



Post-Processing adapted to Additive Manufacturing

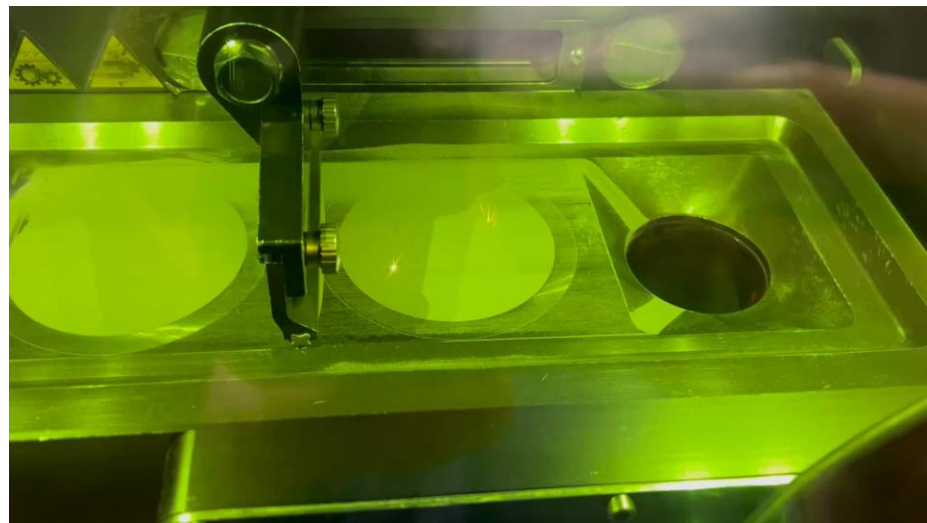
Team Members:

Doruk Sinayuc
Koray Kalam
Sude Yaşar
Laura Ying Cheng

Professors:

Christophe Moser
Eric Boillat
Jürgen Brugger

Additive Manufacturing



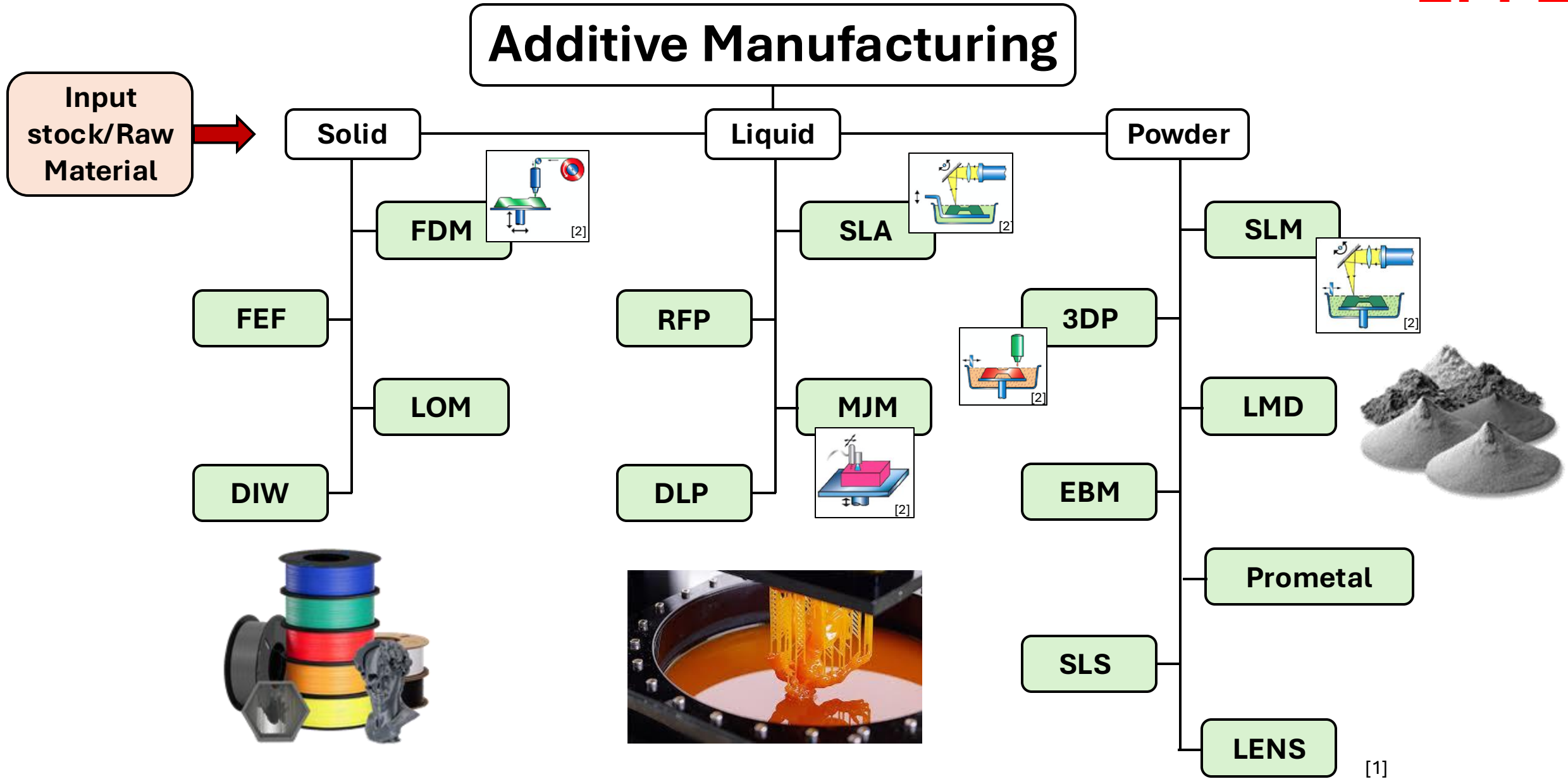
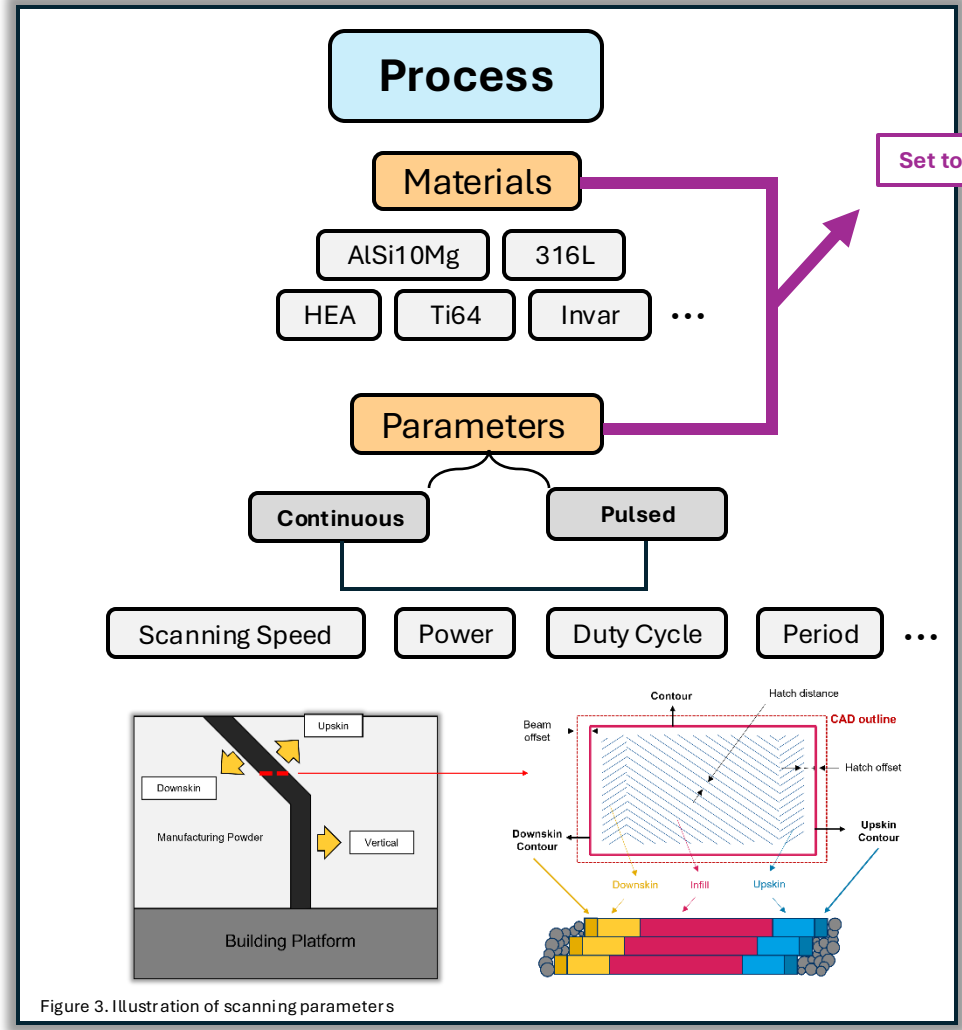
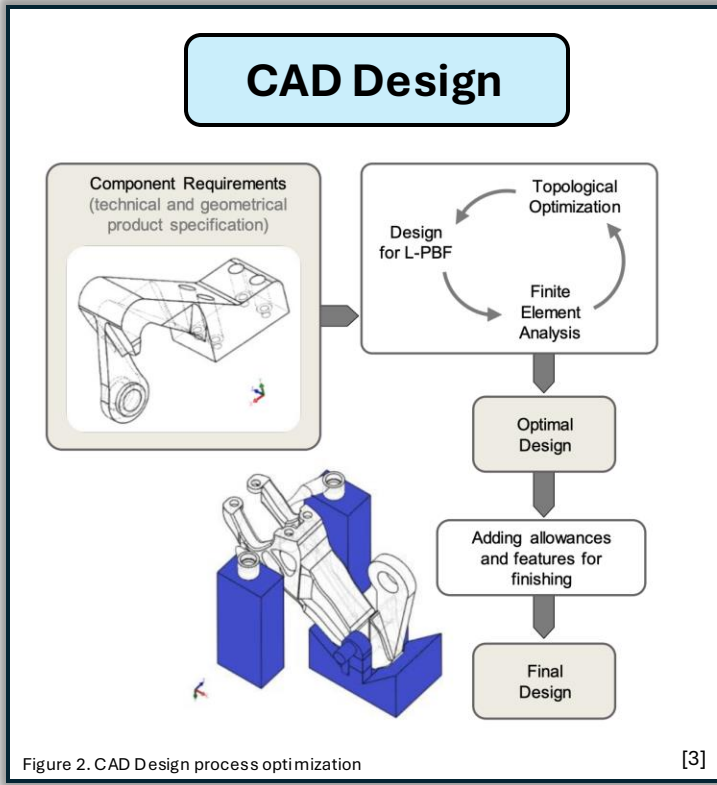


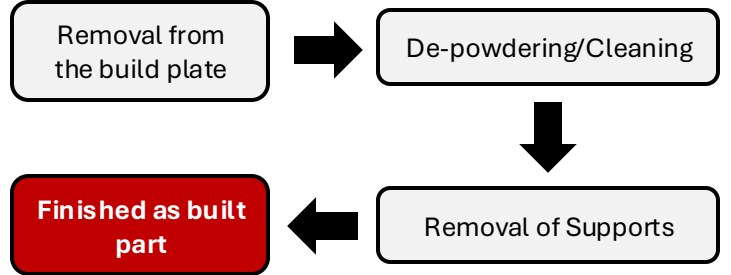
Figure 1. Various AM methods

[1]Abdulhameed, O., Al-Ahmari, A., Ameen, W., & Mian, S. H. (2019). Additive manufacturing: Challenges, trends, and applications. *Advances in Mechanical Engineering*, 11(2). <https://doi.org/10.1177/1687814018822880>
 [2] Tamburrino, F., Barone, S., Paoli, A., & Rationale, A. v. (2021). Post-processing treatments to enhance additively manufactured polymeric parts: a review. In *Virtual and Physical Prototyping* (Vol. 16, Issue 2, pp. 221–254). Taylor and Francis Ltd. <https://doi.org/10.1080/17452759.2021.1917039>

SLM The flow process of obtaining the final part with L-PBF

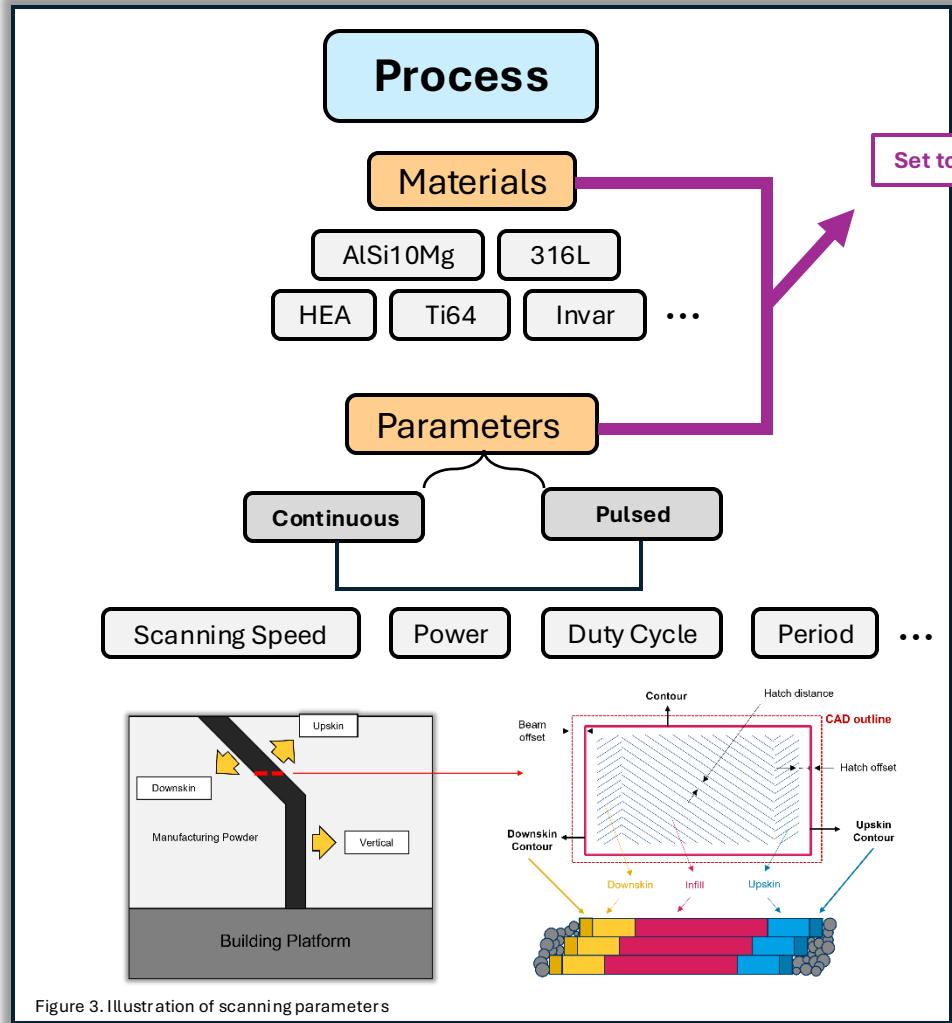
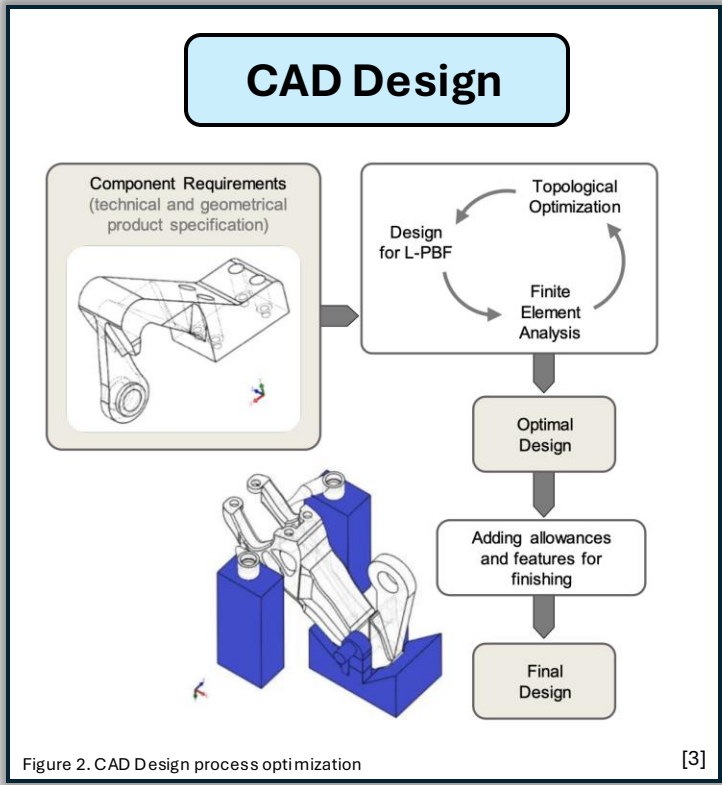


- Properties**
- Mechanical Properties
 - Electrical Properties
 - Geometrical Deviation
 - Roughness

