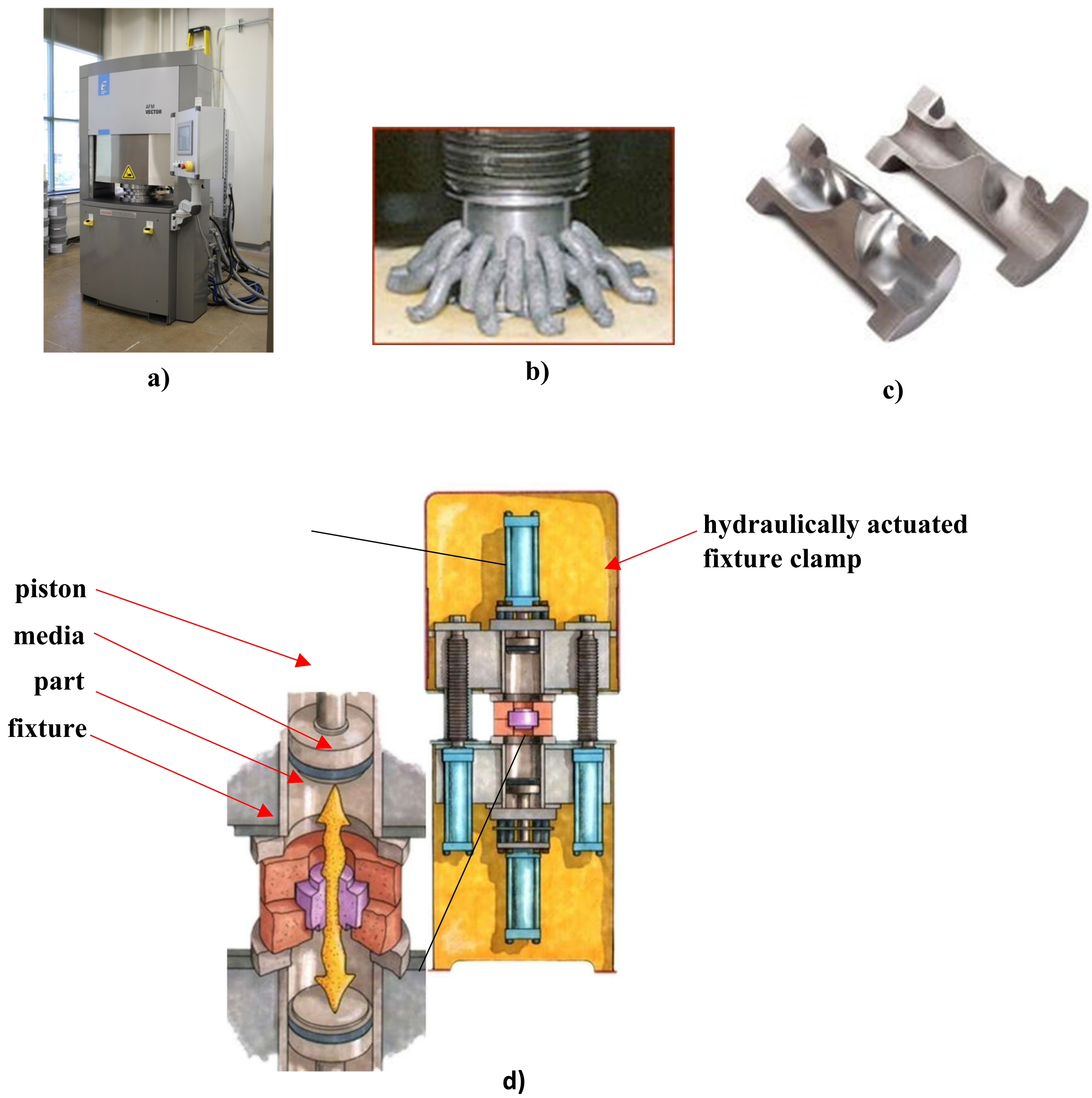


Figure 3. Vector 150 Abrasive Flow Machine: a) Vector 150 in Penn State Lab; b); viscous abrasive media*; c) parts typically machined*; d) fixture, part, reciprocating pistons and media in motion*; *courtesy of Extrude Hone

