AMPOWER INSIGHTS

Additive Manufacturing **Material performance optimization**

Increasing properties of
Ti-6Al-4V parts
by AM specific HIP treatments

INSIGHTS GAINED:

- Titanium in Additive Manufacturing
- Material characteristics of Ti-6Al-4V from LB-, EB-PBF & BJT
- HIP cycles for Additive Manufacturing

Vol. 7
Part 1 of 2
May 2020

Insights gained

Titanium in Additive Manufacturing
Material characteristics of Ti-6Al-4V from LB-, EB-PBF & BJT
HIP cycles for Additive Manufacturing

Management summary

Titanium, specifically Ti-6Al-4V, is the most commonly used metal in Additive Manufacturing. Due to its high specific strength and biocompatibility it is used for demanding applications in aviation and the medical industry. Therefore the requirements regarding material performance for titanium AM parts are extremely high.

To increase the part performance hot isostatic pressing (HIP) is commonly used for highly demanding applications and has become a common post- process for titanium AM parts as well. However, the typically used temperature-pressure-cycles for AM are derived from HIP processes originally used for casting parts. Therefore they fall short to consider specific characteristics of AM materials which should be amplified or annihilated by the HIP process to optimize the resulting material performance.

Ampower Insights Vol. 7 **PART 1** investigates AM specific material characteristics of LB-, EB-PBF and BJT which should be amplified or annihilated by an optimized HIP treatment and derives four specific temperature-pressure-cycles optimized for Ti-6Al-4V.

In **PART 2**, to be published in Q3 2020, the resulting material performance of the optimized HIP cycles for all three AM technologies is presented. Resulting porosity, microstructure, tensile strength and fatigue properties will be investigated with over 200 specimen.

Download this paper at
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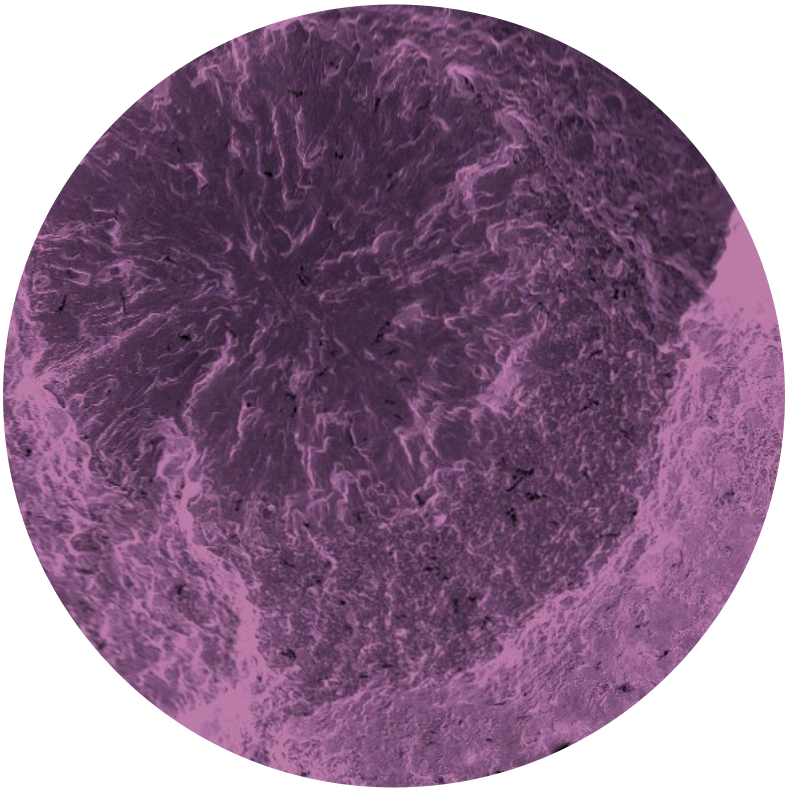


About AMPOWER

AMPOWER is the leading consultancy in the field of industrial Additive Manufacturing. AMPOWER advises their clients on strategic decisions by developing and analyzing market scenarios as well as compiling technology studies. On operational level, AMPOWER supports the introduction of Additive Manufacturing through targeted training programs as well as identification and development of components suitable for production. Further services include the setup of quality management and support in qualification of internal and external machine capacity. The company is based in Hamburg, Germany.