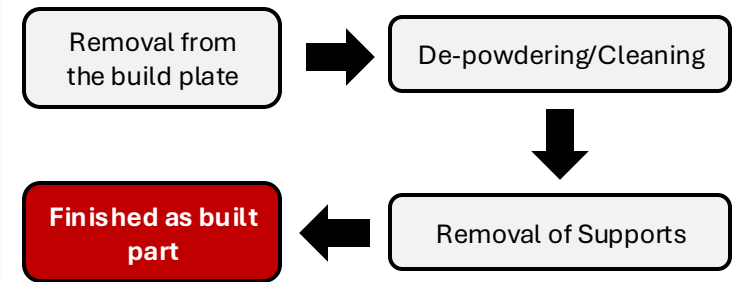
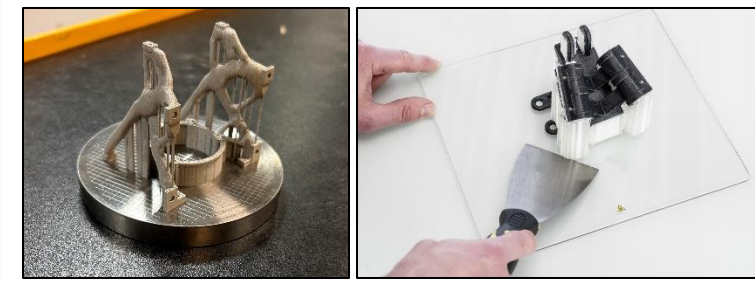


[3] Priarone, P. C., Lunetto, V., Atzeni, E., & Salmi, A. (2018). Laser powder bed fusion (L-PBF) additive manufacturing: On the correlation between design choices and process sustainability. *Procedia CIRP*, 78, 85–90. <https://doi.org/10.1016/j.procir.2018.09.058>

SLM The flow process of obtaining the final part with L-PBF



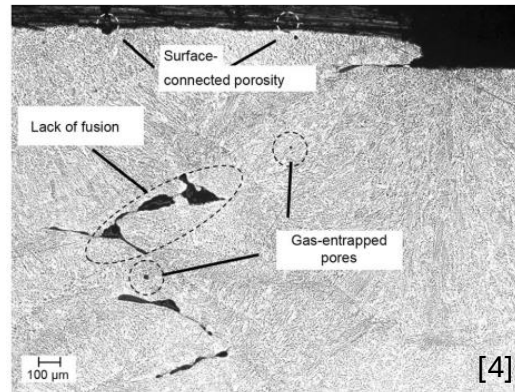
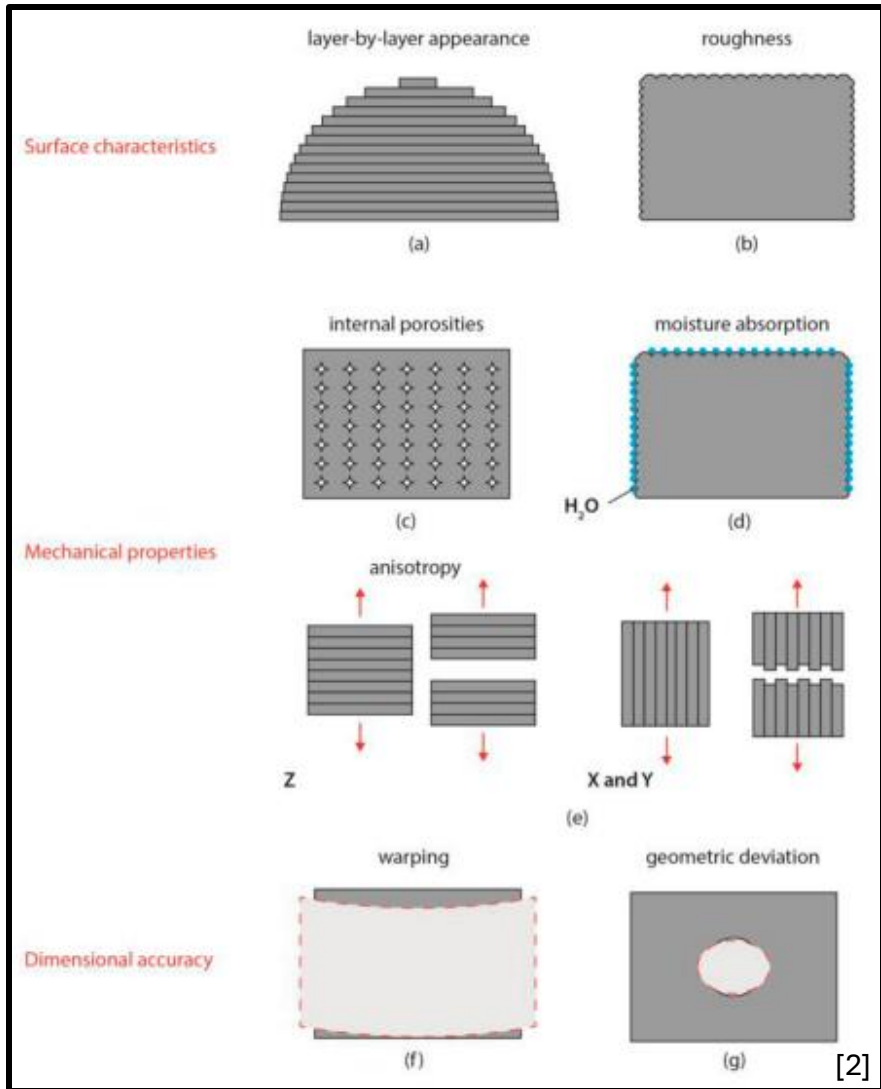
- Set to maximize performance
- Properties
 - Mechanical Properties
 - Electrical Properties
 - Geometrical Deviation
 - Roughness



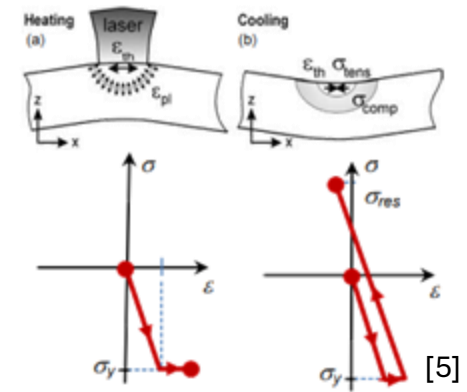
Part ready to be used?

[3] Priarone, P. C., Lunetto, V., Atzeni, E., & Salmi, A. (2018). Laser powder bed fusion (L-PBF) additive manufacturing: On the correlation between design choices and process sustainability. *Procedia CIRP*, 78, 85–90. <https://doi.org/10.1016/j.procir.2018.09.058>

Defects



Residual stress



	VAT Photopolymerization	Material Extrusion (ME)	Material Jetting (MJ)	Binder Jetting (BJ)	Powder Bed Fusion (PBF)
ISSUE					
Layer-by-layer appearance	medium	high	low	medium	medium
Roughness	low	high	low	high	high
Internal porosities	low	medium	low	high	medium
Anisotropy	low	high	low	high	medium
Shrinkage	medium	medium	low	medium	medium
Warping	medium	high	low	low	high

[2]

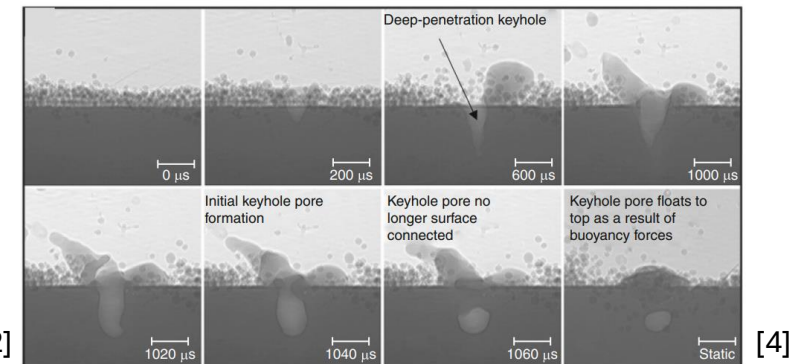


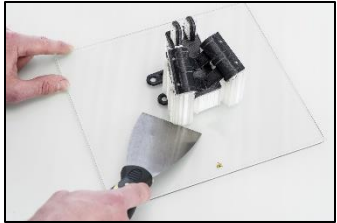
Figure 4. Defects seen in AM

[2] Tamburrino, F., Barone, S., Paoli, A., & Razionale, A. v. (2021). Post-processing treatments to enhance additively manufactured polymeric parts: a review. In *Virtual and Physical Prototyping* (Vol. 16, Issue 2, pp. 221–254). Taylor and Francis Ltd.

[4] Brennan, M. C., Keist, J. S., & Palmer, T. A. (2021). Defects in Metal Additive Manufacturing Processes. *Journal of Materials Engineering and Performance*, 30(7), 4808–4818. <https://doi.org/10.1007/s11665-021-05919-6>

[5] Li, C., Liu, Z. Y., Fang, X. Y., & Guo, Y. B. (2018). Residual Stress in Metal Additive Manufacturing. *Procedia CIRP*, 71, 348–353. <https://doi.org/https://doi.org/10.1016/j.procir.2018.05.039>

Finished as built part



Post-Processing

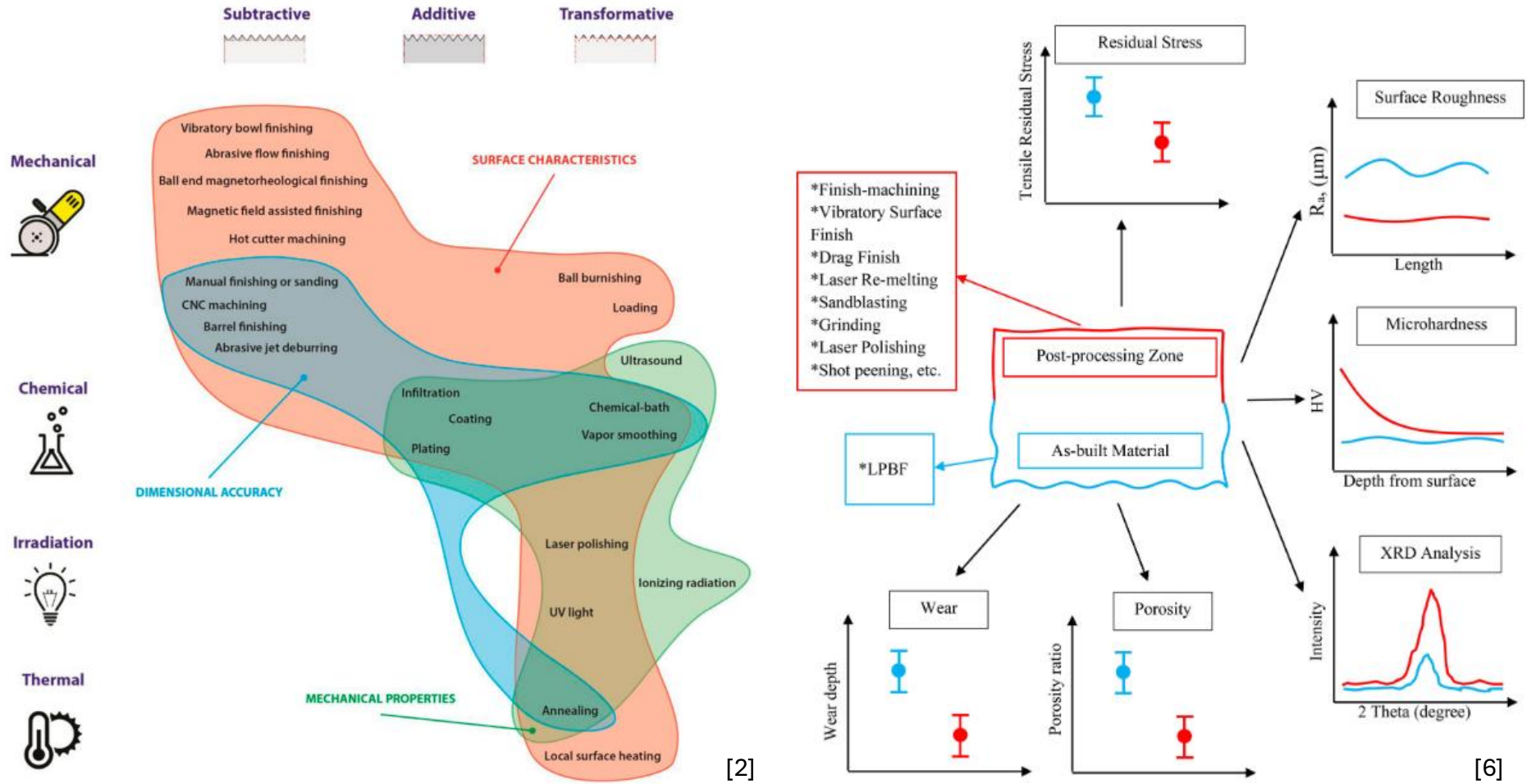
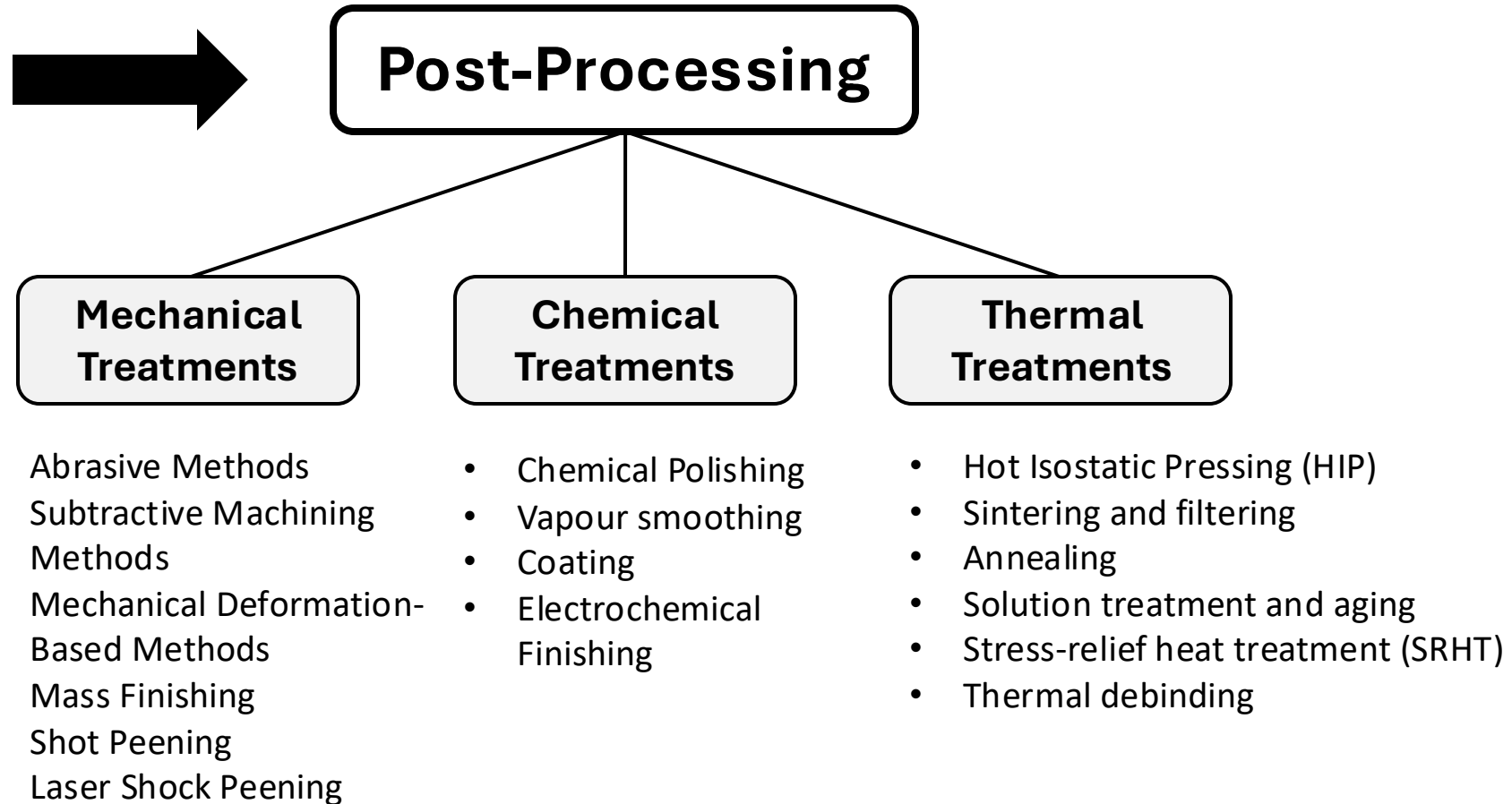
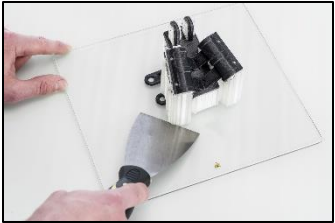


Figure 5. Categorized post processing methods and the effect of post-processing in certain properties

[2] Tamburrino, F., Barone, S., Paoli, A., & Razionale, A. v. (2021). Post-processing treatments to enhance additively manufactured polymeric parts: a review. In *Virtual and Physical Prototyping* (Vol. 16, Issue 2, pp. 221–254). Taylor and Francis Ltd.
 [6] Khan, H. M., Karabulut, Y., Kitay, O., Kaynak, Y., & Jawahir, I. S. (2020). Influence of the post-processing operations on surface integrity of metal components produced by laser powder bed fusion additive manufacturing: a review. In *Machining Science and Technology* (Vol. 25, Issue 1, pp. 118–176). Bellwether Publishing, Ltd. <https://doi.org/10.1080/10910344.2020.1855649>

Finished as built
part



Mechanical Treatments

- Abrasive Methods
- Subtractive Machining Methods
- Mechanical Deformation-Based Methods
- Mass Finishing
- Shot Peening
- Laser Shock Peening

Abrasive Methods - Sand Paper Polishing

Advantages

- **Preliminary process** – easy to apply
- Can achieve **fine surface quality**
 - Average surface roughness (Ra) decreased from 14.4 μm to 0.407 μm [Tiwary 2019]
- Applicable to **metals, polymers, and ceramics**

Disadvantages

- Desired dimensions **may not be preserved**
- Reduces Ra, but may also **introduce surface wear and scratches**



Abrasive Methods - Fine Abrasive Finishing

Working Principle

- Polishing is performed using **fine abrasive particles** suspended in a **carrier medium** (liquid, paste, or air) placed **between the polishing tool and the workpiece surface**.

