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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Post Processing Methods for Additively Manufactured Parts

SESSION 1: WELCOME

21 January 2021

Harry BIKAS – LMS

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Agenda

Day 1 (21.01.2021)

Welcome	09:00-09:30	30
General considerations (Part 1)	09:30-10:20	50
Coffee break	*10:20-10:25*	*5*
General considerations (Part 2)	10:25-11:15	50
Coffee break	*11:15-11:20*	*5*
Thermal treatment (Part 1)	11:20-12:15	55
Lunch break	*12:15-13:00*	*45*
Thermal treatment (Part 2)	13:00-14:00	60

Day 2 (22.01.2021)

Plastic deformation methods	09:00-10:00	60
Coffee break	*10:00-10:10*	*10*
Subtractive manufacturing (Part 1)	10:10-11:00	50
Coffee break	*11:00-11:05*	*10*
Subtractive manufacturing (Part 2)	11:10-12:00	50
Lunch break	*12:00-12:45*	*45*
Finishing operations	12:45-13:55	80
Concluding remarks	13:55-14:00	5

LMS: Introduction

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The Laboratory for Manufacturing Systems & Automation (LMS) is oriented on research and development in cutting edge scientific and technological fields. LMS is involved in a number of research projects funded by the CEU and European industrial partners. Particular emphasis is given to the co-operation with the European industry as well as with a number of "hi-tech" firms. LMS employs approximately 100 researchers.

LMS

Laboratory for Manufacturing Systems & Automation

- Participation in more than **180 R&D Projects**
- Coordination of more that **50 EU Competitive R&D projects**
- Organization of more than **10 International conferences.**
- Publication of more than **700 Scientific articles**

LMS is organized in Three Different Groups

- Manufacturing Processes
- Manufacturing Automation, Robots & Virtual Reality Applications
- Manufacturing Systems

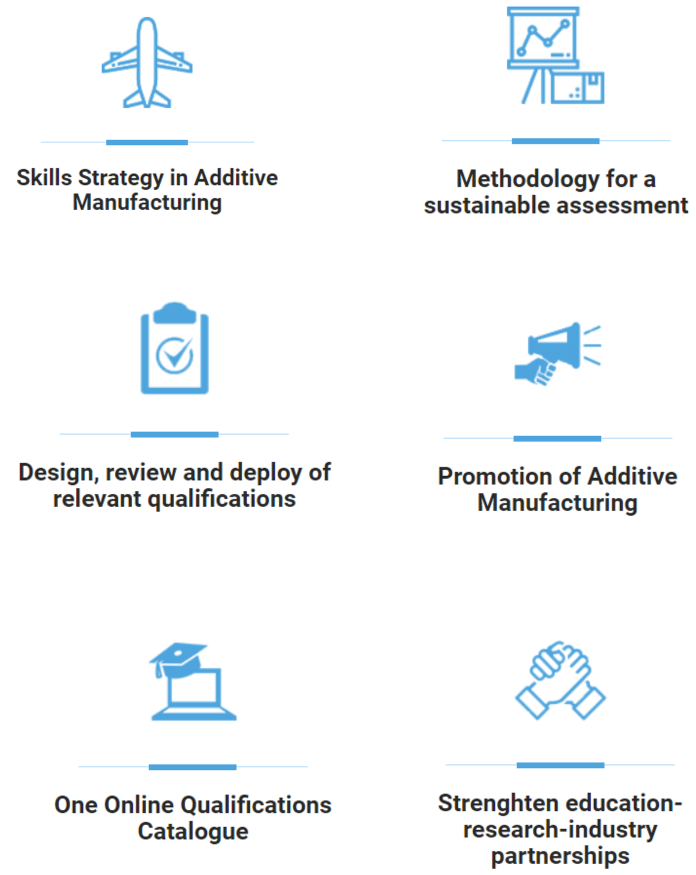
SAM: The Project

Co-funded by the Erasmus+ Programme of the European Union

SAM is a European initiative that aims to address the workforce development for Additive Manufacturing (AM) by developing a shared skills vision and collaborative learning solutions for the sector at European level.

Objectives:

- ✓ Build a sector skills strategy in AM;
- ✓ Assess and anticipate skills (gaps and shortages) in AM;
- ✓ Support with data the AM European Qualification System and foster wideness of its scope;
- ✓ (Re)design professional profiles according to the industry requirements;
- ✓ Develop specific relevant qualifications to be delivered for the AM Sector;
- ✓ Increase the attractiveness of the sector to young people, whilst promoting gender balance;
- ✓ Strengthen education-research-industry partnerships and encourage creativity "in companies and relevant educational and scientific institutions";
- ✓ Track students, trainees and job seekers and promote match making between job offer and search.



Please find out more info at: www.skills4am.eu/

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Course structure

- 2-Day event
- Active participation of audience is expected
- Follow-up exam/assessment on a separate date (will be communicated via e-mail)
- SAM certificate of attendance awarded to participants
    - Need to attend both days and successfully complete assessment
    - Will be issued after fulfilling the Satisfaction feedback form - 1 month to be issued
    - Will contain information about the attended CU and accomplished Assessment.

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Assessment

- Multiple-choice questions directly related to the program of the Unit of Learning Outcomes / Competence unit
- Invigilator from EWF will give access to the exam the day of the exam, using MS Teams Forms as supporting tool for the assessment
- Students are advised to have good internet connection and cameras on to access the exam
- The students must wait for permission to initiate the exam (and access the link)
- Questions/doubts during the exam shall be addressed in the chat box ONLY
- In order to pass the exam, the student must reach at least 60% correct answers
- Failing the exam, the student will be entitled to a maximum of 3 reassessments
- If case of failing 3 times, the student must attend the CU again before repeating the exam
- Students who feel that the evaluation process was unfair have the right to appeal directly to EWF.
- The results of the exam will be released 1 week after the exam occurrence

Evidences

- To prove attendance and participation, evidences will be collected during each training course
- Evidences include
  - Attendance list (including your names and e-mails)
  - Photographic evidence/screenshots
  - Results of the assessment
  - Results of the feedback surveys
- **Participating in the training course means that you automatically accept the aforementioned data collection policy!**

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skills4am.eu

Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

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Post Processing Methods for Additively Manufactured Parts

SESSION 3: THERMAL TREATMENT

21 January 2021

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Outline

- Introduction
- Preheating as a method for AM optimization
- Heat Treatment
- Heat Treatment Methods
- Schematic representation of the change in microstructure
- Heat Treatment Equipment – Heating Stations
- Heat Treatment Equipment – Temperature uniformity
- Heat Treatment Equipment – General
- Temperature measurement
- Heat Treatment parameters
- Heat Treatment procedures
- Heat Treatment record
- International Standards

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Thermal treatment

- Thermal treatment is a process which preserves a material in an elevated temperature for a certain time interval
- Cooling of the material can be performed rapidly or in a slower rate depending on the desired mechanical properties
- Thermal treatment is a post-process step that is used very commonly in Additive Manufacturing
- Pre-heating of an AM part also presents an interesting tool for optimization of the process

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Need for preheating

- During the building process high thermal gradients are exhibited between the topmost and bottom layers/build plate of the part
- These high thermal gradients result in formation of residual stresses and distortion of the part
- A tool for reduction of the thermal gradients can optimize the AM process
- Preheating of the part presents itself as a potential tool to reduce the thermal gradients

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Preheating methods

- Several methods exist for preheating
- Heating of the build chamber/powder (PBF)
- Heating of the build plate (DED/PBF)
- In cases of deposition on existing parts (DED) preheating can be applied by heating the surface of the part with laser or induction methods

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Benefits of preheating

- Reduction of residual stress and deformation of the built part
- More homogenous microstructure
- Improved bonding of bottom layers with the build plate
- Reduction of crack susceptibility
- Improved mechanical properties

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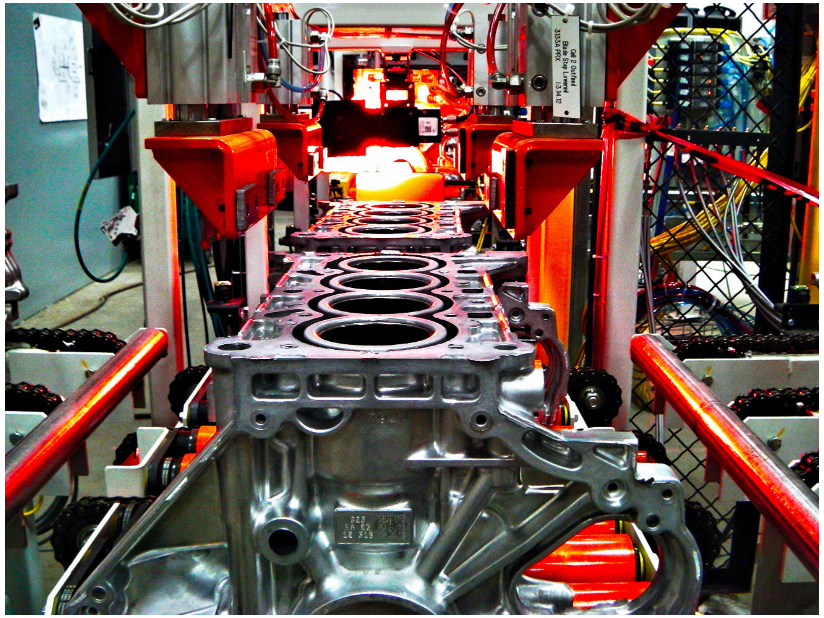
*Most commonly, **heat treatment** is applied in the open air or controlled chambers. These, may or may not involve vacuum containment. Vacuum conditions offer the best performance for post-printing heat treatment.*

- Post-processing: Using Heat Treatment to Ensure Mechanical Strength
- First, heat treatment can have de-tensioning effects.
- Second, heat treatment can optimize the properties of products such as:
  - ductility and hardness
  - decrease the residual stresses
  - increase the density
  - enhance the fatigue life

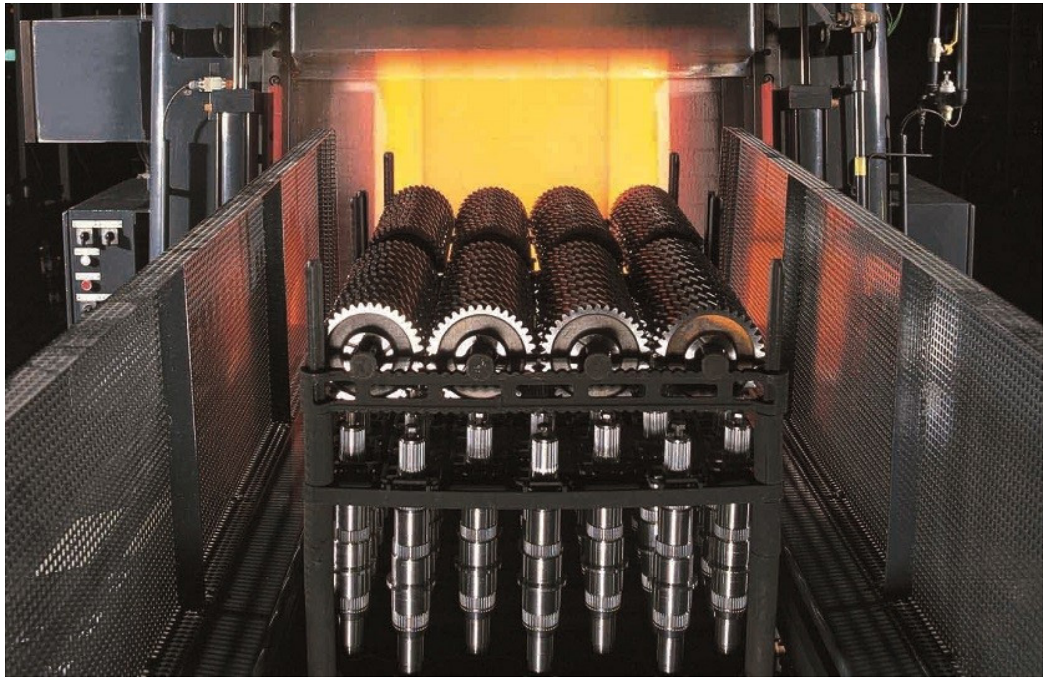


Heat Treatment
https://www.can-eng.com/News/Blog/what-is-heat-treatment

Heat Treatment

Heat treatment **general equipment** include:

- Heating equipment
- Loading and unloading equipment
- Media that provide controlled heat treatment atmosphere
- Temperature measurement and recording equipment
- Quenching liquids
- PPE and other safety equipment



Heat treatment equipment
https://www.bodycote.com/services/heat-treatment/

Info: Heat treatment can easily cost $500 to $2,000 depending the material and how many parts are being treated.

