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

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CU 01: DED-ARC

Session: 4.3 Metallurgy of Directed Energy Deposition

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FOR SAM PILOT ATTENDEES AND TRAINERS ONLY

MM17,21

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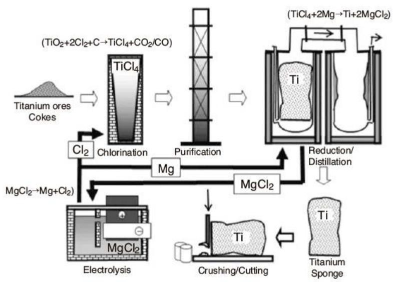
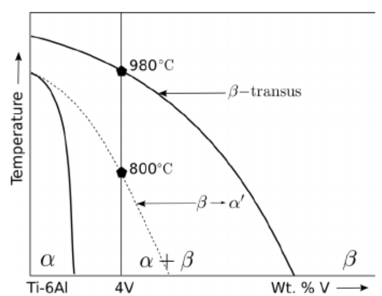
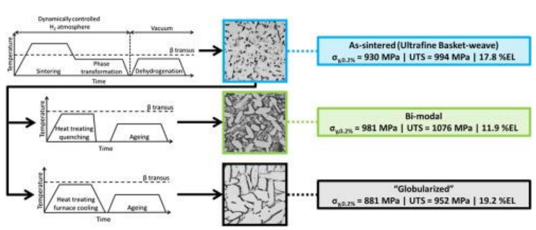
What is Metallurgy?

Kroll Process







Source: https://ars.els-cdn.com/content/image/1-s2.0-S1359646215002286-fx1_lrg.jpg

Metallurgical engineering

Extractive metallurgy - extraction of specific minerals / elements from ores: Chemistry and Geology

Physical metallurgy - research of alloys, creating new alloys, modifying existing alloys, and thorough understanding of what is going on "behind the scenes

Processing metallurgy - the manipulation of metals, such as rolling, forging, casting, drawing, welding, powder metallurgy, surface engineering

Additive manufacturing (of metals)

Core mechanisms:
- **Welding**
- **Powder metallurgy**

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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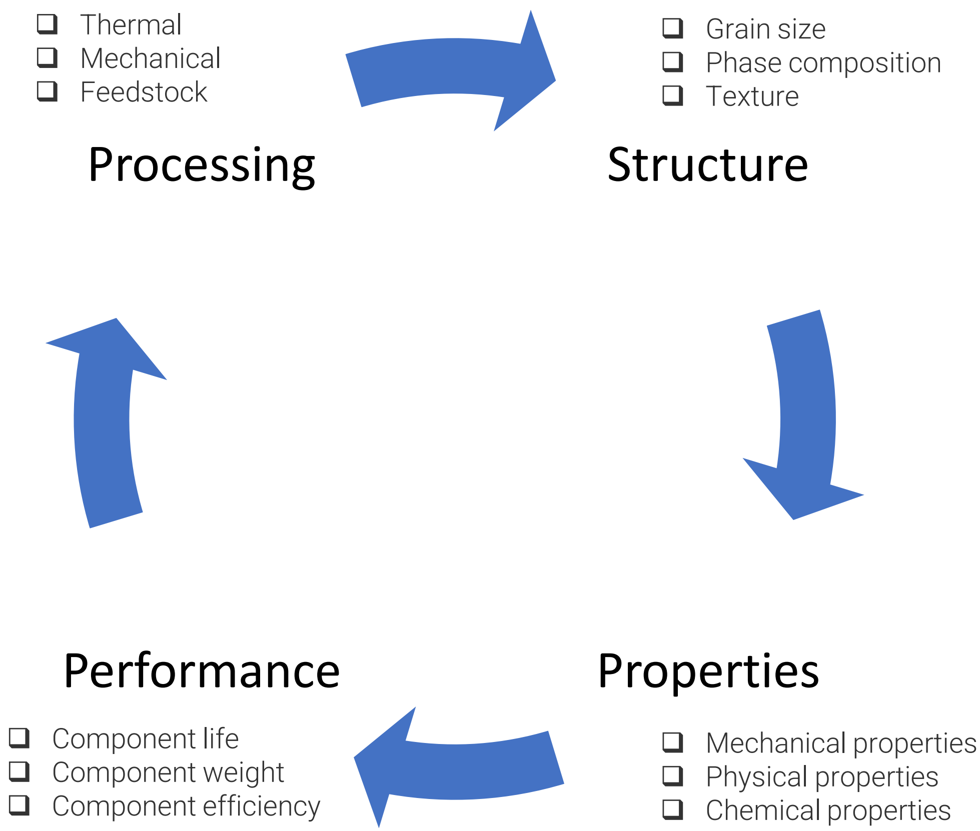
Why is Metallurgy Important?

Metallurgy underpins every aspect of manufacturing a component



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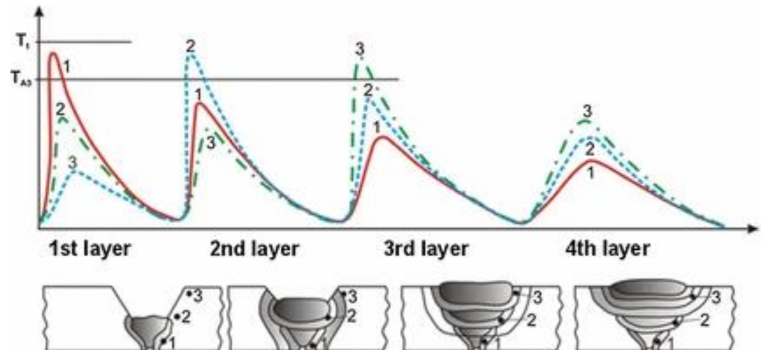
Thermal History



Source: J. Gorka et al, Thermographic assessment of the HAZ properties and structure of thermomechanically treated steel, 2017

The microstructure of components is determined by the chemistry, thermal and mechanical history.

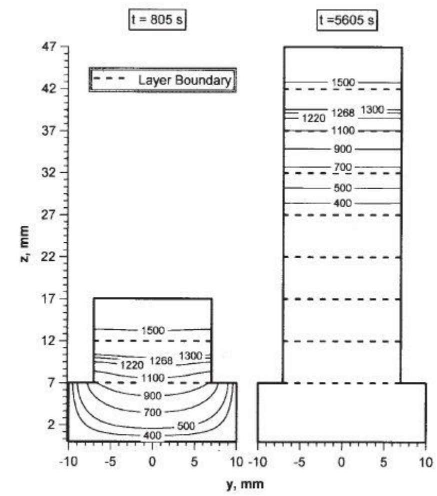
Solidification determines phase distribution and grain morphology, which in turn affect properties.

Various parameters will affect the solidification kinetics, through their effect on the melt pool geometry.

- Energy or power
- Speed
- Concentration of energy or spot size

After solidification, the thermal cycling and cooling of material further influences precipitation kinetics and phase/grain growth.

These factors influence key microstructural parameters like the grain morphology and size, formation of phases, texture and even cracking susceptibility.