Advantages

- Produces **very fine surface finishing**
- Focuses on **surface refinement**, not bulk material removal
- **No loss of dimensional accuracy**

Disadvantages

- Cannot be applied directly to AM parts – **requires preprocessing**
- **Abrasive particle agglomeration** occurs, **necessitating periodic renewal** of the abrasive medium

Abrasive Methods - Fine Abrasive Finishing

SS316L Parts Produced
using LPBF method

End Milling Results

Fine Abrasive Finishing Result

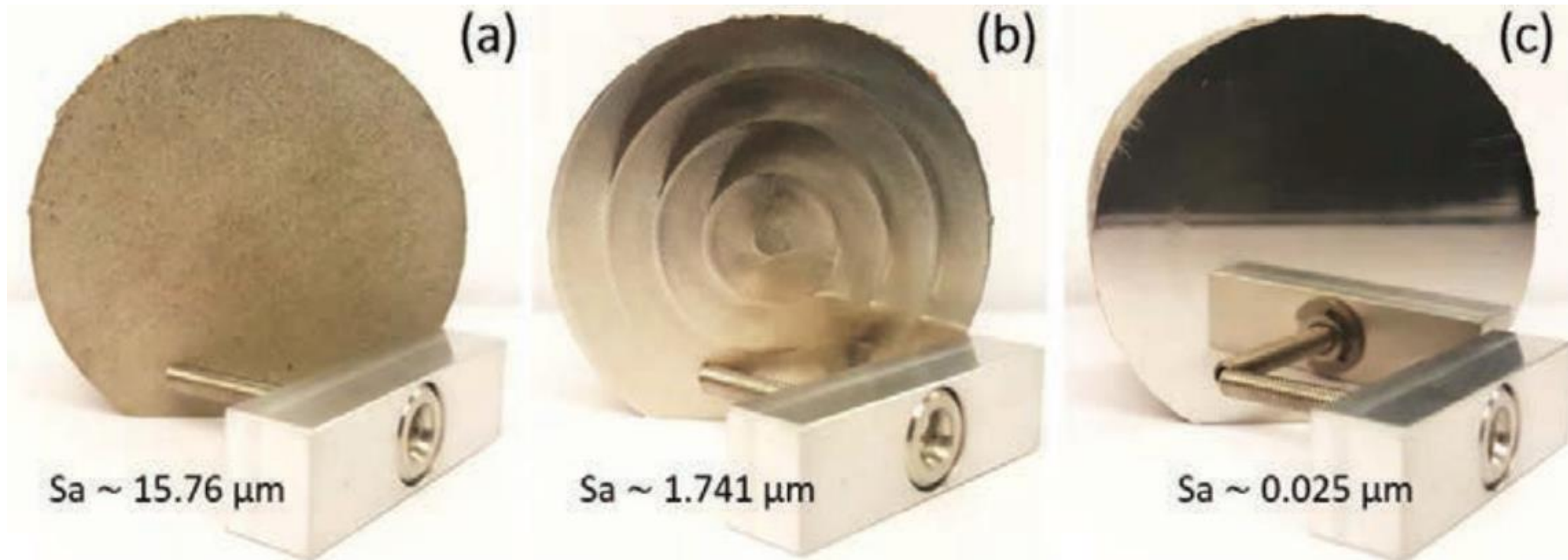


Fig 6. Surface topographies

alumina-based aqueous
suspension

Abrasive Methods - Fine Abrasive Finishing

White-Light Interferometer Results

SS316L Parts Produced
using LPBF method

End Milling Results

Fine Abrasive Finishing Result

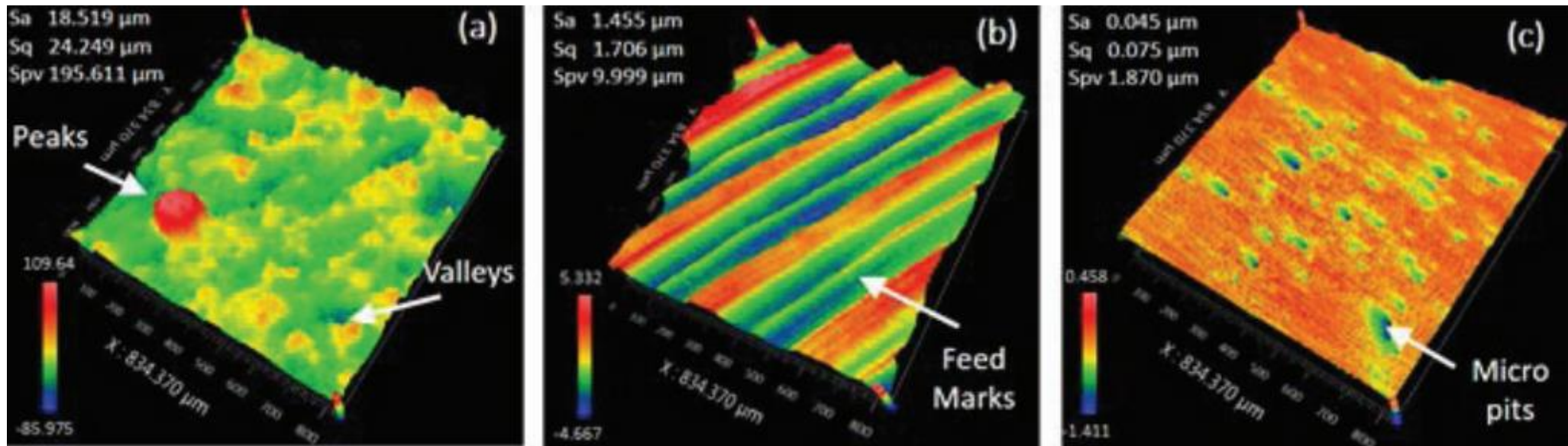


Fig 7. Evolution of the surface morphology

Note: The FAF mechanism improves surface finish and reduces porosity primarily through **material redistribution** rather than material removal.

Abrasive Methods - Abrasive Flow Finishing (AFF)

Working Principle

- A **polymer-based carrier** mixed with **abrasive grits** is **pushed back and forth** through or across the workpiece **cyclically**.
- The **abrasive medium acts as a flexible tool**, continuously deforming and adapting to the shape of the workpiece.

Advantages

- **Adapts** to complex workpiece geometries
- **Removes tensile residual stresses** from the surface

Disadvantages

- **Cyclic**, and **time-consuming**
- **Abrasive medium renewal** required (less frequent than in fine abrasive finishing [FAF])
- **Difficult to model and control** material removal accurately

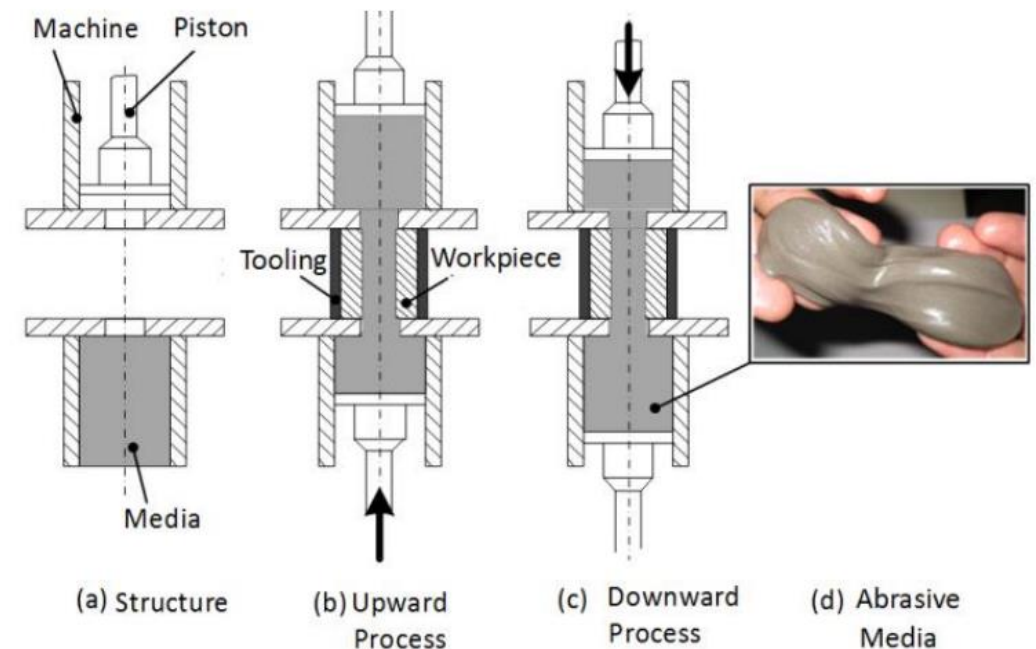


Fig 8. Schematic of the abrasive flow machining setup

Abrasive Methods - Abrasive Flow Finishing (AFF)

Workpiece: Additively manufactured AlSi10Mg aluminum alloy

Reference point: Conic hole at the center to measure material removal after each microscope scan

Microscope: Laser Scanning Microscope (LSM)

Surface defects observed: Unmelted metal powders and agglomeration

First 90 cycles: Major surface defects disappeared

Between 90-360 cycles: Bulk material removal became dominant

Final Surface Roughness (Sa): 1.8 μm

Laser Scanning Microscope Results

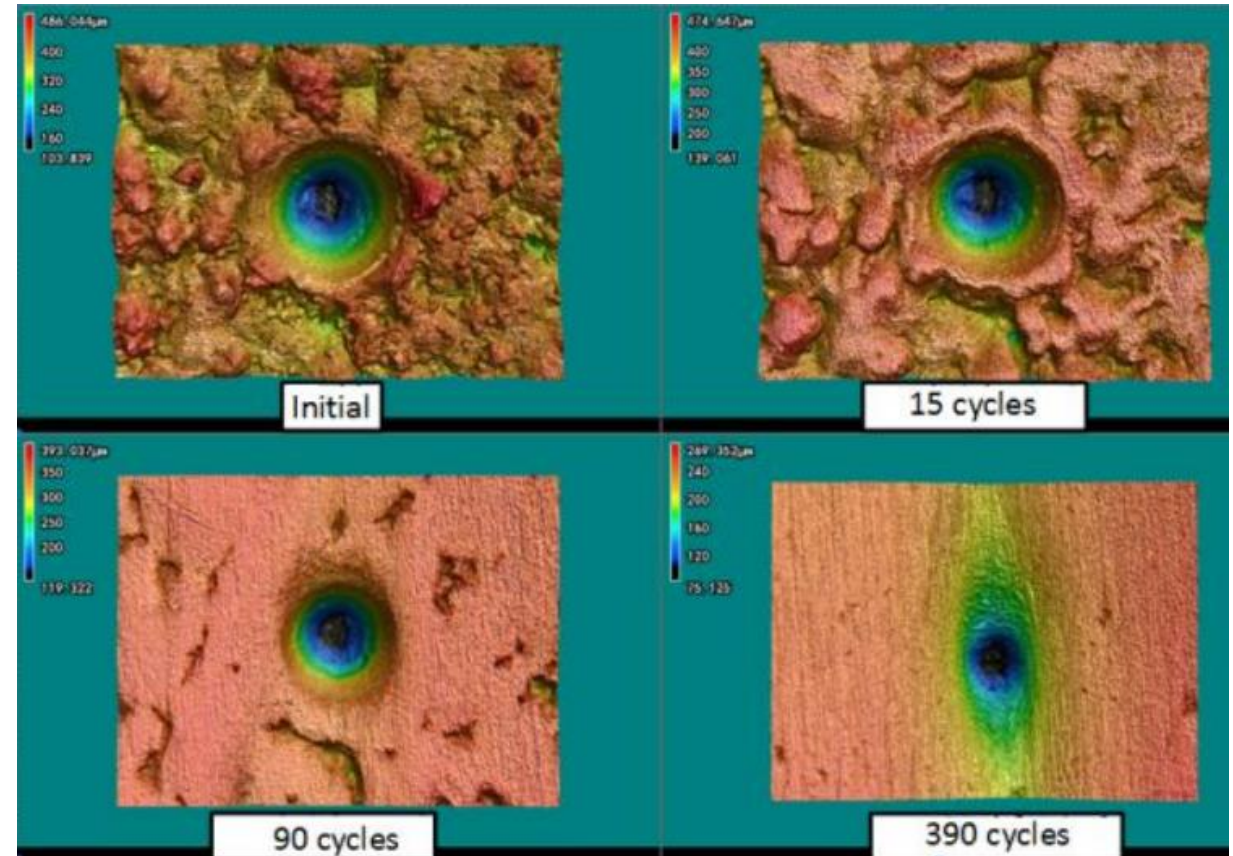


Fig 9. surface morphology of the processed part

Peng et al., 2018, *Procedia CIRP*, 71, 386–389.

Abrasive Methods - Abrasive Jetting (AJ)

Working Principle

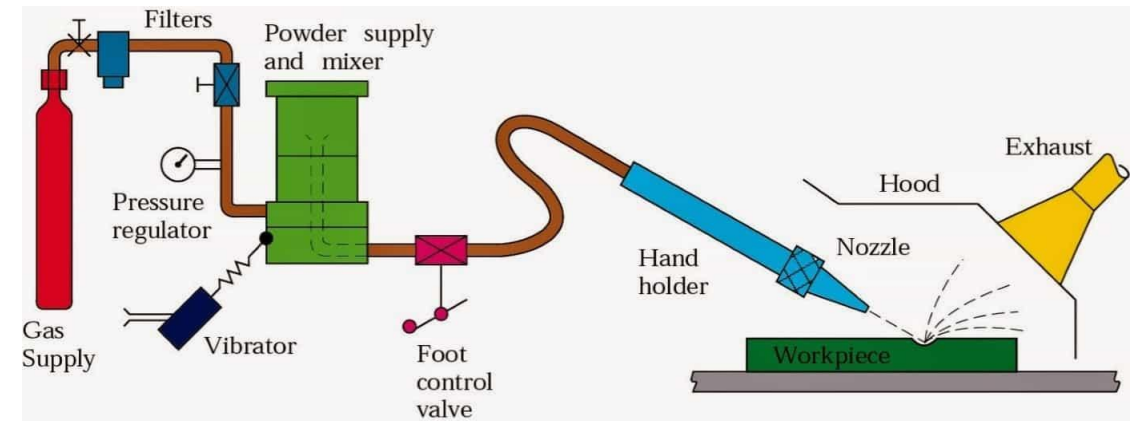
- A high-velocity **stream of abrasive particles** is directed onto the surface to be finished at a **controlled, non-vertical angle**.
- Common abrasives include **aluminum oxide, glass beads, and silicon carbide**.

Advantages

- **Simple and effective** surface finishing technique
- **Improves surface roughness** and removes unwanted residues from AM parts

Disadvantages

- **Limited flexibility** for complex or confined geometries
- **Non-uniform erosion**, if not well designed
- **Material loss and contamination** from residual abrasive particles



Subtractive Machining Methods - Machining

Working Principle

- **Material is removed mechanically** from the additively manufactured part using **cutting tools** such as milling, turning, or drilling.

Advantages

- High dimensional **accuracy and precision**
- Machining is a very **well modelled** and established process

Disadvantages

- **Limited access** for complex geometries
- **Tool wear** due to hard AM surfaces
- **Fixturing and alignment** can be challenging for irregular AM parts



Deformation-Based Methods - Ultrasonic Nanocrystal Surface Modification (UNSM)

Working Principle

- A **hardened tip** (e.g., tungsten carbide ball) vibrates at **ultrasonic frequency (~20 kHz)** while a **static load (~10 N)** is applied to the surface.
- The tip **scans the surface**, inducing **severe plastic deformation** in the near-surface layer.