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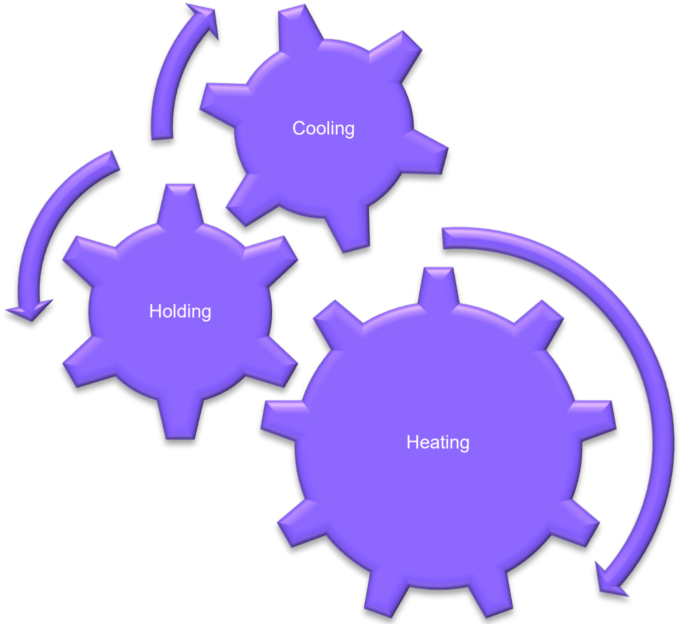
Heat treatment process steps:

- Heating
- Holding
- Cooling



Info:

The final outcome depends on many different factors. These include the time of heating, time of keeping the metal part at a certain temperature, rate of cooling, surrounding conditions, etc. The parameters depend on the heat treatment method, type of metal and part size.

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Common Heat Treatment methods

- Annealing
- Normalizing
- Hardening
- Precipitation Hardening
- Stress relieving
- Tempering
- Homogenization

https://www.industrialheating.com/articles/94448-vacuum-heat-treating-of-3d-printed-components

https://www.tav-vacuumfurnaces.com/blog/50/en/heat-treating-additive-manufacturing

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Annealing

- Heating of the material above its recrystallization temperature for a set amount of time
- The elevated temperature leads to diffusion of the atoms of the material
- The diffusion of the atoms redistributes and eliminates the dislocations of the material and the internal stresses they cause (recovery phase)
- New uniform grains grown to replace those that were deformed by internal stresses (recrystallization phase)
- Then, the material is cooled slowly in air (ferrous metals) or quickly by quenching in water (copper, silver and brass)

Annealing
https://www.thermalvac.com/city-steel/heat-treating-and-annealing

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Annealing

- Annealing is a possible approach for improving mechanical properties of additively manufactured parts.

- Results of case studies of annealing as post-processing of AM parts:
  - Elimination of the effect of build direction on the microstructure of the part
  - Improved fatigue strength
  - Reduced crack propagation (based on Paris law)
  - Improved corrosion behavior

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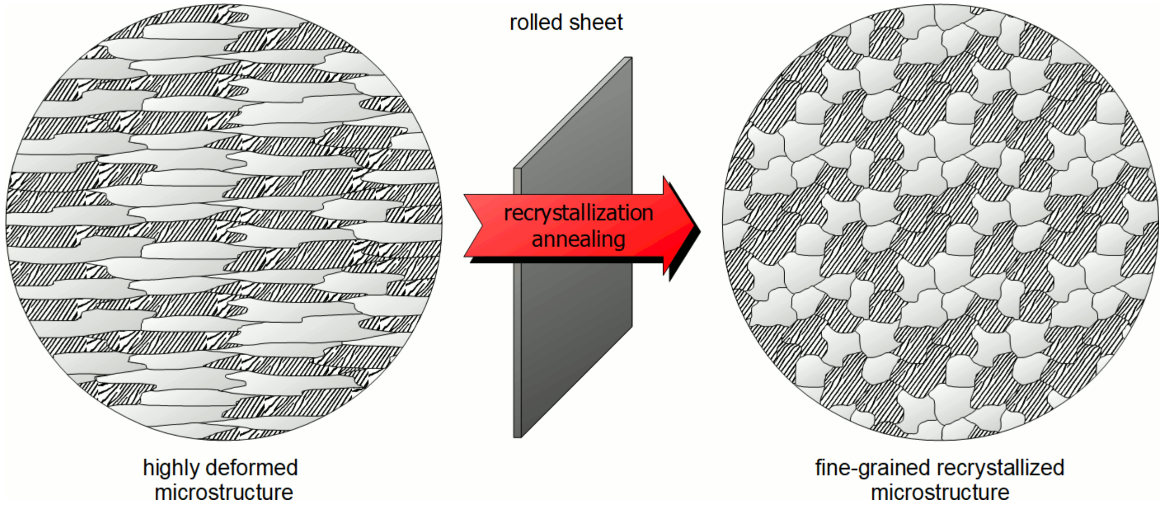

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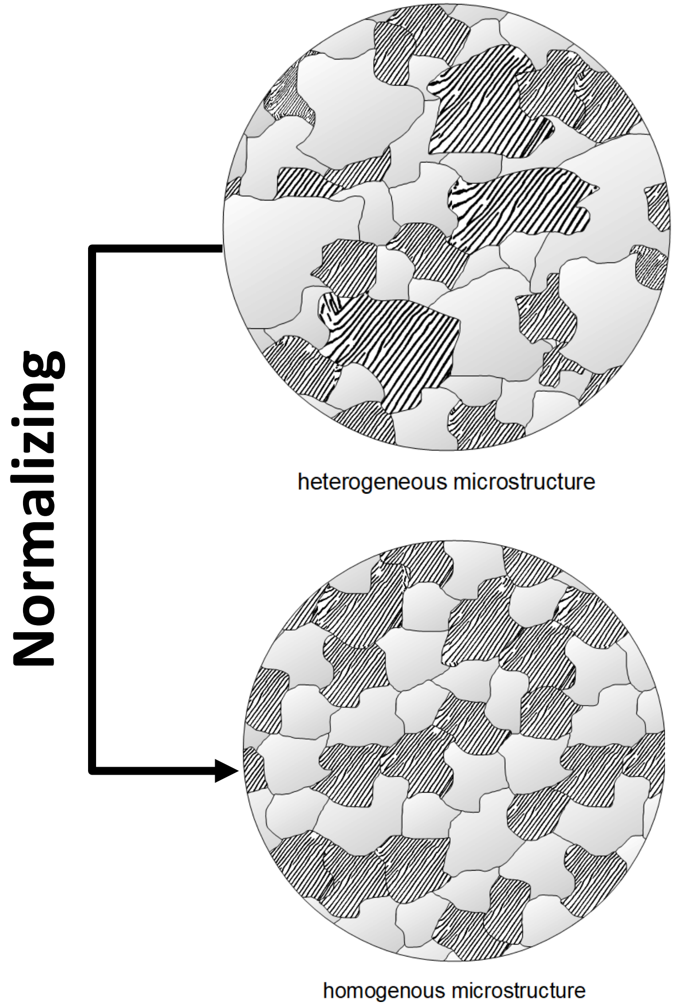
Normalizing

- Normalizing is a heat treatment process applied to ferrous metals only.
- It is applied to enhance their mechanical properties by refining their microstructure
- The metal is heated in a furnace for 1-2 hours and kept between 750-980 °C, depending upon the carbon content in the material.
- The material is then cooled to room temperature in still air or Nitrogen, if run in the vacuum furnace at less than 1 bar pressure
- Normalizing cooling rates are not fast enough to avoid the pearlite nose therefore the resultant grain structure is a mixture of fine pearlite with ferrite or cementite.



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Normalizing

- Post processing heat treatment like normalizing is commonly used to modify the microstructure and, consequently the mechanical properties of an additive manufactured component

- Experimental studies of normalizing of ER70S-6 alloy steel manufactured by WAAM process have shown:
    - Normalizing has eliminated the meta-stable constituents (e.g. bainite) from the as-built microstructure, leading to a more uniform and homogeneous microstructure
    - Microhardness has been decreased with normalizing
    - The anisotropy of the material was minimized with normalizing

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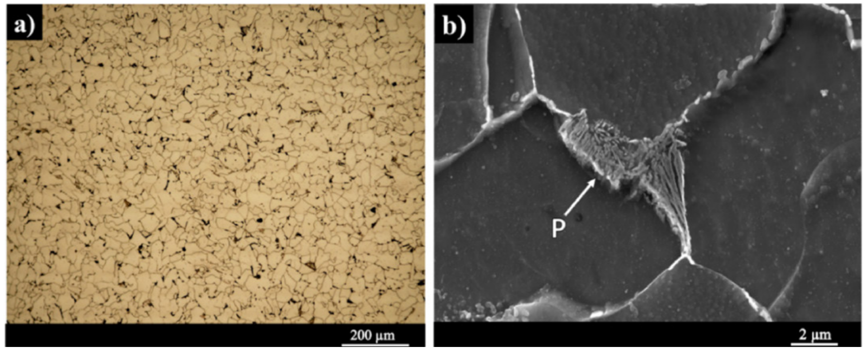

Microstructure of as built (top) and normalized (bottom) sample

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Hardening

- During hardening the material is heating to a temperature within the hardening range, which depends on the material microstructure
- For hypereutectoid steels this is 30-50 oC above the higher critical point and for hypoeutectoid this is 30-50oC above the lower critical point
- The material is then cooled rapidly by quenching in a suitable medium like water, oil or salt bath
- The hardening process provides a hard outer surface, while the core of the material retains its ductility

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Hardening
https://www.efd-induction.com/en/induction-heating-applications/induction-hardening

Hardening

- In general, the process mechanism of Additive Manufacturing provides in-situ hardening during the material build
- However, in some cases, even higher hardness might be required, thus adding a post-processing step of hardening
- Hardening can provide:
  - Increased strength of the material
  - Increased surface hardness

Heat Treatment

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Precipitation Hardening

- Ageing or precipitation hardening is a heat treatment method mostly used to increase the yield strength of malleable metals.
- The metal is treated with a solution at an elevated temperature
- The solute atoms are dissolved to form a single phase solution
- Solid impurities or precipitates that exist in the metal are used for the strengthening process
- The metals are required to be maintained in an elevated temperature for many hours for the precipitation to occur; hence this process is called ageing

Precipitation Hardening
https://www.metalsengineering.net/quick-turnaround-on-precipitation-hardening-by-metals-engineering/

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Precipitation Hardening

- Example of microstructure evolution of Inconel 718 alloy processed by (LPBF) and (DED) processes are:
  - In the case of AM samples, the solution-double ageing process does not result in recrystallization, and thus, the layer interface regions still present after the heat treatment.
  - The mechanical properties of IN718 samples are improved
  - Although the Laves and Carbide phases are not completely dissolved, an initial chemical homogenization starts with ageing