Content

PART 1

PART 2

To be published Q3 2020

Introduction

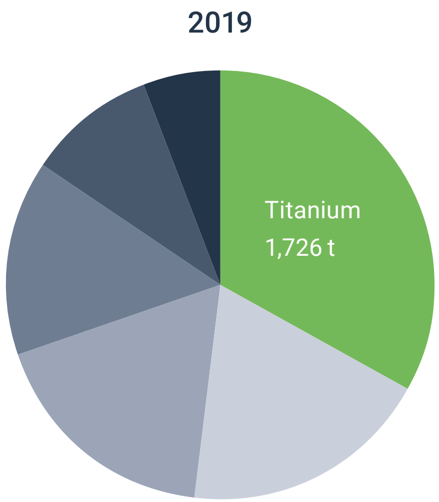
Titanium in Additive Manufacturing

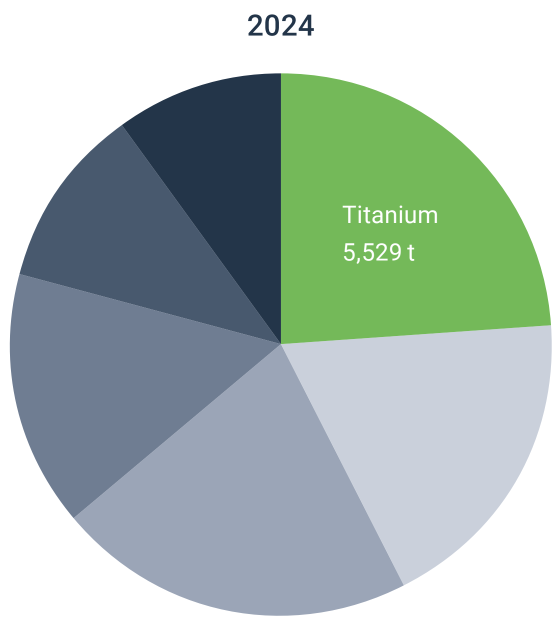
Titanium alloys show excellent specific strength and corrosion resistance and therefore are often used for high performance applications in aviation and racing or for medical products. Overall Ti-6Al-4V is the most commonly used titanium alloy due to its well-balanced and high mechanical properties.

The use of titanium in high-cost applications in aviation and medical industry and inherent difficulties in conventional machining processes promote many business cases for AM applications. Consequently titanium alloys have the largest share of metals in Additive Manufacturing.

In 2019, a total of 1,726 t of titanium feedstock was used in AM parts. The vast majority of feedstock used was powder for LB- and EB-PBF processes. It is expected that the share of wire for AM deposition technologies will increase in the future. In the next 5 years the need for titanium AM feedstock will continue to grow, losing however overall share to other alloy groups.

Of all titanium alloys Ti-6Al-4V and pure titanium are the most common in Additive Manufacturing. Ti-6Al-4V is used in light- weight applications such as aviation brackets and racing parts as well as loaded implants. For lower loaded implants pure titanium is often used.