Advantages

- Significant surface **roughness reduction**
 - Ra decreased from 18 μm to 3.5 μm [Ma et al., 2020]
- **Dry process** – no abrasive medium or chemicals required
- Reduces tensile residual stress
- Significant **reduction in porosity**

Disadvantages

- **Limited access** for complex geometries
- Possible **tool wear**
- Surface hardening may lead to **brittleness**, process optimization is required

Deformation-Based Methods - Ultrasonic Nanocrystal Surface Modification (UNSM)

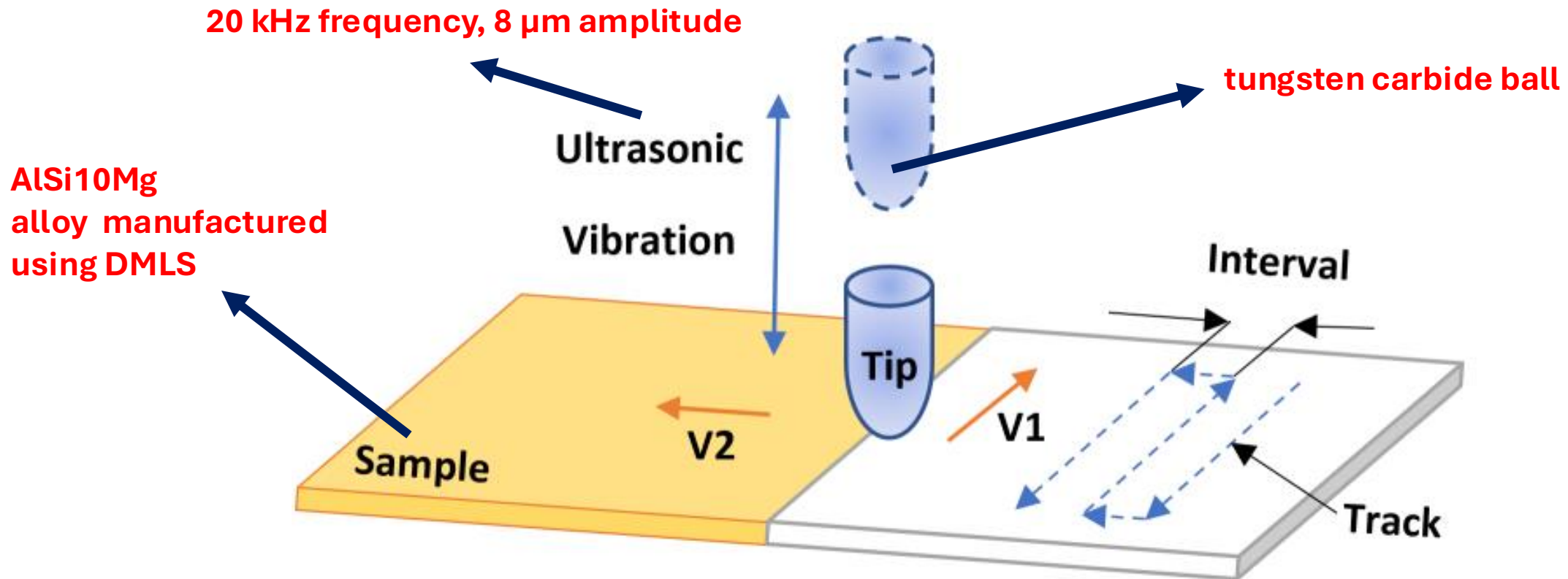


Fig 10. Schematic of the UNSM process

Cavitation

- Cavitation is usually a **problem in propeller systems** because it damages blade surfaces. It happens when low-pressure areas in water create vapor bubbles. When these bubbles collapse, they produce tiny jets and **shock waves** that hit nearby surfaces.
- The same effect can also be **used in a controlled way** for surface finishing. Controlled cavitation shocks that **gradually smooth the surface** and **reduce roughness**.



Deformation-Based Methods - Cavitation Abrasive Finishing (CAF)

Working Principle

- An **ultrasonic generator** (≈ 20 kHz) produces vibrations that generate **controlled cavitation bubbles** in a liquid medium.
- These bubbles **collapse near the surface**, creating **shock waves** that erode surface peaks and smooth irregularities.
- When **micro-abrasive particles** are added to the liquid, shock waves **accelerate these particles**, producing **additional material removal**

Advantages

- **Can remove partially melted particles**
- No direct tool contact
- **Suitable for hard materials** like inconel 625

Disadvantages

- Process **control is complex**
- **Limited to parts that can be immersed**
- **Potential non-uniform finishing** for smooth surfaces

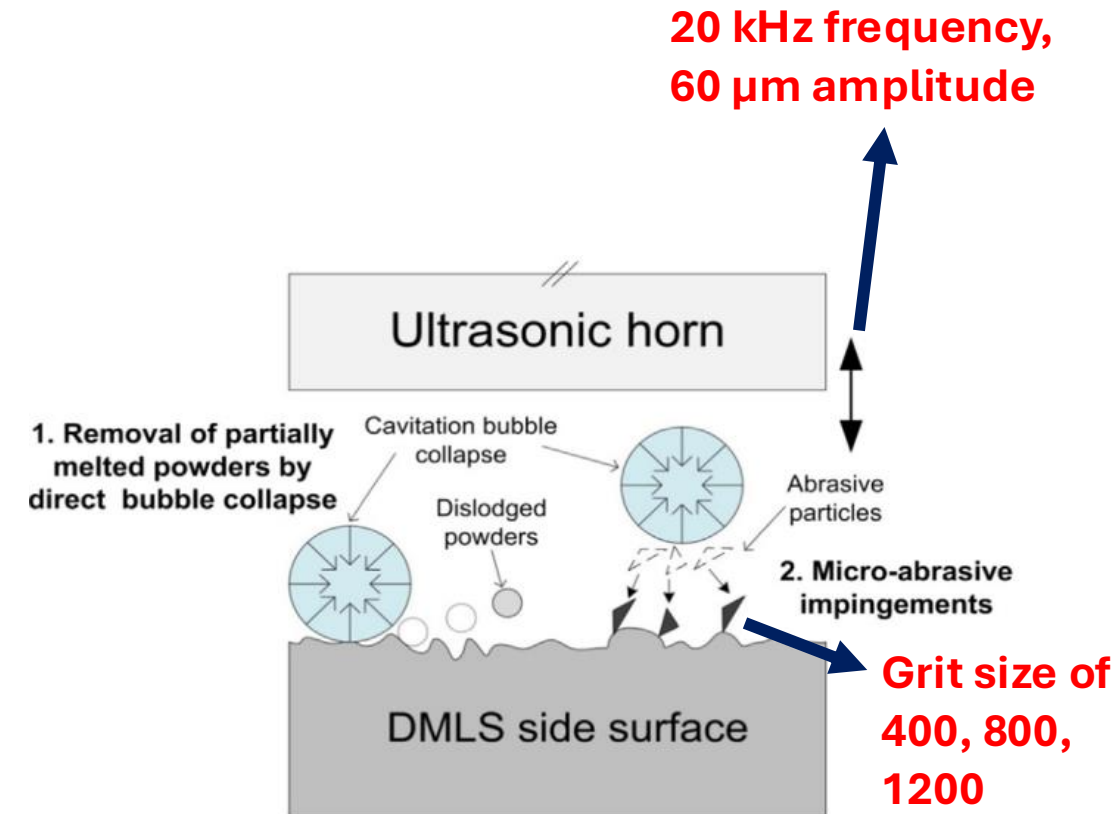


Fig 11. UCAF mechanism

Mass Finishing

Working Principle

- Mass finishing uses abrasive media motion to remove surface irregularities and produce uniform, smooth finishes on multiple complex parts simultaneously

Advantages

- Can process **multiple parts simultaneously**, reducing cost and time
- Suitable for **complex AM geometries**, including internal surfaces

Disadvantages

- Process **control is complex**
- Depends on **many parameters**
- **Limited control** over localized or selective surface finishing areas



Figure 12. Mass Finishing Operation. *Image Source:* [Gefinal.de](https://www.gefinal.de)

Mass Finishing – Abrasive Media

Loose, free-flowing abrasive materials that contact the part surface during motion to remove irregularities.

Shape & Size

- The shape must match the part geometry to ensure access to **narrow or internal regions** and avoid media lodging
- Over time, media **wear and mass loss** can reduce finishing efficiency

Material

- **Ceramic:** High strength, aggressive cutting (hard metals, plastic)
- **Plastic:** Softer materials (aluminum, brass, copper, plastic)



Fig 13. Abrasive media*

Mass Finishing – Compound

A compound is a **lubricating, cleaning and process-enhancing chemical** available in **liquid or powder form** and mixed with water at specific ratios.

Advantages

- Provide lubrication, reduce friction, and improve the overall efficiency
- Extends the life of the media
- Prevents glaze formation on media
- Provides rust prevention
- Cleans and/or bleaches metals



Fig 14. Compound *Image Source: Massfin.com*

Mass Finishing – Types

- **Vibratory Surface Finishing**
- **Centrifugal Disc Finishing**
- **Centrifugal Barrel Finishing**
- Drag Finishing
- Stream Finishing
- Rotary Barrel Finishing



Fig 15. Mass Finishing Types. Video source: belairfinishing.com

Note:
Single digit Ra:1-9 μm

Mass Finishing – Roughness Prediction with Machine Learning Model

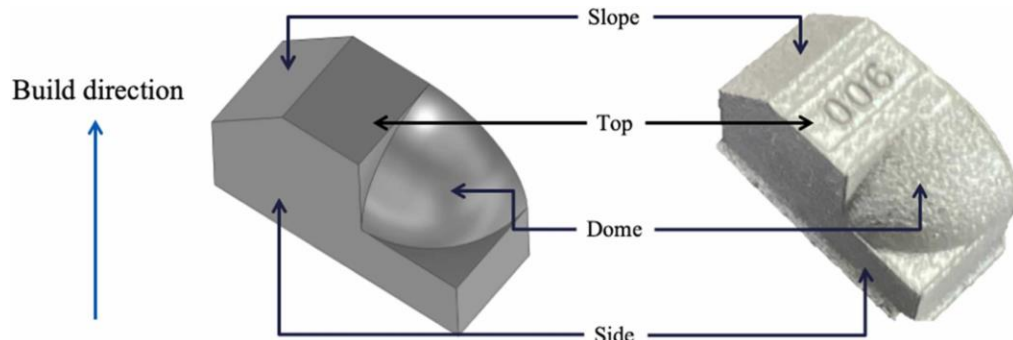


Fig 16. Titanium Alloy Samples (L-PBF)*

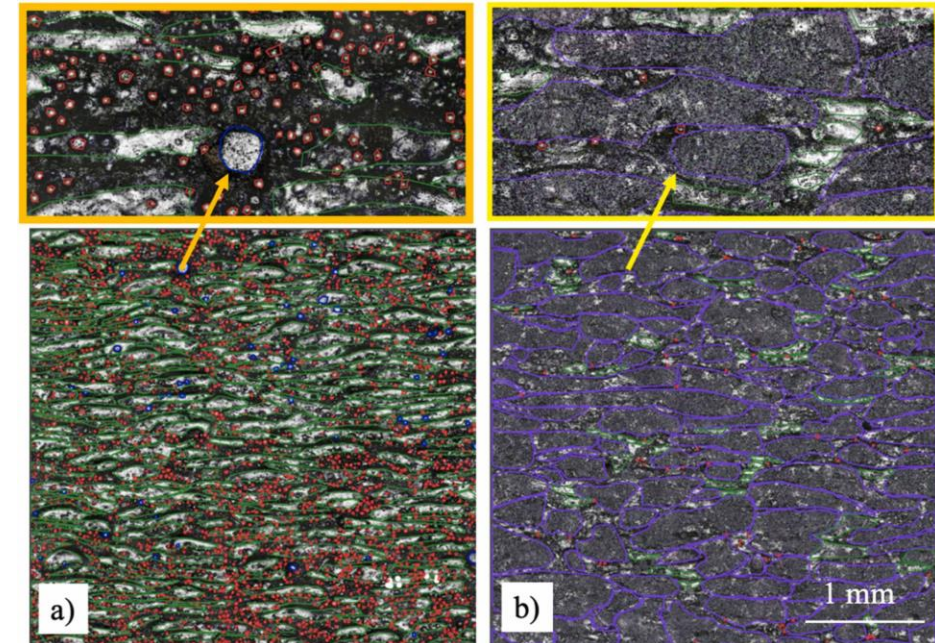


Fig 18. Surface Feature Annotations*

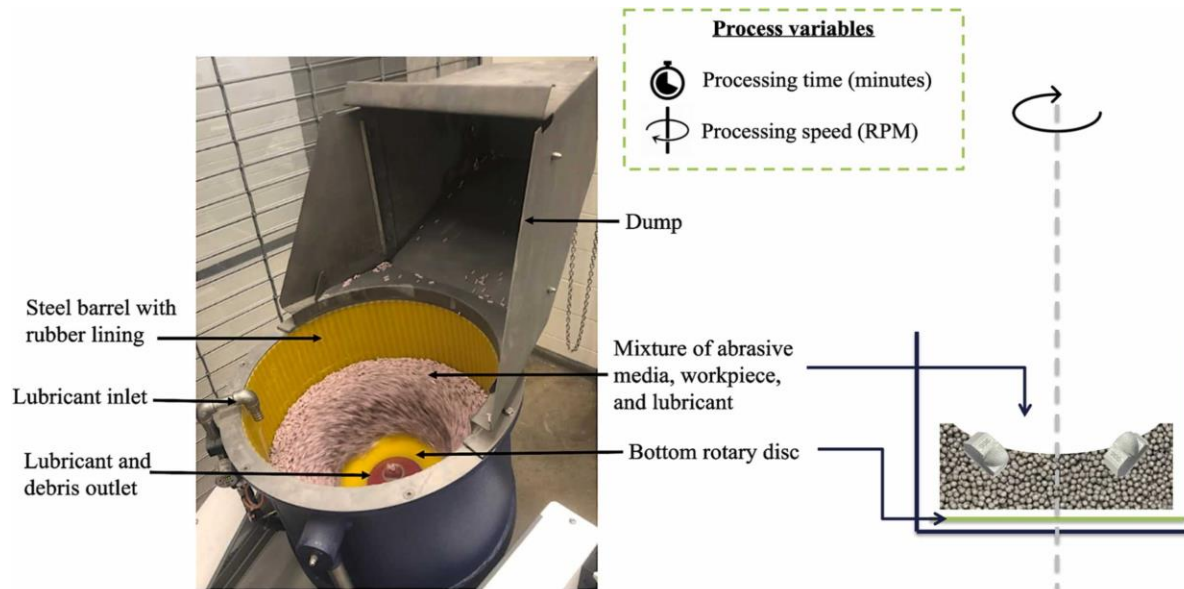


Fig 17. Centrifugal Disc Finishing Operation*

*Fan, F., Jalui, S., Shahed, K., Mullany, B., & Manogharan, G. (2025). Mass finishing for additive manufacturing: Tribological analysis, surface topology, image processing, predictive model, and processing recommendations. *Tribology International*, 204, Article 110486. <https://doi.org/10.1016/j.triboint.2024.110486>

Fatigue Life Enhancement

Importance of Fatigue Life for AM parts

- Most failures occur due to fatigue under repeated loading
- Fatigue process:

Microcrack initiation → Crack propagation → Fracture

AM related factors reducing fatigue life

- Surface Roughness
- Internal defects
- Tensile Residual Stress

Inducing Compressive Residual Stress with:

- Shot Peening
- Laser Shock Peening

Shot Peening

Working Principle

- Small, hard spherical particles are blasted at high velocity onto the surface, causing localized plastic deformation, work hardening, and the formation of compressive residual stresses (CRS) through constrained lateral expansion of the surface layer

Advantages

- Introduces beneficial compressive residual stresses and enhance fatigue life of parts
- Scratch resistant surfaces

Disadvantages

- Requires **careful selection of shot media hardness**
- May cause **over-peening**, leading to undesirable surface deformation or reduced surface quality

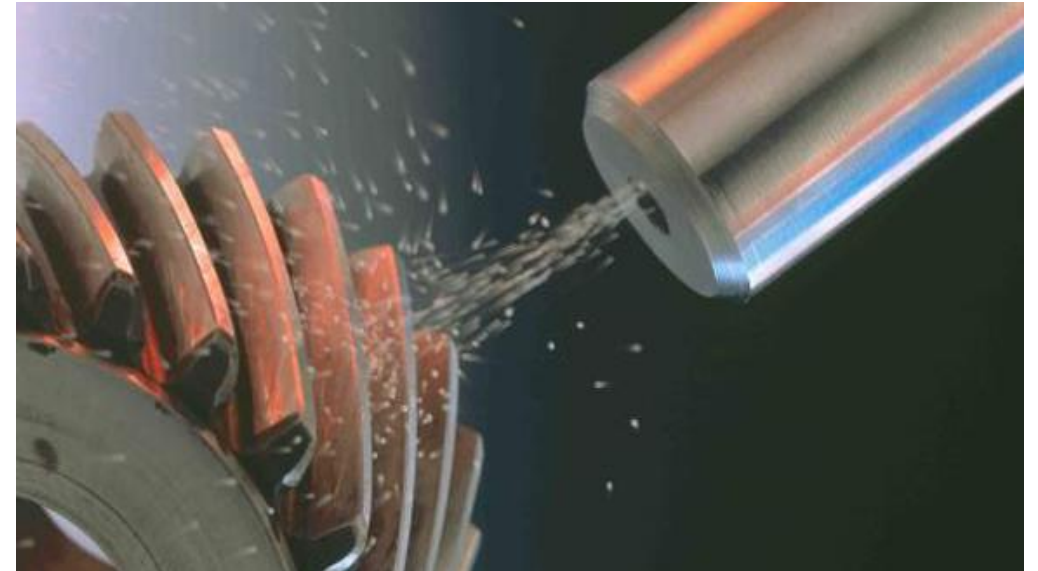


Fig 21. Shot peening operation. *Image source: sintoamerica.com*

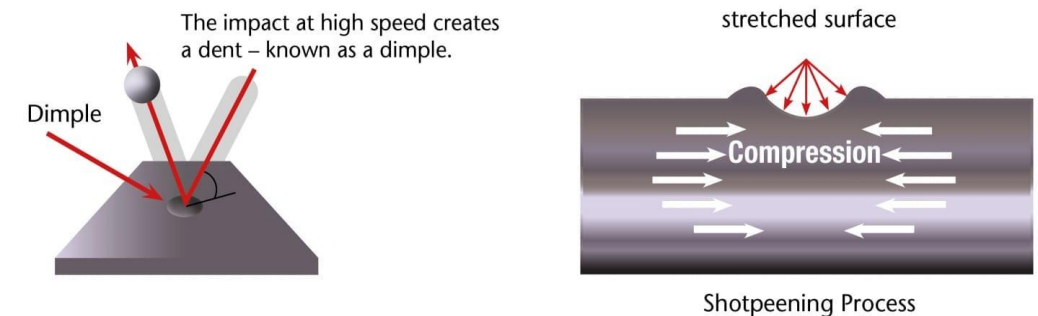


Fig 22. CRS mechanism for shot peening. *Image source: sbot.co.at*

Laser Shock Peening

Working Principle

- A high-energy pulsed laser creates a high-pressure plasma on the surface; a confining layer (e.g., water) forces this plasma to generate a strong shockwave into the material, producing deep plastic deformation and deep, high-magnitude compressive residual stresses.