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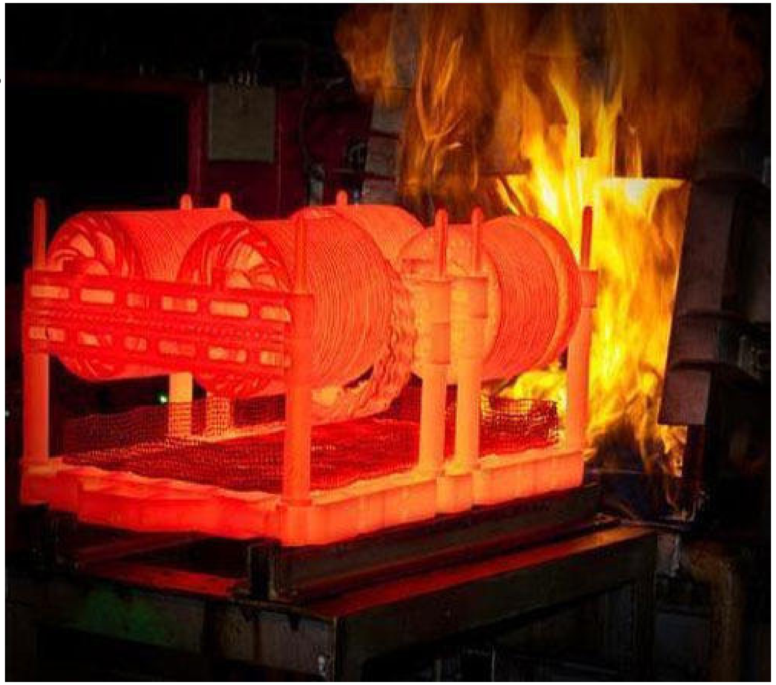
Stress relieving

- This method heats the metal to a temperature just below its lower critical point. The cooling process is slow and therefore uniform.
- Stress relieving parts before removal from the substrate is still often a critical post-processing step.
- Stress relief is often necessary for parts that require high dimensional accuracy
- The removal of the detrimental effects of the residual stresses for fatigue and fracture critical parts can be achieved with stress relieving heat treatments
- Stress relieving temperatures are often much lower than the critical/recrystallization temperature so that the microstructure is mostly unaltered



Stress Relieving
https://www.metalsengineering.net/thermal-stress-relief-provides-crucial-step-in-manufacturing-success/

Tempering

- Tempering is a heat treatment method that is generally used to achieve greater toughness by reducing the hardness of an alloy
- Therefore, it is a very suitable method for AM post-processing, where in-situ hardening of the material is present during build
- The material is heated below its lower critical point for a certain period of time
- Then the material is cooled naturally in still air

Tempering

https://www.nghexin.com/defects-of-quenching-tempering-and-prevention/

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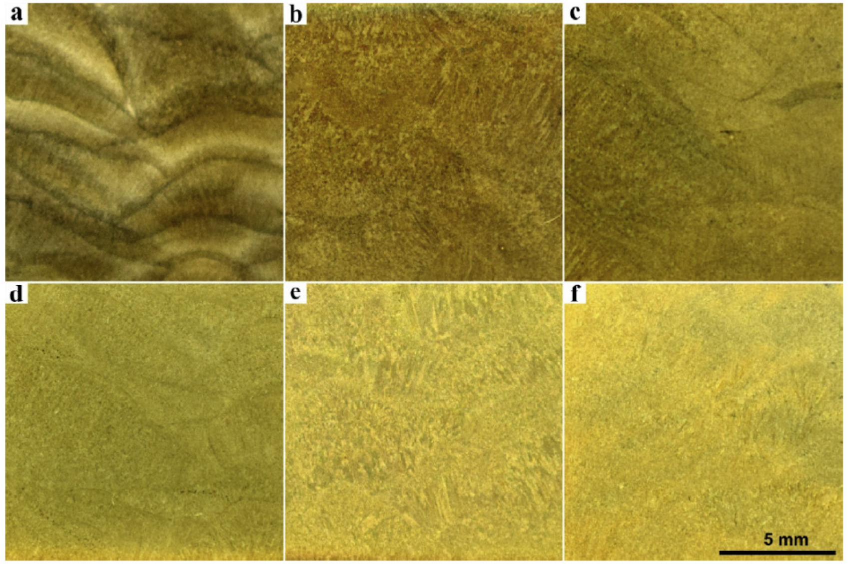
Tempering

- A case study on the effect of tempering in the microstructure and mechanical properties on Nickel-aluminum bronze (NAB) manufactured by WAAM has shown:
  - Tempering has been proved capable of increasing the tensile strength of the NAB alloy significantly.
  - After the tempering processes, the layer bands are further modified gradually with the increase of tempering temperature, and for high tempering temperatures, the layer bands almost disappear.
  - After the tempering processes, the additive manufactured samples hav become relatively homogeneous



Elimination of layer bands with increase of tempering temperature

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Hot Isostatic Pressing

- During HIP the metal is compressed in a chamber in an elevated pressure and temperature
- An inert gas (usually Argon) is used in the chamber
- The compression of the metal is achieved through the high operating pressure of the inert gas
- The ability of HIP to heal the defects that are induced in the parts during the Additive Manufacturing process (mainly void formation) makes it an attractive post-processing method

HIP chamber

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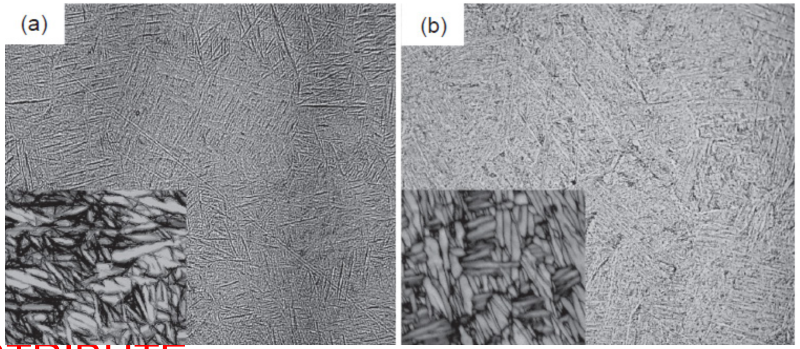
Hot Isostatic Pressing

- A case study on application of HIP as a post-process in Titanium alloy samples manufactured by LPBF has shown the following:
  - HIP can effectively close the porosities that have been observed in the as-built samples
  - HIP provided a coarser microstructure than the as-built part
  - HIP at high temperatures can eliminate the anisotropy of the AM produced part
  - HIP reduced crack propagation
  - However, HIP also reduced the strength of the part, compared to its as-built state



Microstructure of samples as built (left) and after HIP (right)

Heat Treatment

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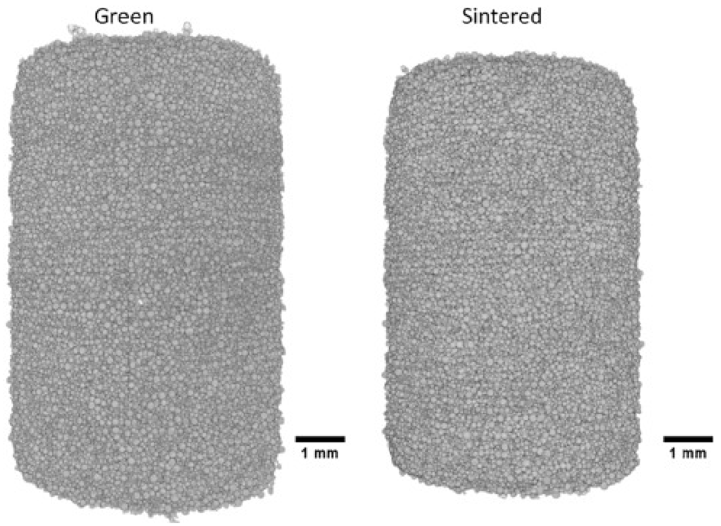
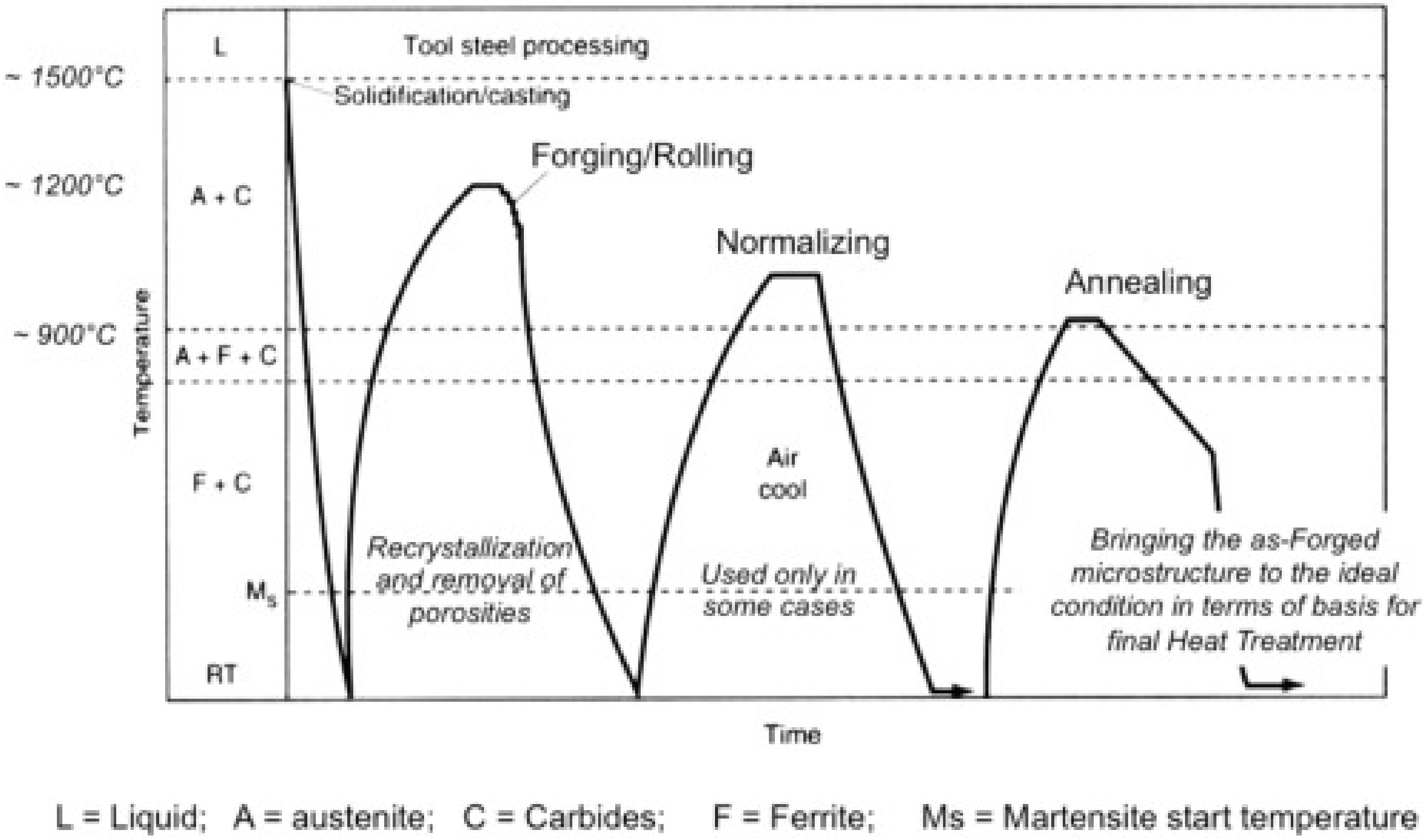
Sintering

- Sintering is the process of fusing particles together into a solid mass by using a combination of high pressure and high temperature without reaching the liquefaction point of the material
- For metal Binder Jetting, sintering is an essential post-processing step, for parts that are load bearing
- The bonding that the binder offers to the metal part cannot withstand high mechanical loading
- Sintering leads to evaporation of the binder and increases the density of the part manufactured by Binder Jetting



Schematic representation of the change in microstructure



Schematic representation of the transformations that occur from solidification until annealing. [Parker, Greg. "Encyclopedia of materials: science and technology." (2001): 3703-3707.]