Source: S. Kelly and S. Kampe, Microstructural evolution in laser-deposited multilayer Ti-M-4V builds: Part I microstructural characterization 2004

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Factors affecting weldability

1. Solidification range
2. Solidification shrinkage
3. Coefficient of thermal expansion
4. Thermal conductivity
5. Hydrogen solubility
   - Hydrogen induced cold cracking
6. Precipitation strengthening (or hardenability)
   - Ductility dip and strain age cracking
   - Hardenability of HAZ
7. Reactivity with the environment (e.g. oxygen)
8. Microstructural condition
   - Coarsened grain structure in HAZ
   - Low melting point carbides
   - Heat treatment condition

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Metallurgy of DED

Source: TWI, https://www.twi-global.com/technical-knowledge/job-knowledge/arc-based-additive-manufacturing-137

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Materials processed with DED – Arc

Steels	Nickel alloys	Titanium	Aluminium	Others
• Stainless steels (316L, 304L, 420, 17-4PH) • Tool Steels (Maraging steel, H13, S7) • Mild steel • HSLA steels	• In625 • In718 • In690 • Waspalloy • Hastelloy-X • Haynes 230 • Monel K-500 • Invar	• CP Ti • Ti-6Al-4V • Ti-5553 • Ti-6242 • Ti-6246	• 2xxx (2024, 2219) • 4xxx (4047, 4043) • 5xxx (5087, 5356) • 6xxx (6061)	• Stellite • Magnesium (AZ31) • Zirconium • Tungsten • Tantalum • GRCop-84 • CoCr

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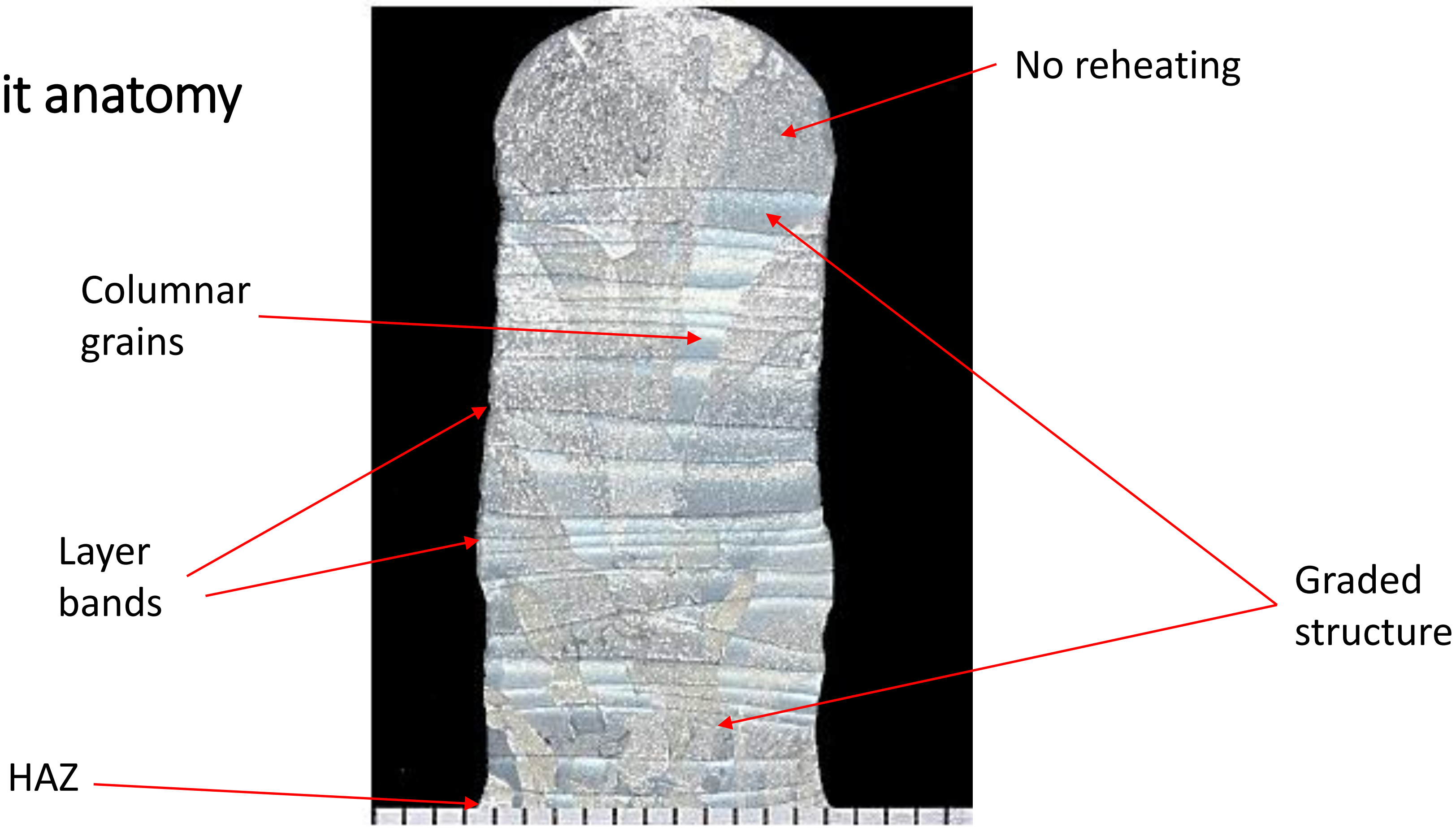
Deposit anatomy



Source: TWI, https://www.twi-global.com/technical-knowledge/job-knowledge/arc-based-additive-manufacturing-137

Heat Affected Zone

Can be considered the same as welding.

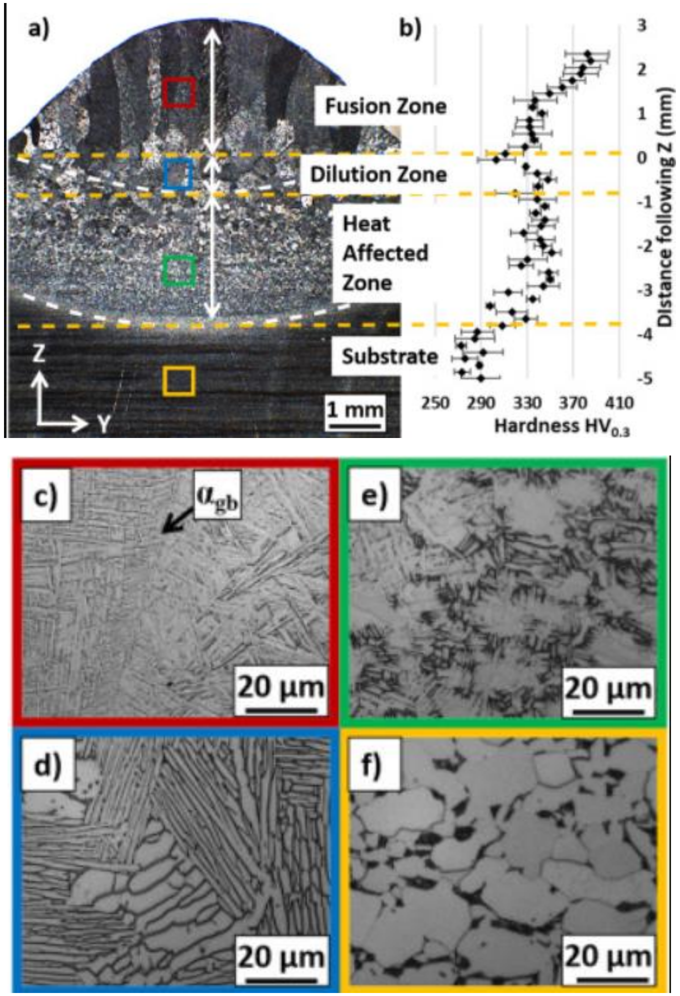
The introduction of a heat source to the substrate (or previously deposited) material will result in a heat affected zone (HAZ).

This locally alters the microstructure, and therefore properties

- This needs careful considered if used in a repair scenario.

Coarsening of the grain structure in the HAZ, can reduce material ductility and toughness making the HAZ more susceptible to failure.

This concept can be useful to consider for each new deposition added, treating the resulting banded structure as a series of HAZs.



Source: A. Ty et al, Influence of deposit and process parameters on microstructure and mechanical properties of Ti6Al4V obtained by DED-W (PAW), 2022

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Dilution

Definition “ The mass of original substrate or previously deposited track melted, divided by the sum of the combined mass of substrate and added materials melted” (Pinkerton 2010).

