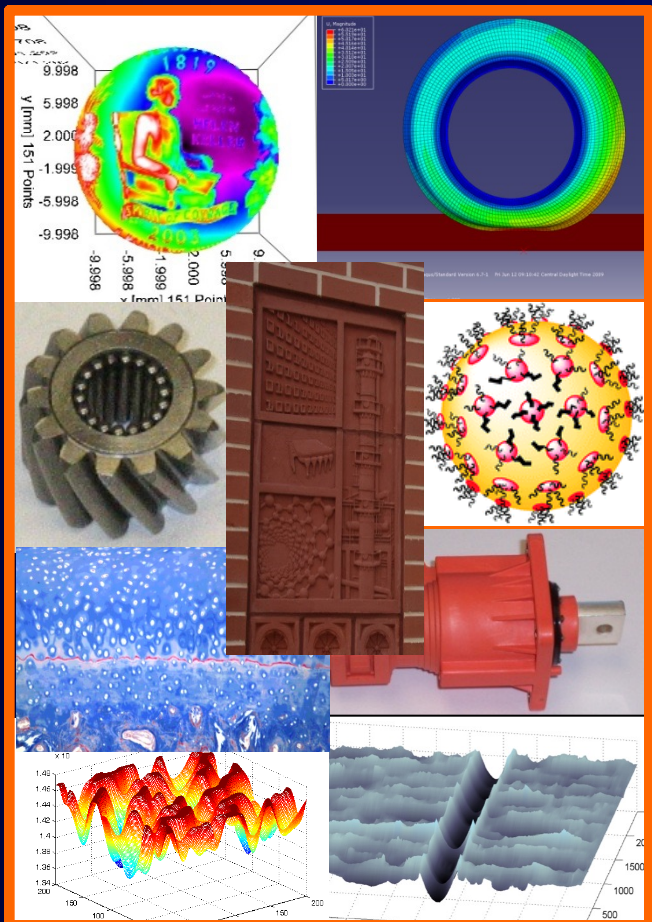

Metalworking Fluids in Hybrid Manufacturing

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+Department of Industrial and Systems Engineering

Auburn University

AUBURN UNIVERSITY

TRIBOLOGY AND LUBRICATION SCIENCE MINOR

The Interdisciplinary Center for Advanced Manufacturing Systems (ICAMS)

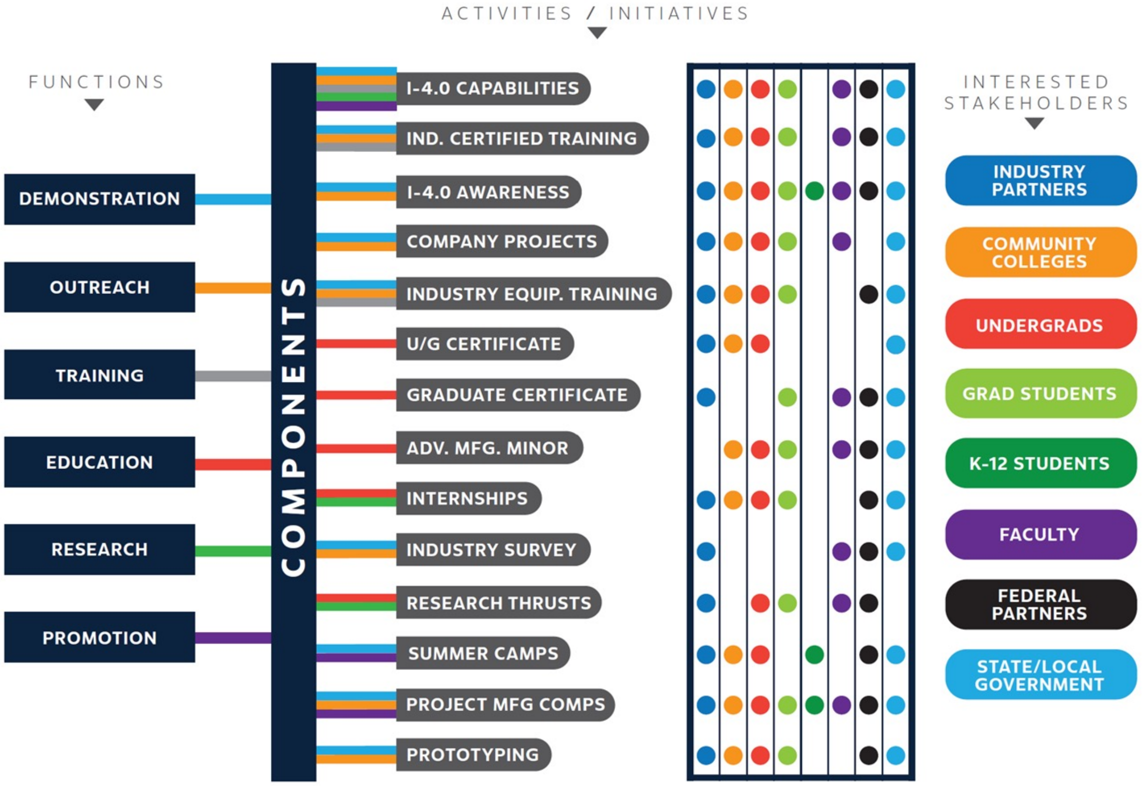
Dr. Gregory A. Harris, P.E. – Director, ICAMS
Auburn University

What ICAMS Does

Vision

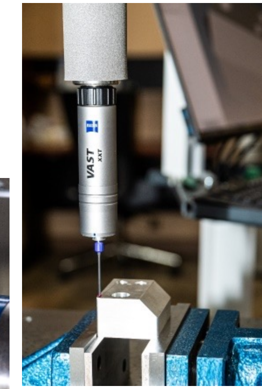
ICAMS strives to be the premier center for Advanced Manufacturing Technology demonstration, research, education, and adoption in the US.

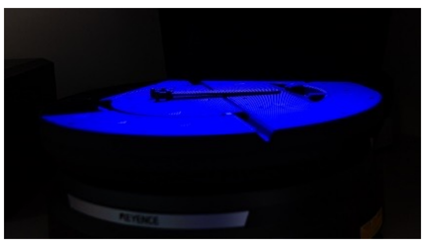
ICAMS features a functioning advanced manufacturing factory, and uses engagement with SMMs, to educate and train the next generation of engineers needed to ensure a successful digital transformation of the industrial supply network.