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Furnaces

- Usually operate in temperatures above 550^{o}C
- Can be classified according to their operating principles
- Method of heating:
  - Combustion of fuel (gas or oil)
  - Electricity
- Movement of workpiece:
  - Batch style: Workpiece remains stationary and is loaded/unloaded for each heat treatment cycle
  - Intermittent: Workpiece moves periodically
  - Continuous: Work moves continuously withing the heating station
- Internal atmosphere: Air or use of protective atmosphere
- Internal pressure: Atmospheric pressure or vacuum
- Exposure of workpiece to atmosphere: Open or closed

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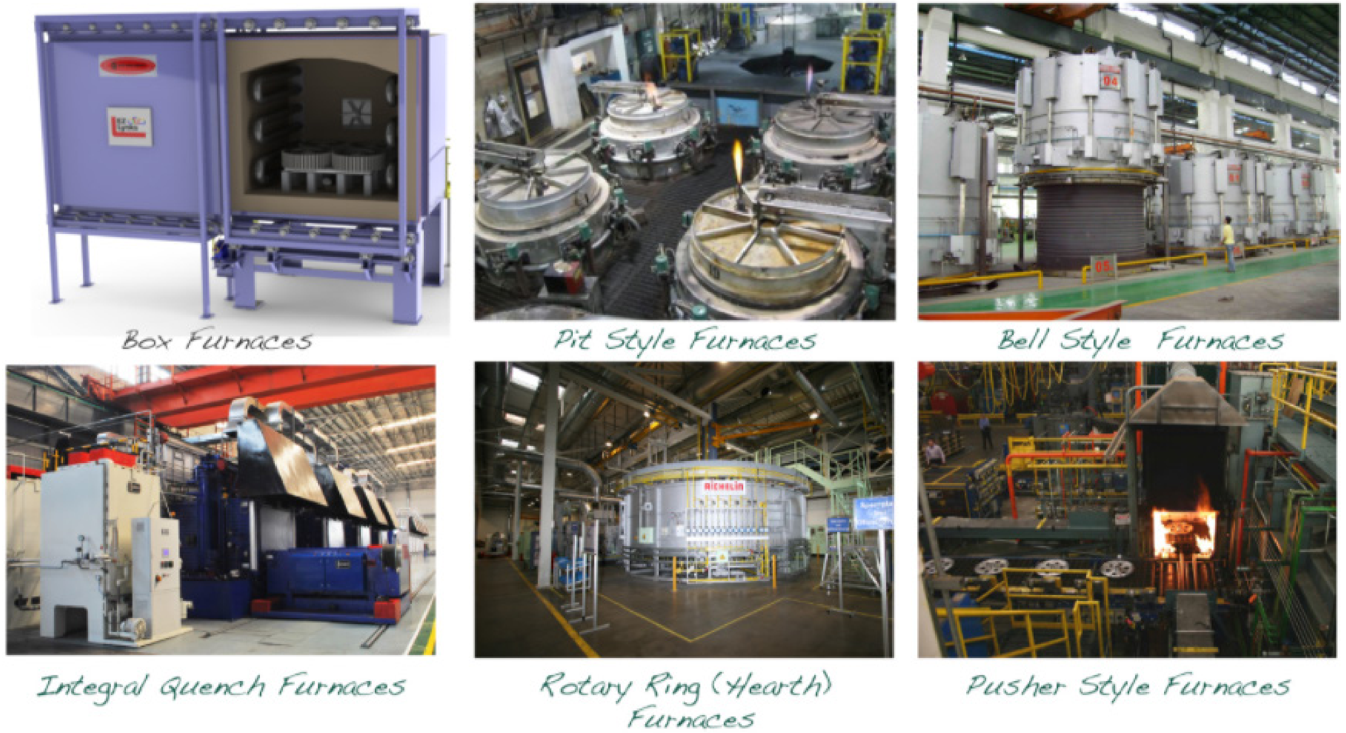
Furnaces



Batch style furnaces

Continuous furnaces

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Ovens

- Usually operate in temperatures below 550°C
- Thus, their applicability for metal heat treatments can be limited
- Utilize convection for heating the workpiece through air or inert gas circulation
- Quality and velocity of gas flow plays a key role in the ability of the oven to maintain temperature uniformity
- Oven construction varies considerably from furnace construction
- Small bench top units can be found in the market
- Method of heating:
  - Combustion of fuel (natural gas or hydrocarbons)
  - Electricity

Industrial oven

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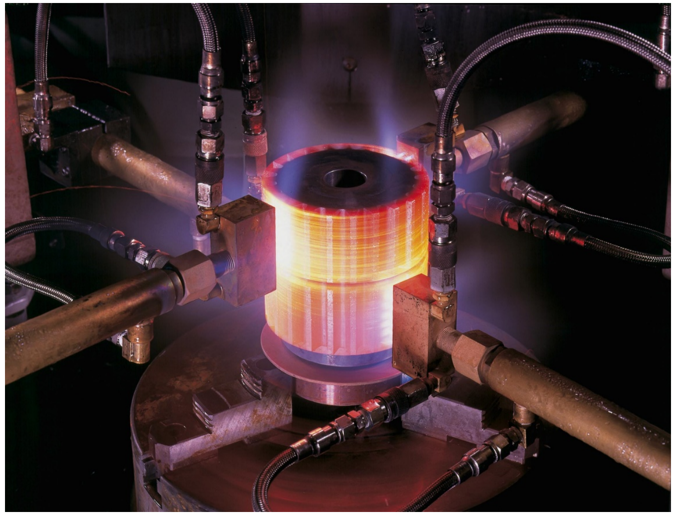
Applied energy

- This method directs the energy source directly on the workpiece to perform the heat treatment
- The energy source can be:
  - Induction heating
  - Flame
  - Laser
- Offers localized heating
- The heating and cooling of the workpiece are performed in increments
- Ideal method for local modifications of the workpiece microstructure (e.g. surface hardness increases while maintaining a softer core)

Induction heating



Flame heating

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Temperature uniformity measurement

- It is performed in an empty furnace with thermocouples
- At least four measurements shall be taken, two at the top of the furnace and two at the bottom
- Minimum two temperature ranges for uniformity measurement
  - One equal to the maximum working temperature of the furnace
  - One about half the maximum working temperature
- Uniformity must be performed no more than 36 months of the first validation or when a repair or rebuild is performed

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Media for controller atmosphere

- Air
- Ammonia
- Argon
- Butane
- Carbon Dioxide
- Carbon Monoxide
- Helium
- Hydrocarbons
- Hydrogen
- Methane
- Nitrogen
- Oxygen
- Propane
- Steam
- Sulfur Dioxide

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Quenching liquids

- The selection of quenching liquid will affect the rate and uniformity of cooling
- This will affect the final material properties that will be achieved
- However, too fast cooling might also induce risks of cracking or warping of the material
- Selection of quenching liquid is determined by the following factors:
  - Required level of mechanical properties that must be achieved
  - Workpiece cross-section
  - Carbon content (in steel products)
- Popular quenching liquids include
  - Water
  - Caustics
  - Mineral oils
  - Synthetic oils

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PPE and other safety equipment

- During the heat treatment process the operator might need to handle a glowing hot workpiece (e.g. during unloading)
- Also, when quenching is required splashes of hot oil might reach the skin of the operator
- In order to avoid heat-related injuries the following equipment is necessary for performing heat treatments:
  - Certified face shields
  - Certified safety glasses
  - Heat resistant protective clothing
  - Heat resistant protective gloves

Temperature measurement

- During the heat treatment the temperature shall be determined at a minimum number of measurement points
- The measurement points might be on the workpiece or in the furnace atmosphere

Furnace volume V m^3	Number of measuring points
$V < 40$	2
$40 \leqslant V < 60$	3
$60 \leqslant V < 80$	4
$80 \leqslant V < 100$	5
$V \geqslant 100$	6

Heat Treatment parameters

Depending on the type of heat treatment, the following parameters need to be specified, according to ISO/TR 17663:

- Loading temperature
- Heating rate
- Holding temperature
- Holding time
- Cooling rate
- Unloading temperature

Heat Treatment procedures

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- The manufacturer of the AM part must prepare a heat treatment procedure specification and provide it to the heat treatment facility
- This ensures that the work is conducted correctly and the post-processed part has the desired mechanical properties
- The heat treatment procedure specification shall include the following information, according to ISO/TR 17663
  - Type of heat treatment (e.g. annealing, normalization, hardening, etc.)
  - Method of heat treatment (e.g. furnace, inductive, etc.)
  - Location and number of measuring points for the temperature
  - Requirements for shielding gas
  - Heat treatment parameters
  - Supporting or loading of the products or components
  - Type of cooling
  - Identification of the product or components (e.g. designation, numbering)
  - Environmental conditions (e.g. protection from wind and rain)
  - Range of heated zone and area of isolation

Heat Treatment record

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- The heat treatment facility shall provide the following information for each heat-treated product
  - Identification of the product or component
  - Information of material
  - Heat treatment equipment
  - Type of heat treatment
  - Method of heat treatment
  - Loading temperature
  - Heating rate
  - Holding temperature
  - Holding time
  - Cooling rate
  - Cooling method
  - Unloading temperature
  - Type of temperature measurement and number and location of measuring points
  - Place and date of heat treatment

International Standards

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No.	Reference	Title
1	ASTM E 112	Standard test method for determining average grain size
2	ASTM E562	Standard test method for determining volume fraction by systematic manual point count
3	ISO 643	Steels – micrographic determination of the apparent grain size
4	ASTM A991	Standard test method for conducting temperature uniformity surveys of furnaces used to heat treat steel products
5	ISO 2107:2007	Aluminium and aluminium alloys — Wrought products — Temper designations
6	ISO 4885:2018	Ferrous materials — Heat treatments — Vocabulary
7	ISO 15787:2016	Technical product documentation — Heat-treated ferrous parts — Presentation and indications
8	ISO 17663:2009	Welding -- Quality requirements for heat treatment in connection with welding and allied processes
9	ISO 13916:1996	Welding — Guidance on the measurement of preheating temperature, interphase temperature and preheat maintenance temperature
10	ISO 13916:2017	Welding — Measurement of preheating temperature, interpass temperature and preheat maintenance temperature
11	ISO 4885:1996	Ferrous products — Heat treatments — Vocabulary

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Laboratory for Manufacturing Systems and Automation (LMS)
Department of Mechanical Engineering and Aeronautics
University of Patras, Greece

Thank you

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

Project No. 601217-EPP-1-2018-1-BE-EPPKA2-SSA-B

Post Processing Methods for Additively Manufactured Parts

SESSION 4: PLASTIC DEFORMATION METHODS

22 January 2021

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Outline

- Plastic deformation
- Peening processes
- Shot Peening
- Shot Peening Advantages and Disadvantages
- Laser Peening
- Laser Peening Advantages and Disadvantages
- Shot Peening vs Laser Peening
- Rolling

Plastic deformation

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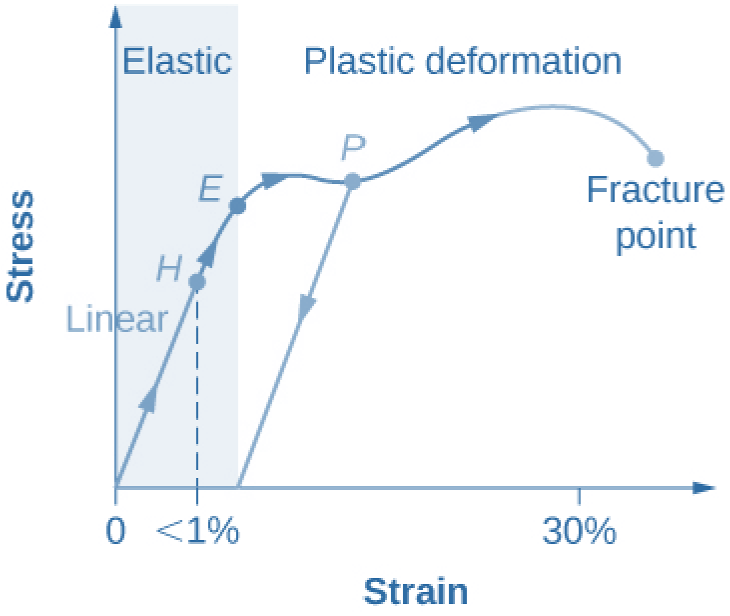
What is plastic deformation?