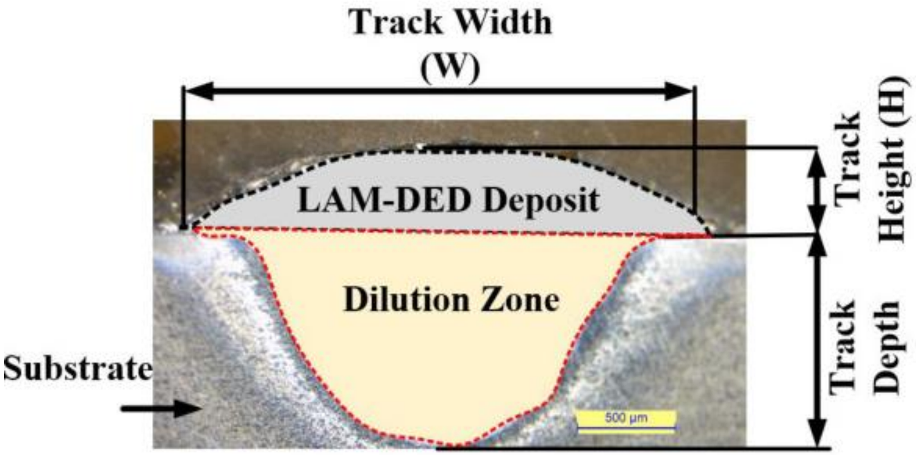
This is an important metric to investigate for DED.

- Too high a value indicates excessive remelting
- Too low a value can indicate insufficient remelting and thus incomplete bonding to the substrate/previous layer

Furthermore, during processing the remelting of the substrate material and creation of HAZ will cause an intermixing of materials into the deposited material.

This will alter the microstructure and properties locally.

Potential to cause brittle phases could result in poor adherence to the substrate.



Source: A. Jinoop et al. Laser Additive Manufacturing using directed energy deposition of Inoonel-718 wall structures with tailored characteristics, 2019

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Graded microstructures

Deposition of material is on an evolving substrate throughout the building process.

Therefore, the thermal history differs from the bottom of the deposit/part to the top:

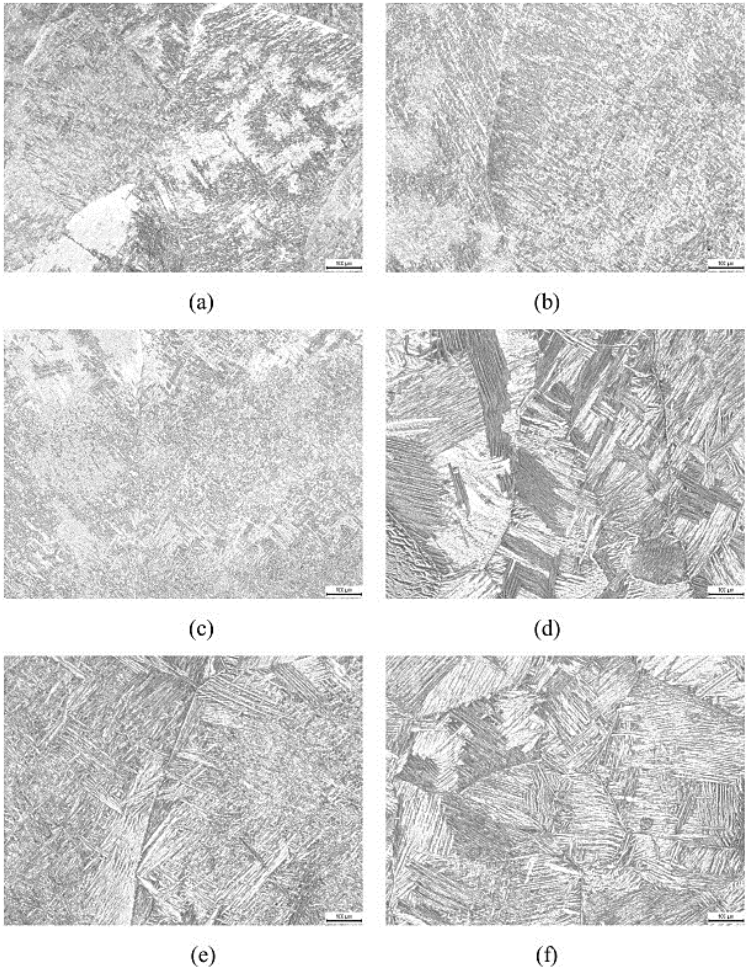
- Initially rapid cooling due to substrate influence
- Multiple reheat cycles caused by subsequent deposition
- Fewer/no reheat cycles in last deposit/s

Furthermore, the deposition strategy often doesn’t allow for complete cooling between tracks/layers allowing heat to accumulate.

All of this results in microstructures that evolve across the deposit.

This affect is geometry dependant, due to the specific changes in tool path length and heat accumulation.

Careful management of temperature is needed to ensure a consistent/known output.



Source: B. Wu et al, Effects of heat accumulation on microstructure and mechanical properties of Ti6Al4V alloy deposited by wire arc additive manufacturing, 2018

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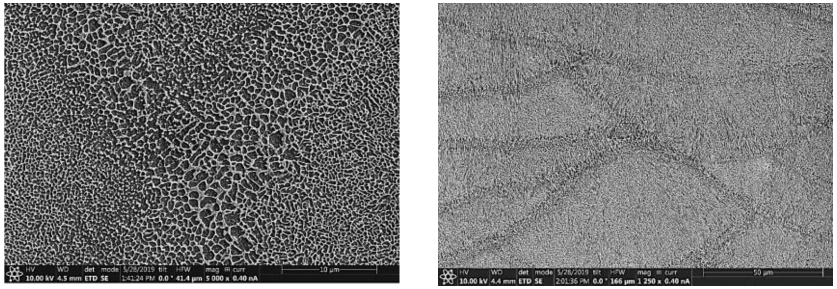
Layer bands

Each layer deposited has a HAZ, which includes both full remelting and reheating of the underlying material.

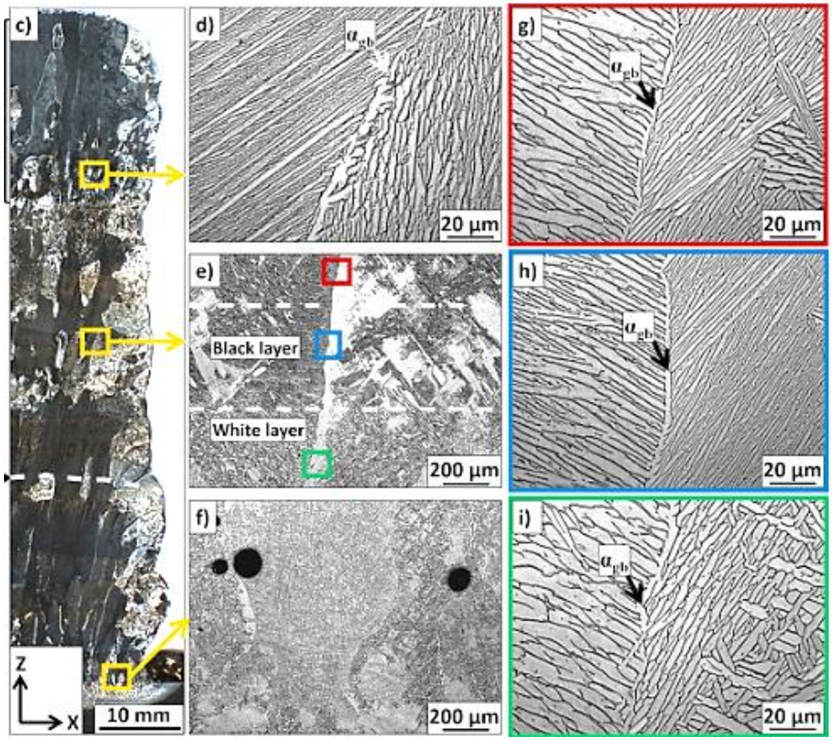
This creates a layered pattern of material that has been fully remelted and only reheated.