The Coolpulse 1000 is illustrated in Fig. 4a. It is a new technology that was created specifically to smooth the topography and edges of metallic, AM parts. It is capable of processing any surface that can be exposed to the presence of an electric field and free flowing, electrolyte fluid. The electric field is established by electrically connecting the part as an anode to a DC wave generator. A cathode, connected to the same electrical source, is placed in proximity of the surfaces to be processed. The pair is submerged in a neutral PH, electrolyte bath. Material removal occurs when the generator is energized and metallic ions migrate from the part surfaces as part of the electro-chemical circuit (Fig 4b). As the metallic ions traverse across the bath, they chemically react with hydroxide ions to form solid, metal hydroxides that are later filtered from the electrolyte. Fluid flow is needed to flush these metal hydroxides from the machined region otherwise the material removal rate dissipates and a re-cast layer may form on the part surface.

A typical part that is processed using this technology is illustrated in Fig. 4c. Two approaches of cathode implementation may be used. For external edge deburring or the smoothing of simple external surfaces, the cathodes may take on a simple shape such as a set of flat plates (Fig. 4d) or a tube that surrounds the part. Electrolyte within the bath is forced to flow between the part and cathode surfaces. Internal cavities and edges are not affected due to the Faraday Cage effect, which negates the electric field strength in these regions (Fig. 4e). If these interior features are to be processed, a conformal cathode(s) (Fig. 4f) must be created and assembled within proximity of the part surfaces, with a typical stand-off of 4 mm. Doing so will dramatically improve the electric field strength in these regions (Fig. 4g) and allow processing to occur, provided that electrolyte fluid can traverse the gaps.

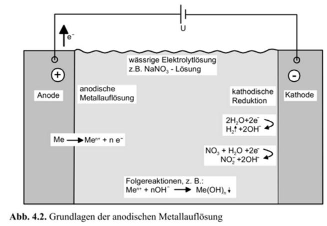
The localized metal removal rate is a function of the localized current density of the surface which in turn is a function of the localized field strength. This is controlled in part by the wave generator voltage, but also by the proximity of the cathode and part surface. It should be noted that even within a local area, the current density varies at the topographic level with the highest current density occurring at the highest roughness peaks. Consequently, during processing, material loss occurs across the complete topography, but more rapidly at the peaks. The asymptotic surface roughness that may be achieved is heavily influenced by electrolyte fluid flow. Turbulent flow or stagnant flow may lead to surfaces with widely varying texture.

In addition to the four processing technologies, three other systems were acquired. They are a Walther Trowel AB04 weir tank, a HD camera system, and equipment for creating a mini-ECM cell. The AB04 weir tank, which is illustrated in Fig. 5, serves as a soap-water solution reservoir and filtration system. Solution is pumped to either the TT-45 or MV-21 during processing where it serves as a lubricating and washing agent for the parts and media. The dirty solution is pumped back into the weir tank where individual storage cells are used to settle out the particulates.

The camera system is shown in Fig. 6. It is comprised of a PCO-Tech high speed, HD camera and an Infinity Photo Optical zoom lens. The high-speed camera is capable of providing 2128 frames per second at full resolution. The lens assembly constitutes a telescopic microscope that can provide resolution 4 μm/pixel. In harmony, the lens/camera assembly provides a viable approach to perform strain mapping at high speeds to record and analyze material phenomena occurring at short time scales. The system will be used to track media flow and metal surface machining in experiments involving all four superfinishing technologies. This data will be used to achieve a better scientific understanding of the processes. With this knowledge, we intend to re-engineer them in order to improve their ability to smooth geometrically complex, additively manufactured parts.