Plastic deformation is the permanent distortion that occurs when a material is subjected to tensile, compressive, bending, or torsion stresses that exceed its yield strength and cause it to elongate, compress, buckle, bend, or twist.



Typical stress-strain plot for a metal: The graph ends at the fracture point.
https://openoregon.pressbooks.pub/bodyphysics/chapter/elasticity-and-hookes-law/

Plastic deformation

Why is plastic deformation considered for AM post-processing?

Apart from altering the shape of a part plastic deformation can achieve the following:

- Reduction of tensile residual stresses
- Introduction of compressive residual stresses
- Reduction of crack propagation
- Crack closure
- Strain hardening

Therefore, plastic deformation can address several of the issues of AM

Peening Processes

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Peening is a process of working the surface of a metal part

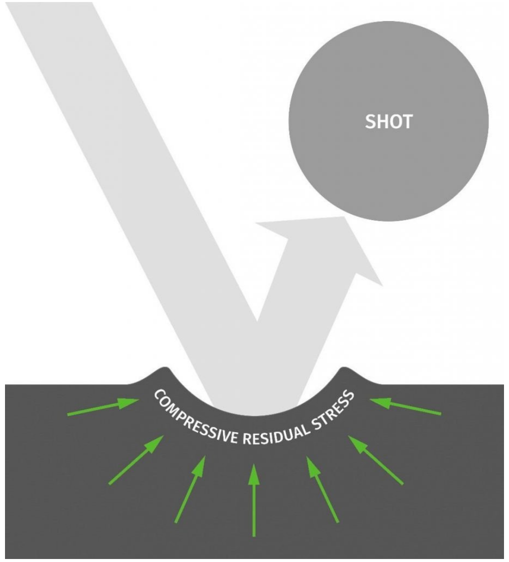
Peening can be performed by the following means:

- Spherical shots
- Needles
- Hammers
- Laser

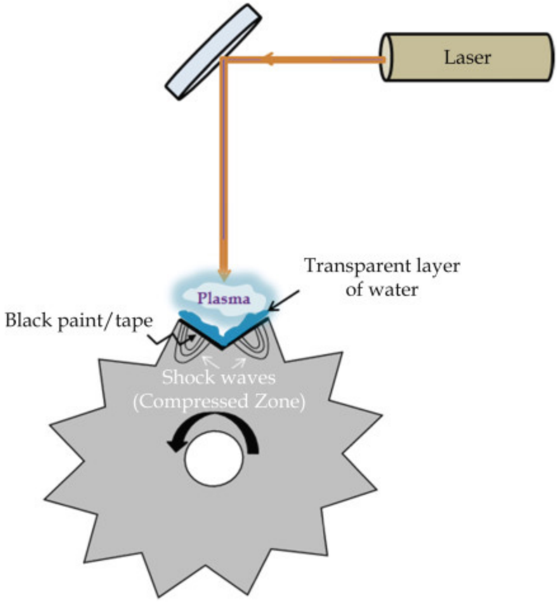
During peening the outer surface attempts to expand laterally but is prevented from doing so by the elastic nature of the sub-surface, bulk material

Therefore, tensile stresses are eliminated and compressive residual stresses are induced

Shot and Laser Peening



Shot Peening
https://www.stresstech.com/stresstech-bulletin-14-shot-peening-residual-stresses/



Laser Peening
Masaki, K., K. Yamashiro, and Y. Sano. "Effects of laser peening on plane bending fatigue properties of friction stir welded A6061-T6 alloy." Proceedings of the 1st International Joint Symposium on Joining and Welding. Woodhead Publishing, 2013./

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Shot Peening methods

- **Wheel Blasting** - Blast wheels utilize rapidly spinning paddles to propel shot media via centrifugal force.
- **Air Blasting** - Air blast systems propel shot media using a stream of high-pressure air.
- **Flapper Peening** - Rotary flap peening is performed using rubberized fabric flaps with embedded shot media attached to a rotating shaft

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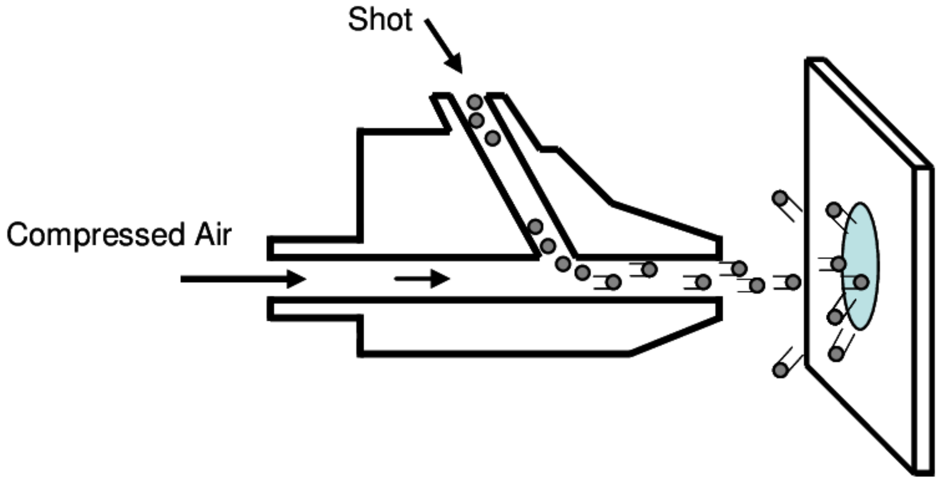
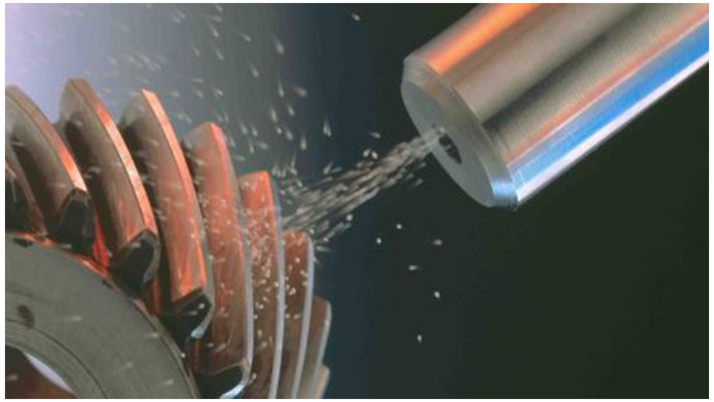
Shot Peening System

- A first line feeds compressed air to the peening nozzle
- A second line feeds the shots to the peening nozzle
- The nozzle or the workpiece is moved to cover the whole surface of the part



Shot Peening process parameters

- Shot density
- Shot size and hardness
- Air pressure
- Impact angle
- Distance between nozzle and workpiece
- Number of passes
- Nozzle-workpiece relative speed



Shot Peening
https://www.lsptechnologies.com/resources/what-is-shot-peening/

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Shot Peening media & particles

Common types of shot media include:

- Cast Steel Shot
- Glass Bead Shot
- Ceramic Bead Shot
- Cut Wire Shot

Steel Shot
https://www.finishingsystems.com/abrasives/steel-shot/

Info:

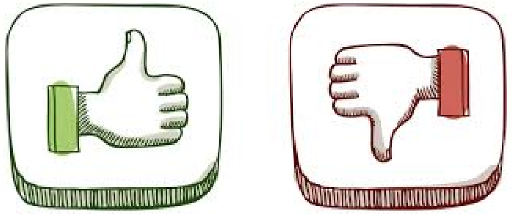
Metallic shot media may be composed of copper, steel, aluminum or other alloys, but shot media must be at least as hard as the workpiece to induce plastic deformation.

Shot Peening

Shot Peening Advantages and Disadvantages

Advantages

- Microstructure refinement
- Surface hardening
- Introduction of compressive residual stresses
- Elimination of surface defects
- Enhancement of fatigue strength



Disadvantages

- During the shot peening process, the work piece needs to be fixed
- Sometimes only an average surface finish is achieved at the end of the process

Laser Peening

- Laser peening (LP) is an important post processing method for metal parts.

- It is commonly used to enhance the fatigue lifetime of:
  - jet engine fan and compressor blades
  - aircraft structures
  - nuclear spent fuel storage canisters.

Laser peening machine

https://www.lsptechnologies.com/laser-solutions/procudo-laser-peening-system

How Laser Peening works – Step by step

STEP 1 | STEP 2 | STEP 3 | STEP 4 | STEP 5

- Step 1 - The high energy laser beam hits the metal surface.
- Step 2 - A plasma shock wave applies pressure to the metal, reshaping its microstructure.
- Step 3 - Distorted metal pushes up against surrounding metal structures.
- Step 4 - Surrounding metallic structures adapt to the expanding metal.
- Step 5 - Healthy compressive residual stresses form.