The complex reheating and remelting affects the material microstructure in different ways (depending on material) including:

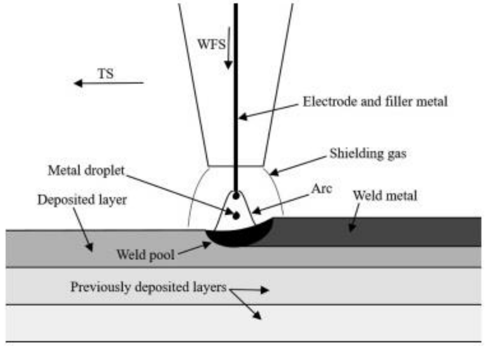
- Grain size changes
- Precipitation of different phases
- Distributions of phases
- Texture effects



Source: MTC



Source: A. Ty et al, Influence of deposit and process parameters on microstructure and mechanical properties of Ti6Al4V obtained by DED-W (PAW), 2022



Source: M. Arana et al, Influence of deposition strategy and heat treatment on mechanical properties and microstructure of 2319 aluminium WAAM components, 2022

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Columnar grains

Highly directional heat input used in DED usually results in large columnar grains.

Formed due to a mechanism called epitaxial growth where the growth of a previous crystallite is preferred to nucleation of a new one.

Conserves the original crystal structure and orientation (texture).

Results in the growth of large aligned grains across layers and across many mm of material.

Highly dependant on the deposition strategy.

In general, larger energies typically result in more remelting of preceding layers, promoting more epitaxial growth and a more columnar and orientated structure.

Affects material properties and can result in significant anisotropies.

Source: TWI, https://www.twi-global.com/technical-knowledge/job-knowledge/arc-based-additive-manufacturing-137

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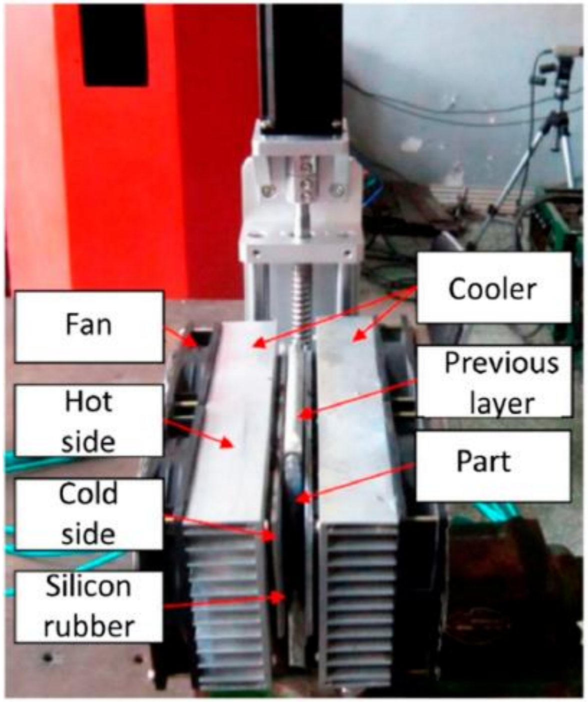
Managing temperature

Large amount of heat introduced in the process of DED-arc and managing this heat delivered is key to overall success.

Managing the temperature of the deposit during manufacture can have multiple effects:
1. Microstructure
2. Mechanical properties
3. Residual stress
4. Defects and/or failure

Dwell periods can be introduced into the process to allow the deposit to cool, thus controlling the temperature between depositions:
- Interpass temperature (the temperature at which next deposition begins to keep the process stable)

Two common methods of setting interpass temperature:
- Fixed dwell time
- Variable dwell time based on temperature measurement



Source: T. Rodrigues et al, Current status and perspectives on wire and arc additive manufacturing (WAAM), 2019

Novel methodologies are now being investigated but some (like thermoelectrical cooling) may limit design freedom significantly.

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Residual stresses

Large transient thermal gradients in beam-based AM, result in constrained thermal expansions and contractions.

If the stress exceeds the yield stress of the material, warping or plastic deformation will occur, if it exceeds the local UTS then cracking will result.

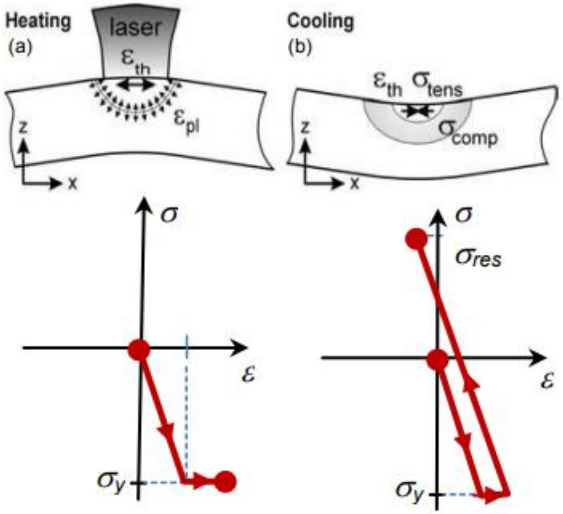
Stresses can negatively affect the mechanical properties but also can act as a driving force for microstructural change.

Build plate heating and deposition strategy changes can help with reducing residual stresses but are process and geometry specific.

- Some early work is being conducted on using mechanical methods for stress reduction (and property improvement).

Typically, stresses are managed with post process heat treatment.

Source: T. Rodrigues et al, Current status and perspectives on wire and arc additive manufacturing (WAAM), 2019



Residual stress formation model: (a) heating-phase, (b) cooling-phase

Source: D. Svetlizky et al, Directed energy deposition (DED) additive manufacturing: physical characteristics, defects, challenges and applications, 2021

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Cracking

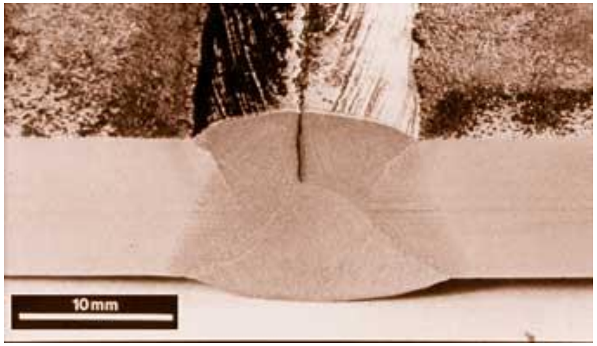
Two types of broad cracking classification can occur in DED:
1. Macroscopic
2. Microscopic

Macroscopic cracking can occur due to residual stresses that locally exceed the ultimate tensile stress of the material.

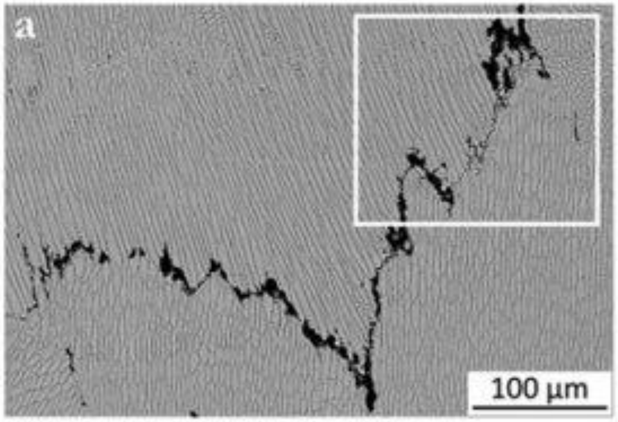
Macroscopic cracking can also occur due to interaction with defects, contamination or due to poor adherence to the substrate or previous layer.

Methods to resolve macroscopic cracking typically involve reducing the residual stresses (usually through controlling thermal gradients) whilst ensuring a good, clean deposit.