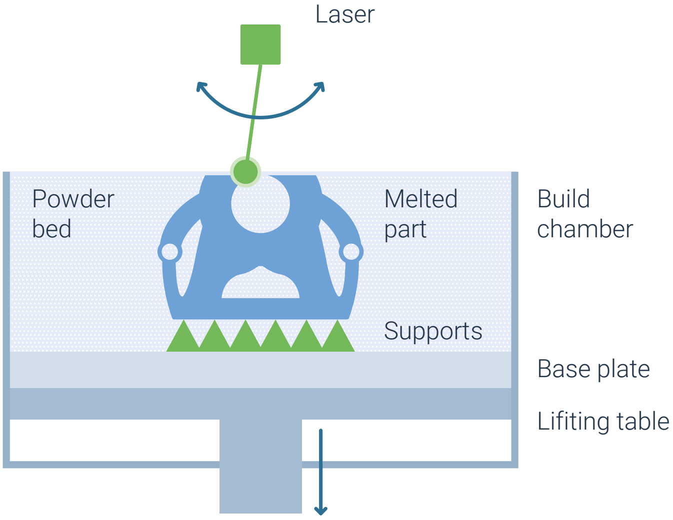




Source: AMPOWER Report 2020, www.additive-manufacturing-report.com

Powder bed AM technologies

The majority of titanium AM parts are built with powder bed technologies. While Powder Bed Fusion (PBF) is used to produce light weight components for aviation and racing as well as medical implants. Binder Jetting is typically used to produce smaller medical instruments from titanium.

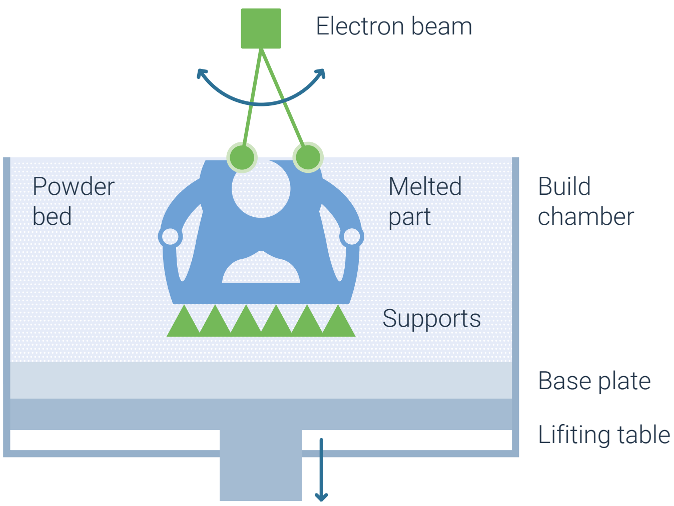


Laser Beam Powder Bed Fusion

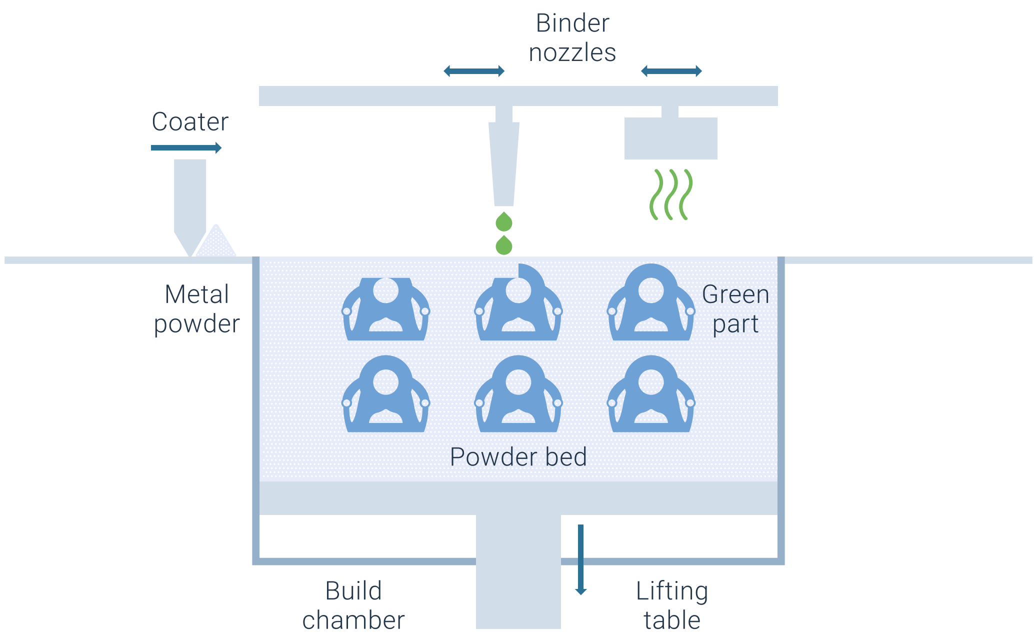
LB-PBF is a direct Additive Manufacturing technology in which a laser beam directly creates the final metal part by melting powder particles. The process creates solid material with part densities of > 99,5 %. Typically the process runs at room temperature melting powder layers between 30 to 60 µm thickness. Therefore the process is characterized by extremely fast cooling of the material resulting in a very distinguished microstructure.