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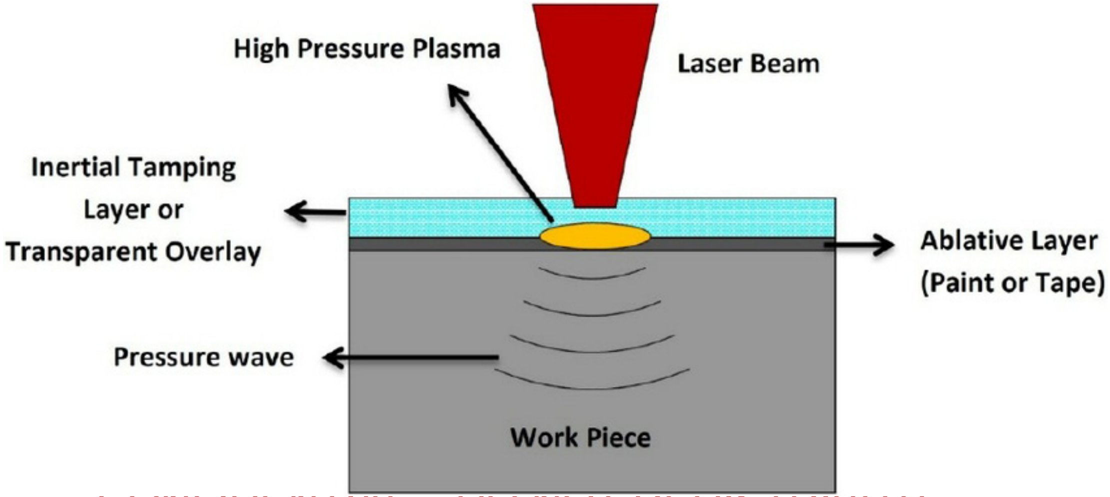
Laser Peening highlights

- A sacrificial layer is usually used on the material surface
- If not, a thin layer of recast material is present after peening that can be polished off
- Use of a water tamper increases the generated pressure by an order of magnitude



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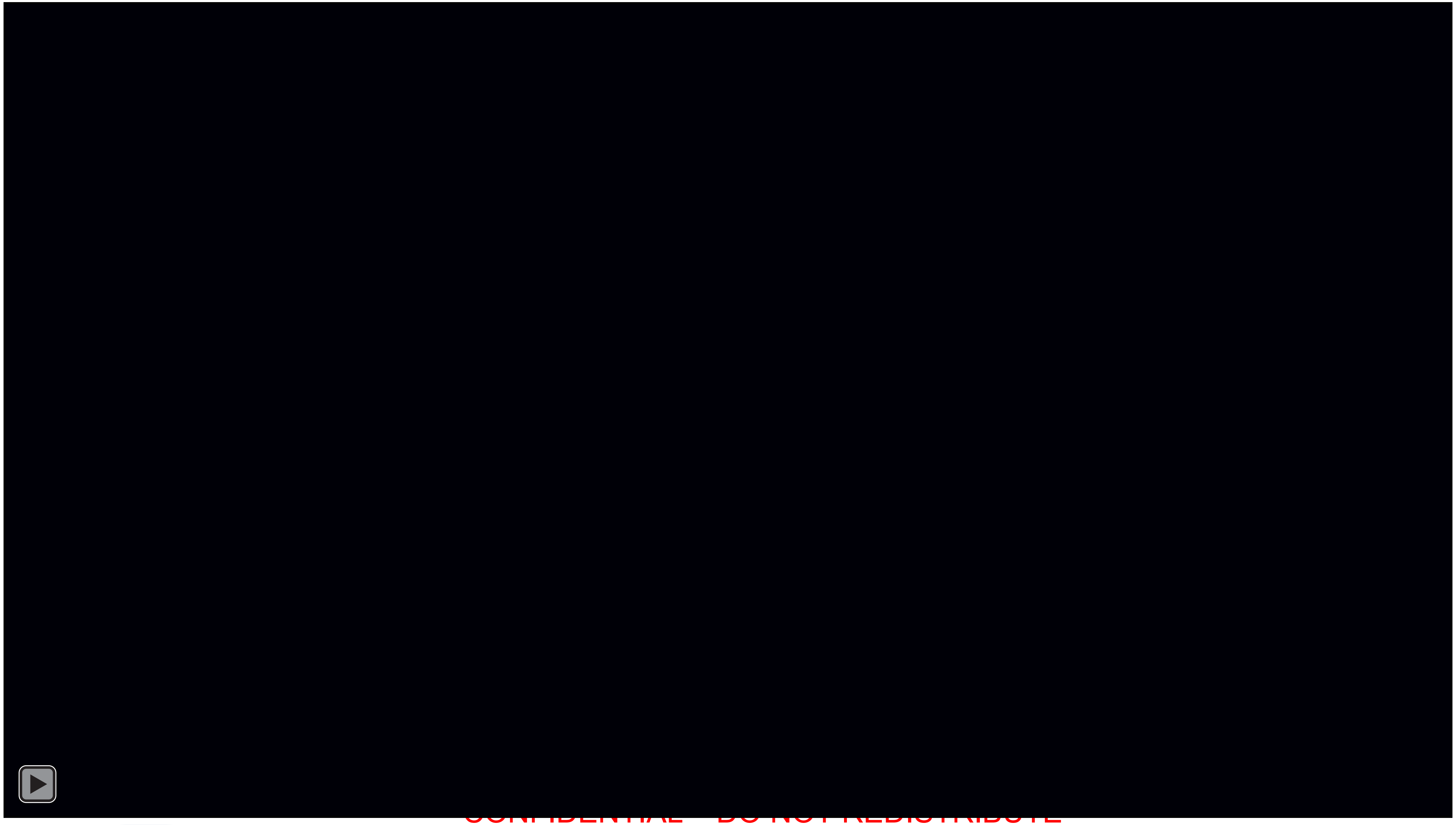
Laser Peening process parameters

- Laser wavelength
- Laser power
- Laser pulse duration
- Laser beam spot size
- Number of shots
- Sacrificial layer
- Temporal pulse shape

Laser Peening



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Laser Peening and Additive Manufacturing

- Laser peening replaces the tensile stresses created in AM parts during the AM process with compressive residual stresses
- Laser peening reduces voids near the surface created by AM
- Laser peening eliminates the need for processing the entire part and provides localized part enhancement
- Laser peening has the ability to enhance the fatigue lifetime and strength of AM parts.

Laser Peening Advantages and Disadvantages

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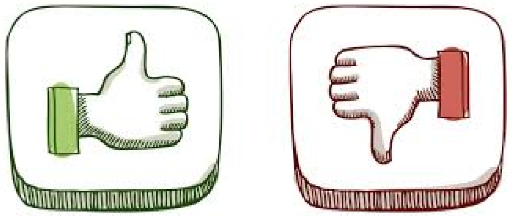
Advantages

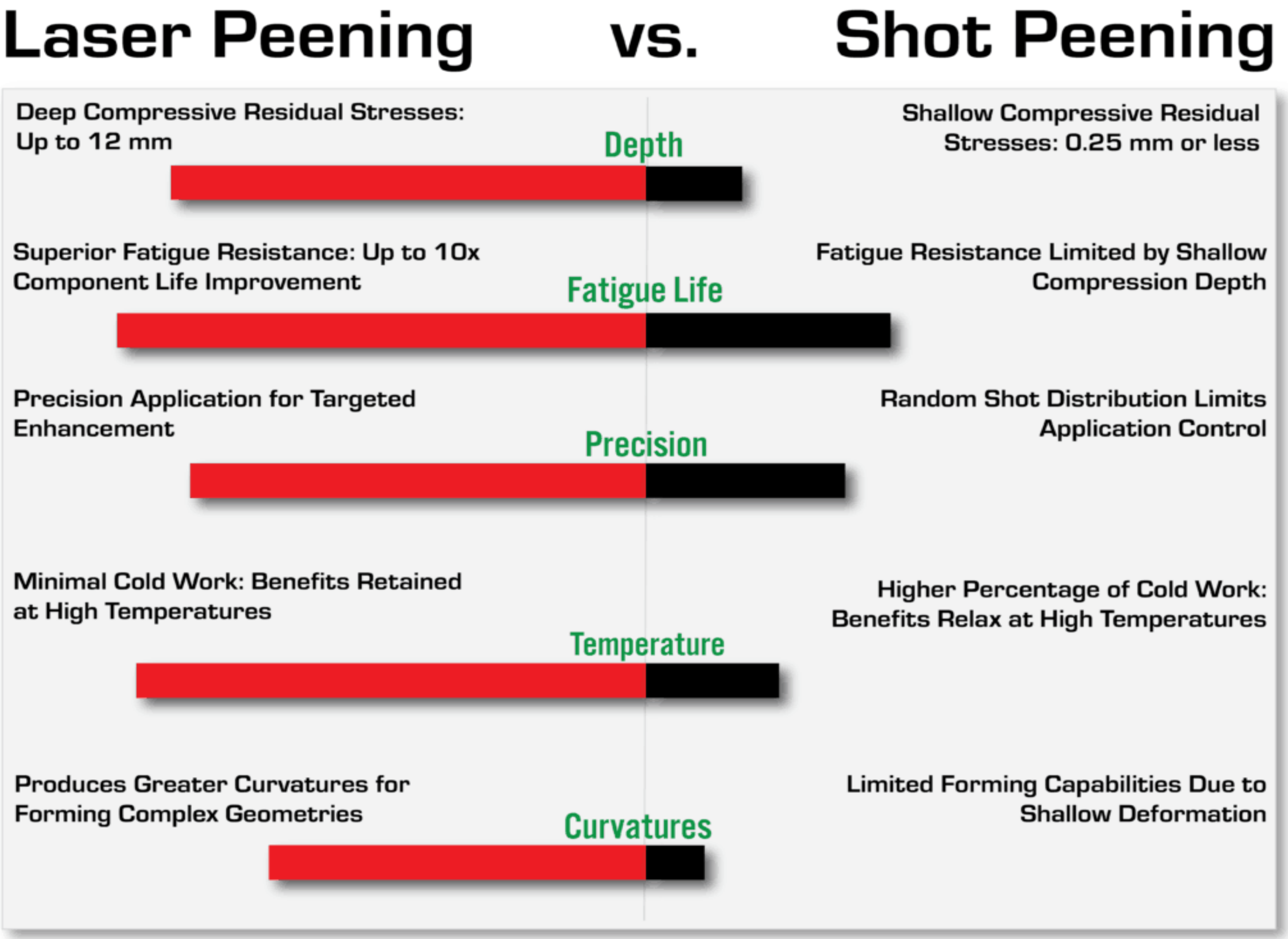
- Deeper Protection
- Longer Component Life
- High Temperature Durability
- Precision Modeling and Application
- Production Line Integration
- Flexible Parameters



Disadvantages

- Dimensional variation which leads to distortion of the components.
- The lack of non-destructive testing technology for quality control and quality assurance.
- Internal rupture of components due to over-processing.

Shot Peening vs Laser Peening



https://www.lsptechnologies.com/why-laser-peening/shot-peening-vs-laser-peening/

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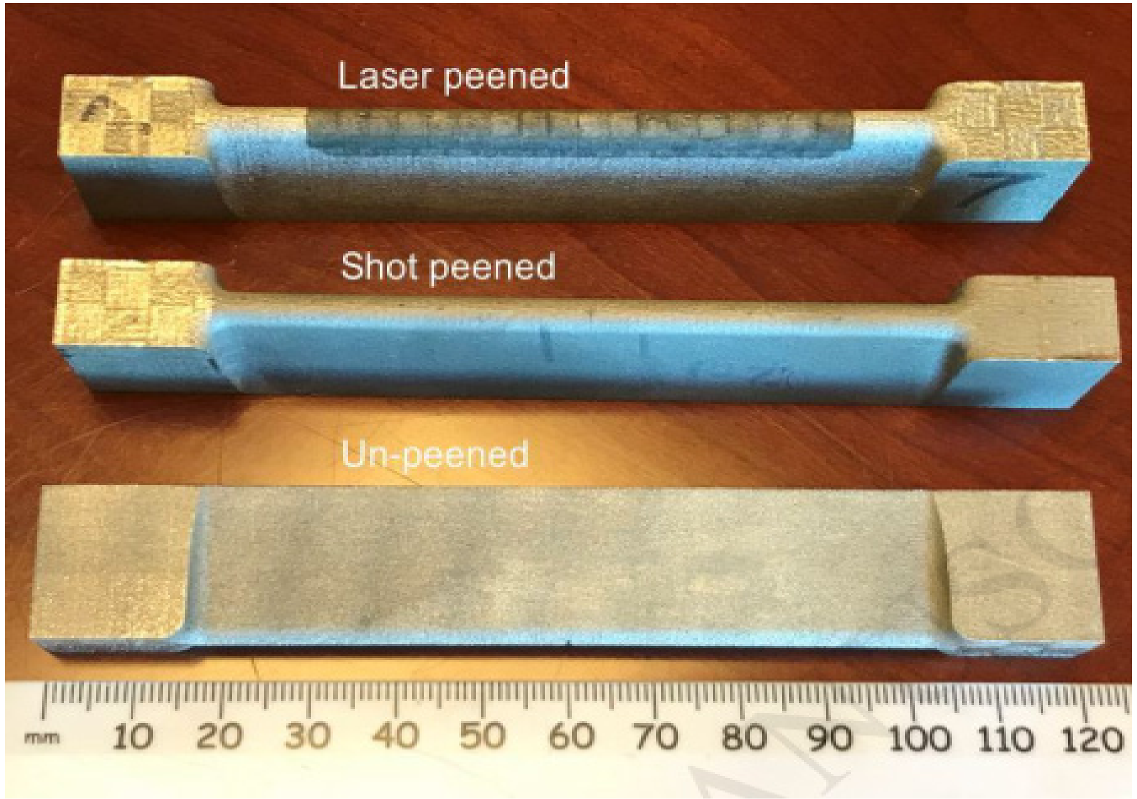
Shot and Laser Peening before and after