Microscopic cracking is related to specific metallurgical processes of which there are three commonly cited mechanisms:
- Solidification cracking (Hot tearing)
- Liquation cracking
- Ductility dip or strain age cracking



Source: TWI, https://www.twi-global.com/technical-knowledge/job-knowledge/defects-solidification-cracking-044,



Source: B. Carroll et al, Functionally graded material of 304L and Inconel 625 fabricated by directed energy deposition: characterisation and thermodynamic modelling, 2016

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Microcracking

Solidification cracking or hot tearing

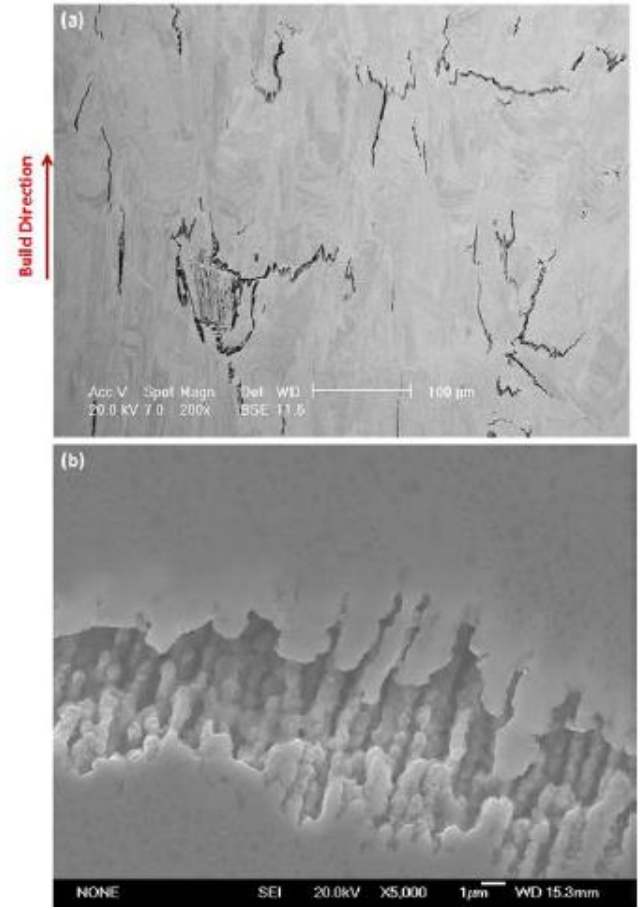
- Occurs in the solidifying melt pool or mushy zone
- Insufficient filling between dendrites
- Regions tear under the stresses induced by solidification

Liquation cracking

- Typically occurs in lower energy welding conditions
- Occurs where melting of grain boundary phases (e.g. low melting point carbides)
- Under stresses during solidification these liquid films at grain boundaries act as crack initiation points

Ductility dip or strain age cracking

- Two opposing actions, relaxation of stresses (slow) and precipitation of strengthening phases (faster).
- Ageing increases strength but decreases ductility, remaining residual stresses and further stress from precipitation of phases can result in strains that locally exceed the limited ductility.



Source: L. Carter et al, Laser powder bed fabrication of nickel-base superalloys: Influence of parameters. Characterisation, quantification and mitigation of cracking, 2012

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Heat treatment

Why thermally post process?

To remove residual stresses

- Remove inherent residual stresses formed in the build
- Prevent distortion

To develop the microstructure

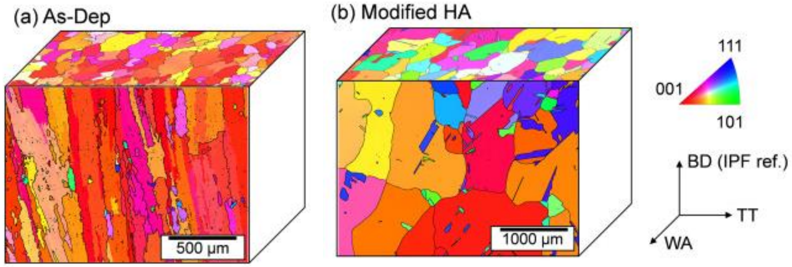
- Reduce anisotropy
- Provide strengthening responses
- Control of grain size, phase distribution and texture

To densify the material

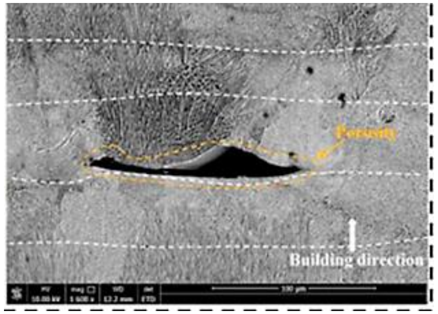
- Close gas pores and lack of fusion porosity
- To improve properties
- Also used to develop the microstructure

In short, we thermally post process to mitigate challenges associated with DED.

Source: T. Rodrigues et al, Current status and perspectives on wire and arc additive manufacturing (WAAM), 2019



Source: C. Seow et al, Wire + arc additively manufactured Inconel 718: Effect of post-deposition heat treatments on microstructure and tensile properties, 2019



Source: M. Xia et al, Porosity evolution and its thermodynamic mechanism of randomly packed powder-bed during selective laser melting of Inconel 718 alloy, 2017

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Heat treatments – Stress relief

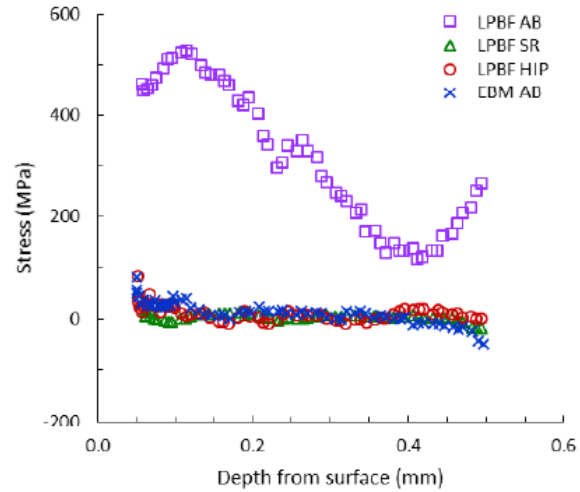
Thermal energy induces recovery allowing the reduction of residual stress by dislocation combination and annihilation.

Thermal energy can come from heat treatment or hot isostatic pressing.

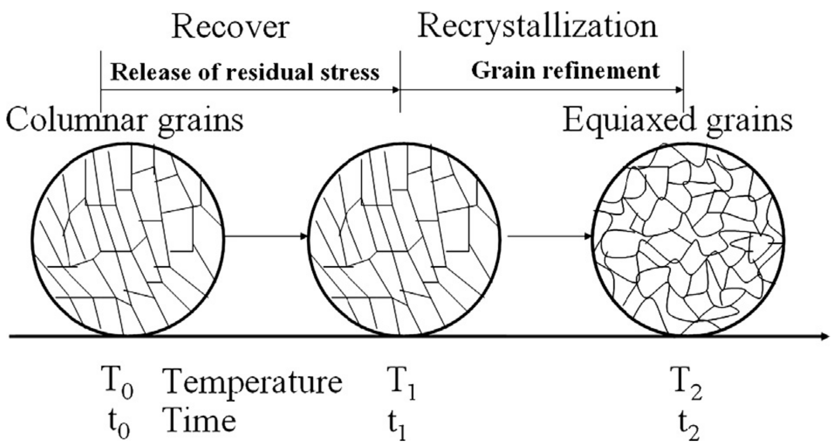
Aim of a pure stress relief cycle is to achieve recovery of residual stresses without microstructural change.

However, sometimes heat treatment cycles also cause microstructural affects like recrystallisation.

Heat treatments that are higher in temperature and of the same hold or longer than the standard stress relief cycle, will also achieve a stress relieving effect.