The mini-ECM cell is illustrated in Fig. 7. The cell is located in the Material Science and Engineering Dept. at Penn State. The purchased equipment includes a (1) MetroOhm BOOSTER20A power booster that can supply up to 20 A current using the existing computer-controlled potentiostat-galvanostat (wave form generator), (2) MetroOhm AUT.RRDE rotating disk electrode (RDE) in a test vessel which controls the electrolyte flow conditions by varying the rotating speed of the electrode using (3) the motor controller for controlling electrode rotation speed. The cell will be used to study the fundamentals of the ECM process, and to do process development on a small scale to develop new electrolyte solutions, cathode materials, and electro-chemical pulse signatures. The knowledge and technology developed using this cell will be later ported to the Cool Pulse 1000 for final validation and use.

a)



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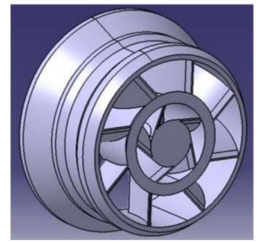

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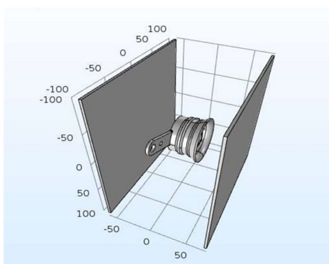

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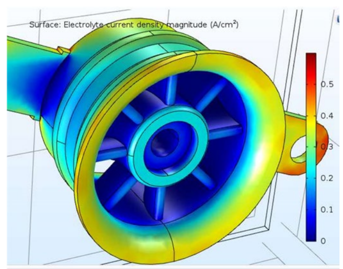

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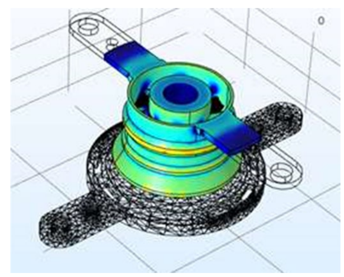

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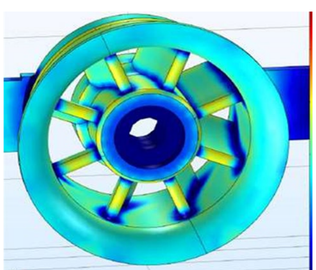

g)

Figure 4. CoolPulse 1000 Electro-Chemical Finisher: a) Coolpulse 1000 in Penn State Lab; b) electro-chemical reaction within Coolpulse*; c) part typically machined*; d) part between two cathode plates*; e) E field resulting from plate cathodes*; f) part enclosed within conformal cathode assembly*; E field resulting from conformal cathode assembly*; courtesy of Extrude Hone