Facility footprint

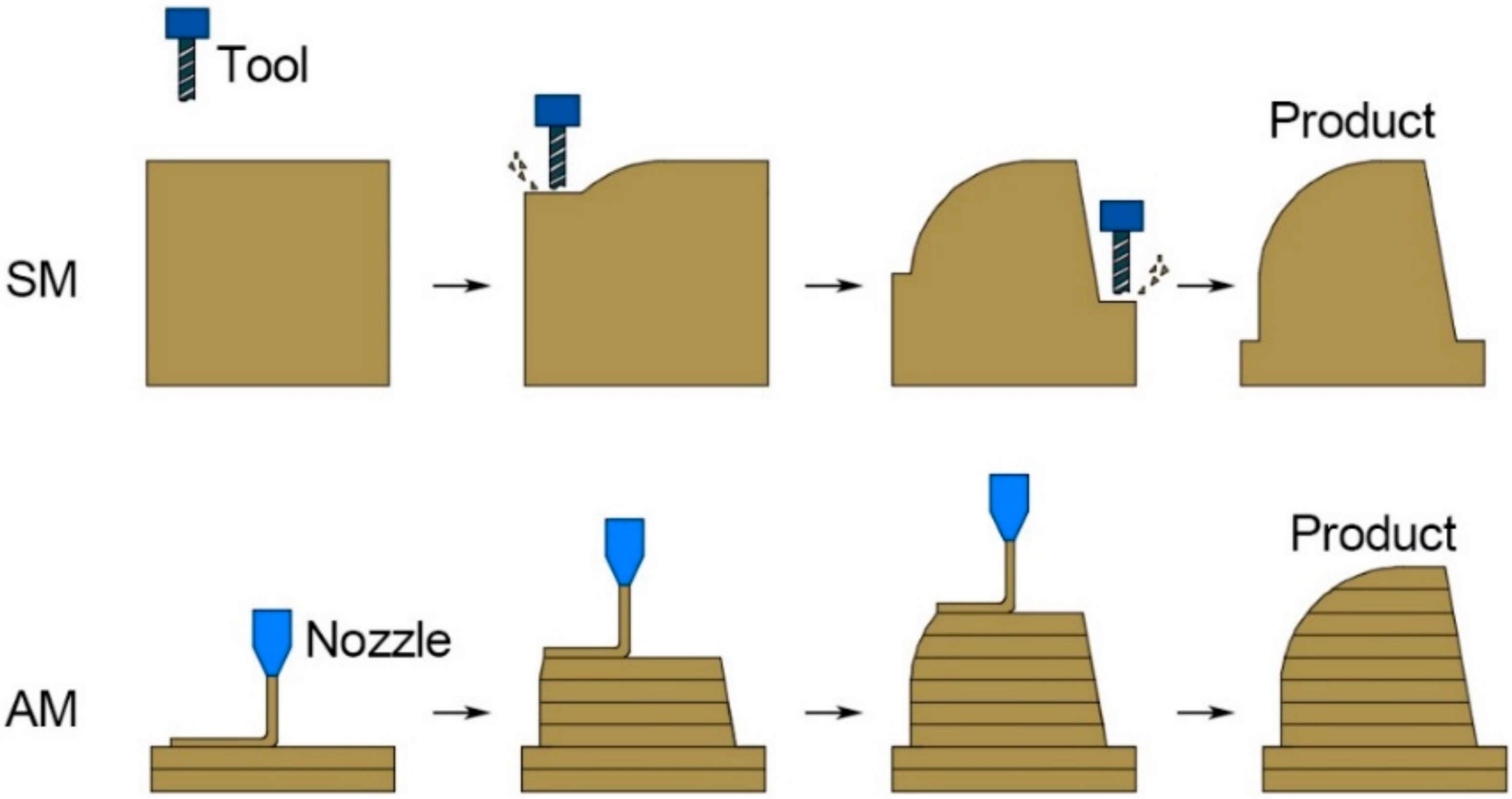
Advanced Manufacturing - ICAMS



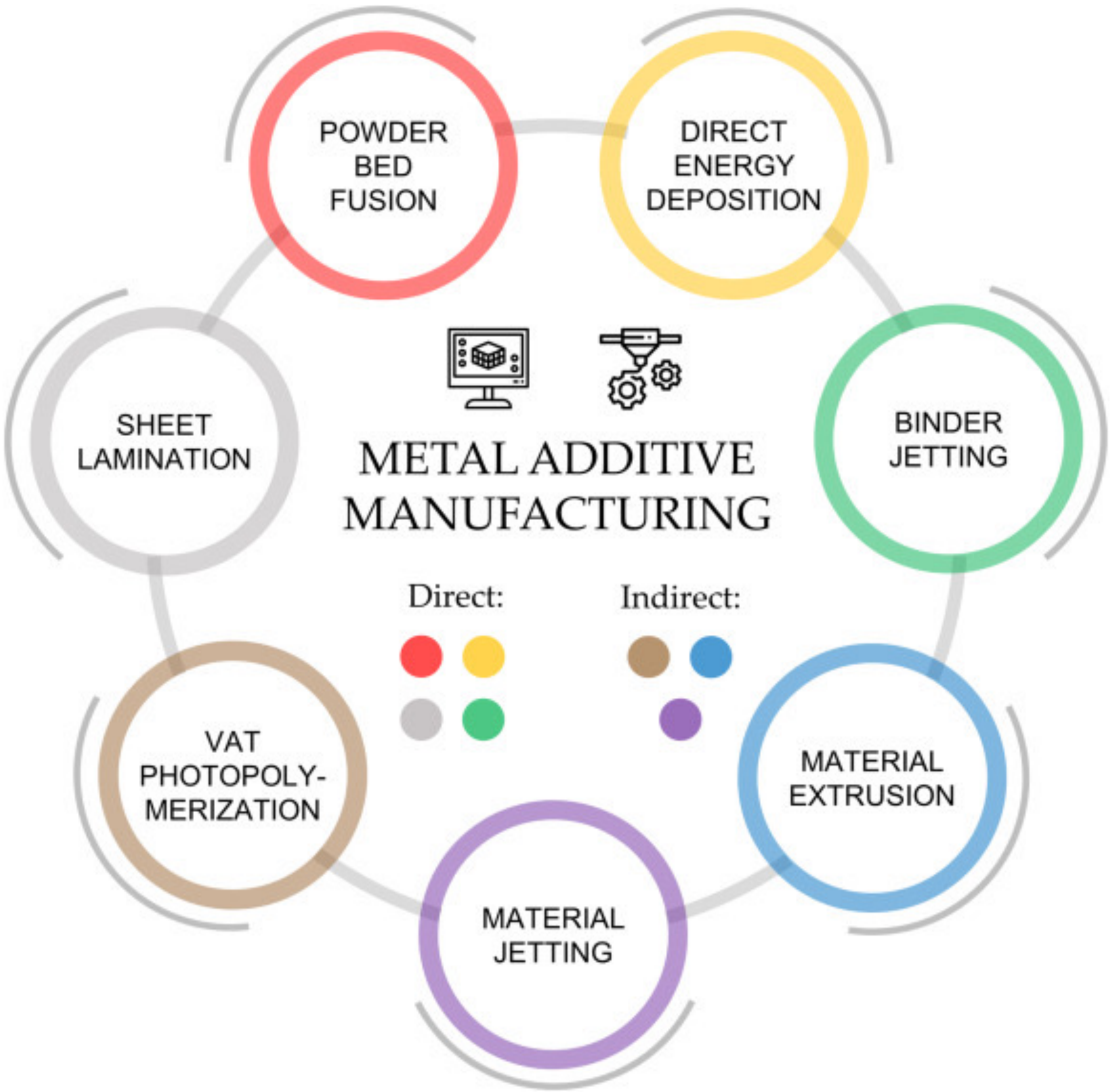


Aubie @ ICAMS

Additive vs. Substractive Manufacturing

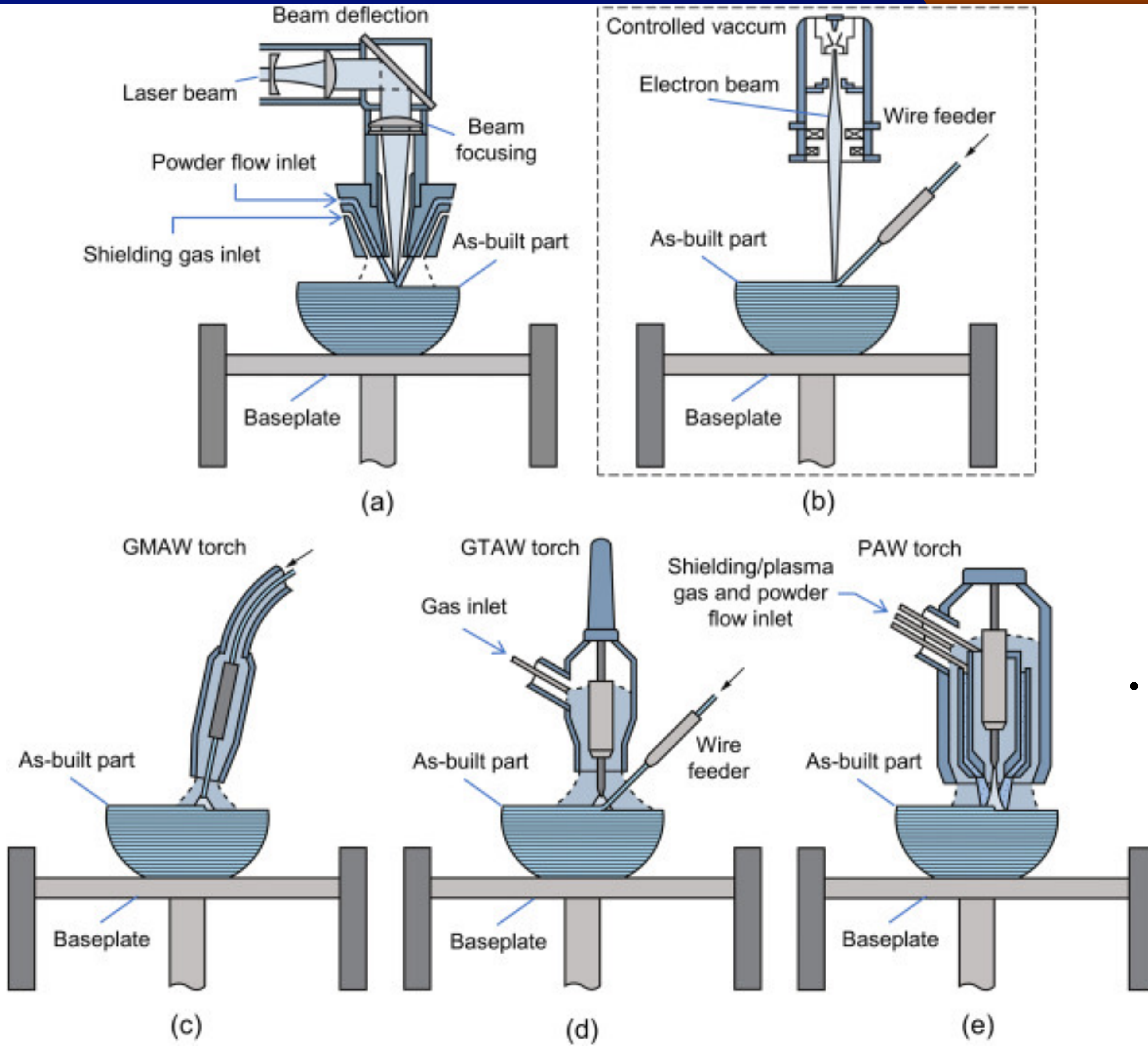


Types of Additive Manufacturing



- Pragana, J. P. M., et al. "Hybrid metal additive manufacturing: A state–of–the-art review." *Advances in Industrial and Manufacturing Engineering* 2 (2021): 100032.

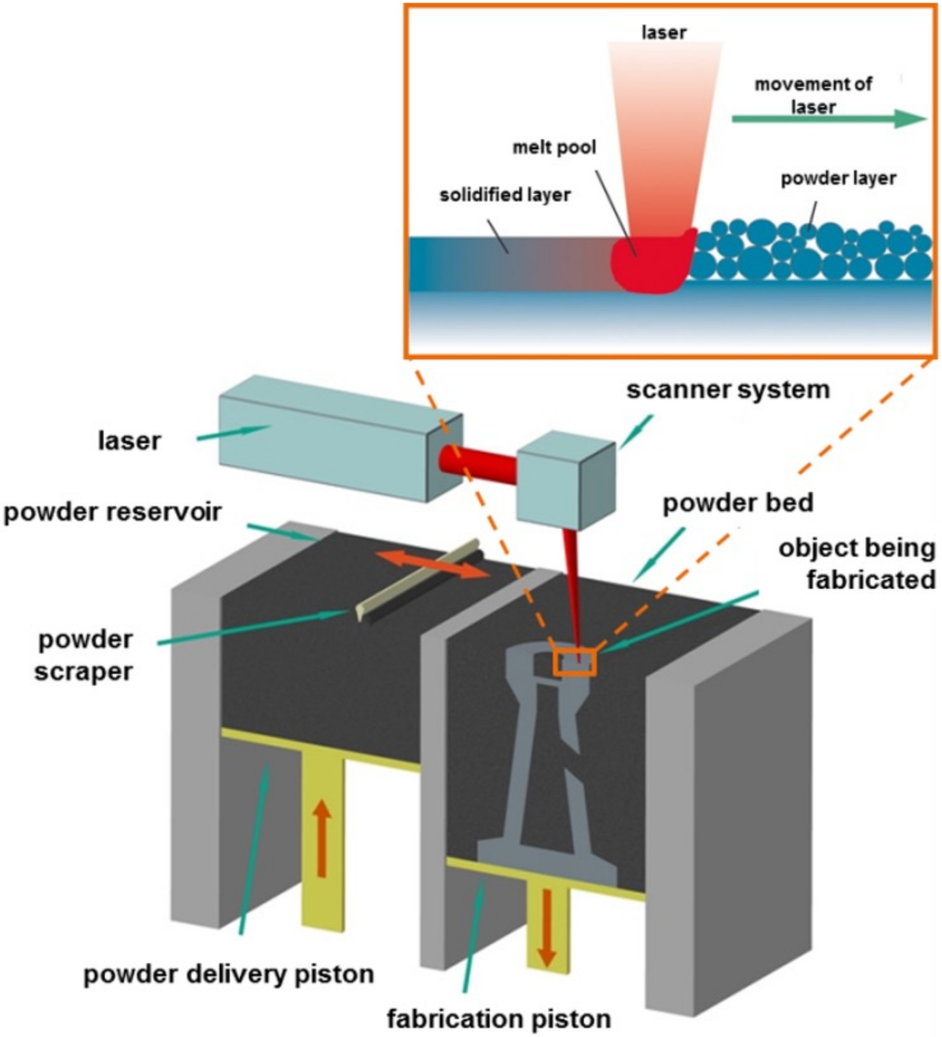
Direct energy deposition



- Pragana, J. P. M., et al. "Hybrid metal additive manufacturing: A state–of–the-art review." *Advances in Industrial and Manufacturing Engineering* 2 (2021): 100032.

Laser Beam Powder Bed Fusion (LB-PBF)

EOS M290



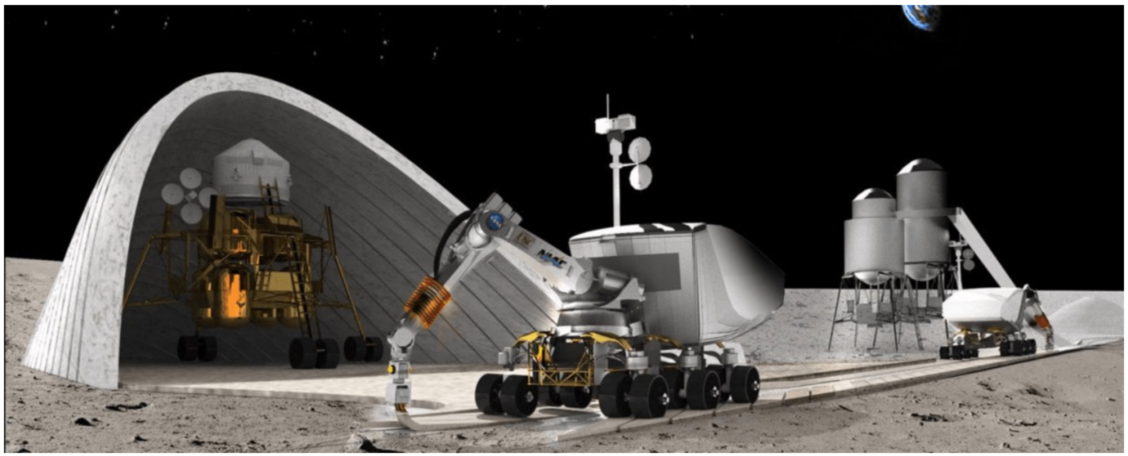
P.D. Nezhadfar, Rakish Shrestha, Nam Phan, and Nima Shamsaei. "Fatigue behavior of additively manufactured 17-4 PH stainless steel: Synergistic effects of surface roughness and heat treatment." International Journal of Fatigue 124 (2019): 188-204.

Machining Additive Parts

- Additive manufacturing can use material more efficiently, create geometries previously not possible, create custom parts without extensive manufacturing process.
- Can combine an assembly of many parts into one printed part.
- Additive manufacturing has many limitations, such as cost, surface finish, bulk material defects such as voids.
- Difficult to finish interior surfaces.
- Surface fatigue could be an issue of additively manufactured parts.

Remote Repairs and Construction

- Transportable additive manufacturing can be used to fabricate customized tools, parts and other materials in remote locations.



https://amchronicle.com/insights/the-role-of-additive-manufacturing-in-space-exploration/

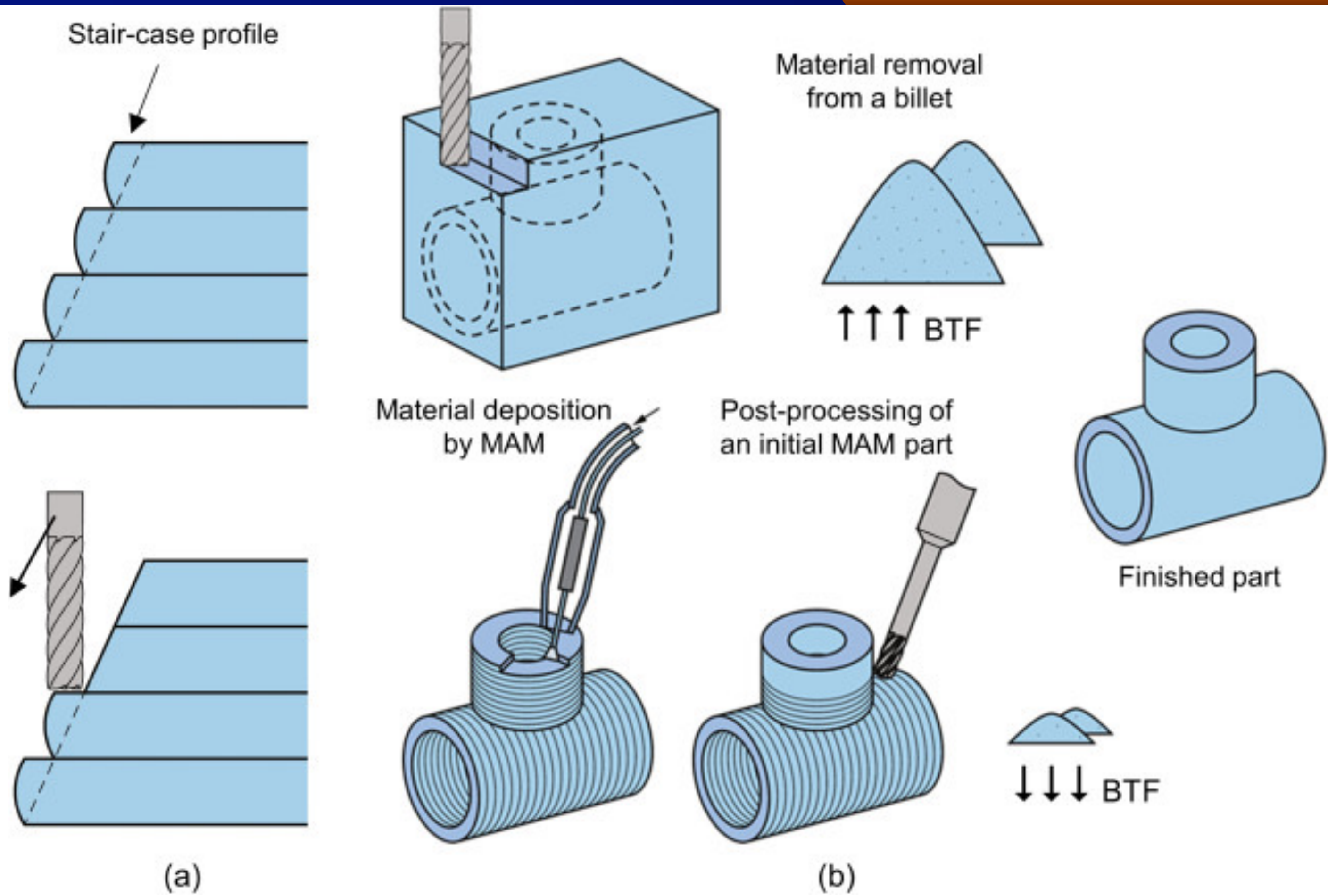
- Custom ‘bio’ parts possible that fit patients specifically.

www.bastech.com/2014/02/11/direct-metal-3d-printing-benefits-dental-lab/

What is Hybrid Manufacturing?

- Combining additive and subtractive processes.
- By combining both processes, their strengths can overcome the weaknesses of the other.

Hybrid Machining

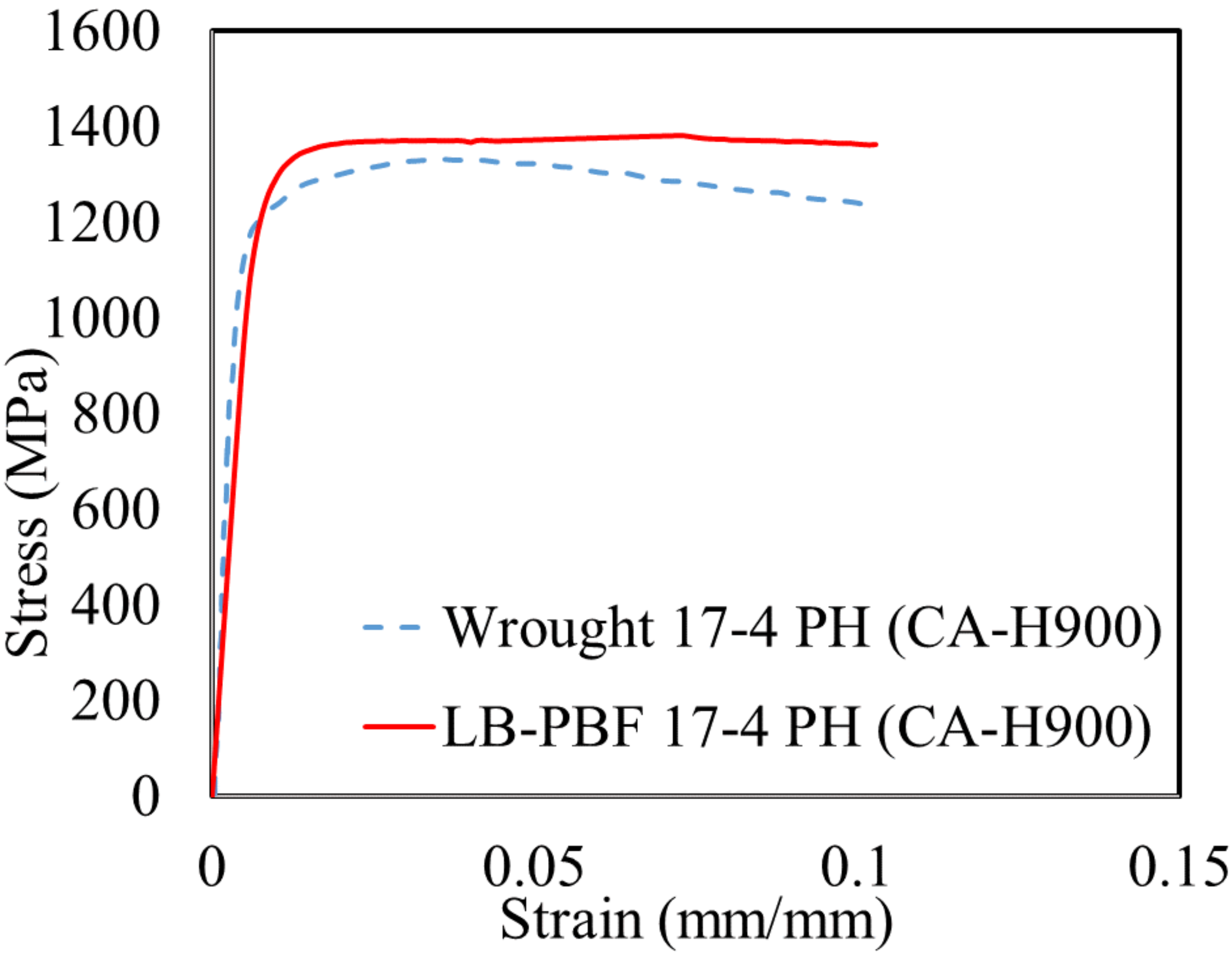


- Pragana, J. P. M., et al. "Hybrid metal additive manufacturing: A state–of–the-art review." *Advances in Industrial and Manufacturing Engineering* 2 (2021): 100032.