Source: MTC



Source: MTC

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Heat treatment – microstructural development

Highly material dependent

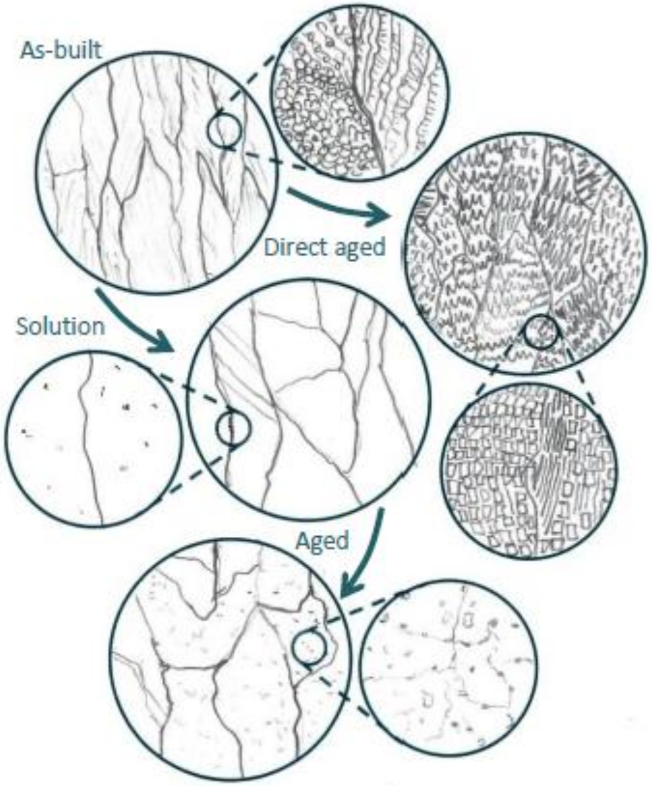
- Solid solution strengthened (e.g. 316L)
- Precipitation strengthened (e.g In718)
- Dispersion strengthened (e.g. GlidCop)

The specific thermal properties of each material and the type of strengthening it undergoes is critical to determining the correct heat treatment.

Highly process dependent

- Process conditions will determine the starting microstructure.

Due to the unique nature of thermal history in DED and other AM technologies the requirement for heat treatment will remain but the specific cycle required to achieve the desired effect may change.



Source: MTC

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Heat treatment – densification

Fluctuations in the DED process can cause defects and are difficult to eliminate.

For critical applications, these defects may not be acceptable.

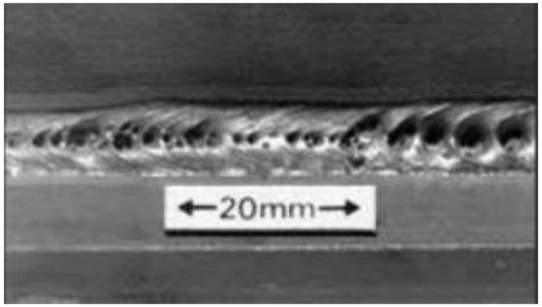
Therefore, we may look to a thermal post process to densify the material and 'heal' defects.

This is commonly achieved through hot isostatic pressing (HIP).

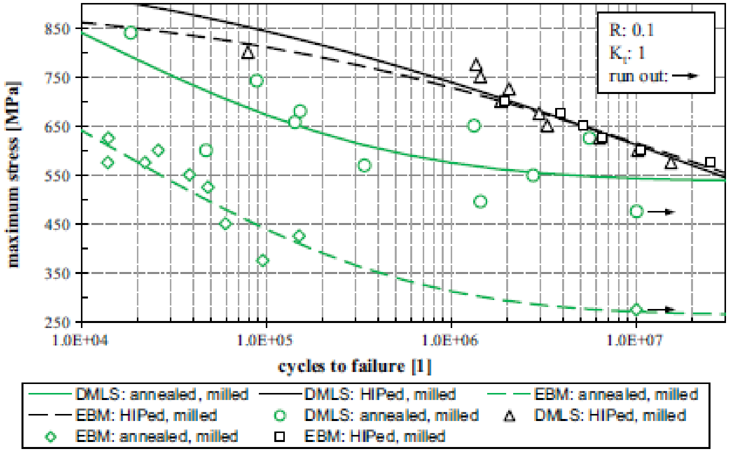
HIP utilises high temperature, high pressure inert gas to collapse and diffusion bond 'heal' defects.

For less complex DED components forging may also be an option, although is less common.

Removal of defects can give significant improvement in certain properties like fatigue.



Source: TWI, https://www.twi-global.com/technical-knowledge/job-knowledge/defects-imperfections-in-welds-porosity-042



Source: Greitemeir et al. Fatigue performance of additive manufactured Ti6Al4V using electron and laser beam melting, 2017

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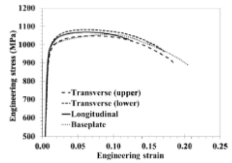
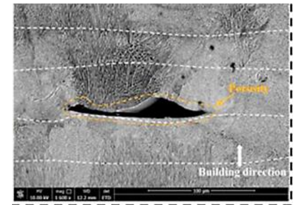
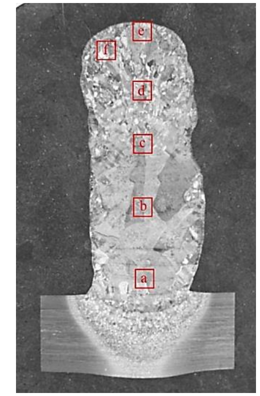
Anisotropy

Source: B. Carroll et al, 2015

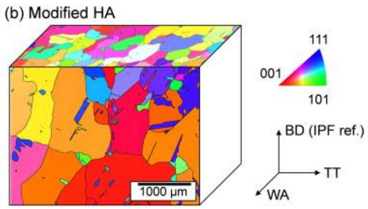




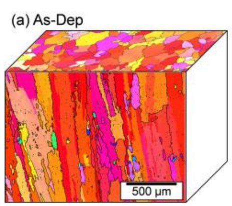
Source: M. Xia et al, 2017



Source: B. Wu et al, 2018



Source: C. Seow et al, 2019



Defects

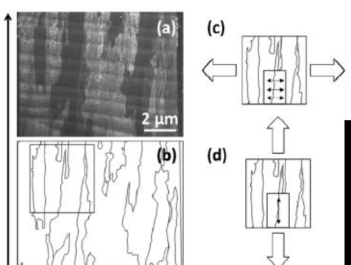
Heat treatment

Graded structures

Anisotropy

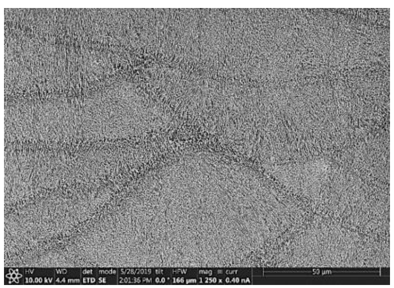
Columnar grains

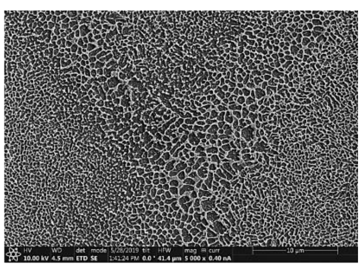
Layer bands



Source: B. Carroll et al, 2015

Source: TWI





Source: MTC

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Typical DED microstructures

Source: TWI, https://www.twi-global.com/technical-knowledge/job-knowledge/arc-based-additive-manufacturing-137

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Typical microstructures Titanium-6Al-4V

Fully transformed Widmanstatten (lamellar) α+β structures.

Columnar prior β grains.

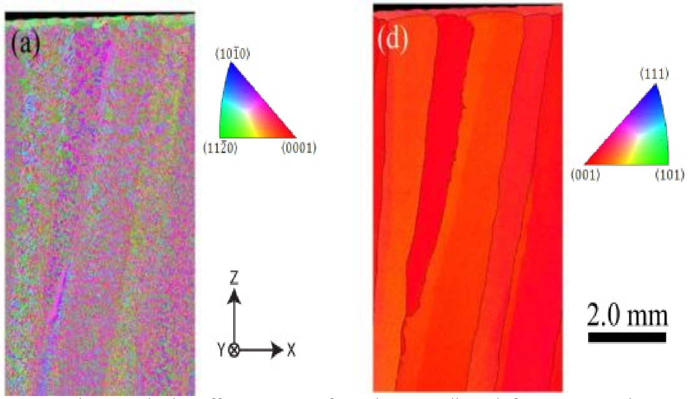
Grain boundary α and α colonies.

Highly orientated prior β grain textures with preferred (001) growth direction in the build direction.