Advantages

- Much deeper and stronger compressive residual stresses than conventional shot peening
- Minimal surface roughening

Disadvantages

- **Costs** are **significantly higher** than conventional SP
- Requires **specialized, high-precision setup**, increasing complexity

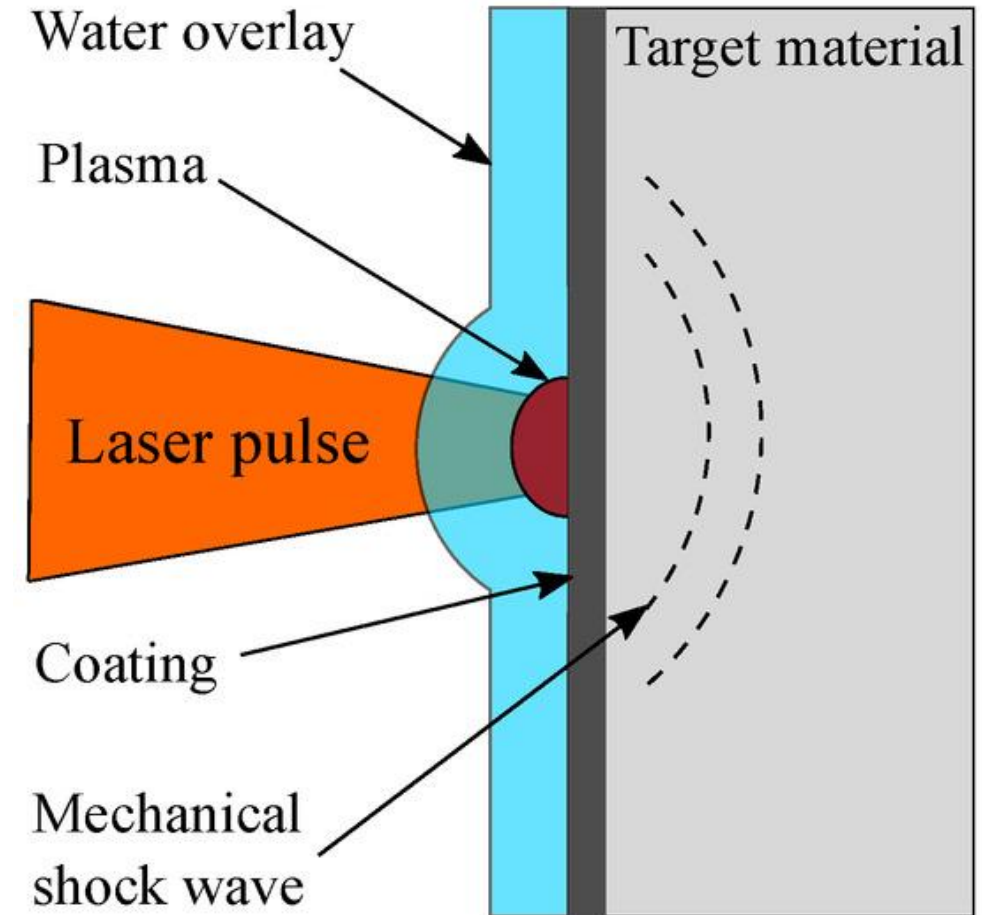


Fig 23. Laser Shock Peening Scheme*

Laser Shock Peening vs Shot Peening

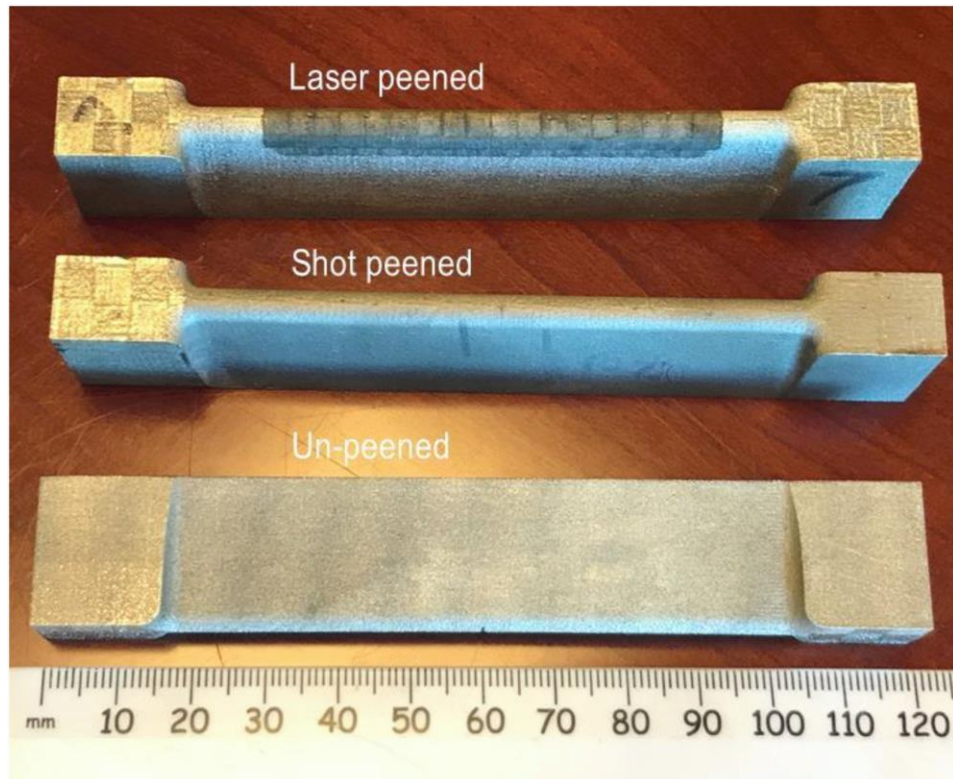


Fig 24. AM Fatigue test samples with 4-point bend design*

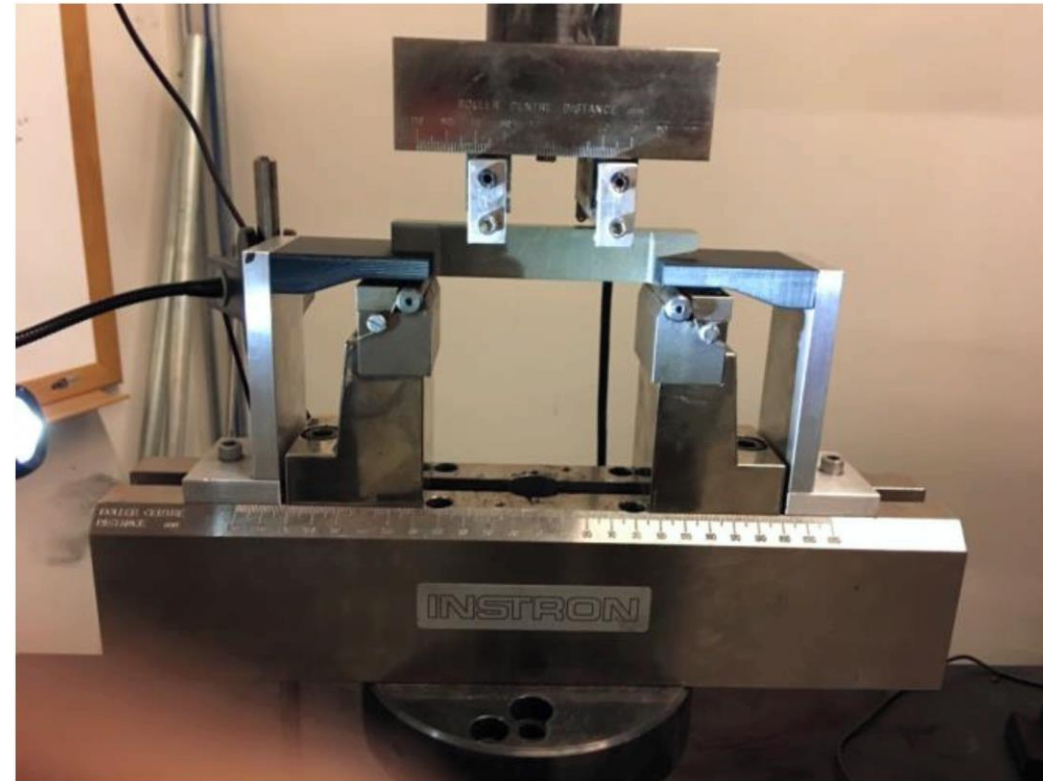


Fig 25. AM sample loaded on Instron fatigue rig *

*Hackel, L., Rankin, J. R., Rubenchik, A., King, W. E., & Matthews, M. (2018). Laser peening: A tool for additive manufacturing post-processing. *Additive Manufacturing*, 24, 67–75. <https://doi.org/10.1016/j.addma.2018.09.013>

Laser Shock Peening vs Shot Peening - Results

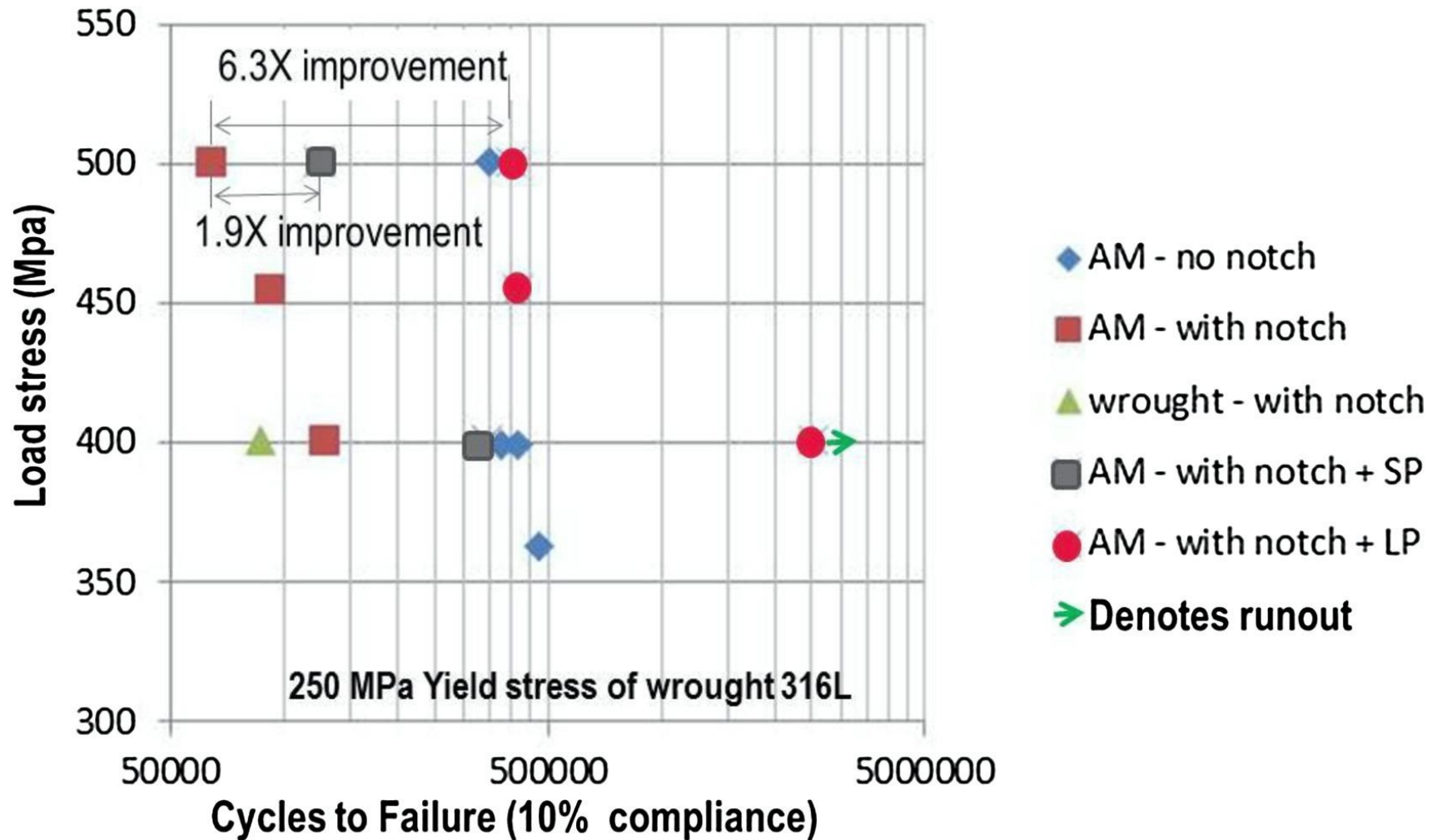


Fig 26. Fatigue lifetime test results*

*Hackel, L., Rankin, J. R., Rubenchik, A., King, W. E., & Matthews, M. (2018). Laser peening: A tool for additive manufacturing post-processing. *Additive Manufacturing*, 24, 67–75. <https://doi.org/10.1016/j.addma.2018.09.013>

Chemical Treatments

- ➔ Chemical Polishing
- ➔ Vapour Smoothing
- ➔ Coating
- ➔ Electrochemical finishing

Chemical Polishing

- A technique for enhancing the appearance of a surface

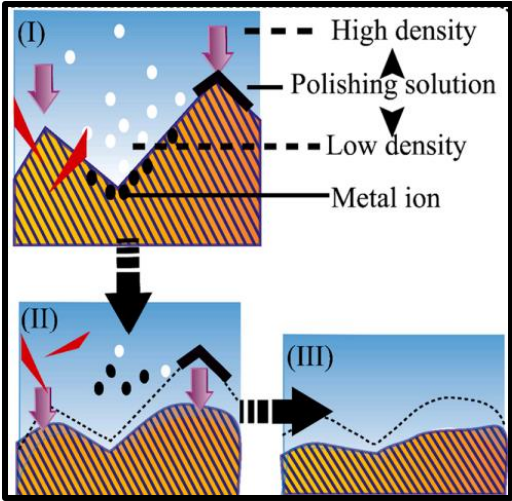
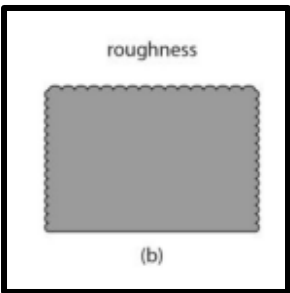
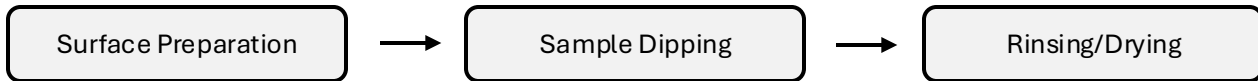
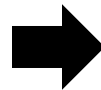


Figure 27. mechanism of chemical polishing

- The content of the **chemical solution**, the **temperature** and the **duration** is optimized