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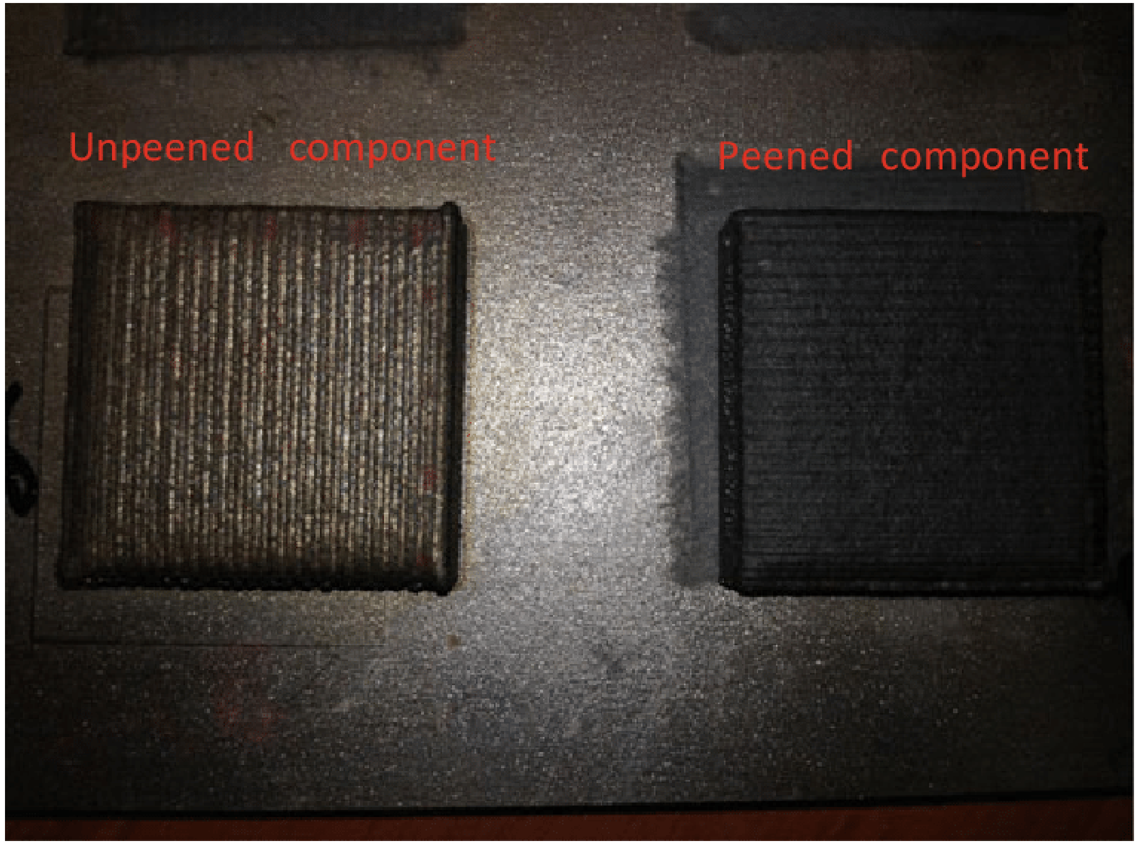
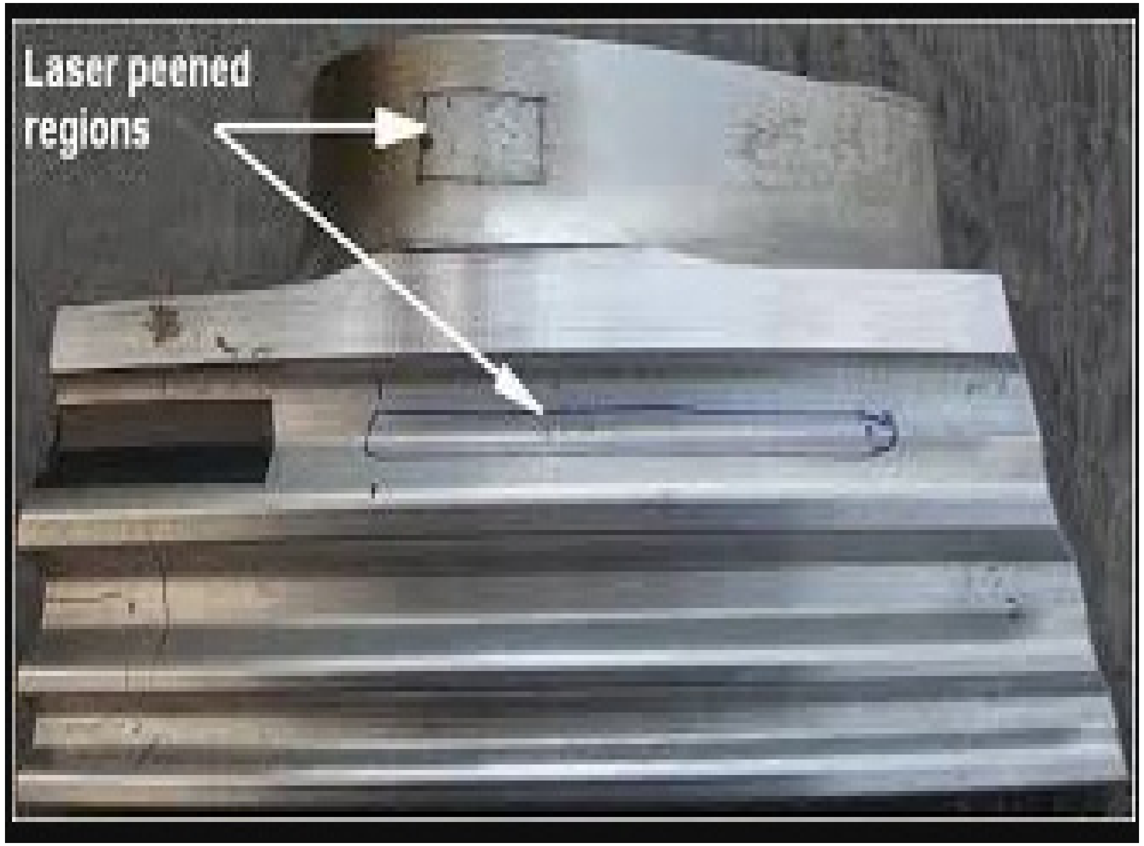
Shot and Laser Peening before and after



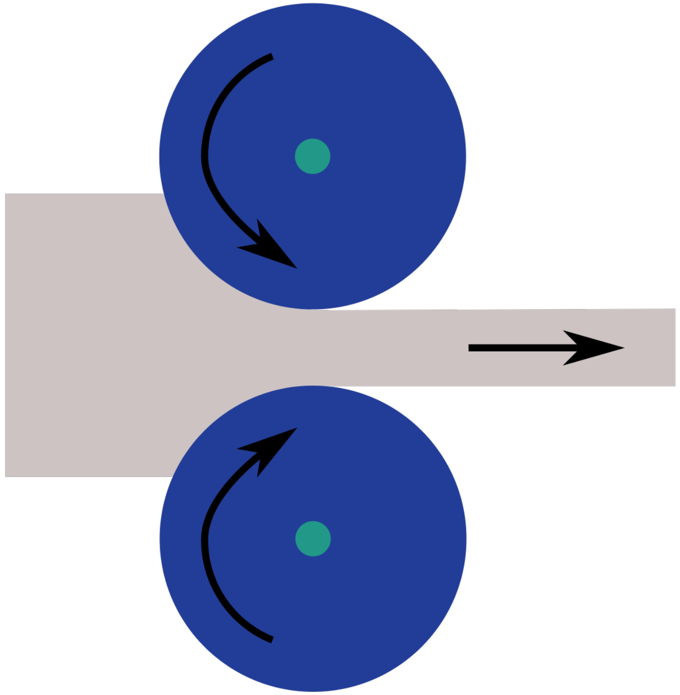


Rolling

- Rolling is a forming process where the stock is passes through rollers to reduce its thickness and make it uniform and impact its mechanical properties as well

- Rolling can be run on a cold or hot component

- There are several types of rolling processes
  - Ring rolling
  - Roll bending
  - Roll forming
  - Profile rolling, etc.



Rolling

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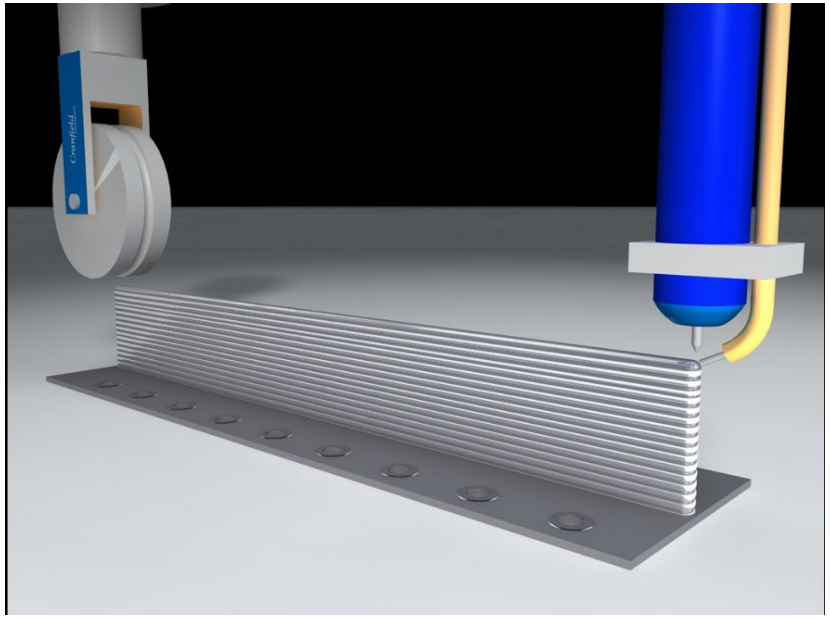
- Rolling has not yet seen broad industrial implementation as a post-processing method for AM
- However, there is extensive research on post-processing parts manufactured by WAAM with ring rolling
- Research has been conducted on:
  - Inter-pass rolling, where the part is rolled every time a layer is built
  - Rolling of the finished part



Rolling

Rolling

In order to post-process an AM part with rolling, special considerations must be made in its design phase

- Areas of intersections where the rollers cannot run must be avoided in the design
- Track width and wall thickness of the part should allow the rollers to run

Rolling

Several benefits have been observed on WAAM parts post-processed by rolling

- Reduction of surface waviness
- Reduction of porosity
- Introduction of compressive residual stresses
- Increased part strength due to work hardening