Figure 5. AB04 Weir Tank

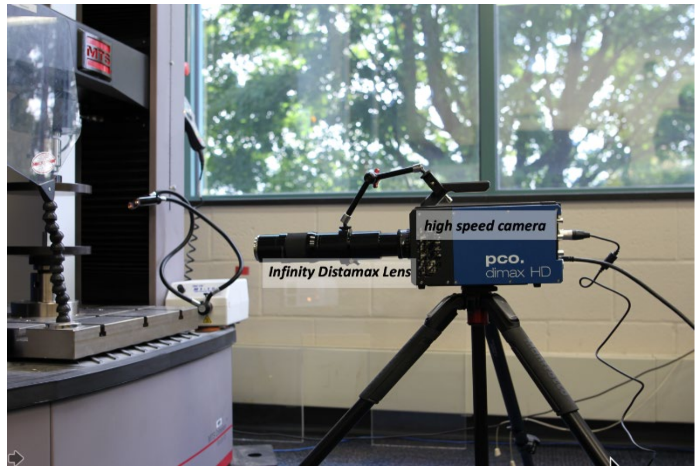

Figure 6. High Speed Camera System

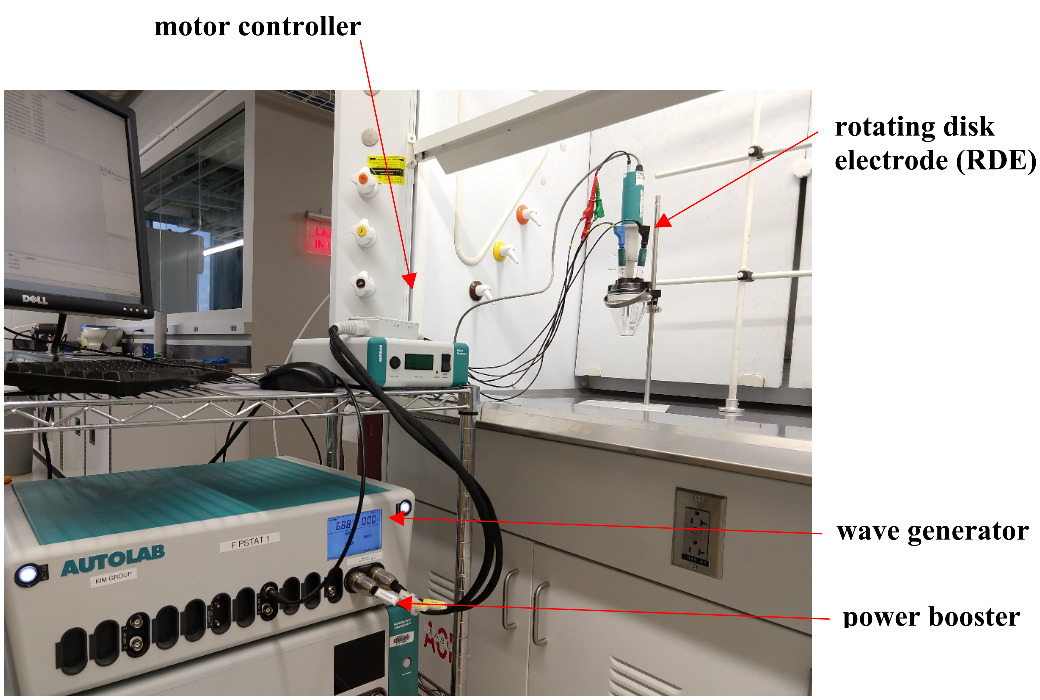

Figure 7. Mini-ECM Equipment

Partnerships

With the establishment of the Superfinishing Laboratory, IME has directed its energy toward fundamental processing research, process capability enhancement, the development and publication of "design-for-finishing" knowledge for the AM community, and the education of engineering students. IME has also made the lab available to personnel from the Center for Innovative Materials Processing 3D (CIMP-3D) and Engineering Shop Services (ESS).

CIMP-3D of the Applied Research Lab (ARL) at Penn State is a world leader in the research and development of metal printing processes. It has a strong history of funding from private and government agencies, with the U.S. Navy being its largest sponsor. CIMP-3D and its sponsors currently have an interest in understanding the relationships between printed surface texture, fatigue, and corrosion as well as how to best superfinish printed surfaces to achieve optimal performance. They currently have invested in the training of their engineering personnel on the operation of the superfinishing processes and are actively using them on a project currently sponsored by NAVAIR.

EES provides contract manufacturing services for the Penn State academic community as well as for ARL They have also invested in training their technical staff on the use of the processes with the intention of providing contract finishing services to the Penn State community. It is anticipated that these services will be widely used by Penn State faculty wishing to study the effect of surface texture on fatigue resistance, corrosion resistance, fluid flow, and heat transfer.

IME has also established a partnership with Extrude Hone and Walther Trowal. Both organizations have agreed to provide unlimited access to their processing engineering staff for technical advice. Extrude Hone has also generously agreed to provide AFM media free of charge to support fundamental research as well as provide advice on media formulation under a non-disclosure agreement. They have also agreed to open up the controller of the CoolPulse 1000 so that Penn State personnel can carry out fundamental process research. Lastly, they have expressed support for funding fundamental research at the university. In return, IME will keep Extrude Hone current with its research and steer its engineering students towards internships at Extrude Hone.

On Going Projects

CIMP 3D is currently engaged in the following NAVAIR sponsored project:

- Title: NAVAIR Additive Manufacturing – O&M, RDT&E
- Sponsor: NAVAIR
- Period of Performance: 07/17/2018 to 07/16/2019, 08/15/2018 to 08/14/2019
- Total Award Amount: $2,000,000, $1,000,000 (both partially funded)
- Contact: Greg Welsh (gregory.welsh@navy.mil)
- PI: E.W. Reutzel

The objective of the project is to support NAVAIR in developing and implementing AM for fleet use, in the same vein as the AM Ti6Al4V link and fitting, a critical safety item flown in a V-22 Osprey in a flight demonstration in July 2016. Efforts include the development and assessment of methods to assess and improve the quality of AM builds.