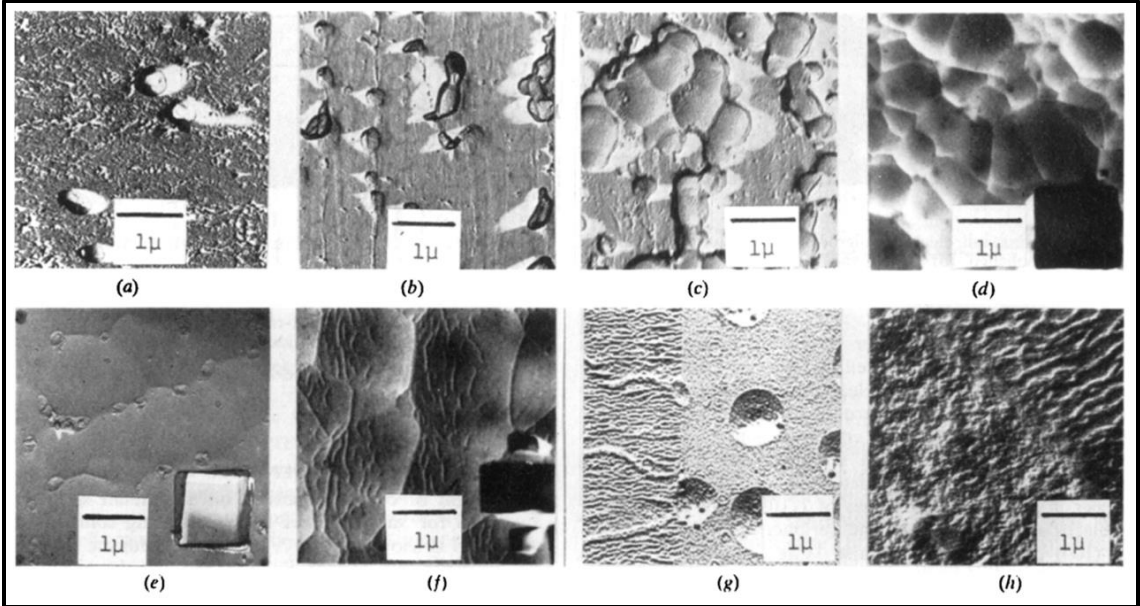
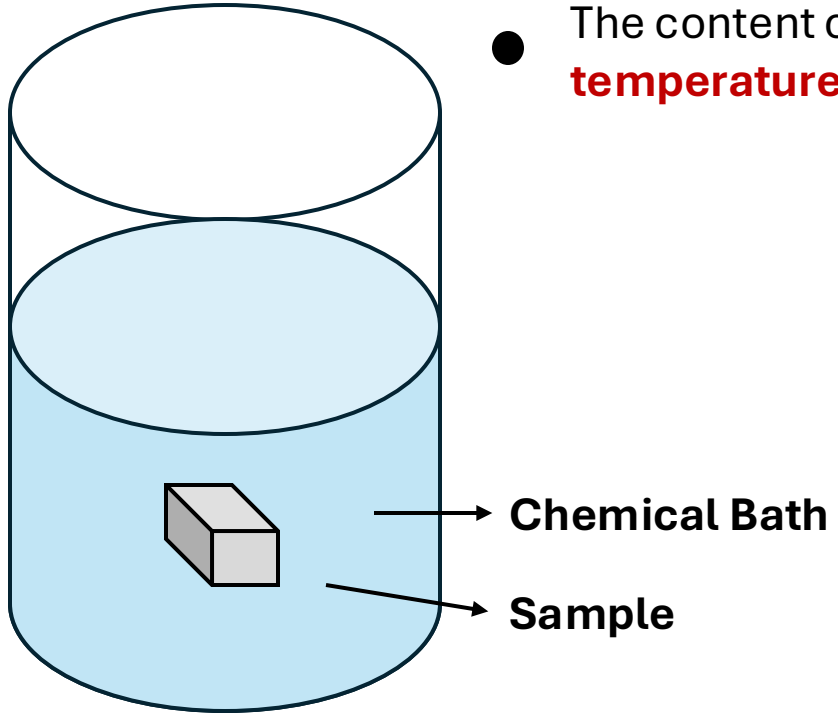


Figure 28. Evolution of polishing with time

[1] Basha, M. M., Basha, S. M., Jain, V. K., & Sankar, M. R. (2022). State of the art on chemical and electrochemical based finishing processes for additive manufactured features. *Additive Manufacturing*, 58, 103028. <https://doi.org/https://doi.org/10.1016/j.addma.2022.103028>

Chemical Polishing

- A technique for enhancing the appearance of a surface

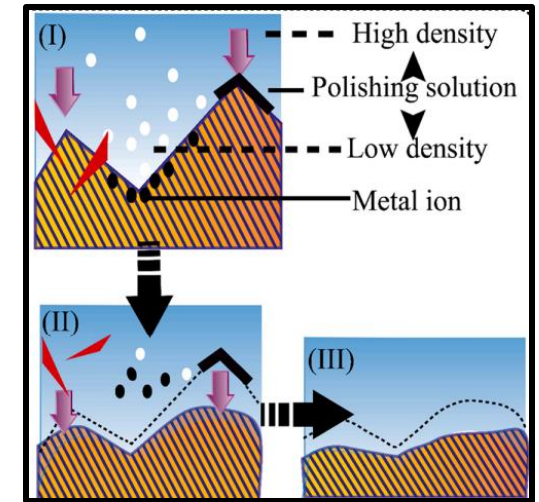
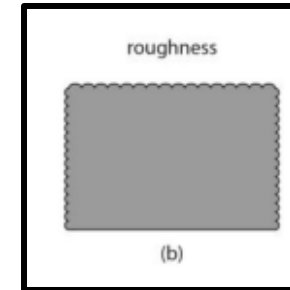
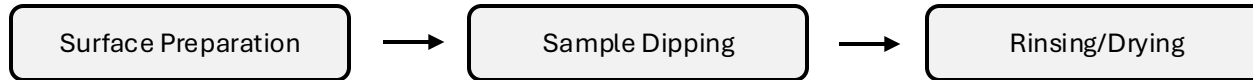
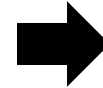
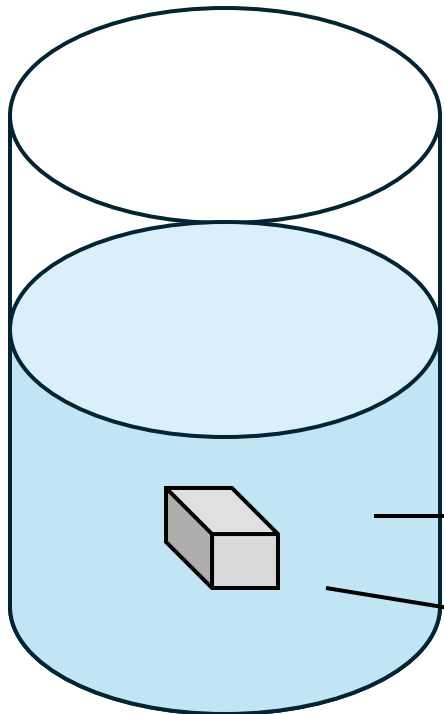


Figure 27. mechanism of chemical polishing

- The content of the **chemical solution**, the **temperature** and the **duration** is optimized



Temperature →

Time →

Chemical Bath →

Sample →

Tyagi et al. [2]

Galantucci et al. [1]

75°C
30 – 90 mins
H_3PO_4, HCl, HNO_3
SS316

RT
420 seconds
90% Acetone 10% Water
ABS

Roughness (S_a)

13.88 → 5.22 μm

31.53 → 2.53 μm

Vapour Smoothing

- A technique for enhancing the appearance of a surface
 - The secondary bonds of the polymer in the surface layer are dissolved
 - A semi solid slurry is formed where reflow of the surface fills the valleys decreasing roughness

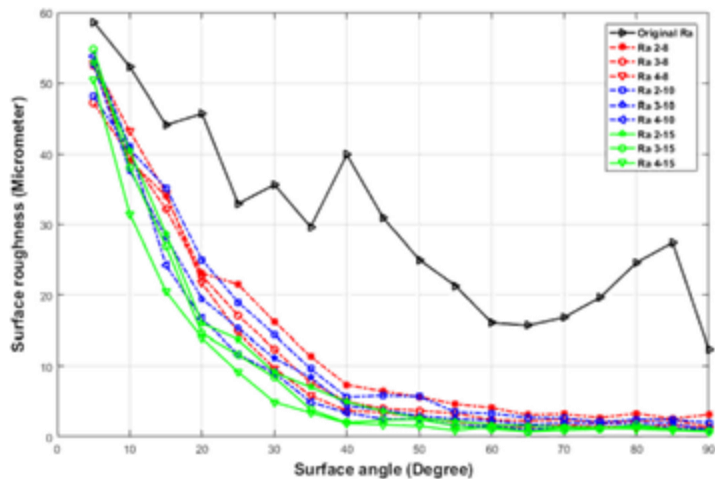
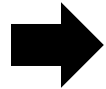


Figure 29. Roughness change with different cycle and durations

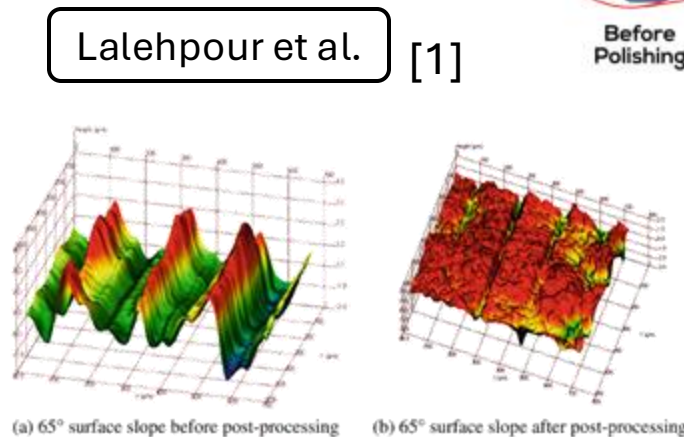


Figure 30. Illustration of the surface roughness

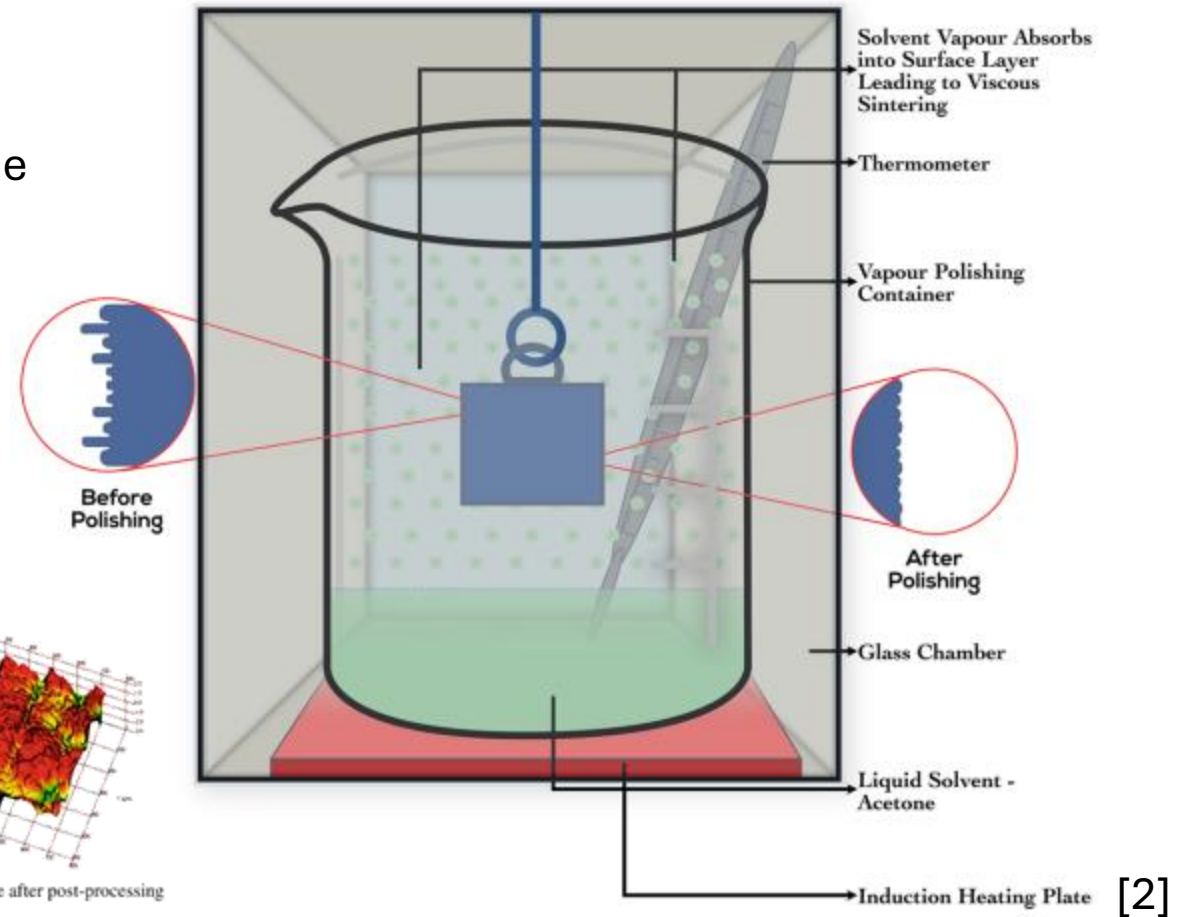


Figure 31. Set-up for vapour smoothing

[2]

Coating

- There are many coating techniques utilized

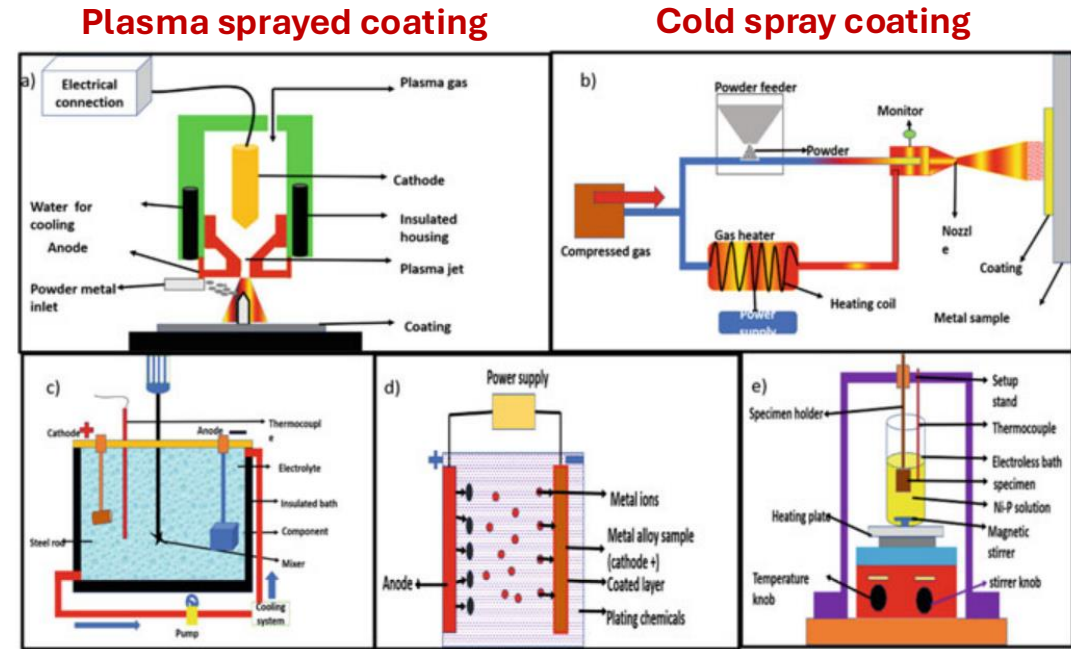
Hardness Wear Resistance Corrosion resistance

Mechanical Properties Roughness

- Must be careful for;

Adhesion of the coating with the substrate

Geometrical Deviation



[1]

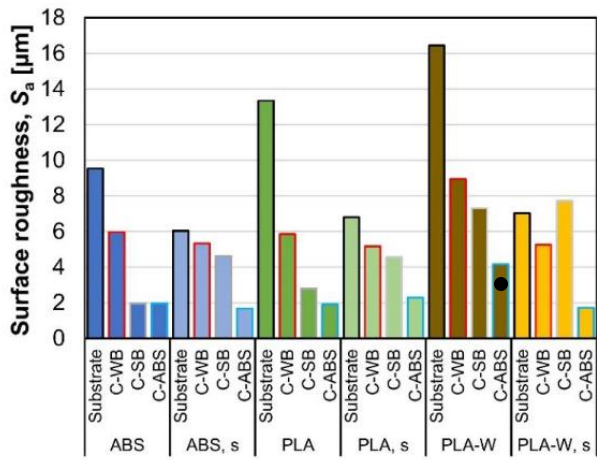
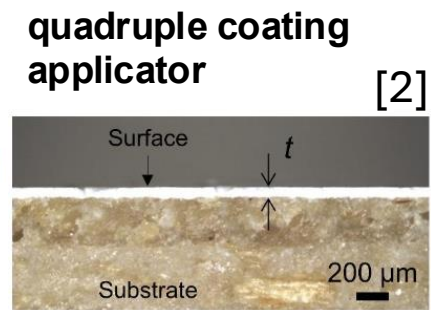
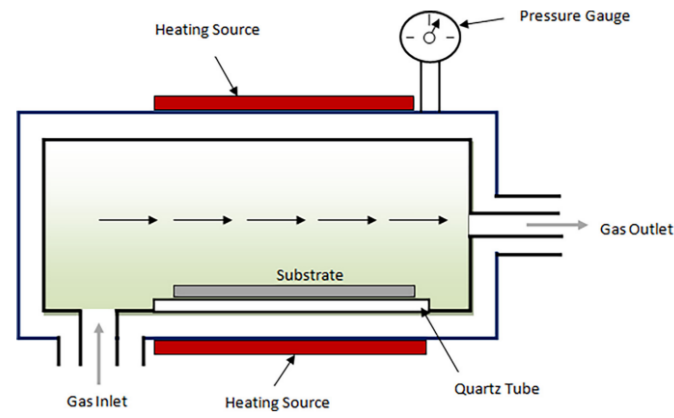