Electron Beam Powder Bed Fusion

Similar to LB-PBF the EB-PBF process directly melts metal powder in a build chamber to create the final part. Besides using an electron beam, the largest differences between the processes are the pre-heating of the powder bed to temperatures between 600°C to 1100°C. The high process temperature results in slower cooling of the single layers and therefore coarser microstructure compared to LB-PBF.



Pioneer in printing titanium with Binder Jetting Technology (BJT) is DIGITAL METAL from Sweden. Utilizing the advantages of BJT, economic production of larger batch sizes, high resolution and realization of small features, it is mainly used to print medical instruments for dental or surgical applications from titanium.



Binder Jetting Technology

BJT uses a 2-step or indirect process to create the solid metal part. In the first step the metal powder is "glued" together to form the green body. In this state the part is a composite of a polymer matrix and metal powder and therefore quite fragile. Only in the second step, the sintering process, the green body is sintered at high temperatures to a solid metal part. In the sintering process the polymer matrix is dissolved and the resulting part is 100 % metal. However, depending on material and process parameters a residual porosity of 1 to 6 % is usual in BJT components.

Hot isostatic pressing

Hot isostatic pressing (HIP) is a manufacturing process using high temperature and pressure to densify metal or ceramic materials. In powder metallurgy it is commonly used to create compact solids and parts from powder feedstock. Depending on the feedstock material and targeted results different temperature-pressure-curves are used in the HIP process.

Additionally to the application in powder metallurgy HIP processes are often used to densify conventional casting parts. The HIP process increases the part density by a combination of compression and diffusion bonding of inherent porosity. Especially for high performance applications in aviation or the reduction of surface porosity on polished surfaces a post-process densification by hot isostatic pressing is used.

Since typical AM applications are often in the area of high performance aviation brackets or polished medical implants the HIP process has become a common post process especially for titanium AM parts. However, due to the lack of norms, specifications and widely available HIP facilities, many AM parts are treated in temperature-pressure-cycles together with and optimized for casted titanium parts.