Laser powder bed fusion (L-PBF) and directed energy deposition (DED) processes are capable of creating geometrically complex, near net shapes. For applications in which fatigue is not a concern, these parts are subjected to primary machining processes to create functional surfaces. However, for applications in which fatigue is a concern, it has been standard practice to machine off the entire skin of the part for purposes of creating fine textured surfaces. Unfortunately, these parts are typically comprised of difficult to machine metal alloys, and are slow and expensive to machine.

CIMP 3D is currently investigating the use of superfinishing processes to smooth the textures of printed parts intended for fatigue applications. The advantage of secondary machining processes is that numerous part surfaces, large or small, may be simultaneously processed, thus reducing both the lead time and cost of smoothing the non-functional surfaces of AM parts.

An initial study is being carried out using ASTM E66 fatigue specimens printed from Ti_6Al_4 powder using the L-PBF process. The plan is to use all four technologies to polish these specimens while documenting machining time and the evolution of surface texture and stock removal. A second planned study will use these technologies to superfinish a redesigned, printed bracket from the H-53 Super Stallion.

Initial trials with the fatigue specimens have been executed using the TT-45 centrifugal disk finishing machine in combination with PI 4 X 10 ACT media. Fig. 8 illustrates the samples before and after 30 minutes of processing. The average surface roughness (Ra) of the "as printed" specimens was 25.0 µm. The average surface roughness of the processed specimens was 5.4 µm with an average material loss less than 0.02 mm. This study is to be continued with processing time increased to eventually realize an average surface roughness ≤ 25.0 µm.

Fig. 9 shows the tooling and specimen set up for processing in the CoolPulse 1000. The machine is to be run in "cathode" mode where it is assumed that the cathode conforms to the part surface to within a distance of 4mm +/- 3 mm. For this application, the cathode is intended to polish half the specimen. It will be subsequently flipped and polished in a second cycle. The cathode was printed from 420 stainless steel using a binder jet AM-post sintering process and was subsequently infiltrated with bronze. The supporting fixture was printed from ABS using a fused deposition AM process. The cathode and base for the Super Stallion bracket have been recently completed.

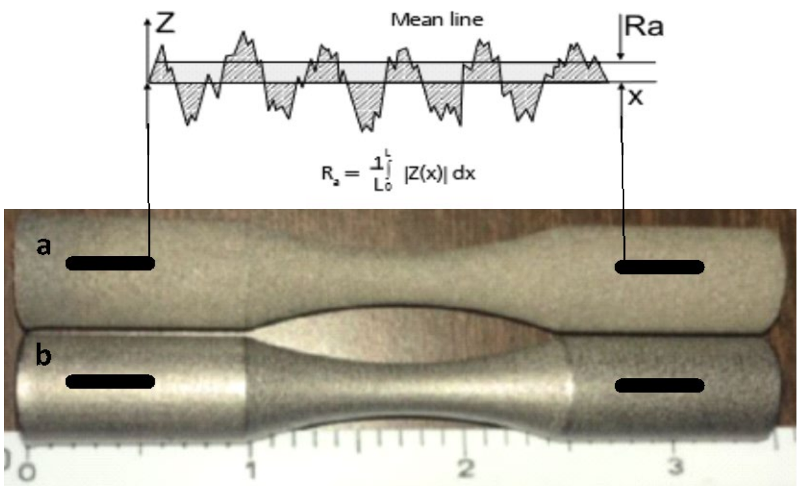

Figure 8. Fatigue Specimen: a) fatigue specimen in the as printed built condition with an average surface roughness Ra = 25.0 um; b) fatigue specimen after 30 minutes of processing with the TT 45 with Ra = 5.4 um