Attributes

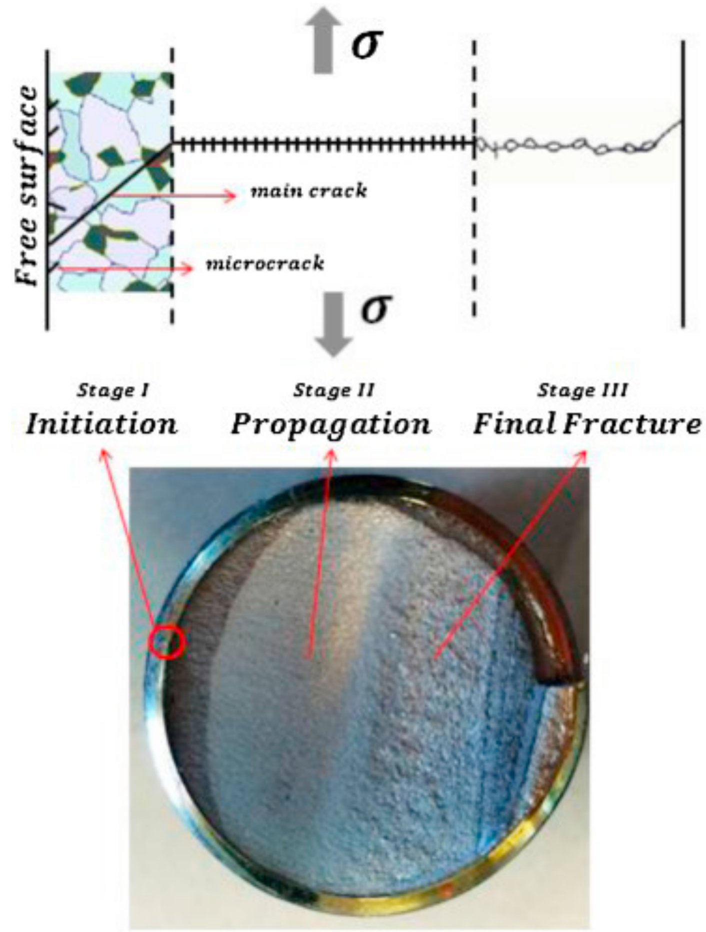
- Tolerances
  - Continuously improving and improved by hybrid machining.
- Roughness
  - Can be improved with hybrid if surfaces are accessible.
- Strength
  - Single load cycle
  - Repeated loading (fatigue)

Elastic and Plastic Properties



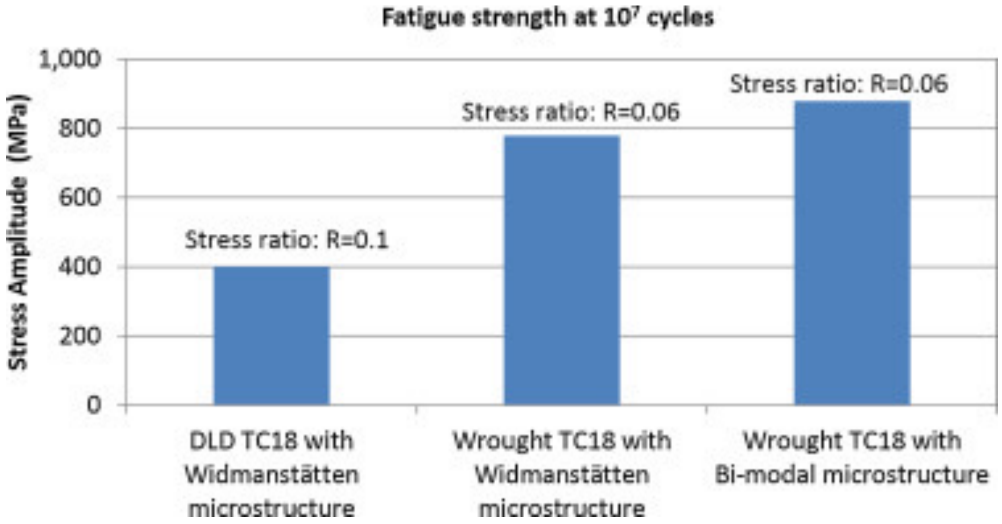
Strength vs. Fatigue

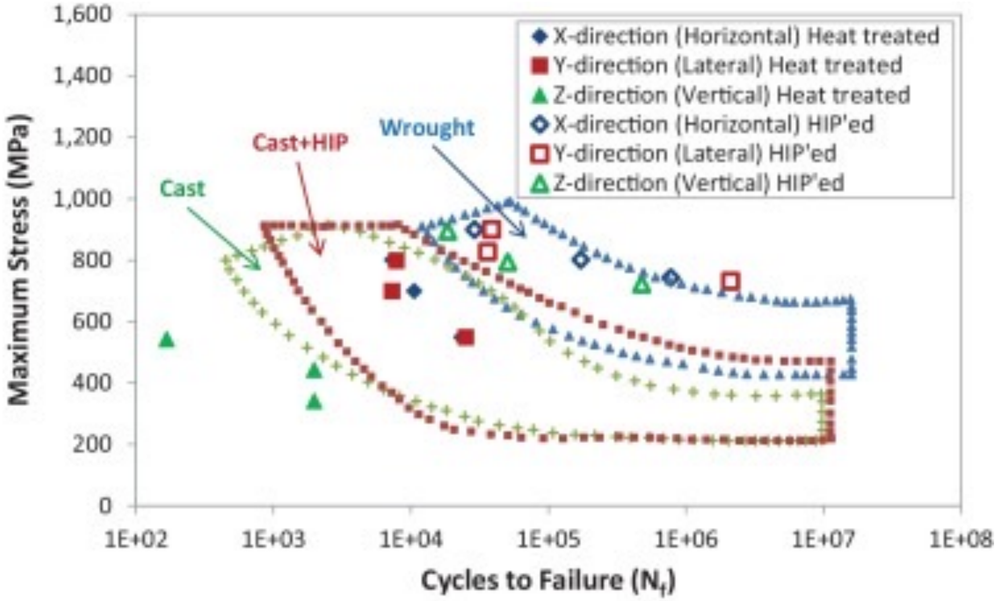
- The tensile strength of additive materials is comparable and, in some cases, higher than that of wrought counterparts (Shamsaei et al. 2015).
- This is attributed to the fine microstructure obtained because of rapid cooling during the fabrication process.
- Additive materials showed less fatigue resistance as compared to the wrought counterparts due to the presence of defects inherent to additive process.
- Could this cause a change in wear or surface fatigue?



N. Shamsaei, A. Yadollahi, L. Bian, and S. M. Thompson, "An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control," *Addit. Manuf.*, vol. 8, pp. 12–35, Oct. 2015.

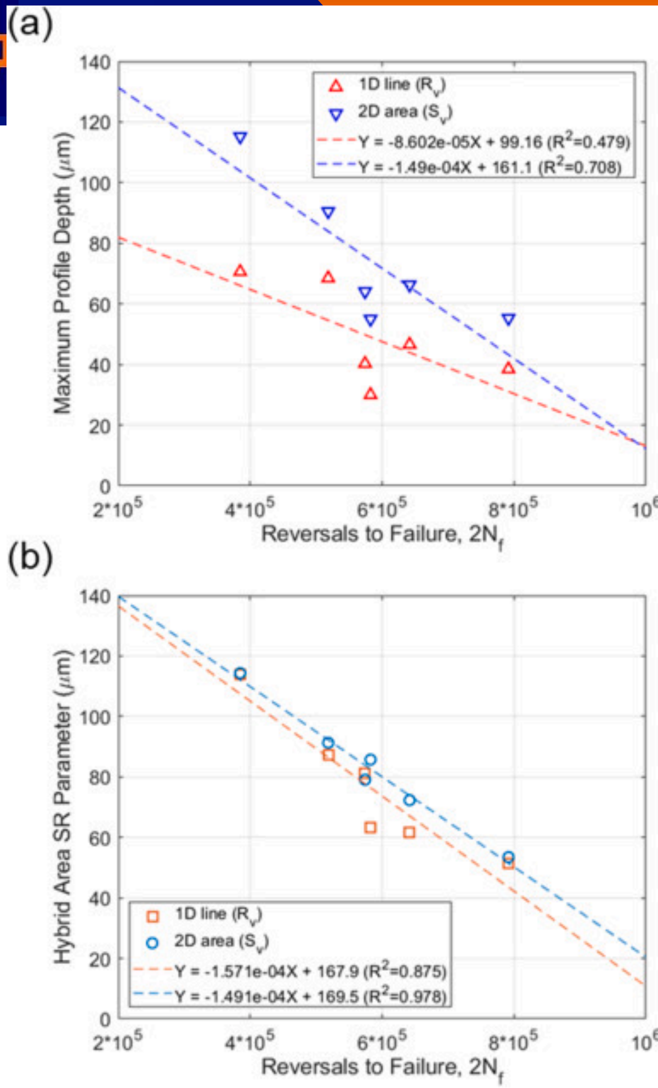
Fatigue Differences

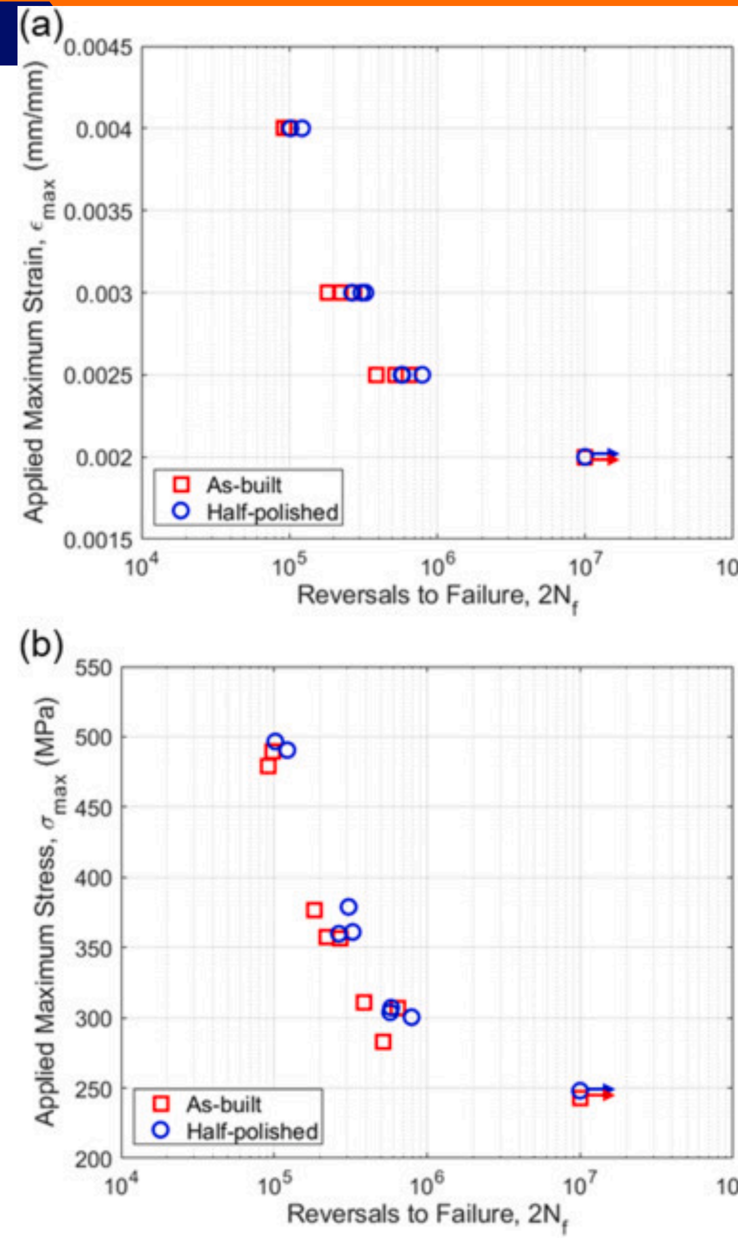




N. Shamsaei, A. Yadollahi, L. Bian, and S. M. Thompson, "An overview of Direct Laser Deposition for additive manufacturing; Part II: Mechanical behavior, process parameter optimization and control," *Addit. Manuf.*, vol. 8, pp. 12–35, Oct. 2015.