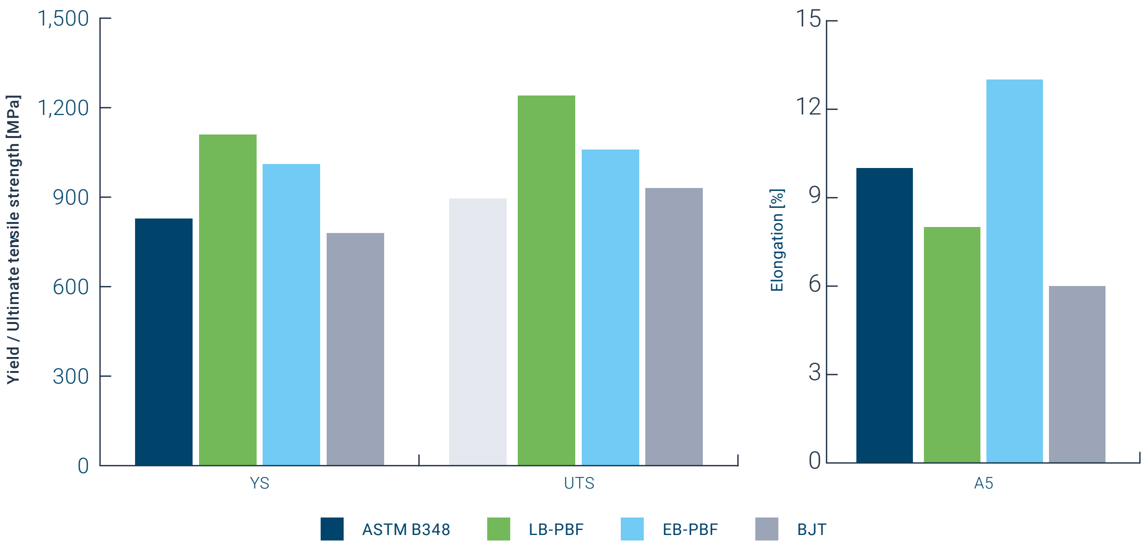
Photo: courtesy of Quintus Technologies

Properties of AM titanium

Titanium alloy Ti-6Al-4V

Titanium can exist in two crystal structures, close-packed hexagonal α-phase and body-centered cubic β-phase. Ti-6Al-4V is an α+β titanium alloy, meaning both phases can be present in the solid blank. The microstructure is either lamellar or globular or a mixture, depending on the thermo-mechanical history of the production route. Simple cooling from melting temperature results in a solely lamellar microstructure.

Typical tensile properties of AM Ti-6Al-4V in as build condition



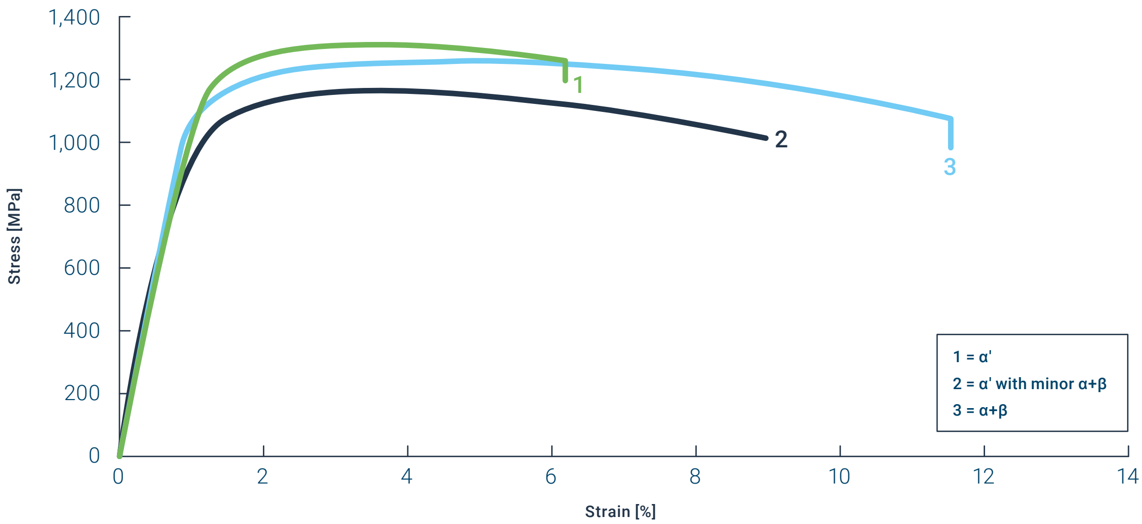
Additively manufactured Ti-6Al-4V shows excellent tensile strength. Especially material from PBF processes exceed the required values of plate material by far. The fine microstructure resulting from fast cooling during the manufacturing process results, especially for LB-PBF material, in yield strength above 1,100 MPa. The EB-PBF material shows slightly lower strength but increased ductility compared with the laser process. The elevated temperature during the EB-PBF process causes coarser microstructure and therefore loss in strength but gain in ductility. To increase the ductility in LB-PBF post-process heat treatments are very common. The overall lower values for BJT are explained by the high remaining porosity of 6 % after the sintering process. The material properties of BJT Ti-6Al-4V are not primarily driven by the microstructure but by premature failure at pores.