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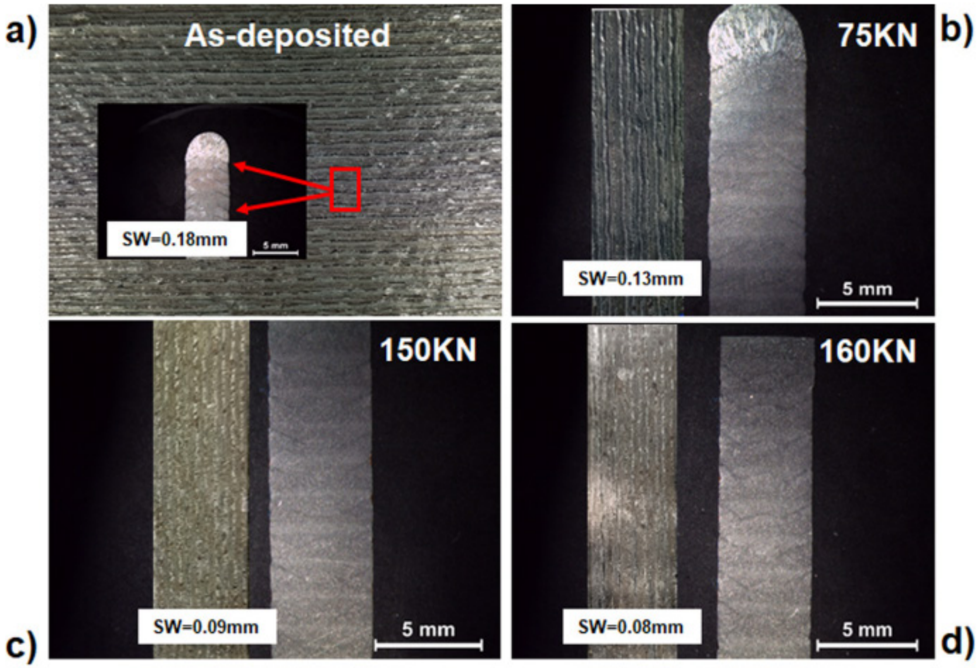
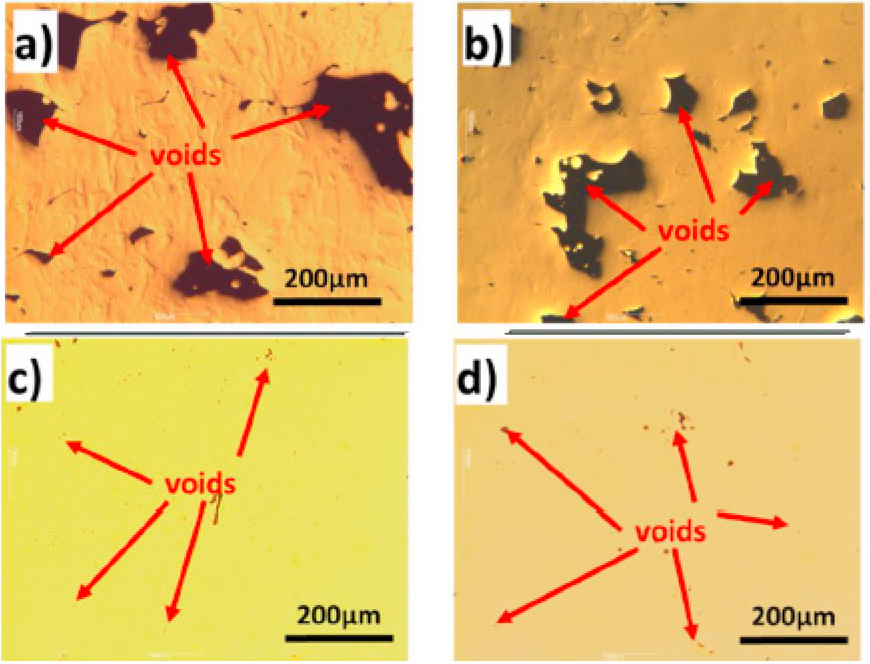


Macrostructure showing the effects of rolling load on surface waviness.



Reduction of voids from the as built state (top) through rolling (bottom)

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Thank you

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General Considerations

1. Which are the main metal AM process families?
    a. Vat photopolymerization, Powder Bed Fusion, Material Jetting
    b. Binder Jetting, Powder Bed Fusion, Directed Energy Deposition → Correct
    c. Material Extrusion, Material Jetting, Sheet Lamination
    d. Sheet Lamination, Powder Bed Fusion, Material Extrusion
2. Which are the main quality challenges of metal AM?
    a. Void formation, residual stresses and anisotropy
    b. Layer by layer appearance, surface roughness and divergence between design and execution
    c. (a) and (b) → Correct
    d. Porosity, scanning strategy and powder removal
3. What is the main cause of quality issues on metal AM?
    a. Layer by layer deposition
    b. Thermal nature of processes
    c. Feedstock type and impurities
    d. All of the above→ Correct
4. Which of the following statements are correct as it regards post-processing?
    a. It is the last step in the AM production chain→ Correct
    b. It is not needed
    c. It reduces the mechanical properties of the parts
    d. It improves surface finish→ Correct

Thermal treatment

1. Which of the following methods can be used for preheating in DED?
    a. Heating of the powder
    b. Heating of the build chamber
    c. Heating of the build plate → Correct
    d. None of the above
2. Which of the following is not a benefit of preheating?
    a. More homogenous microstructure
    b. Reduction of crack susceptibility
    c. Improved bonding of bottom layers with the build plate
    d. Improved surface quality → Correct
3. Which heat treatment process is used to eliminate dislocations of the material?
    a. Annealing → Correct
    b. Hardening
    c. Sintering
    d. Preheating
4. Which of the following is highly connected with metal Binder Jetting?
    a. Hardening
    b. Sintering → Correct

c. Precipitation hardening
d. Normalizing

5. Which of the following heating stations does not belong in the applied energy category?
   a. Induction heating
   b. Oven → Correct
   c. Flame
   d. Laser
6. Which of the following is not used as a quenching liquid?
   a. Caustics
   b. Mineral oils
   c. Steam → Correct
   d. Caustics
7. Which of the following is incorrect?
   a. Sintering can increase the part hardness → Correct
   b. Loading temperature and cooling rate are heat treatment parameters
   c. AM provides in-situ hardening
   d. Ovens usually operate below 550^{o}C
8. Which of the following is correct?
   a. Annealing decreases the ductility of a part
   b. The typical procedure of heat treatment is heating, followed by cooling and finally holding
   c. Argon, Nitrogen and Helium can be used to control the heat treatment atmosphere → Correct
   d. Hardening decreases the strength of the material
9. Which of the following is correct?
   a. Quenching might lead to cracking or warping of the material → Correct
   b. Furnaces can only be closed structures
   c. There is no need for temperature measurement during heat treatment
   d. Furnaces cannot operate in vacuum
10. Which heat transfer mechanism do ovens utilize for heating the workpiece?
    a. Conduction
    b. Convection → Correct
    c. Radiation
    d. All of the above

Plastic deformation

1. Plastic deformation cannot achieve the following:
   a. Crack closure
   b. Surface improvement
   c. Reduction of crack propagation
   d. Dimensional accuracy → correct
2. Which of the following is incorrect?
   a. Glass shots can be used in shot peening
   b. Impact angle and shot density affect the shot peening process

    c. Aluminum shots could be used to process hardened steels with shot peening → Correct
    d. Wheel and air blasting are shot peening methods
3. Which of the following is a disadvantage of shot peening?
    a. Average surface finish → Correct
    b. Surface hardening
    c. Introduction of compressive residual stresses
    d. Enhancement of fatigue strength
4. Which of the following is incorrect?
    a. The use of water tamper in laser peening can increase the generated pressure
    b. Laser peening uses low energy laser beams → Correct
    c. The compressive residual stresses in peening are caused by the distorted surface being pushed by the sub-surface bulk material
    d. Laser power and pulse duration affect laser peening process quality
5. Which of the following is correct?
    a. Laser peening offers deeper protection than shot peening → Correct
    b. Laser peening provides more cold working than shot peening
    c. Shot peening provides superior fatigue life than laser peening
    d. Shot peening is more useful for complex geometries than laser peening
6. Which of the following is incorrect?
    a. Rolling can be performed either inter-pass or at the end of the AM process
    b. Rolling can increase the strength of the part
    c. Rolling can improve the surface of the part
    d. Rolling can be performed in any part geometry → Correct
7. Which of the following is not a peening medium?
    a. Laser
    b. Needles
    c. Sand → Correct
    d. Hammers
8. Which of the following is correct?
    a. Shot peening is a flexible process because it does not require part fixturing
    b. Laser peening offers localized part treatment → Correct
    c. Shot peening offers superior surface finish
    d. Laser peening without a sacrificial layer leads to superior surface finish
9. Which of the following design features must be carefully designed in order to post-process an AM part with rolling?
    a. Areas of intersections → Correct
    b. Holes
    c. Thin walls
    d. Bosses
10. Which of the following AM quality related challenges can be most effectively addressed with plastic deformation processes?
    a. Anisotropic microstructure and layer-by-layer appearance
    b. Void formation and layer-by-layer appearance → Correct
    c. Anisotropic microstructure and void formation
    d. Divergence between design and execution and void formation

Subtractive Manufacturing

1. Which of the following outcomes cannot be achieved by subtractive manufacturing as a post-processing method for AM?
    a. Dimensional accuracy enhancement
    b. Surface quality improvement
    c. Fatigue strength improvement → correct
    d. All of the above
2. What is the process mechanism of laser ablation?
    a. Plastic deformation of the part
    b. Melting and evaporation of the material → correct
    c. All of the above
    d. None of the above
3. Which process can fabricate micro-scale features?
    a. Milling
    b. Laser ablation → correct
    c. Grinding
    d. None of the above
4. Which of the following is not a key process parameter for milling?
    a. Cutting speed
    b. Helix angle
    c. Depth of cut
    d. Distance between tool and workpiece → correct
5. Which of the following is a benefit of dry machining?
    a. Longer tool life
    b. Better surface quality
    c. Higher process sustainability → Correct
    d. Lower cutting temperature
6. Which of the following fluids is commonly used for cryogenic machining?
    a. Liquid Nitrogen → Correct
    b. Water
    c. Liquid oxygen
    d. Oil-based coolant
7. Which of the following is correct?
    a. Grain size and workpiece speed are key process parameters of grinding → Correct
    b. Grinding generates tensile stresses on the machined part
    c. Grinding process mechanism is thermal based
    d. Grinding cannot achieve high dimensional accuracy
8. Which of the following is correct?
    a. Wire EDM can process plastics
    b. Wire EDM cannot achieve high dimensional accuracy
    c. Wire EDM is often used for baseplate removal → Correct
    d. A key process parameter of wire EDM is the depth of cut

9. Which of the following is correct?
    a. Commercial machines exist with integrated AM and grinding
    b. Commercial machines exist with integrated AM and milling → Correct
    c. Commercial machines exist with integrated AM and EDM
    d. All of the above
10. Which process should be used for a part that cannot withstand cutting forces?
    a. EDM
    b. Grinding
    c. Milling
    d. Laser ablation → Correct

Finishing operations

1. Which finishing operations are always necessary?
    a. Grinding and blasting
    b. Powder and support removal → Correct
    c. Mass finishing and painting
    d. Abrasive flow
2. Powder removal and handling
    a. Can be done by anyone
    b. Is strictly automated
    c. Should follow specific H&S requirements and SOPs → Correct
    d. Should not be done indoors
3. Support removal
    a. Can be automated
    b. Is a subtractive process
    c. Should be manual
    d. (a) and (b) → Correct
4. Optional finishing operations
    a. Aim at improving the surface finish of the part → Correct
    b. Aim at improving mechanical properties of the part
    c. Aim at reducing process time
    d. Aim at removing support structures
5. Mass finishing
    a. Uses different types of abrasive media
    b. Can be used in batches
    c. Is not labor intensive
    d. All of the above → Correct