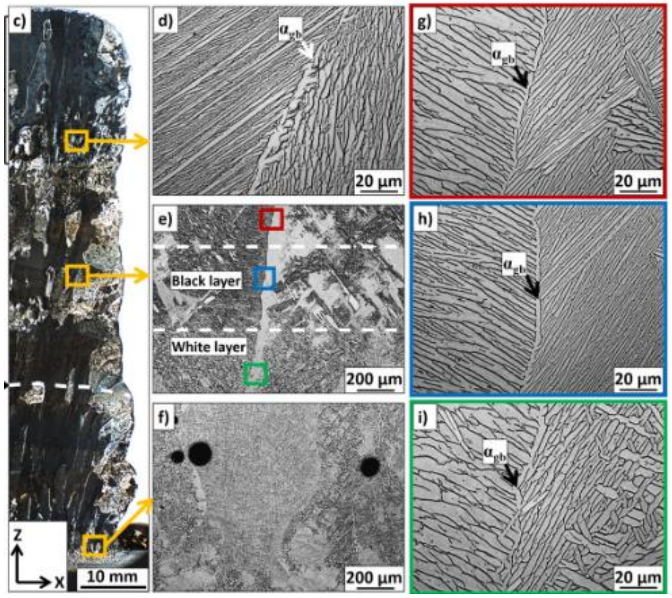
α’ martensite may form, depending on cooling conditions, more likely in last layer.

Gradation of α lath size across layer bands and across the build height likely.

Requires good shielding to prevent formation of α case.

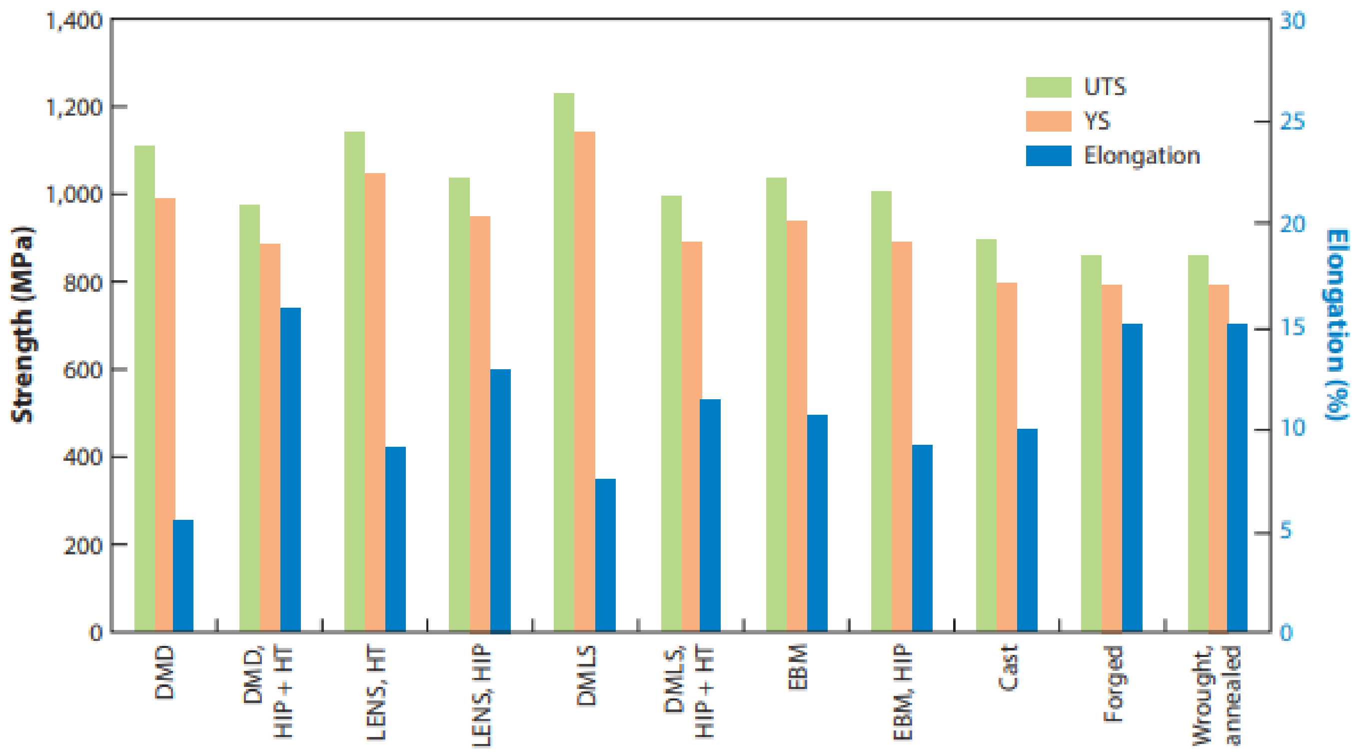


Source: J. Donoghue et al, The effectiveness of combining rolling deformation with wire-arc additive manufacture on β grain refinement and texture modification in Ti-6Al-4V, 2016



Source: A. Ty et al, Influence of deposit and process parameters on microstructure and mechanical properties of Ti6Al4V obtained by DED-W (PAW), 2022

Typical properties
Titanium-6Al-4V



Source: J. Lewandowki et al, Metal Additive Manufacturing: A Review of Mechanical Properties, 2016.

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SECTOR SKILLS STRATEGY IN ADDITIVE MANUFACTURING

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Typical microstructures Inconel 718

Elongated columnar grains, textured along the (001) direction in the build direction.

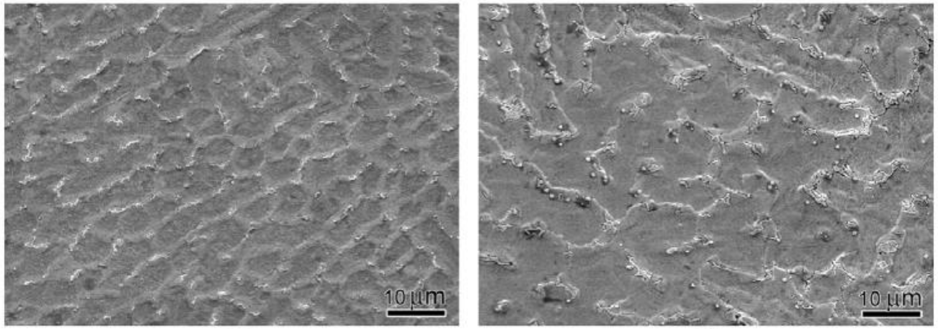
Cellular structure resulting from alloying element segregation to interdendritic regions during solidification.

Gradation of cell size (or dendritic arm spacing) from top to bottom.

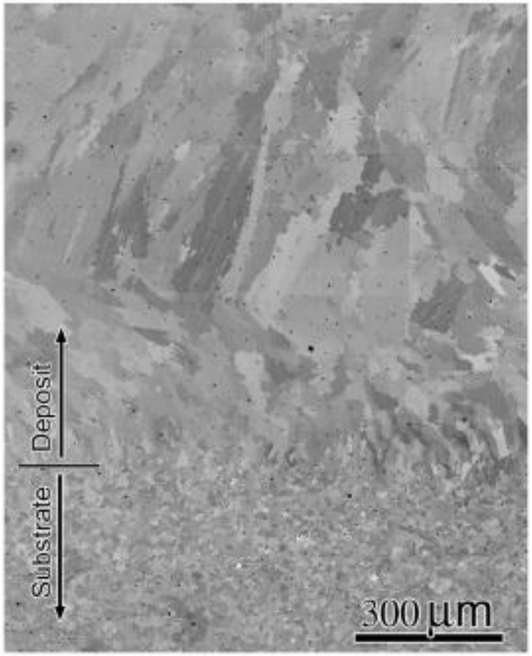
Precipitation of Laves phase and Nb carbides.

Solution HT necessary to allow for redistribution of alloying elements before aging, care with temperature choice needed.

Recrystallisation occurs after HT due to the residual stresses in process and aging results in a fine distribution of γ’’/γ’ particles.