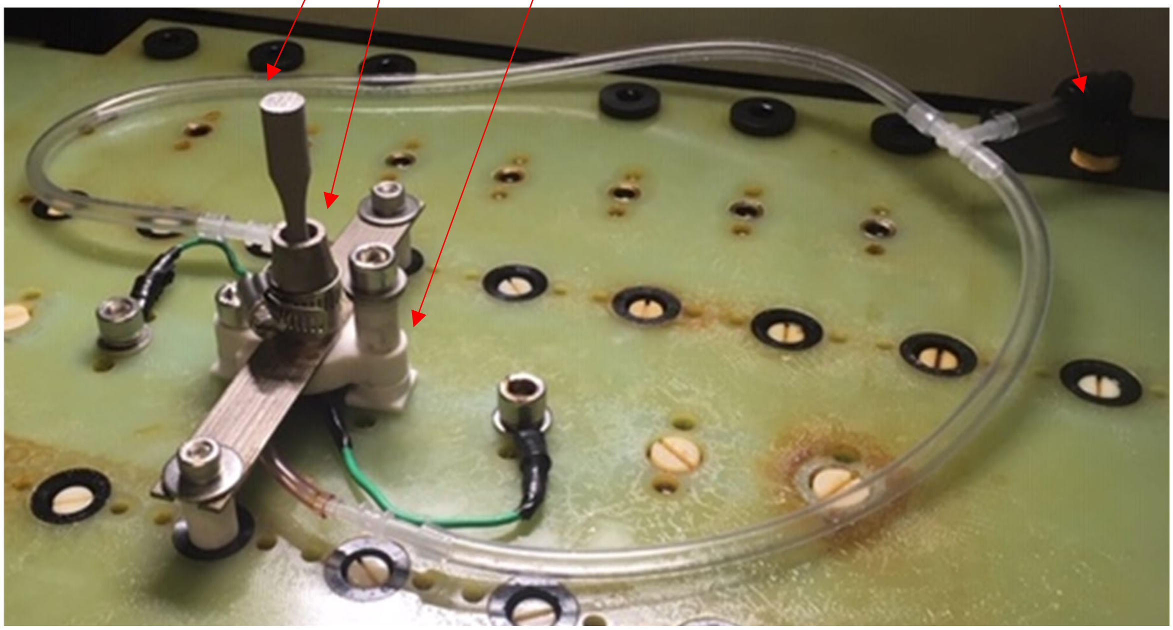

Figure 9. Cool Pulse 1000 Set UP for Machining a Fatigue Specimen

TRAINING
Faculty, engineers, technical staff, and graduate students from IME, CIMP 3D, and ESS have received operation and maintenance training for the machines in the Superfinishing Laboratory. Furthermore, both Extrude Hone and Walther Trowal have agreed to provide technical advice for future projects.

DISSEMINATION
None to report.

PLANS

<u>IME Thesis Research</u>
Presently, two Ph.D. candidates have initiated thesis work in the areas of abrasive flow machining and electro-chemical machining. This past summer they designed and fabricated experimental apparatus for executing finishing experiments on the Vector 150 and the CoolPulse 1000. It is anticipated that these experiments will start by the beginning of October. The students have also been reviewing the research literature to identify research topics. Once this is completed, white papers will be submitted to ONR and other funding agencies to gage interest. We are also seeking a third Ph.D. candidate to do work in the area of multi-vibe finishing. Lastly, we are seeking Schreyer's honors undergraduate students to do thesis work in the lab and take advantage of the Extrude Hone internship opportunities.

<u>IME-PGM De-Burring Project</u>
Precision Grinding & Manufacturing (PGM) is a mid-size contract manufacturer based in Rochester, New York. They specialize in high precision fabrication, with the majority of their work directed toward the defense and biomedical industries. IME and PGM are currently collaborating on a project to investigate the effectiveness of the Cool Pulse 1000 at deburring tight tolerance, internal threads.

MAMLS III Project

CIMP 3D is currently engaged in the following project:

- Title: Understanding Stochastic PBFAM Flaw Formation and Impact on Fatigue
- Source of Support: USAF through America Makes / NCDMM
- Period of Performance: 6/8/2018 to 6/7/2020
- Total Award Amount: $988,000 + $494,886 cost share
- Sponsor: USAF through America Makes/NCDMM
- Subawardees: 3D Systems, Oerlikon, Moog, UTRC
- Contact: Dave Siddle (dave.siddle@ncdmm.org)
- PIs: E.W. Reutzel, A.R. Nassar

The objective of this project is to produce pedigreed L-PBF fatigue data to determine the influence of L-PBF flaws on fatigue properties, and utilize advanced sensing and process modeling to investigate the formation of stochastic flaws. Work includes the analysis of CT scan data of 150 fatigue test coupons. It also employs multiple process sensors, high speed video, and CT scans to understand the physics of stochastic flaw formation.