Figure 32. Change in roughness with various coatings



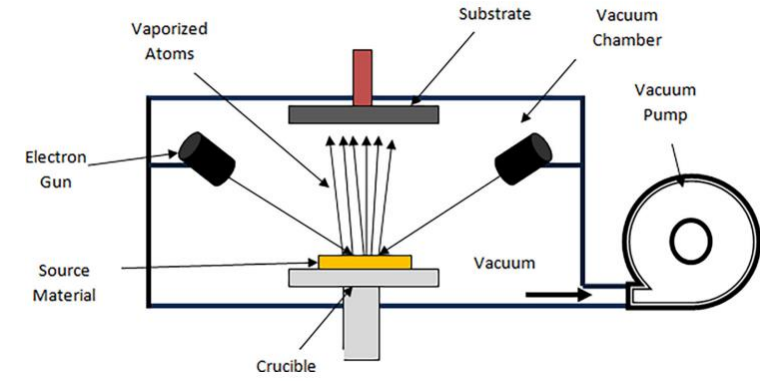
Plasma electrolytic oxidation



[3]

Electroplating

Electroless Ni-P coating



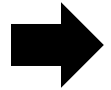
[3]

Figure 33. Coating methods

[1] Khan, M. A., Winowlin, J. T., & Editors, J. (2022). *Innovations in Additive Manufacturing*. Springer. <https://link.springer.com/bookseries/16694>
 [2] Žigon, J., Kari, M., & Pavli, M. (2020). Surface Finishing of 3D-Printed Polymers with Selected Coatings. *Polymers*, 12. <https://api.semanticscholar.org/CorpusID:227244616>
 [3] Singh, S., Kumar, S., & Khanna, V. (2023). A review on surface modification techniques. *Materials Today: Proceedings*. <https://doi.org/https://doi.org/10.1016/j.matpr.2023.01.010>

Electrochemical finishing

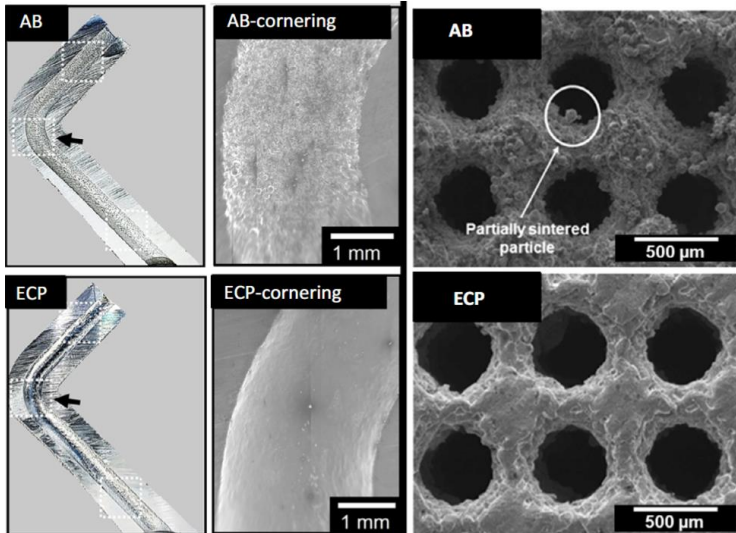
- The sample is anodic in an appropriate electrolytic solution



Material is removed from the surface

- The electrical energy can be modified to increase the rate of chemical reactions
- Material removal is irrespective of the surface roughness

Nickel-based superalloy



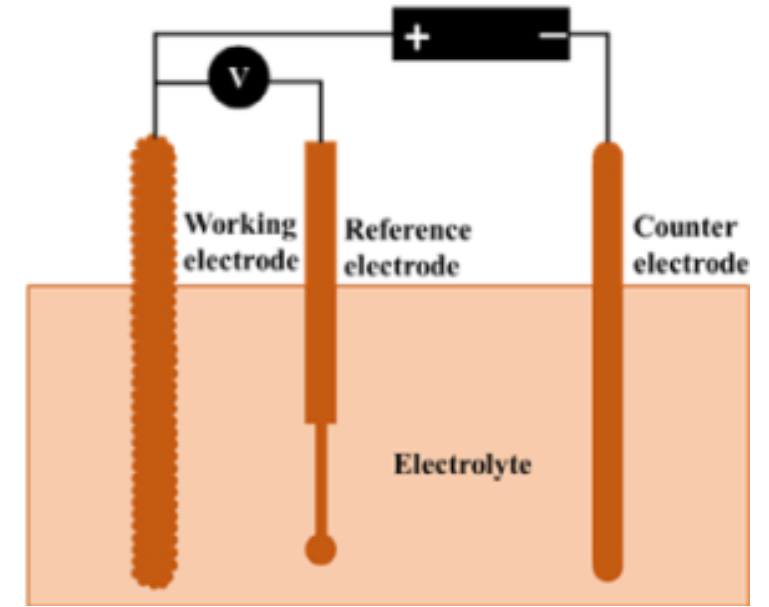
[1]

Roughness (S_a)
 $22.3 \mu m \rightarrow 4.5 \mu m$

Electrochemical finishing

Sample

Anode

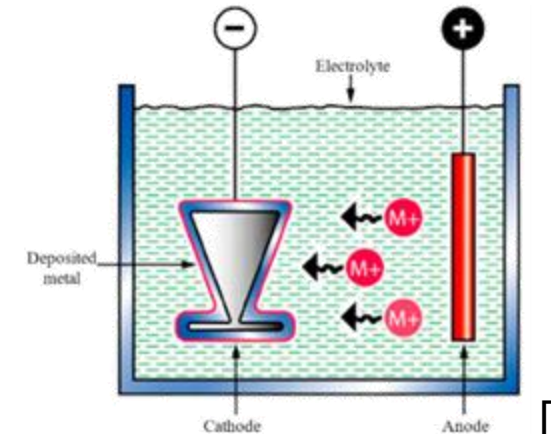


[1]

Electroplating

Sample

Cathode



[2]

Figure 34. Optical and SEM images before and after ECP

Figure 35. The schema of electrochemical finishing and electroplating

[1] Pourrahimi, S., & Hof, L. A. (2024). On the Post-Processing of Complex Additive Manufactured Metallic Parts: A Review. In *Advanced Engineering Materials* (Vol. 26, Issue 10). John Wiley and Sons Inc. <https://doi.org/10.1002/adem.202301511>
 [2] Tamburrino, F., Barone, S., Paoli, A., & Razonale, A. v. (2021). Post-processing treatments to enhance additively manufactured polymeric parts: a review. In *Virtual and Physical Prototyping* (Vol. 16, Issue 2, pp. 221–254). Taylor and Francis Ltd. <https://doi.org/10.1080/17452759.2021.1917039>

Thermal Treatments

- Hot Isostatic Pressing (HIP)
- Sintering and filtering
- Annealing
- Solution treatment and aging
- Stress-relief heat treatment (SRHT)
- Thermal debinding

Hot Isostatic Pressing (HIP)

High-pressure chamber with controlled atmosphere
 Temperature between the T_{solvus} and T_{melting}

Advantages

- Densifying metallic and ceramic parts
- Minimum **porosity** volume of **0.01%**
- Increase fatigue resistance, strength and ductility

Disadvantage

- No microstructure control

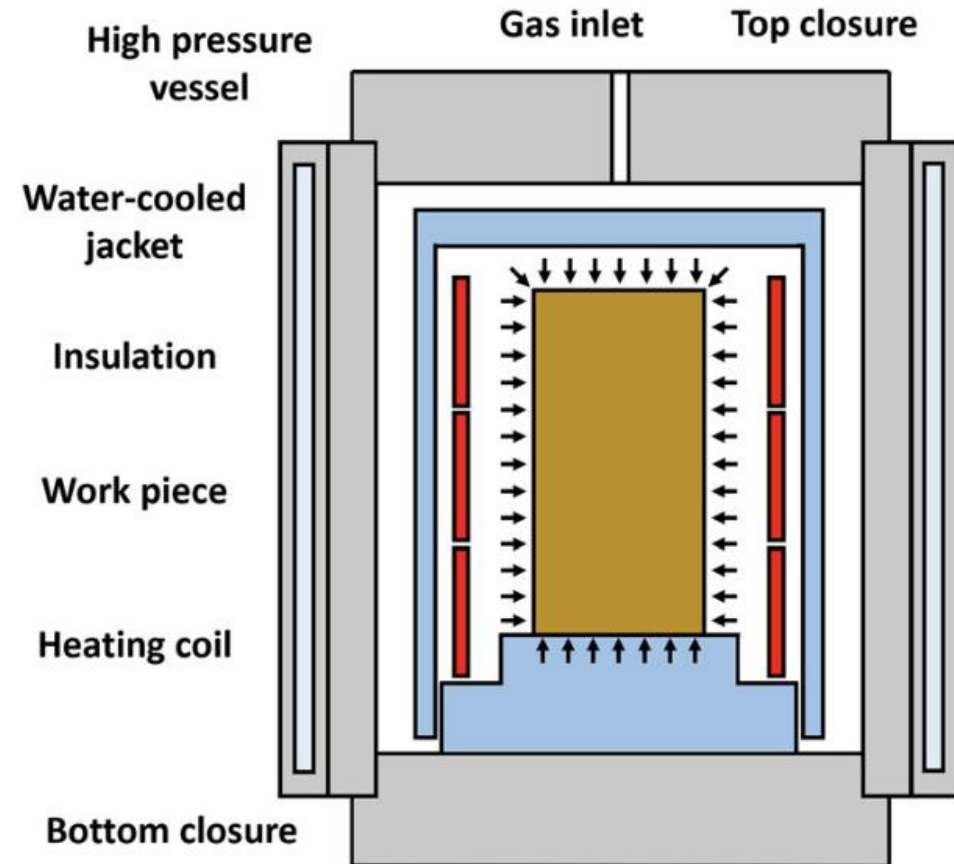


Fig 36. A schematic of a typical HIP process [1]

Sintering and filtering

In sintering, the particle coalescence without liquefaction of them is possible thanks to the controlled heating done below the melting temperature of the main component

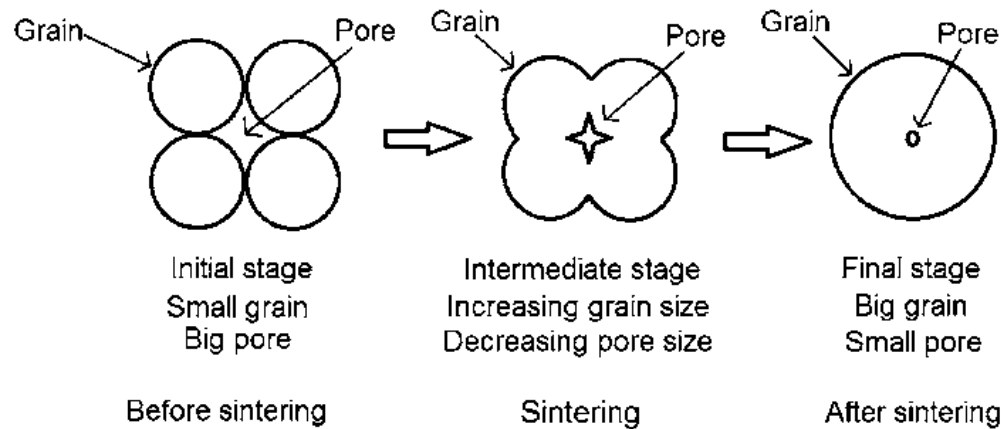


Fig 37. Sintering process

During filtration, the pores in the part is filled with a liquid metal or polymer. The liquid spread into interconnected pores and fills the entire volume.

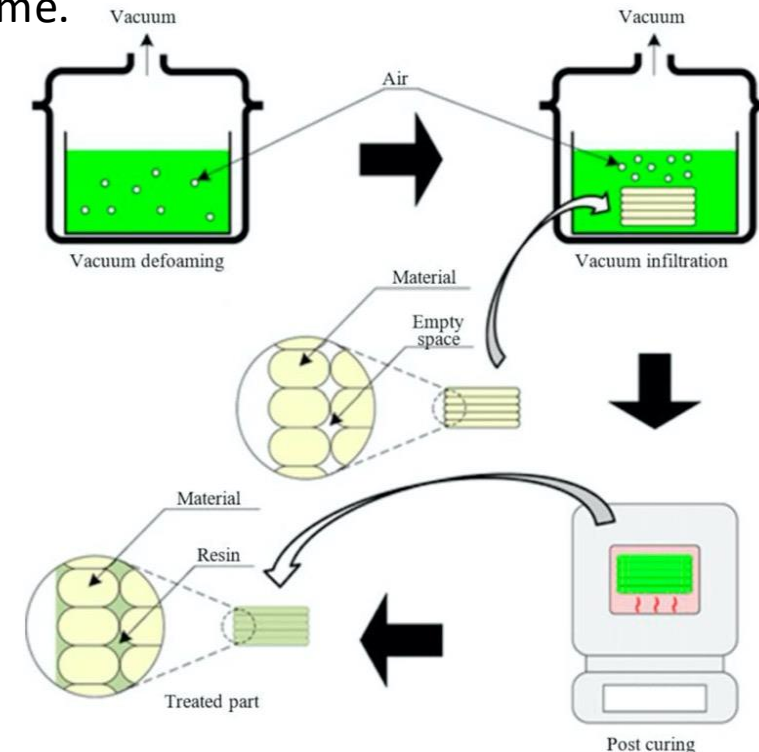


Fig 38. Filtering process [2]

[1] Aytimur, Arda & Kocyigit, Serhat & Uslu, Ibrahim. (2014). Calcia Stabilized Ceria Doped Zirconia Nanocrystalline Ceramic. Journal of Inorganic and Organometallic Polymers and Materials. 24. 927-932. 10.1007/s10904-014-0064-6.

[2] F. Tamburrino, S. Barone, A. Paoli, and A. V. Razonale. Post-processing treatments to enhance additively manufactured polymeric parts: a review. Virtual and Physical Prototyping, 16:221–254, 2021.

Sintering and filtering

Advantages

- Densifying metallic, ceramic and polymeric parts
- Minimum **porosity** volume of **1%**
- Increase compressive and tensile strength

Disadvantages

- No control on the microstructure
- Another heat treatment is needed to reduce internal stresses and to adjust the final microstructure

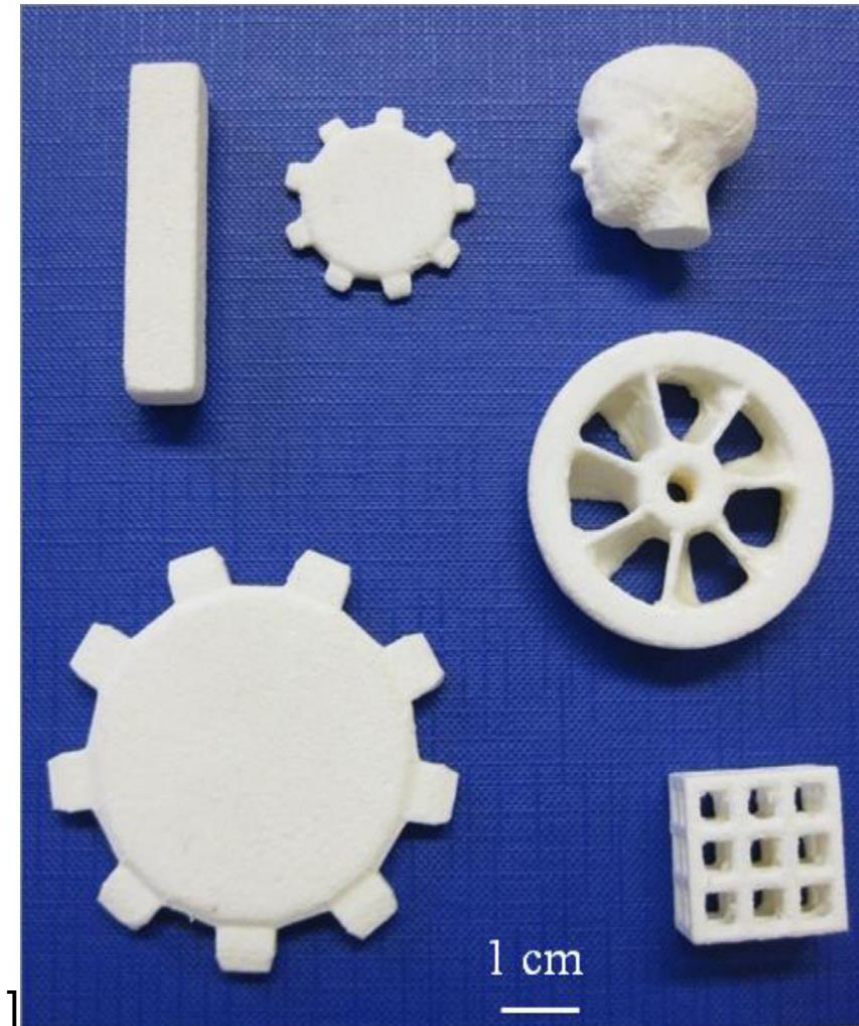


Fig 39. Complex parts produced by the SLS – pressure infiltration – debinding – sintering route. [1]

Annealing

The parts are heated and cooled, the heating and cooling rates are important and need to be controlled because it will impact the final properties.