Goal of optimized HIP treatment
Balance and improve material properties.

Microstructure in LB-PBF

The LB-PBF microstructure is often characterized as extremely fine α-phase or α'-martensite. Depending on the process environment, especially heat management, the microstructure can also result in an ultra-fine α+β-phase due to an in-situ heat treatment and consequent α' decomposition.

Tensile properties resulting from different microstructure



Source: Xu et. al., Additive manufacturing of strong and ductile Ti–6Al–4V by selective laser melting via insitu martensite decomposition. Acta Materialia, 85:74–84, 2015.

The dominant phase (α' compared to α+β) has significant influence on tensile strength and ductility. Xu et. al. have shown that with comparatively small changes of the AM process parameters the resulting Ti-6Al-4V can vary between these two microstructure extremes. Ultra fine α+β resulting in superior mechanical properties combining very high strength >1,200 MPa with high ductility >11 %.

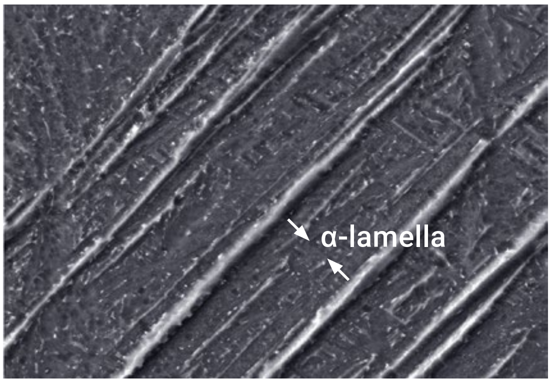
To avoid strongly different part properties, for example from alternating suppliers with different process parameters, the defined post heat and/or HIP treatment therefore should equalize the as build microstructure as much as possible.

Goal of optimized HIP treatment

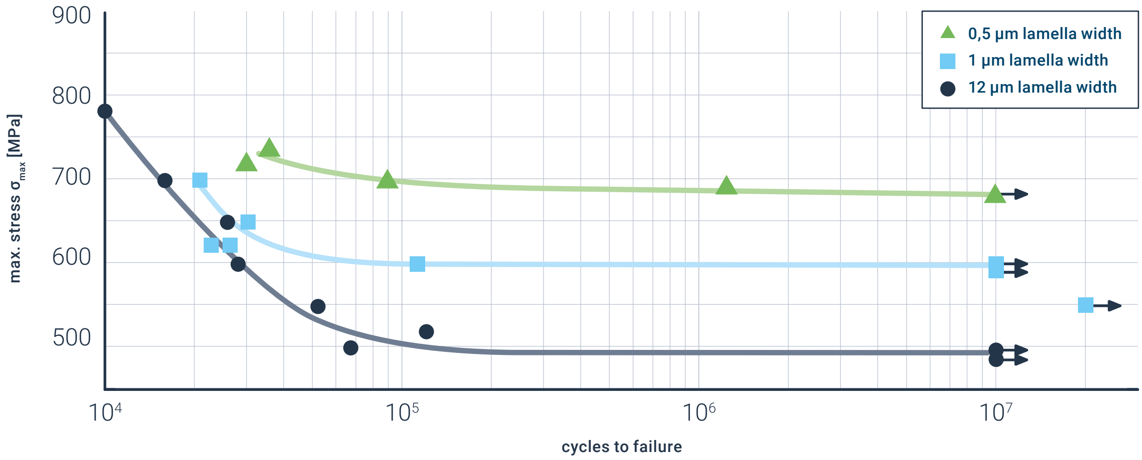
Equalize material properties, independent from starting microstructure.

LB-PBF Ti-6Al-4V shows a very fine lamellar microstructure with α-lamella width below 1 µm. Experience from conventional titanium show that the fatigue strength is significantly influenced by the α- lamella width. The Wöhler results below show the fatigue strength of lamellar conventional Ti-6Al-4V. To maximize fatigue strength of AM titanium the α-lamella width should be kept as thin as possible.