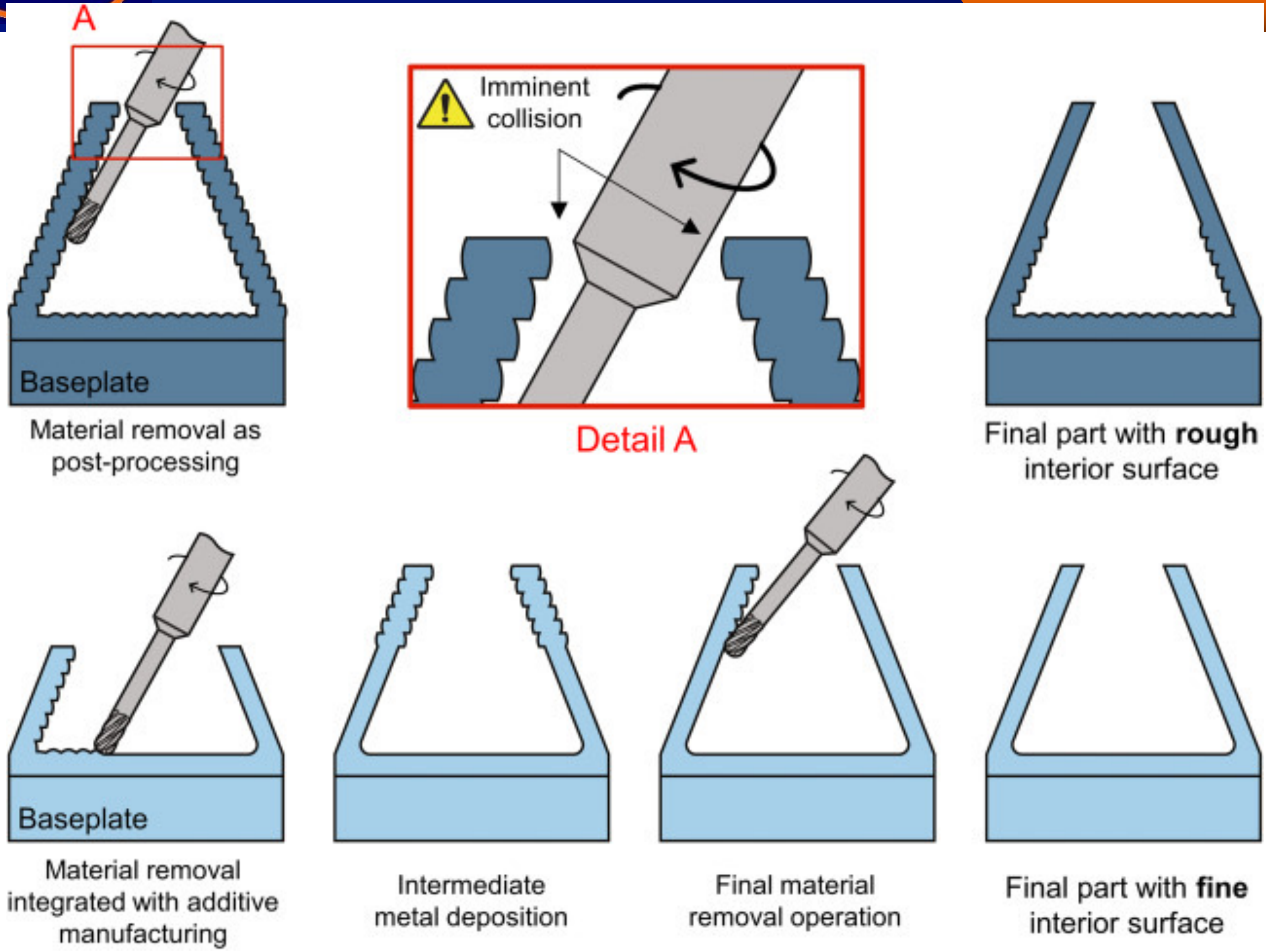
Roughness Affects Fatigue





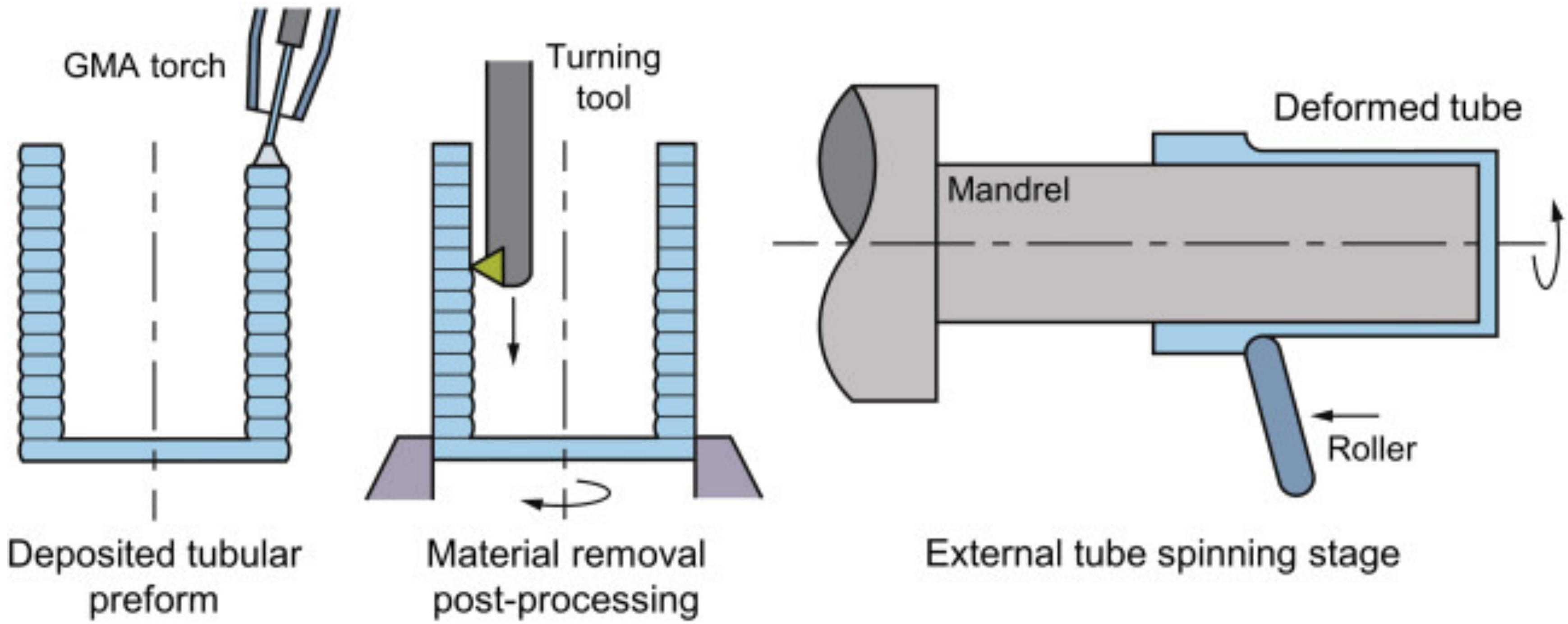
Lee, Seungjong, et al. "Surface roughness parameter and modeling for fatigue behavior of additive manufactured parts: A non-destructive data-driven approach." *Additive Manufacturing* 46 (2021): 102094.

Hybrid Machining Interior Finishing



Pragana, J. P. M., et al. "Hybrid metal additive manufacturing: A state–of–the-art review." *Advances in Industrial and Manufacturing Engineering* 2 (2021): 100032.

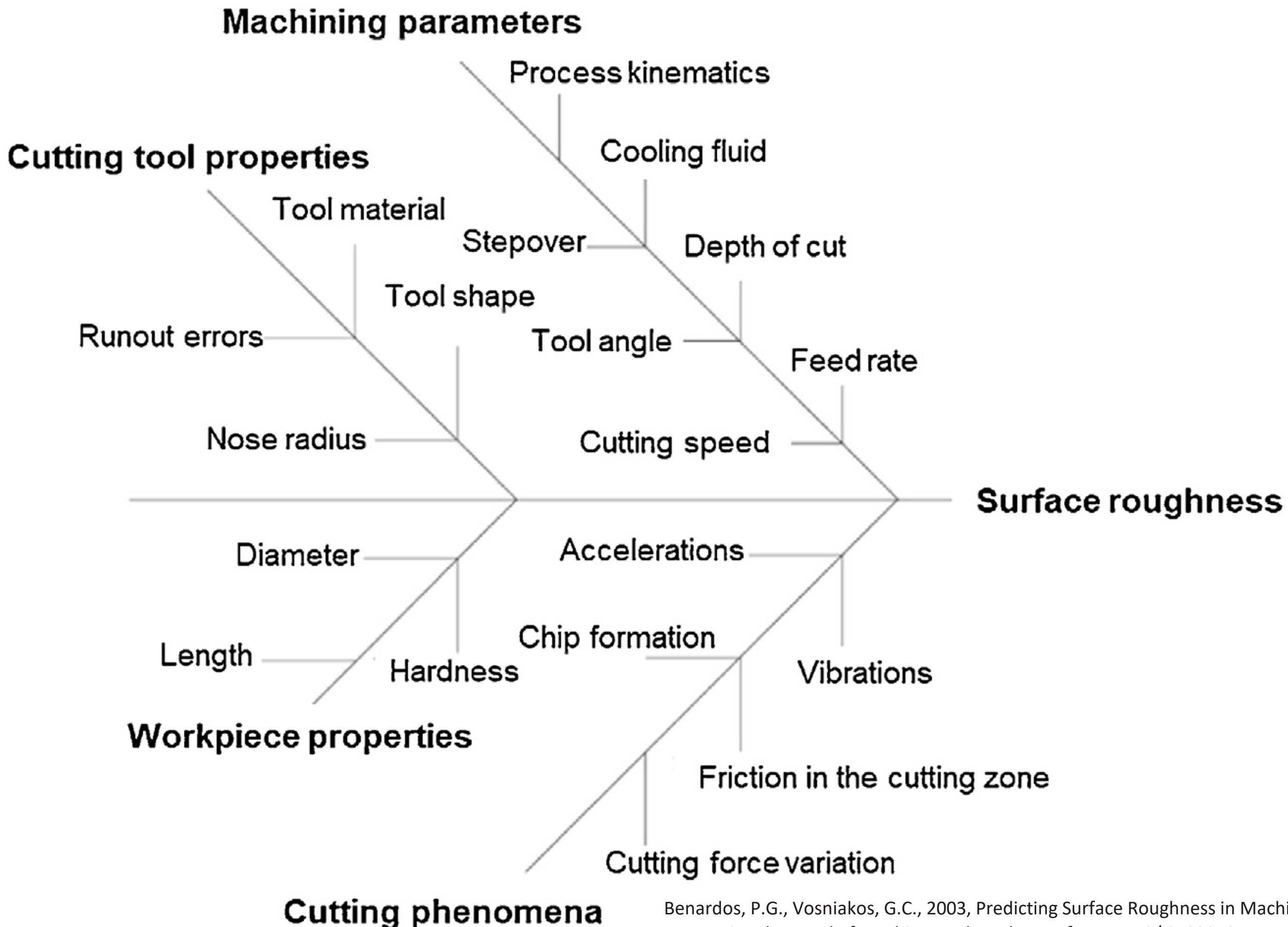
Combined Processes



- Pragana, J. P. M., et al. "Hybrid metal additive manufacturing: A state–of–the-art review." *Advances in Industrial and Manufacturing Engineering* 2 (2021): 100032.

Surface Roughness

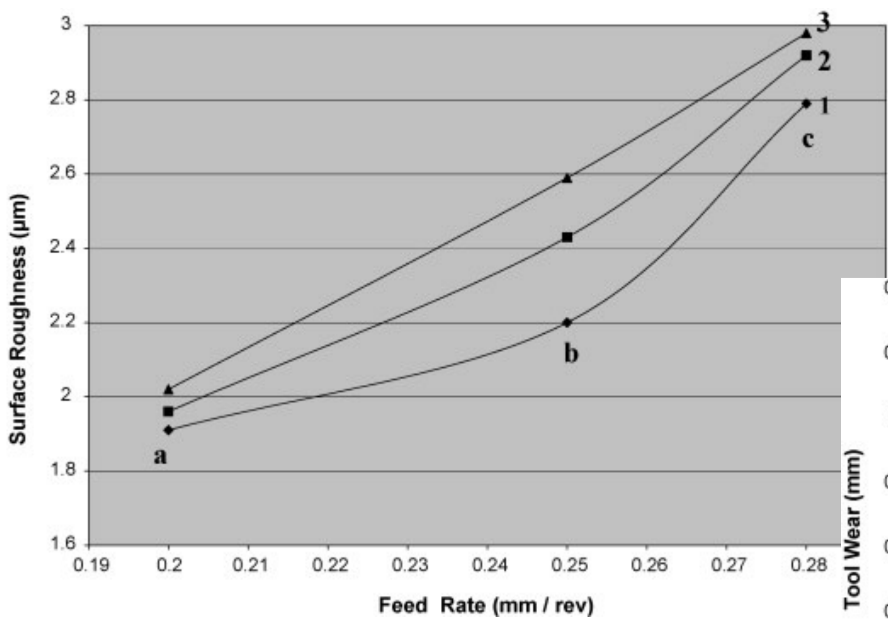
- If the goal of hybrid machining is to improve the finish (roughness), the influences must be discussed.

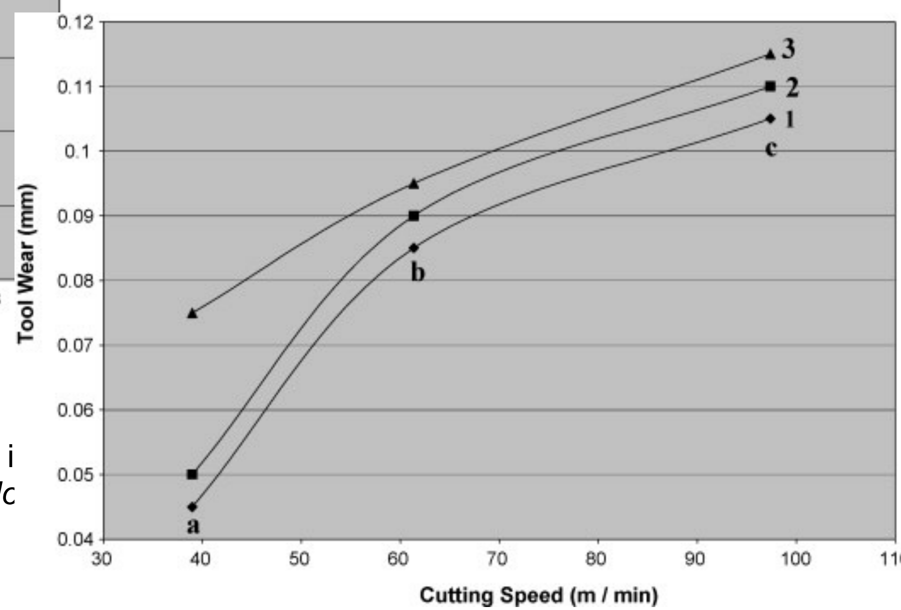


Benardos, P.G., Vosniakos, G.C., 2003, Predicting Surface Roughness in Machining: A Review. The International Journal of Machine Tools and Manufacture, 43/ 8: 833–844. http://dx.doi.org/10.1016/S0890-6955(03)00059-2.

Subtractive Manufacturing Roughness

- Proper lubrication can greatly influence roughness from subtractive machining processes.





- Xavior, M. Anthony, and M. Adithan. "Determining the i during turning of AISI 304 austenitic stainless steel." *Jc* 909.

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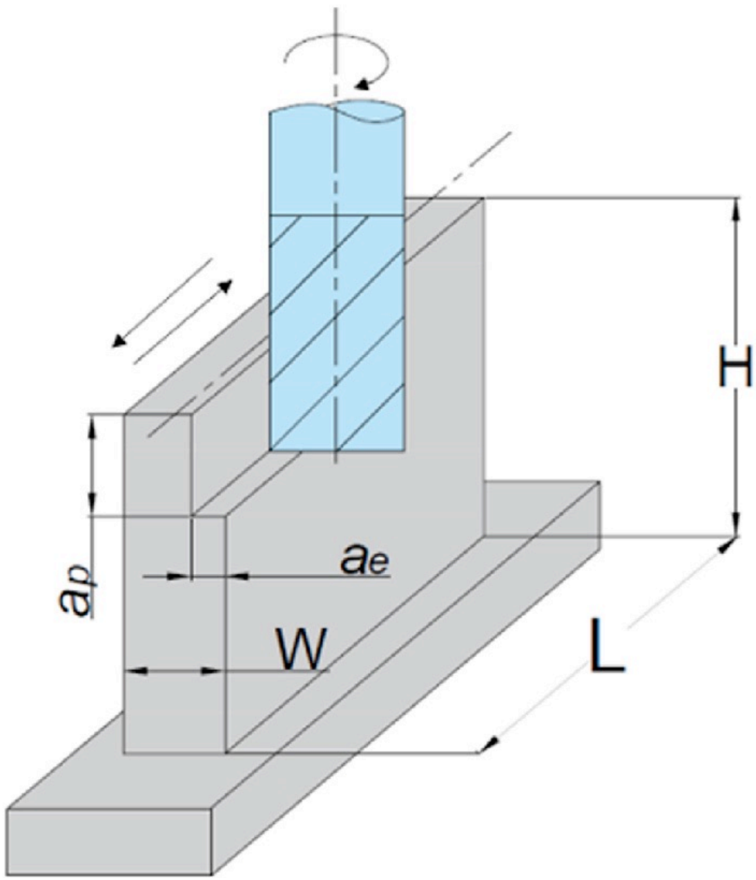
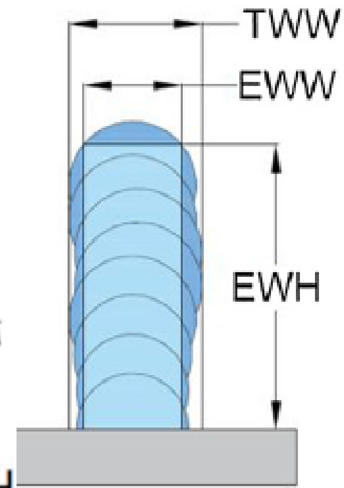
Machinibility of Additive Metal