(a) (b)



Source: R. Ding et al, Electron microscopy study of direct laser deposited In718, 2015

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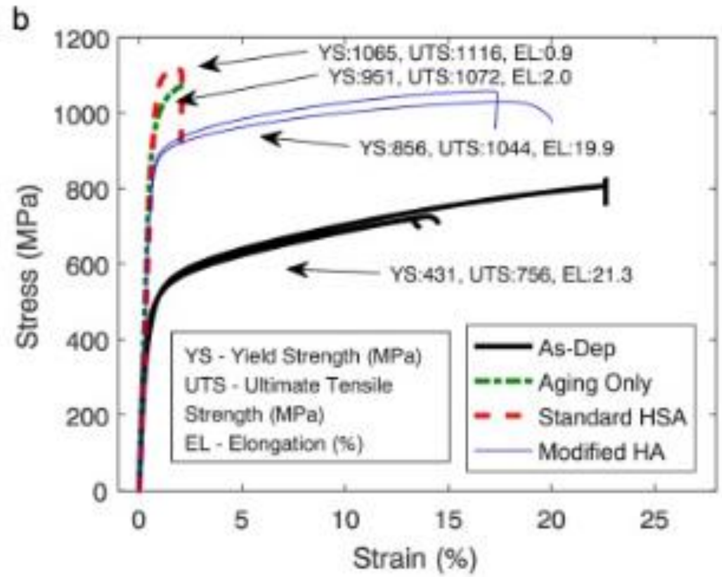
Typical properties In718

Alloy	Condition (as built, HIP, or heat treated)	Specimen orienta-tion	E (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
IN718	As built	*XY*	NA	473 ± 6	828 ± 8	28 ± 2	NA	186
IN718	As built	*Z*	NA	650	1,000	NA	NA	187
	Heat treated			1,257	1,436			
IN718	As built	NA	NA	590	845	11	NA	188
	Heat treated			1,133	1,240	9		

Source: J. Lewandowski and M. Seifi, Metal Additive Manufacturing: A Review of Mechanical Properties, 2016

AMS 5596 wrought plate:
UTS – 1240 MPa
Yield – 1035 MPa
Elongation – 12 %

Heat treatment condition critical to achieving mechanical properties including and beyond tensile properties.



Source: C, Seow et al, Wire + arc additive manufactured Inconel 718: effect of post-deposition heat treatments on microstructures and tensile properties, 2019

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Typical microstructures
316L Stainless Steel

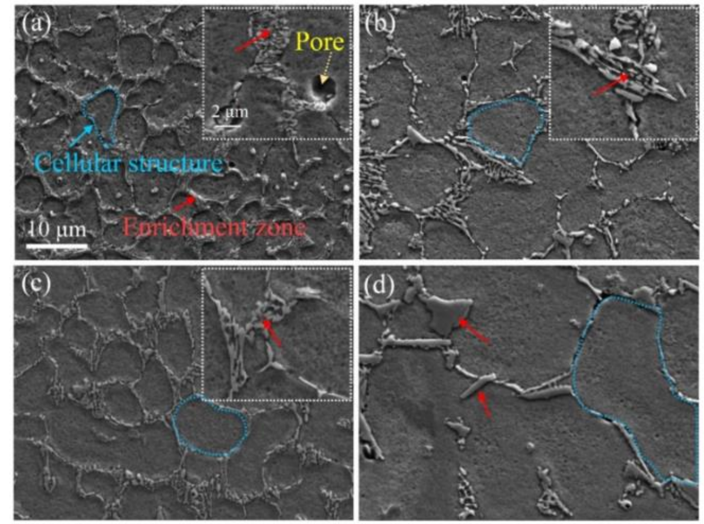
Columnar grain structure with texture (001) aligned to the build direction.

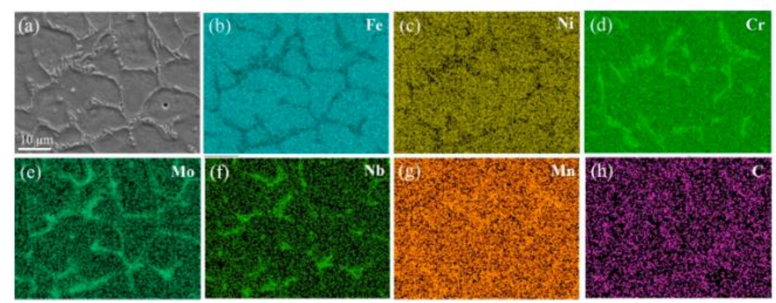
Dendritic cellular structure (similar to In718) due to segregation of alloying elements during solidification.

Reheating cycles and heat accumulation during build can lead to the formation of undesirable secondary phases such as Cr-Rich carbides, Laves phase and σ phase.

Cr carbides and σ phase consume chromium from the austenite matrix and reduce the corrosion resistance of the material in the as-built state.

Heat treatments can be beneficial to homogenise the material, redistributing the key alloying elements.





Source:S. Yang et al, Microstructure and corrosion resistance of stainless steel manufactured by laser melting deposition, 2021

Typical properties 316L

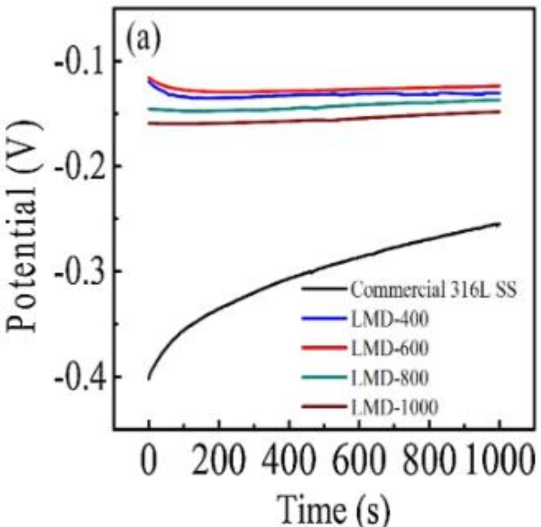
ASTM A240 wrought plate:
UTS – 480 MPa
Yield – 170 MPa,
Elongation – 40%

Alloy	Condition (as built, HIP, or heat treated)	Specimen orienta-tion	*E* (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Hardness	Reference
316L	As built	Z	NA	405–415	620–660	34–40	NA	225
	Heat treated	Z	NA	325–355	600–620	42–43	NA	

Source: J. Lewandowski and M. Seifi, Metal Additive Manufacturing: A Review of Mechanical Properties, 2016

In the as-built state the corrosion resistance of 316L can be acceptable (1).

Heat treatments have been shown to improve the corrosion resistance through redistribution of alloying elements and removal of δ-ferrite (2).



Source:S. Yang et al, Microstructure and corrosion resistance of stainless steel manufactured by laser melting deposition, 2021

1 – S. Yang et al, Microstructure and corrosion resistance of stainless steel manufactured by laser melting deposition, 2021
2 – Y. He et al, Effect of heat treatment on the microstructure and corrosion resistance of 316L stainless steel fabricated by hybrid in-situ rolled wire-arc additive manufacturing, 2023.

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Metallurgy assessment tools

Source: Instron

Source: Instron

Mechanical

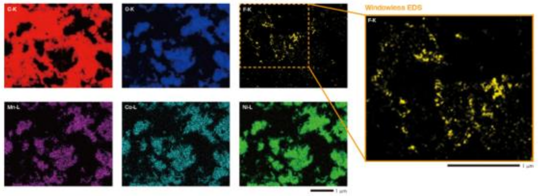
- Tensile
- Load controlled fatigue
- Strain controlled fatigue
- Fracture toughness
- Charpy impact
- Hardness

Source: Struers

Physical

- Laser flash analysis
- Eddy Current
- Mass gain analysis
- Thermogravimetric analysis

Source: Wikipedia



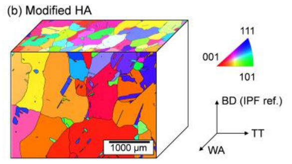
Source: Jeol

Structure

- Mounting
- Polishing
- Optical microscopy
- Scanning electron microscopy
- Electron backscatter diffraction
- Energy dispersive x-ray spectroscopy
- Archimedes density

Source: Jeol

Source: Zeiss



Source: C, Seow et al, Wire + arc additive manufactured Inconel 718: effect of post-deposition heat treatments on microstructures and tensile properties, 2019

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