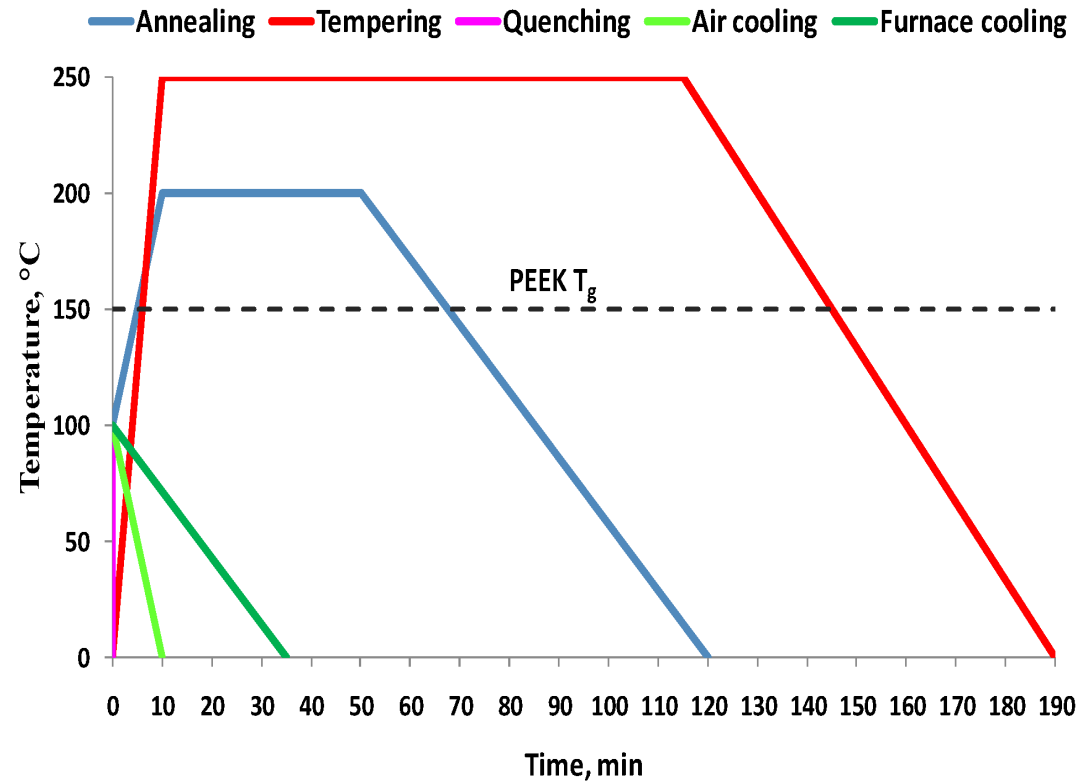


Fig 40. Different heat treatments on PEEK [1]

Annealing

The parts are heated and cooled, the heating and cooling rates are important and need to be controlled because it will impact the final properties.

Advantages

- Reduce internal stress
- Improve toughness and ductility
- for parts with heterogeneous microstructures
- Dimensional stability and improved machinability

Disadvantage

- Can decrease yield strength and hardness

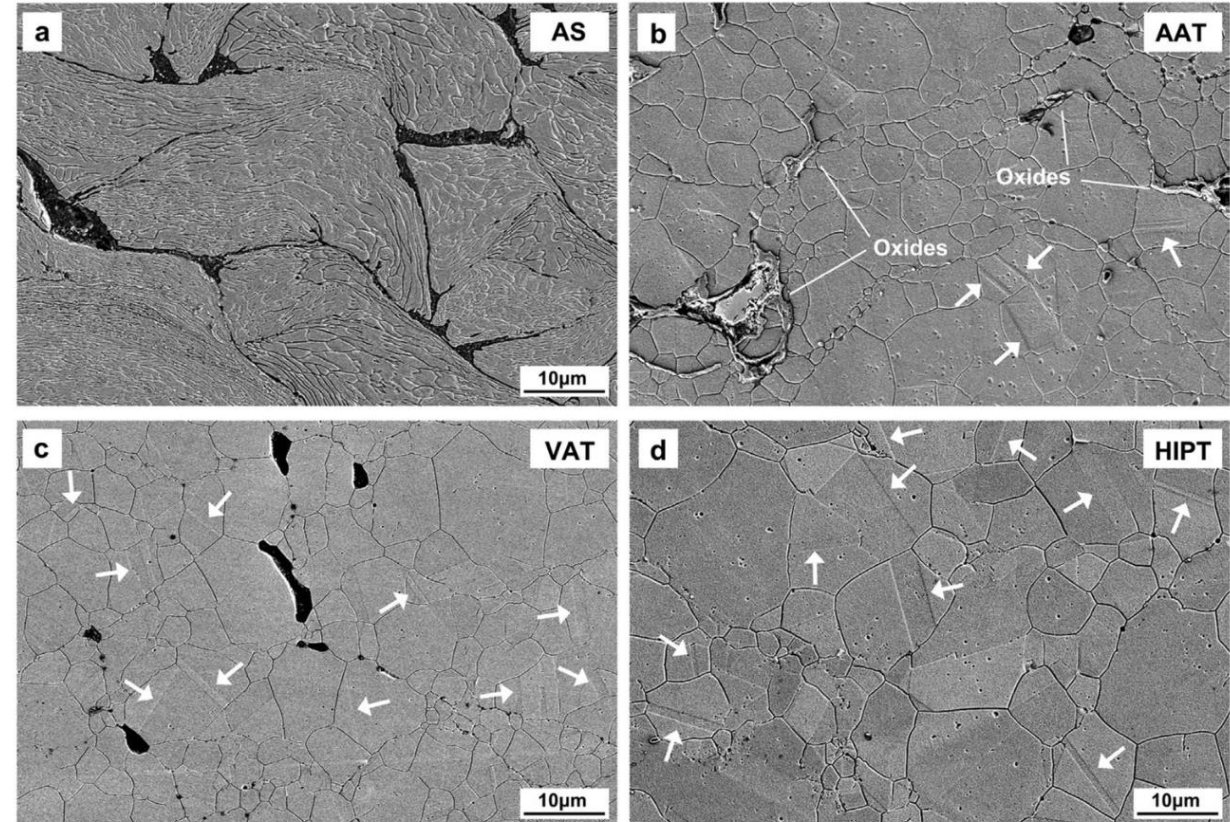


Fig 41. Microstructure evolution of the 316L deposits before and after post-treatments: (a) as-fabricated, (b) air-annealed, (c) vacuum annealed and (d) HIP-treated.[1]

Solution treatment and aging

Solutionizing dissolves segregated solute atoms and homogenizes the alloy matrix, typically around the solvus temperature

Advantages

- Significant increases in yield strength and hardness up to 30–40%
- Maintaining ductility
- More effective than annealing

Disadvantages

- can decreased toughness

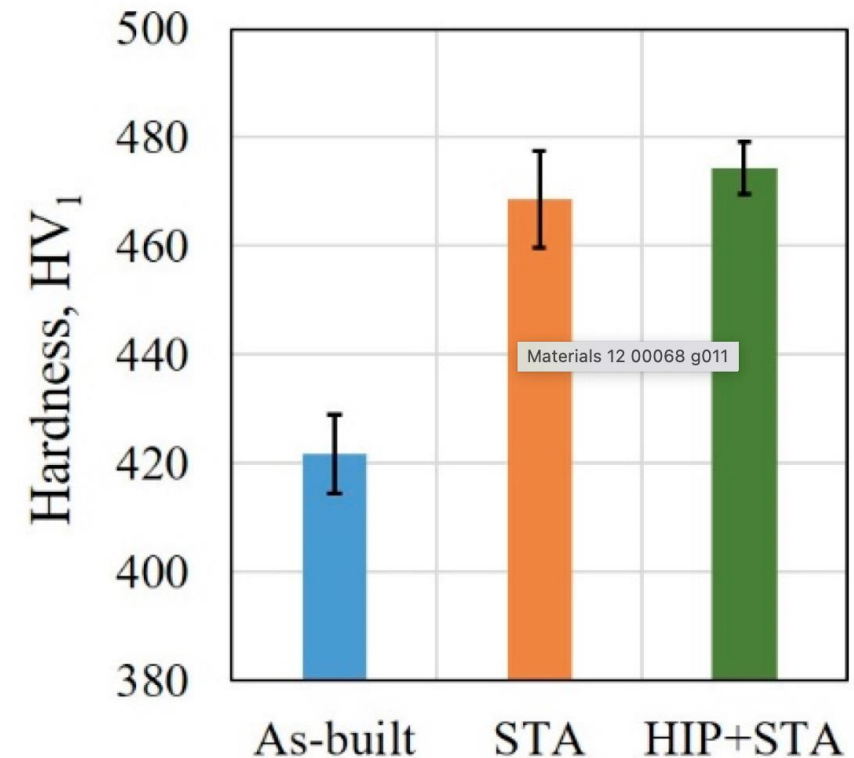


Fig 42. Vickers hardness (HV₁) in the as-built and post-treated conditions. [1]

Stress-relief heat treatment (SRHT)

Advantages

- Lower temperature
- Increase strength
- No microstructure modification
- Dimensional stability and improved machinability

Disadvantages

- Longer process

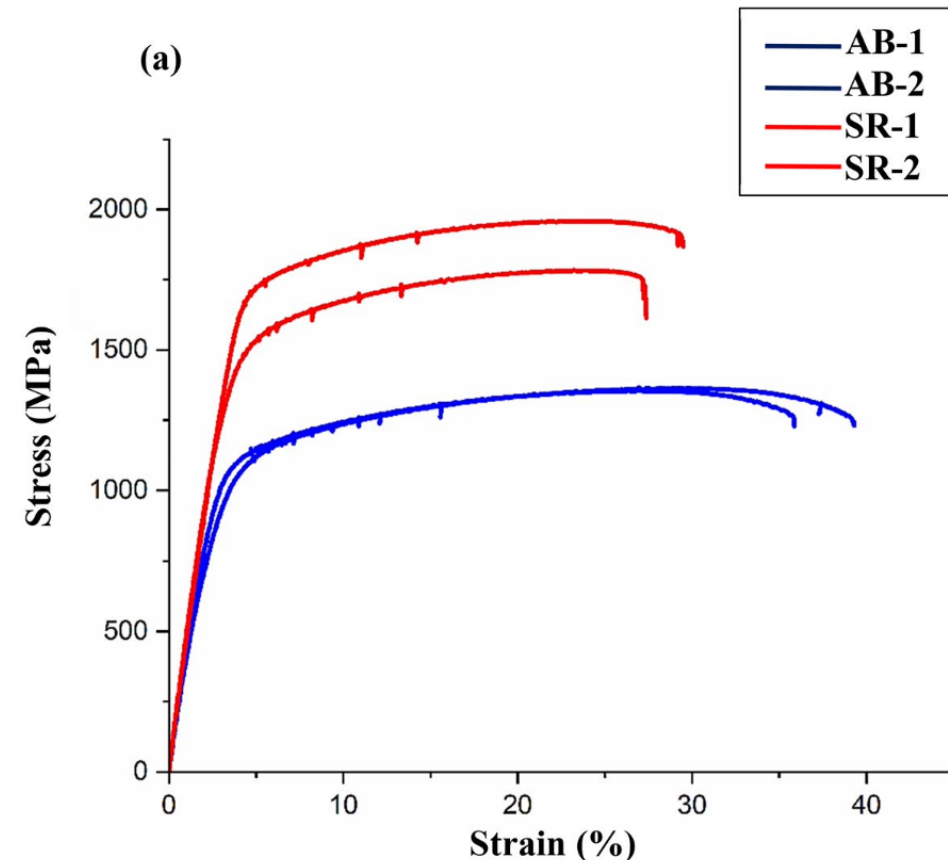


Fig 43. stress–strain curve of as-built and SRHT samples [1]

Thermal debinding

The temperature profile is composed of isothermal plateaus to gradually decompose the binder components and increase their diffusion and evaporation through interconnected pore channels.

Advantages

- remove the organic binder or polymeric additives
- Maintain the structural integrity of the porous “brown part” prior to sintering

Disadvantages

- Can cause swelling, cracking, or delamination of the part

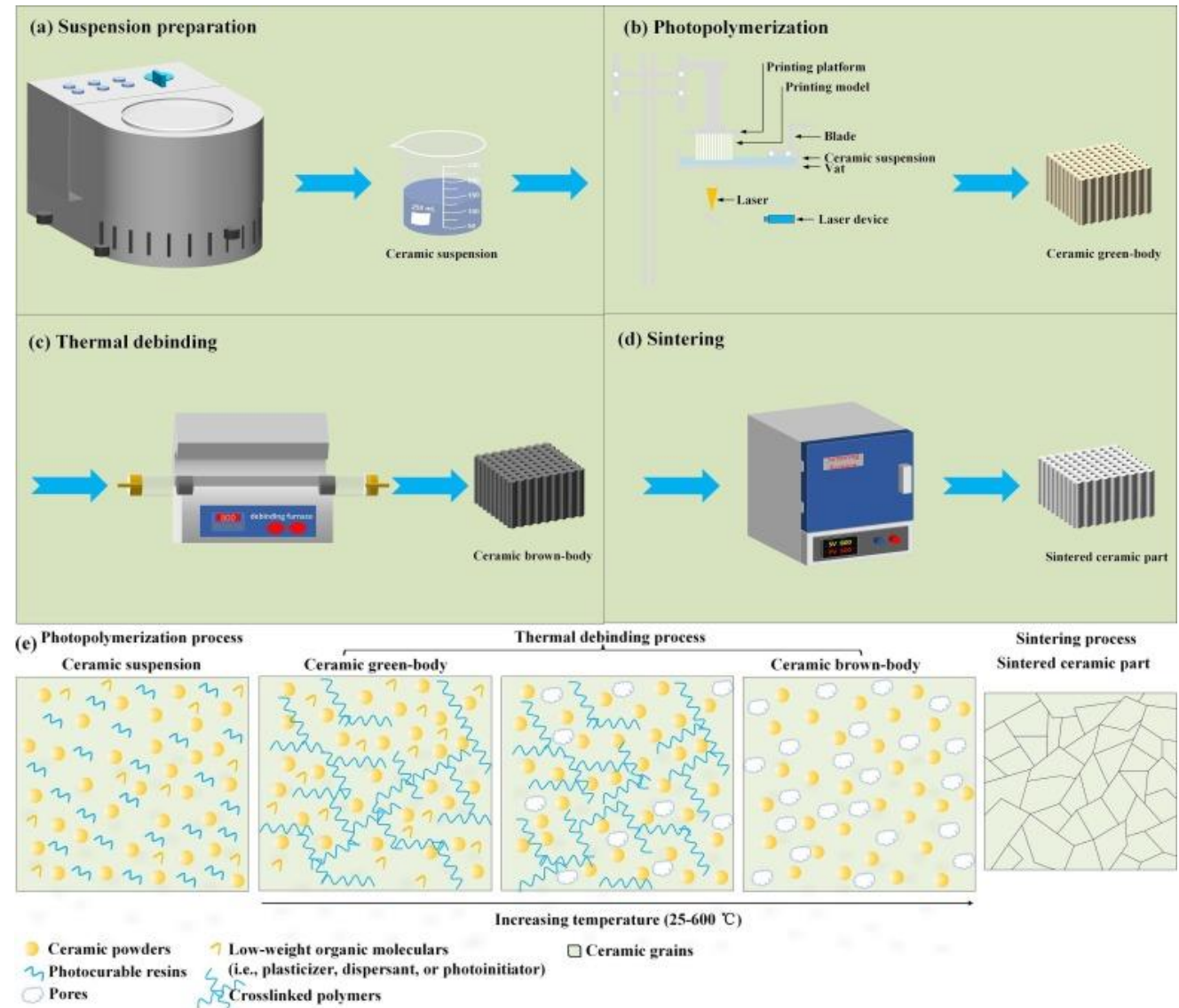


Fig 44. Schematic diagram of fabricating ceramic objects [1]

Conclusion

- ↗ Mechanical properties → Mechanical & Thermal treatments
- ↗ Surface topography → Mechanical & Chemical treatments
- ↗ Density → Thermal treatments
- ↗ Refine microstructure → Thermal treatments
- ↗ Corrosion resistance → Chemical treatments

Chemical treatments particularly is useful for complex geometries