Wire and Arc Additively Manufacturing



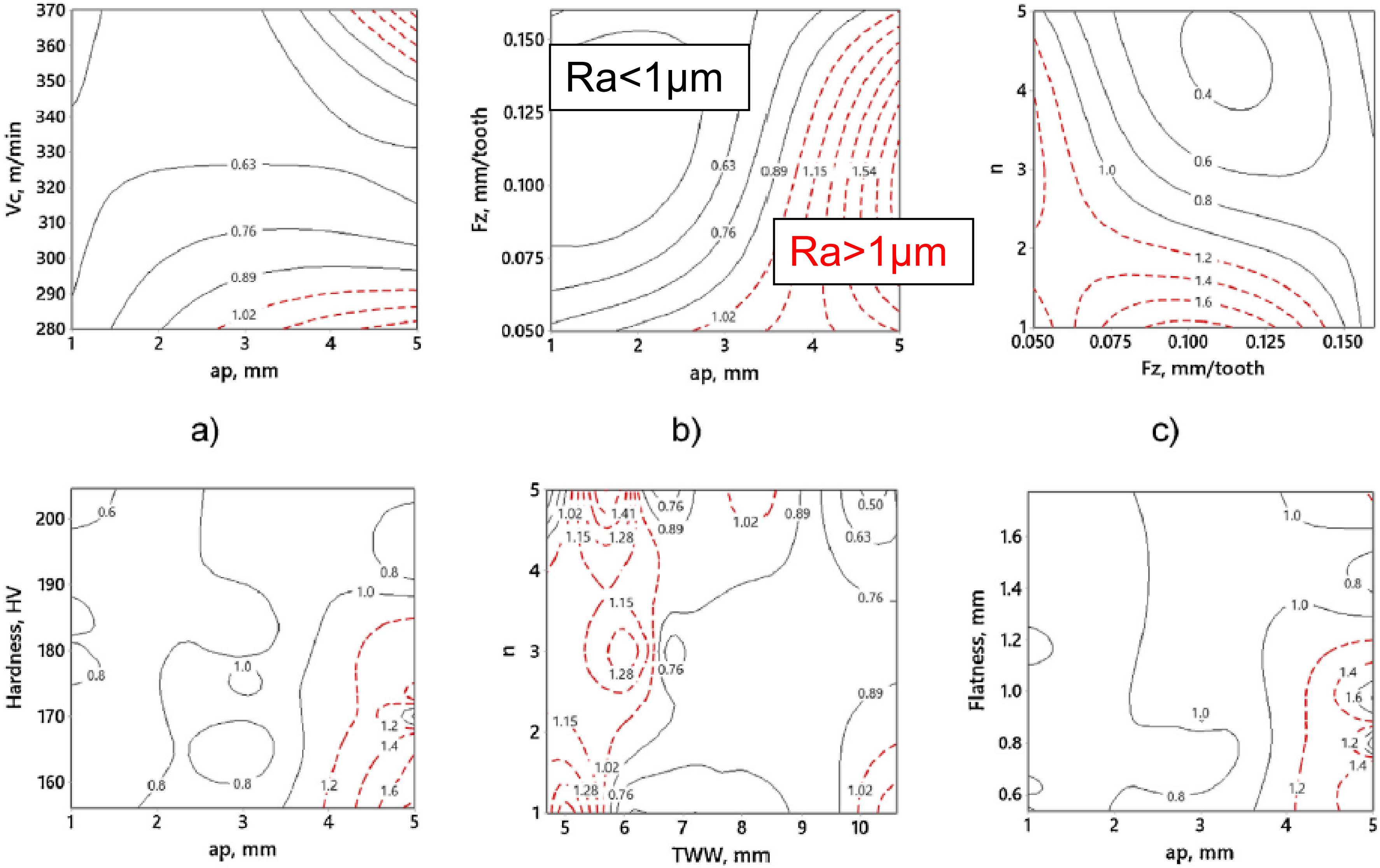


w – bead width;
h – bead height;
TWW – total wall width;
EWW – effective wall width;
EWH – effective wall height.

Wire feed speed, m/min
Travel speed, cm/min
Interpass temperature, °C
Cutting speed V_c, m/min
Feed per tooth F_z, mm/tooth
Axial depth of cut a_p, mm
Number of passes n

- Chernovol, Sharma, Tjahjowidodo, Lauwers, Rymenant, Machinability of wire and arc additive manufactured components, CIRP Journal of Manufacturing Science and Technology, Volume 35, 2021, Pages 379-389, ISSN 1755-5817, https://doi.org/10.1016/j.cirpj.2021.06.022.

Machinibility of Additive Metal

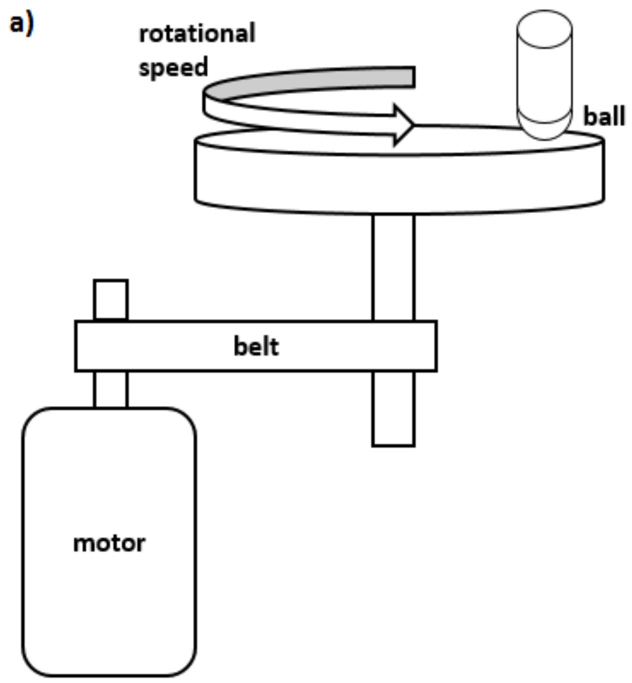


- Chernovol, Sharma, Tjahjowidodo, Lauwers, Rymenant, Machinability of wire and arc additive manufactured components, CIRP Journal of Manufacturing Science and Technology, Volume 35, 2021, Pages 379-389, ISSN 1755-5817, https://doi.org/10.1016/j.cirpj.2021.06.022.

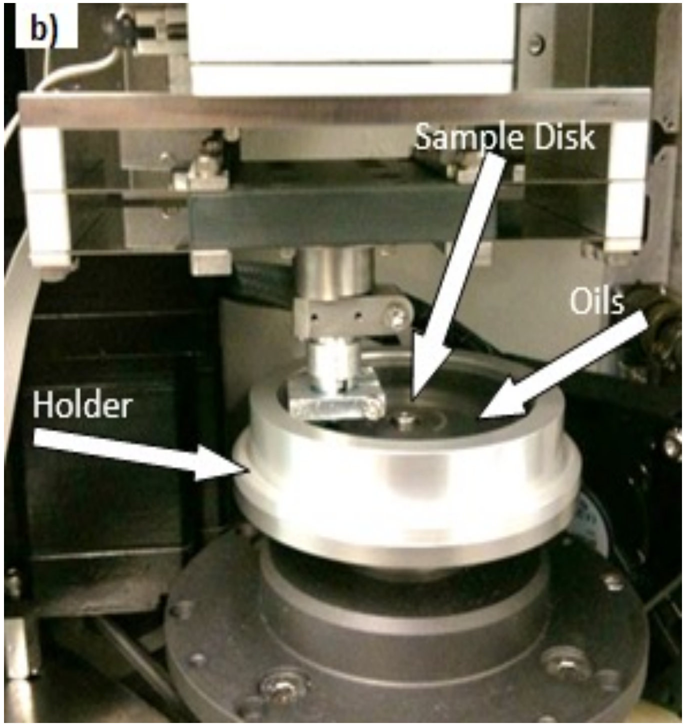
- Machinability is related to friction and wear.
- There are a few studies that study how additively manufactured materials wear differently than other parts.
- May also be an issue when hybrid manufactured parts are used in contacts or bearings.
- Will show one example.
- Sanjeev, K. C., Nezhadfar, P. D., Phillips, C., Kennedy, M. S., Shamsaei, N., & Jackson, R. L. (2019). Tribological behavior of 17–4 PH stainless steel fabricated by traditional manufacturing and laser-based additive manufacturing methods. *Wear*, *440*, 203100. https://doi.org/10.1016/j.wear.2019.203100

Ball on Disk Tribometer Test

- Tested for dry conditions at 10 and 30 N.
- Lubricated condition at 30 N.
- Dry tests run at 0.6 m/s
- Lubricated tests at 0.1 m/s
- Each repeated three times.



Bruker UMT-3



Test Samples

- Wrought samples: Disks of 17-4 PH SS specimens were cut from a wrought cylindrical sample (0.260” thickness) manufactured through traditional machining methods.
- Additive: Argon- atomized 17-4 PH SS powder with the particle size distribution (PSD) of 15-45 μm provided by LPW Technology Inc. in the additive laser sintering process.

Process parameters for 17-4 PH stainless steel provided by EOS Company

Laser power (W)	Scanning speed (mm/s)	Hatching distance (μm)	Layer thickness (μm)
220	755.5	100	40

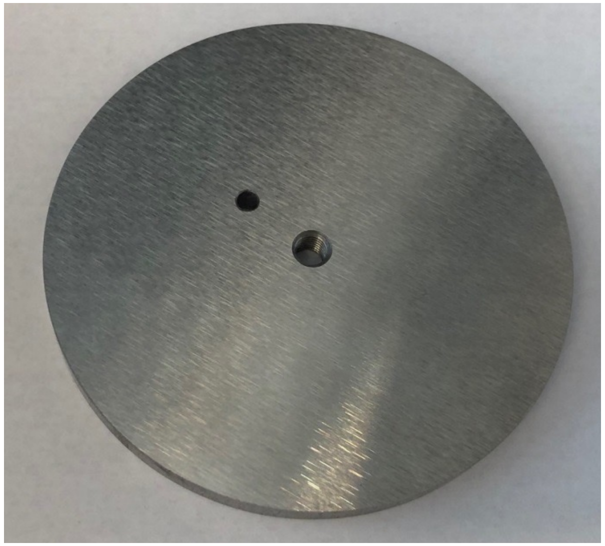
Samples tested

10 mm diameter 52100 high carbon chrome steel balls were used to load against the disk samples. The balls have a Rockwell C hardness between 60 and 67.

All flat samples were subjected to a CA-H900 heat treatment condition and ground finished (hybrid?).

Wrought: 392 ± 24 HV

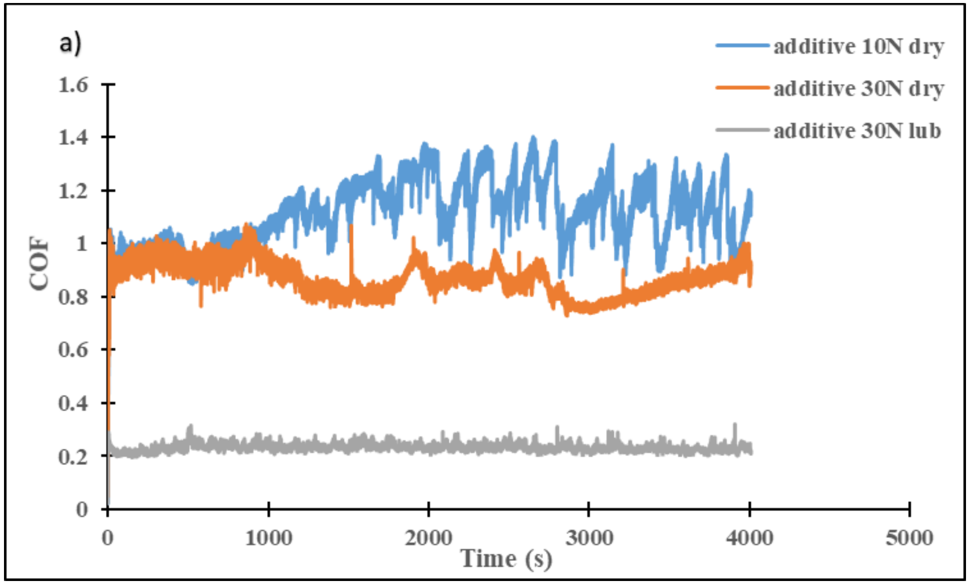
Ra=2.15 µm



Additive: 417 ± 21 HV

Ra=1.26 µm

Example Friction Measurements



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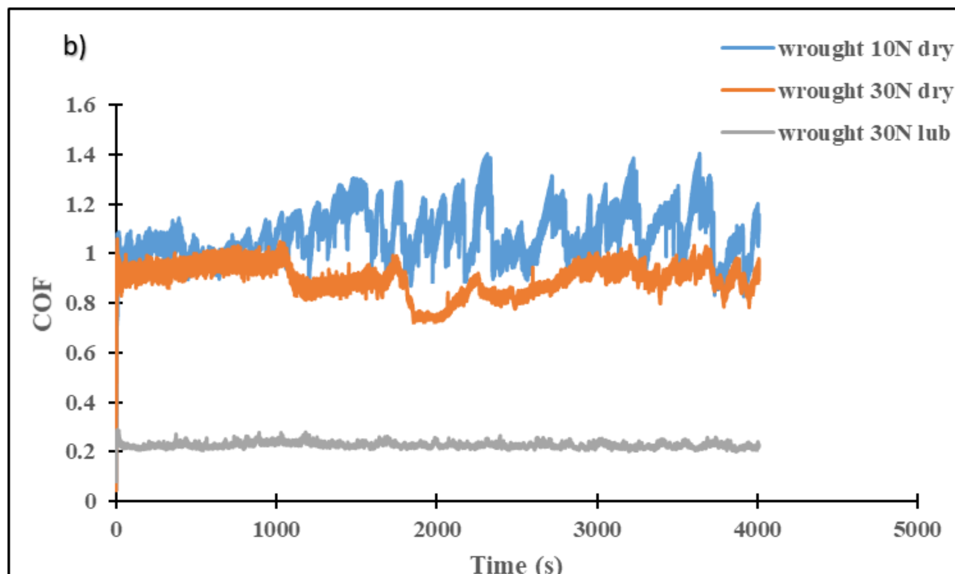
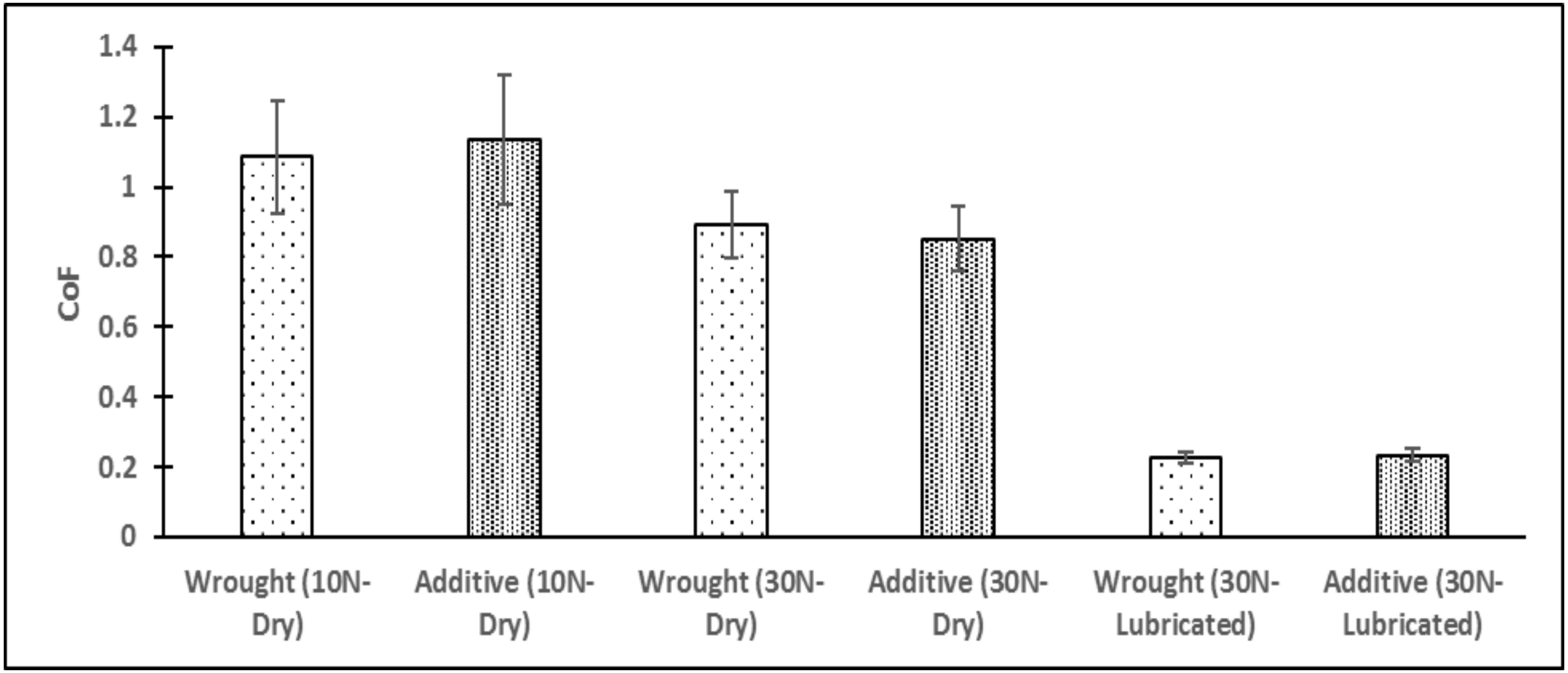