IME and CIMP 3D have agreed to run a supplemental surface finishing study on a subset of the coupons used for this study. Presently it is known that HIP is unable to heal surface interconnected porosity defects that originate during the L-PBF process. It is also known that the surfaces of HIP'd printed parts may be smoothed using abrasive finishing processes to R_a values less than 0.2 µm, but still have surface interconnected porosity defects as shown in Fig. 10. Furthermore, these defects, in combination with the randomly distributed, unhealed porosity defects, severely degrade fatigue strength.

An objective of this supplemental study is to determine whether there is increased likelihood of finding unhealed defects closer to the surface and if so, their spatial relationship to the roughness average surface. This data in combination with equivalent data for interconnected surface porosity defects will be used to derive recommended stock removal specifications.

The validity of these specifications will be tested by using abrasive finishing processes or electrical chemical machining processes to smooth printed surfaces to equivalent levels of roughness using varying depths of material removal, including machining deep into the substrate. These specimens will be CT scanned to examine the resultant defect distributions and later fatigue tested.

Another objective of this study is to determine whether the electro-chemical machining process preferentially removes different alloying elements in Ti_6Al_4. To determine this, SEM and metallography will be performed on a subset of specimens abrasively machined or electro-chemically machined to characterize the intergranular alloy composition at the surface.

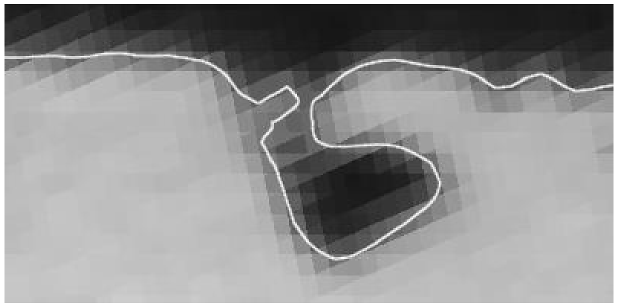

Figure 10. CAT Scan of the Surface of a Ti_6Al_4 Part that was printed using Laser Powder Bed Fusion, Hot-Isostatic Pressed, and Superfinshed with the Image showing a Smooth Surface (R_a < 0.2 μm) and a Surface Interconnected Porosity Defect; Courtesy of CIMP 3D

<u>Curriculum</u>
The secondary machining lab will be used to support student projects in the 2019/2020 academic year for the following courses:

- IE 527 Additive Manufacturing Processes
- ME 566 Metal Additive Manufacturing Lab

These are required courses for the Additive Manufacturing MS degree currently being offered by Penn State. The projects will explore technical issues related to the superfinishing of AM parts including the development of "design for superfinishing rules" for the AM community and the best routes to additively manufacture tooling for the Vector 150 and CoolPulse 1000. Undergraduate honors thesis projects and senior design projects are being planned for the Spring 20 semester. A superfinishing processes courses is being planned as well.

<u>EES Projects</u>
At the time of this writing, EES is currently using the Vector 150 and abrasive flow machining to de-powder, de-burr, and smooth the surfaces of a printed turbine blade for a sponsored research project. This is being done to characterize changes in blade air flow and heat transfer characteristics in response to changes in blade surface roughness. EES is also in the initial stages of designing tooling and AFM processes to support the ARL Underseas System Office in support of the U.S. Navy's undersea programs.

HONORS
None to report.

TECH TRANSFER
None to report.

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14. ABSTRACT
The goal of this Defense University Research Instrumentation Grant is to establish an infrastructure at Penn State to enable research and education in the area of superfinishing processes; with a special focus on additively manufactured parts used for high performance naval applications. The laboratory has been established, graduate student research has been initiated, curriculum integration has been initiated, strategic partnerships within the university have been formed to maximize the R & D usage, and the equipment is currently being used to support U.S. Navy funded projects.

15. SUBJECT TERMS
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