Coefficient Friction

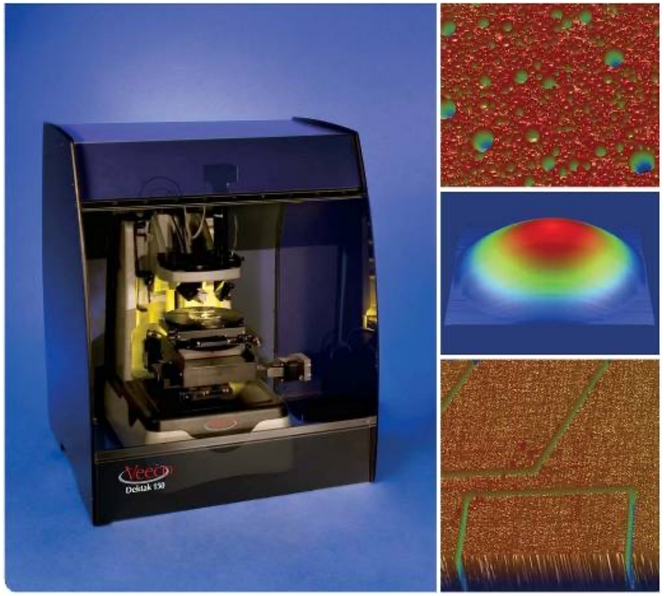


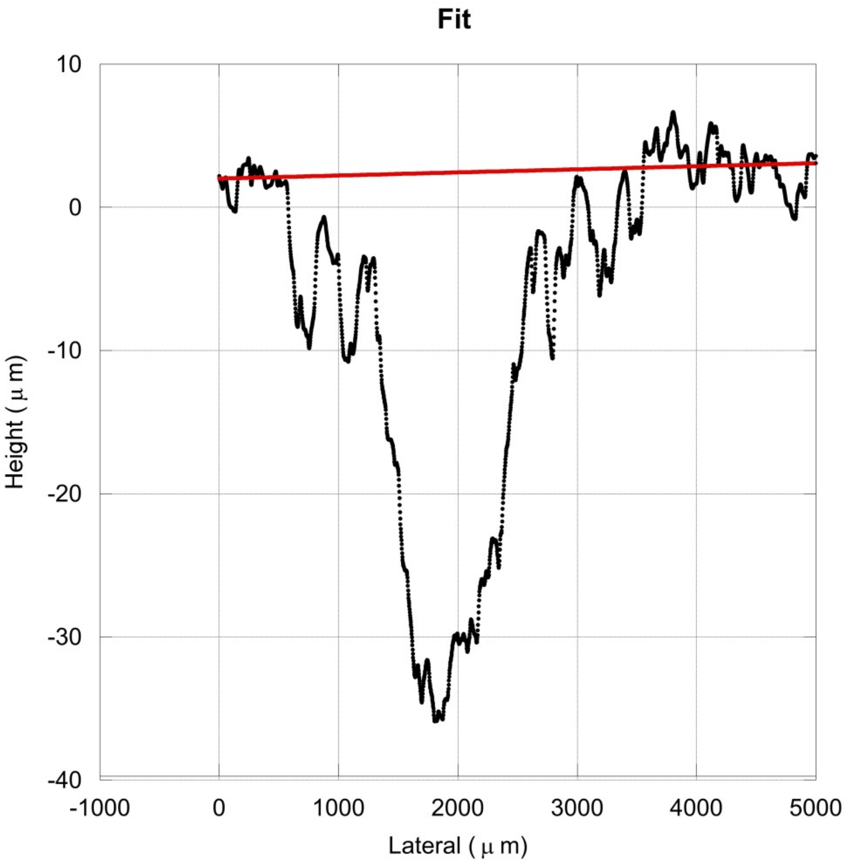
- The CoF appears to be practically the same for each case between additive and wrought samples.

- Sanjeev, K. C., Nezhadfar, P. D., Phillips, C., Kennedy, M. S., Shamsaei, N., & Jackson, R. L. (2019). Tribological behavior of 17–4 PH stainless steel fabricated by traditional manufacturing and laser-based additive manufacturing methods. *Wear*, *440*, 203100. https://doi.org/10.1016/j.wear.2019.203100

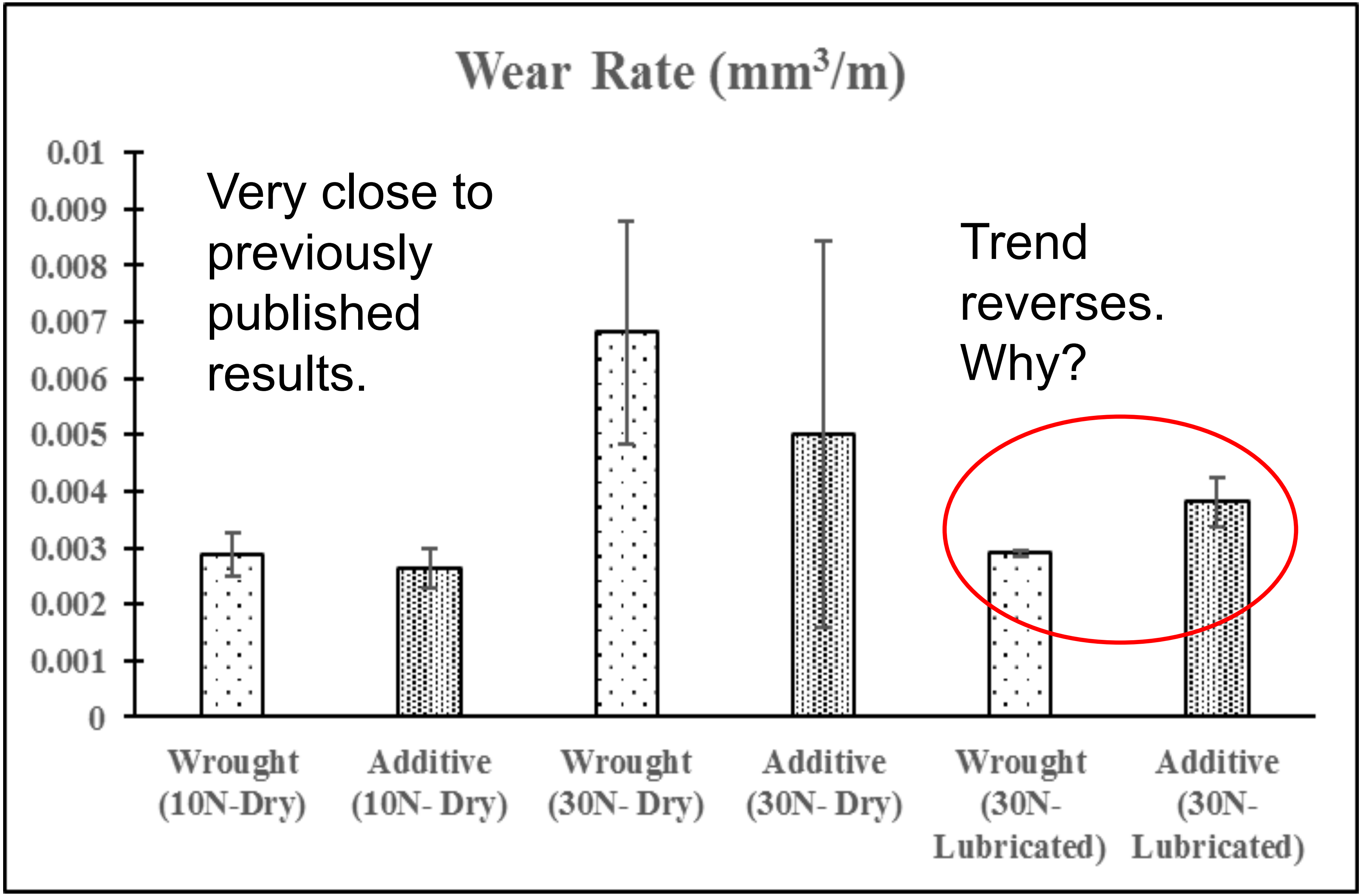
Wear Measurement

- Measuring the wear groove.





Wear

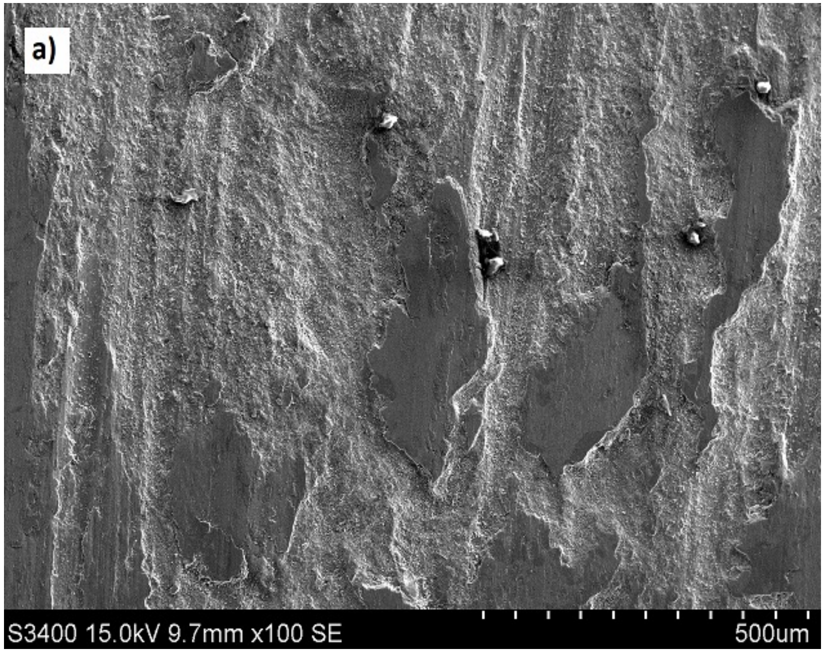


Wear Rate (mm³/m)
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Very close to previously published results.
Trend reverses. Why?
Wrought (10N-Dry)
Additive (10N- Dry)
Wrought (30N- Dry)
Additive (30N- Dry)
Wrought (30N- Lubricated)
Additive (30N- Lubricated)

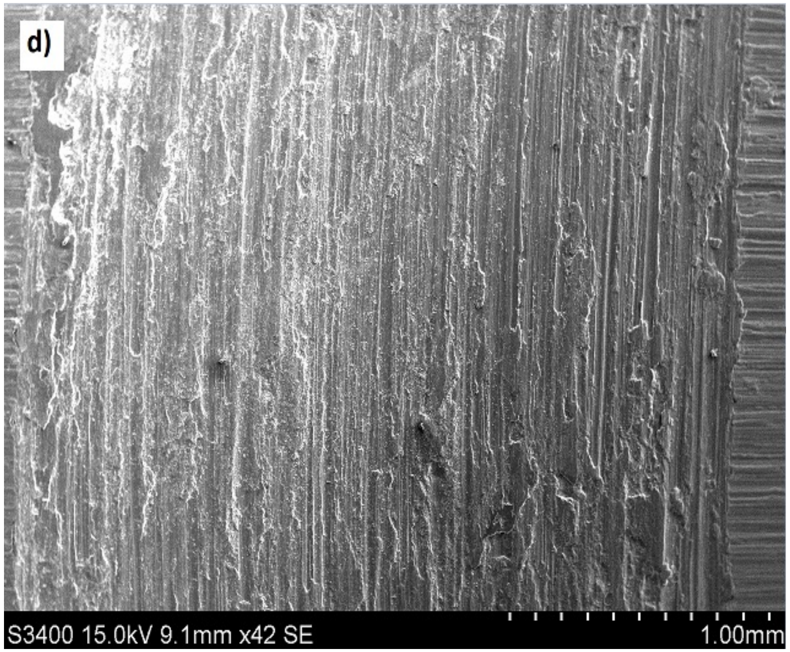
Wear Groove Analysis

- 10 N- Dry: Additive wear rate slightly smaller that wrought.

Additive



Wrought

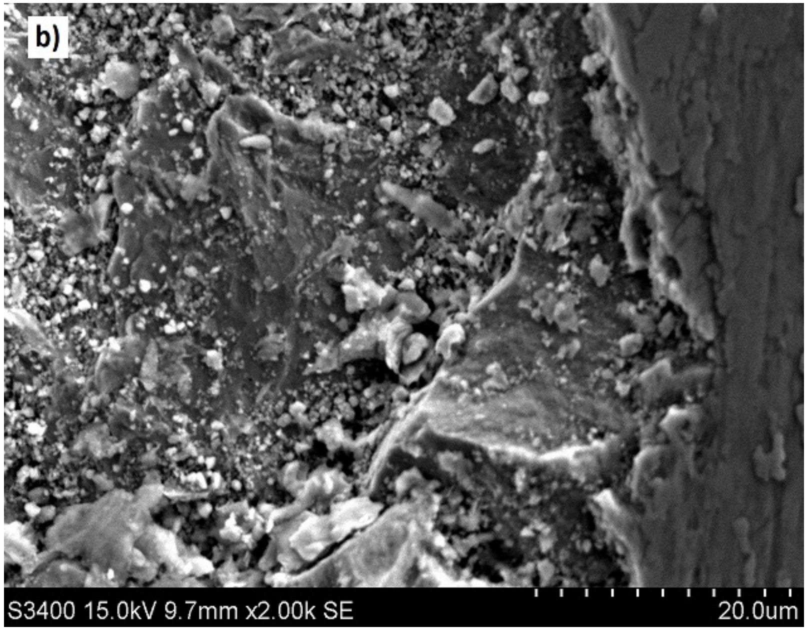


Not a clear difference, but there do appear to be some particles and inconsistencies in the additive wear.

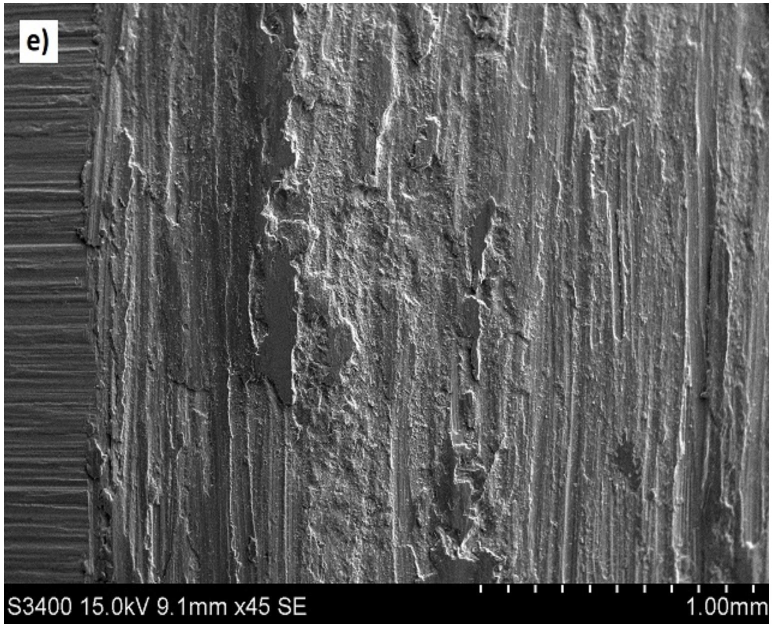
Wear Groove Analysis

- 30 N- Dry: Additive wear rate smaller than wrought, but within experimental error.

Additive



Wrought

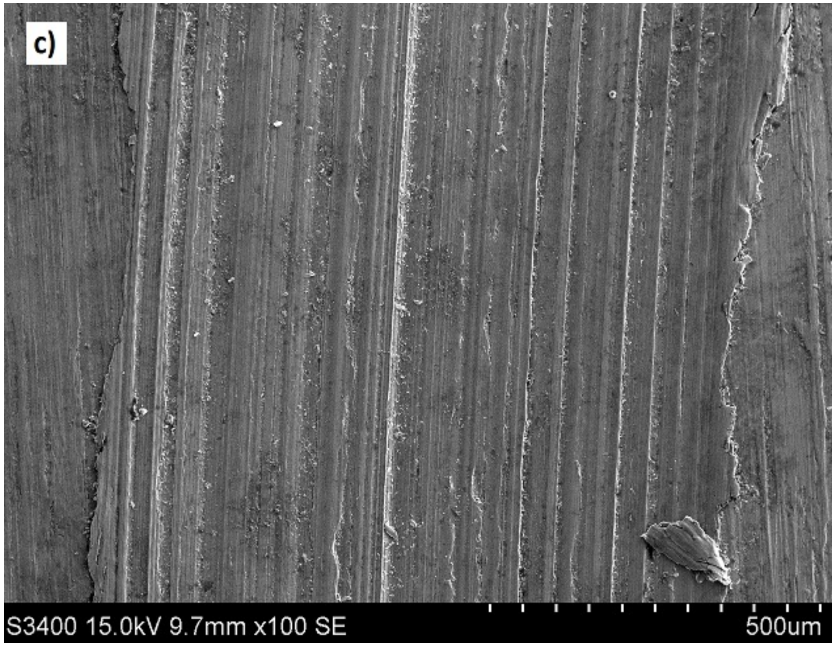


The wear debris in the case of additive samples may be due to the multiple lack of fusion (LOF) voids left from the manufacturing process (Shrestha et al., 2016). The additional wear debris is also indicative of pitting and surface fatigue.

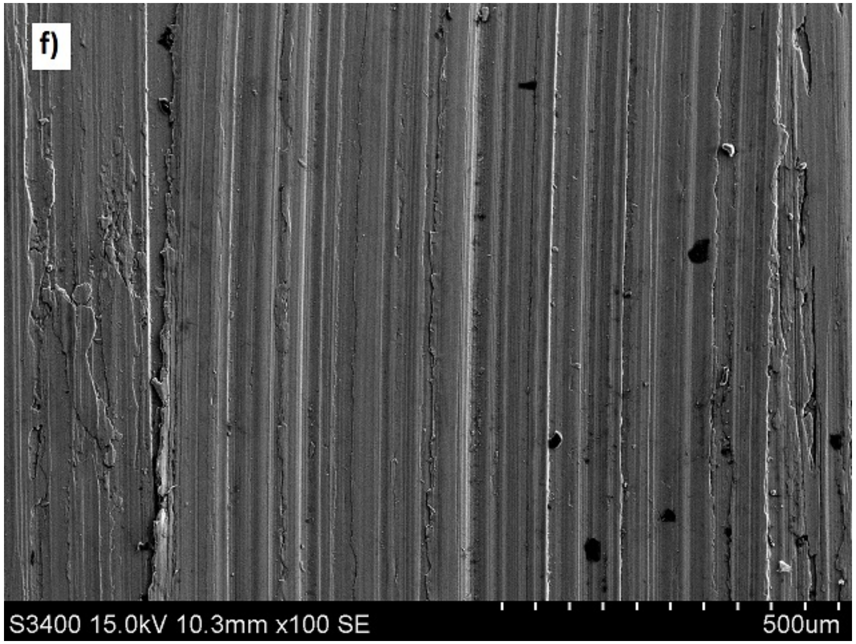
Wear Groove Analysis

- 30 N- Lubricated: Wrought wear rate significantly smaller than Additive.

Additive



Wrought



Both additive and wrought samples had relatively similar worn surfaces

Thoughts on MWF

- Hybrid machining will depend greatly on MWF similar to additive manufacturing.
- The many different processes in hybrid machining will result in many different types of MWF, just as with conventional subtractive machining.
- Due to differences in the additively manufactured bulk material and surface roughness, there could also be additional variations in what MWF are required.

Conclusion

- Additive manufacturing offers some unique capabilities but with some drawbacks.
- Hybrid manufacturing is a combination of additive and subtractive techniques with the aim of improving the total process.
- Hybrid manufacturing will still have similar concerns to conventional subtractive machining, such as how machining parameters and lubricants can influence the product quality.
- Hybrid manufacturing may also have other differences due to the structure of additively manufactured parts.
- It is possible for printed parts to be more susceptible to fatigue and surface fatigue.
- Perhaps these same defects could also influence the machinability of part?
- The ICAMS at Auburn University has the resources needed to research this further.
- Thank you!

- Extra slides

Micro-Indentation Hardness

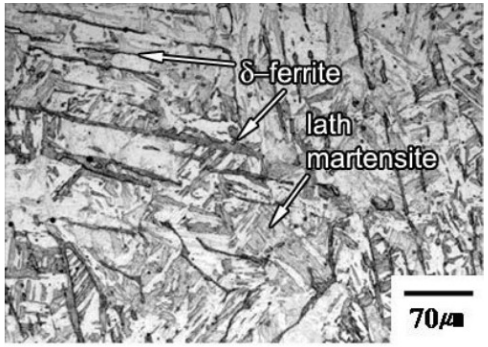
- Micro hardness tests were made of the samples.
- Additive samples: 417 ± 21 HV
- Wrought samples: 392 ± 24 HV
- It is well documented that the hardness influences the wear resistance of conventional wrought samples.
- The additive samples with a slightly higher hardness number are likely to have less wear.
- This could be the reason for the additive samples having lower wear rates than the wrought samples during the dry test.

17-4 PH stainless steel

Martensitic precipitation-hardening stainless steel

Contains 17% Cr, 4% Ni, 3-5% Cu

Microstructure



- Corrosion Resistant
- Strength
- Toughness

Heat treatment

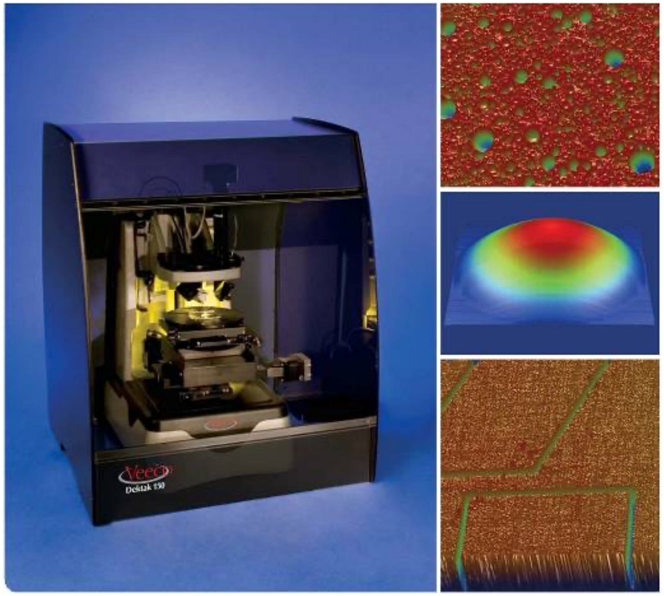
- Aerospace: structural parts
- Oil and petroleum industry: Valves, foils, helicopter deck platforms, etc.
- Biomedical: surgery tools
- Turbine blade design

powermag.com/steam-turbine-blade

- Saidi, D. et al.(2014). Microstructure and fracture mode of a martensitic stainless steel steam turbine blade characterized via scanning auger microscopy and potentiodynamic polarization. Materials Science and Engineering. IOP Publishing.
- P.D. Nezhadfar, Rakish Shrestha, Nam Phan, and Nima Shamsaei. "Fatigue behavior of additively manufactured 17-4 PH stainless steel: Synergistic effects of surface roughness and heat treatment." International Journal of Fatigue 124 (2019): 188-204.

Surface Roughness

- The average roughness of the samples was measured.
- Additive: Ra=1.26 μm,
- Wrought: Ra=2.15 μm
- They were ground in the same process.
- The asperities of a rougher surface are more likely to come into contact under lubricated conditions. This doe NOT explain the lower wear for the lubricated wrought surface.
- Roughness can also reduce adhesion under dry conditions.



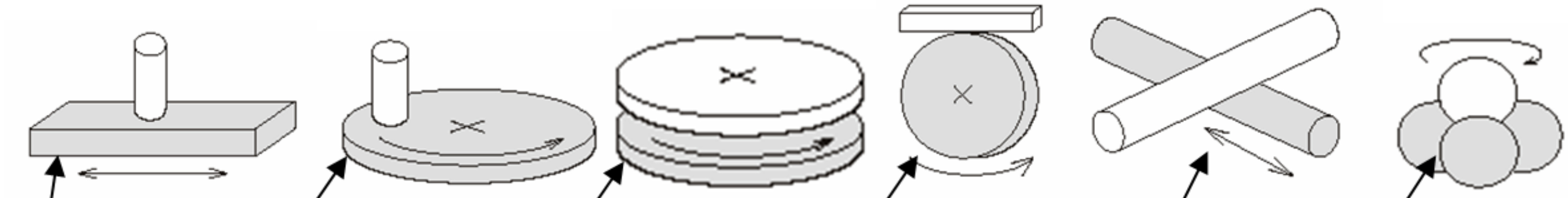
Treatments

- All samples were then subjected to a CA-H900 heat treatment condition.
- This heat treatment procedure includes a solution annealing heat treatment (i.e. condition A (CA)), heat treating at 1050 °C for 30 min and water quenching to room temperature. This is followed by holding at 482°C for 1 hour and then finally, air cooled to the room temperature (H900).
- This treatment increases hardness.
- To remove contaminants and roughness from the surface of the heat-treated parts, the test surfaces of the parts were ground before testing.

Thank You

- Overall additively manufactured parts are comparable to conventional parts.
- Regarding additive metal parts, this is just the beginning…
- Thank you

Test Equipment



Recipricating, Pin on Disk, Thrust Washer, Block on Ring, Cylinder on Cylinder, 4 Ball Test

- A tribometer is a device used to measure the friction and wear between materials.
- Friction is greatly influenced by the environmental and operating conditions.
- Recently a new tribometer (Universal Macro Tester (UMT-3) manufactured by the Center for Tribology, Inc. has been obtained.
- Capabilities include the ability to measure the friction in many different contact and motion geometries.

Equipment types

- 5 axis CNC milling machines
  - Hurco/Haas/DMG
- Muliti-axis Hurco TMX8MYSi lathe (live tooling)
- Mazak 4 axis Friction Stir Welder
- 3 axis CNC milling machines
  - Hurco/Okuma/Haas
- Swiss laser lathe turning center (Tsugami)
- Various UR Co-BOTS
- Custom WAAM Metal Printer
- 3D Desktop Metal Inkjet Printers
- 5 axis OMAX Adaptive Waterjet
- AGF Drill 20 Microdrill (EDM)
- 5 axis wire EDM (Cut E600)
- 5 axis plunge EDM (Form E600)
- 4 axis laser engraver system (Dominator series)
- Manual mills, lathes, saws, polishers, sand blasters, etc
- Powder Coating
- CNC plate grinding
- Various fusion welders (Lincoln)
- Coordinate Measuring Machines
- Keyence bluelight scanner system
- Various Keyence 3D microscopes
- Kistler plate and force dynamometers
- Various research quality sensors
- Industry 4.0 connectivity

Current Graduate Student Research

- Improving the Flow of Data and Information in Manufacturing (Graduating Dec 2022)
- The Effects of Lean Manufacturing on Occupational Safety and Ergonomics (Graduating Dec 2022)
- Technology Acceptance in the Manufacturing Environment (Graduating Dec 2022)
- Mixed Reality Methods in Workforce Development for Manufacturing
- Verification and Validation: Building Trusts in Digital Twins
- Analysis of Manufacturing Program Outcomes at the 4-year Collegiate Level
- Data analytics for hybrid manufacturing
- Letting Data Speak to Small- and Medium-Sized Manufacturers (machine learning)
- Machine learning in additive manufacturing
- Development of graph neural networks
- Help from above: Manufacturing Using drones
- Thermal mapping of the Friction Stir Welding Process
- Observations at the Onset of Low-Speed and High-Speed Orthogonal Machining
- Thermal Prediction at the Production Tip of Wire Arc Additive Manufacturing (WAAM)
- Surface roughness of additive manufactured metals
- Data-driven lead-free solder materials design
- Manufacturing, characterization, and computational analysis of composite filaments for additive manufacturing of fabric
- Implementing of low-cost sensors to legacy manufacturing equipment for monitoring

Metalworking Fluids (MWF)

- Very severe conditions.
- Cooling is a main function.
- Reduced friction and wear can improve surface finish and prolong tool life.
- Allow for higher cutting speeds.
- Prevent corrosion.
- Prevent flammability of volatile chips (newly cut nascent chips can spontaneously combust).
- Anti-bacteria.

MWF

- High cutting speeds-cooling dominates
- Low cutting speeds-friction and wear more important.
- Copper often used

as friction wear

additive.

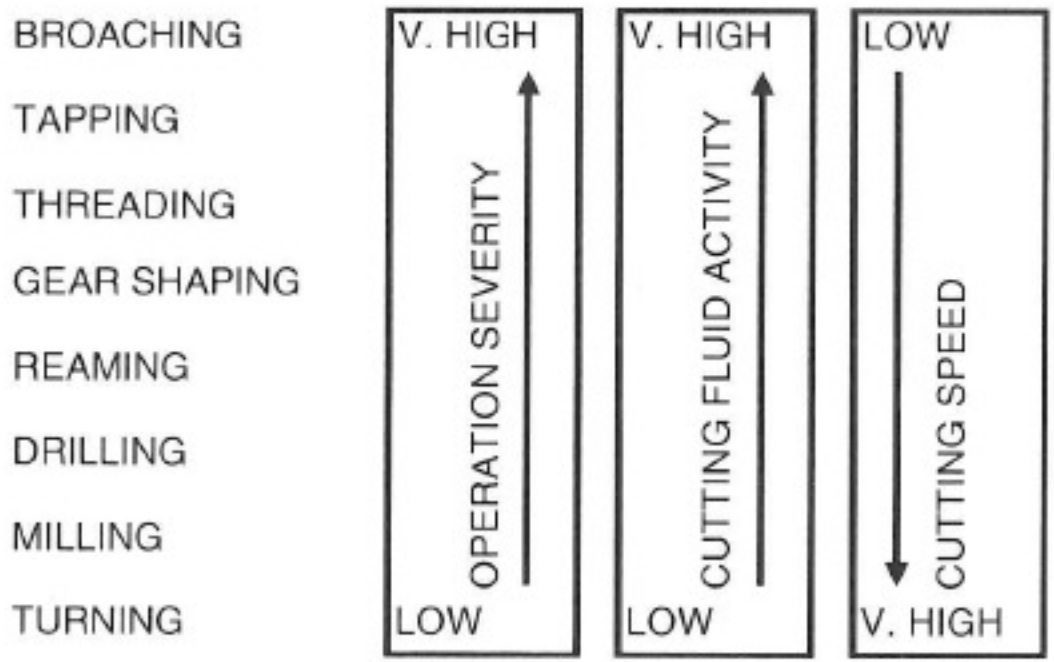
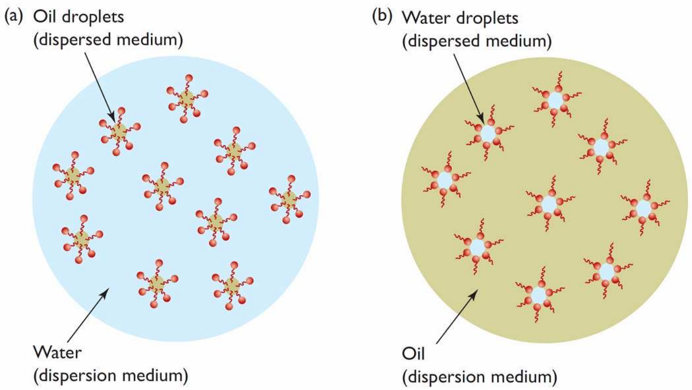
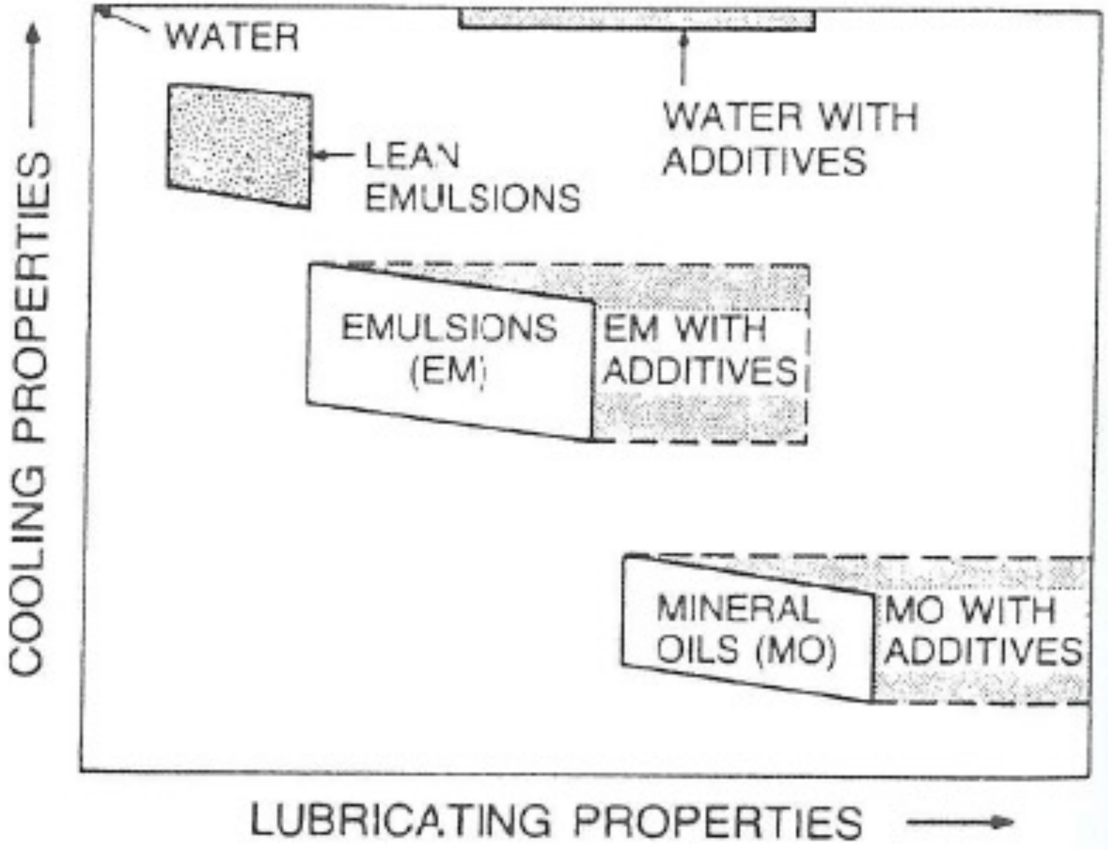


Fig. 8.14 Relative severity of some metal cutting processes, redrawn and adapted from [97]

- Water-based and oil-based.
- Mixture is emulsion.





MWF Formulations

- Water

Oil

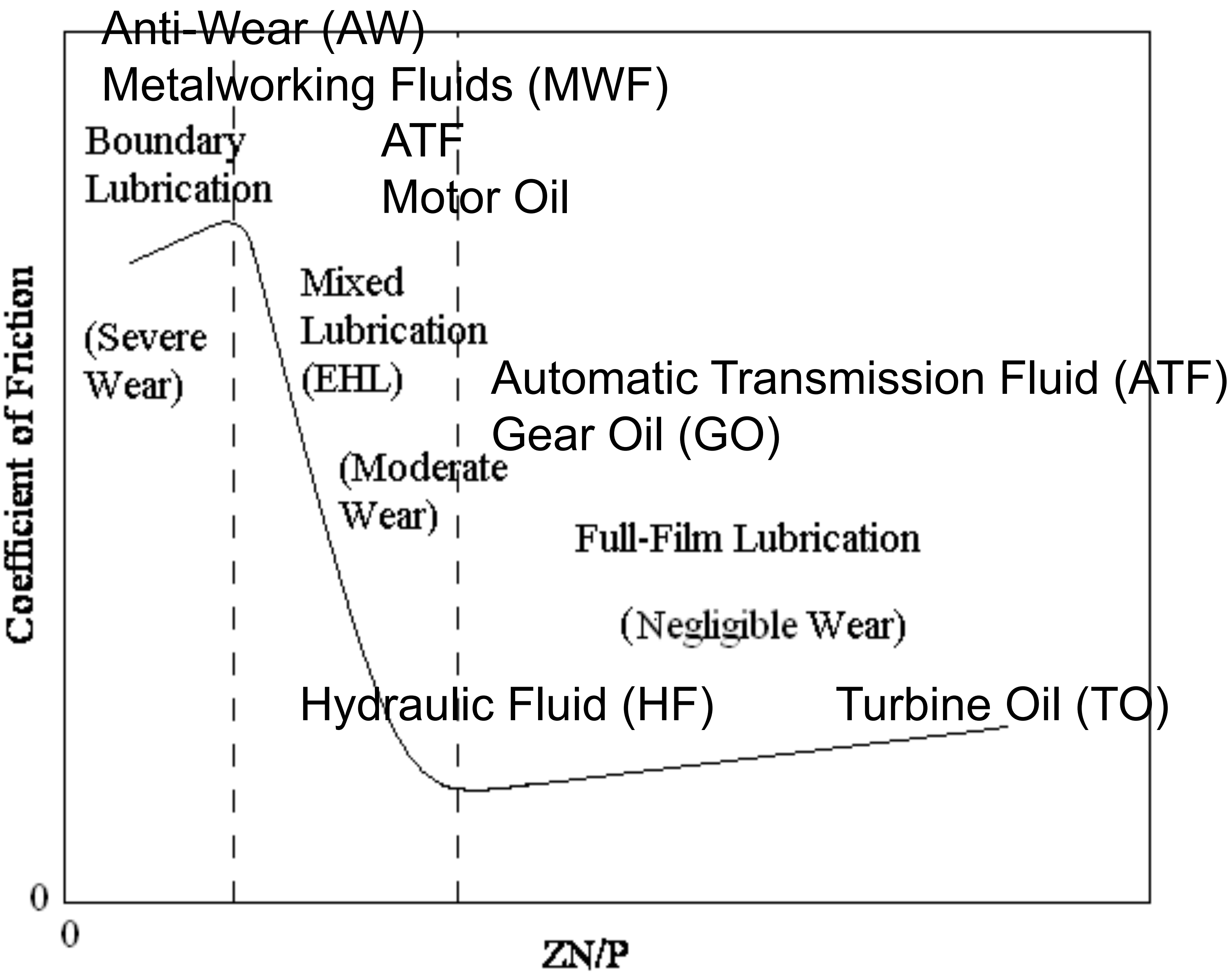
TABLE 38.1
Typical Chemical MWF Formulation

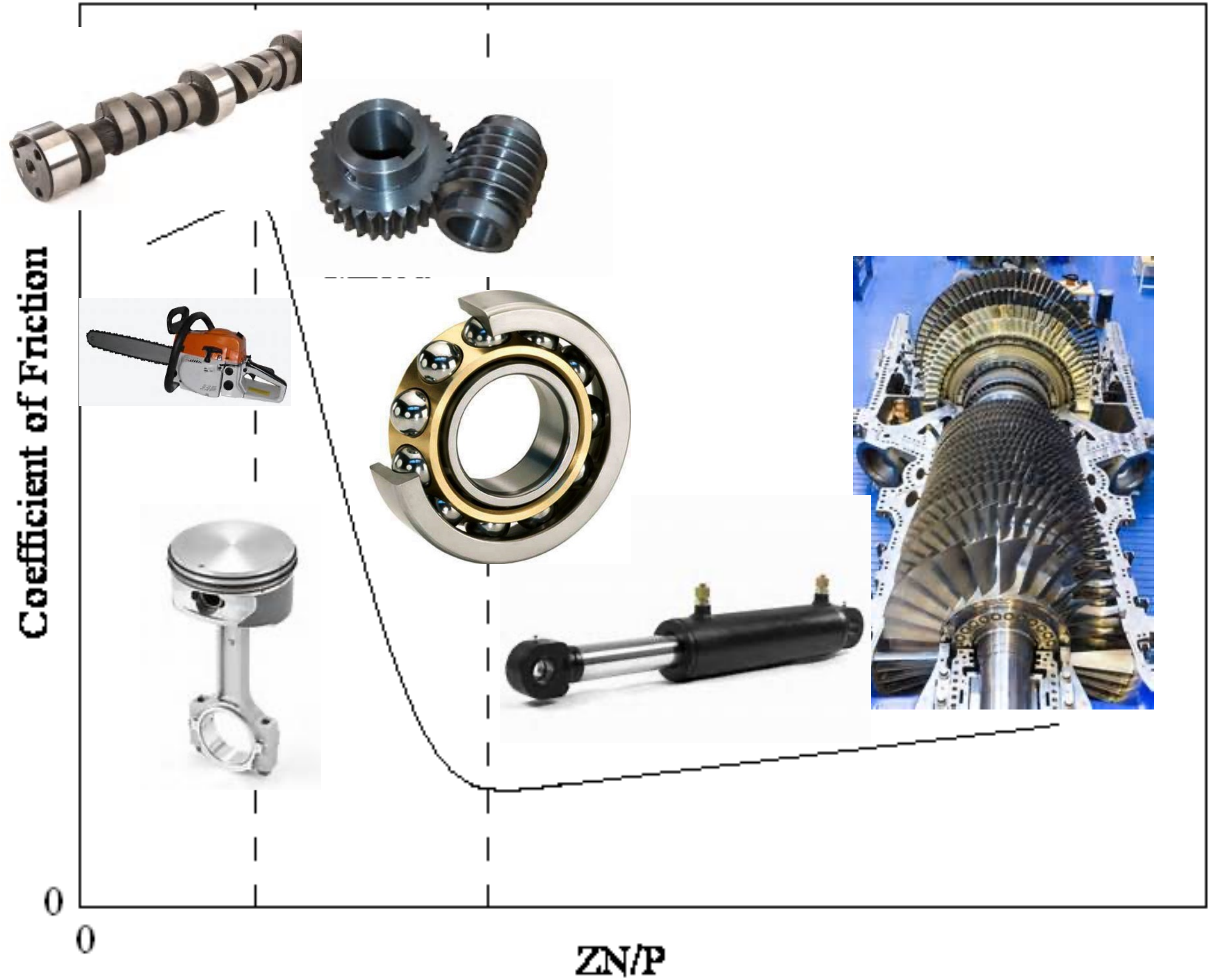
Component	Amount (wt%)
Polyalkylene glycol	10–15
Phosphate ester (or fatty acid)	5–10
Sulfurized fatty acid	0–5
Nonnitrite corrosion inhibitor	15
TEA	10–15
Biocide	—[a]
Water	45–60

[a] Biocide added at concentrations recommended by the manufacturer.

TABLE 38.23
Typical Formulation of a Straight-Oil MWF

Component	Amount (wt%)
Mineral oil	75–100
Corrosion inhibitors	0–5
EP additives	5–20
Boundary lubricity additives	0–10
Antioxidants	0–2

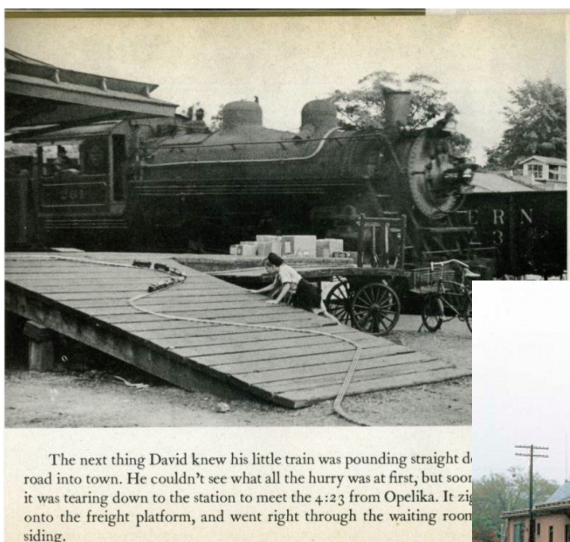

Anti-Wear (AW)
Metalworking Fluids (MWF)
Boundary Lubrication
ATF
Motor Oil
(Severe Wear)
Mixed Lubrication (EHL)
Automatic Transmission Fluid (ATF)
Gear Oil (GO)
(Moderate Wear)
Full-Film Lubrication
(Negligible Wear)
Hydraulic Fluid (HF)
Turbine Oil (TO)
Coefficient of Friction
0
0
ZN/P



Coefficient of Friction
0
0
ZN/P

Auburn's Tribology History

- Wreck Tech Pajama Parade originated in 1896.
- A group of mischievous Auburn students, snuck out of their dorms the night before the football game and greased the railroad tracks.
- According to the story, the train carrying the Georgia Tech team slid through town and didn't stop until it was halfway to the neighboring town of Loachapoka, Alabama.



Fact or Fiction?

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- R. L. Jackson's publications.
- Others as noted on individual slides.