LB-PBF microstructure of Ti-6Al-4V in as build condition



Wöhler curves of lamellar Ti-6Al-4V resulting from different α-lamella width (R = -1)



Source: Peters, M., et. al.. Mechanical Properties of a Titanium Blading Alloy. Technical Report EPRI-Report CS-2933, Electric Power Research Institute, Palo Alto, CA, USA, 1983.

Goal of optimized HIP treatment
Preserve high strength and fine lamellar microstructure.

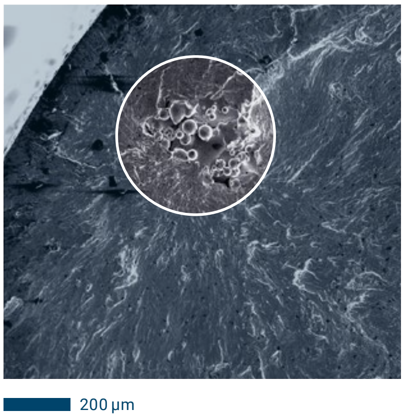
Porosity in AM material

Many AM applications require good fatigue performance to cope with their in-service conditions. Especially aircraft brackets or turbine parts need to show high fatigue strength and withstand multi-million cycles before failure.

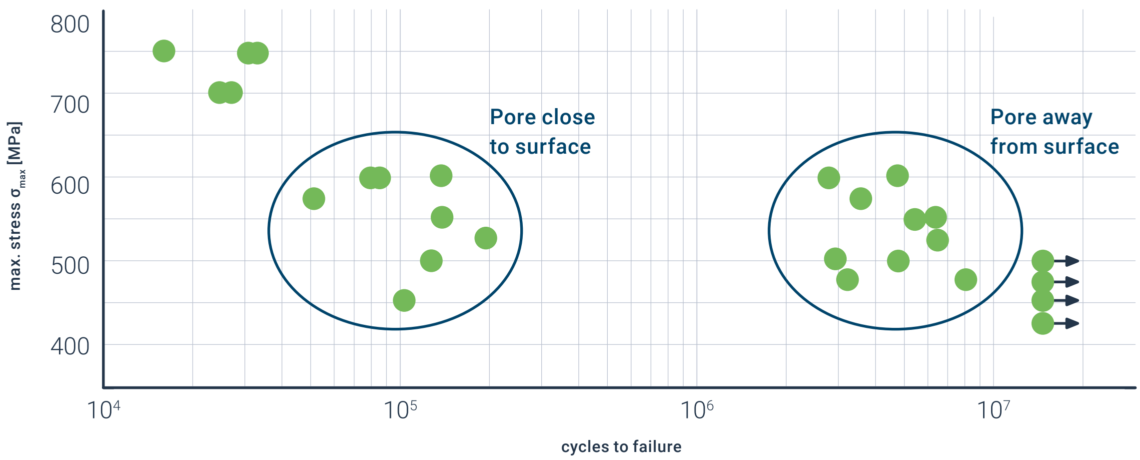
Due to its fine microstructure LB-PBF Ti-6Al-4V should exhibit fatigue strength at 10^7 cycles of at least 700 MPa. However, the fatigue data below shows a reduced fatigue strength of only 500 MPa, a value similar to cast material. The reduction is due to early part failure at inherent porosity. Although the material shows a very high density of >99,5 % the remaining pores are sufficient to reduce the fatigue strength significantly. Especially pores close to the part surface cause early failure.

EB-PBF specimen show similar effects and resulting fatigue properties. BJT material with its increased inherent porosity will result in even worse fatigue strength. To achieve the highest possible fatigue performance material densification and pore closure is inevitable for all powder bed AM technologies.

Failure causing pore in fatigue test



Wöhler results of polished LB-PBF Ti-6Al-4V tested at R = 0.1



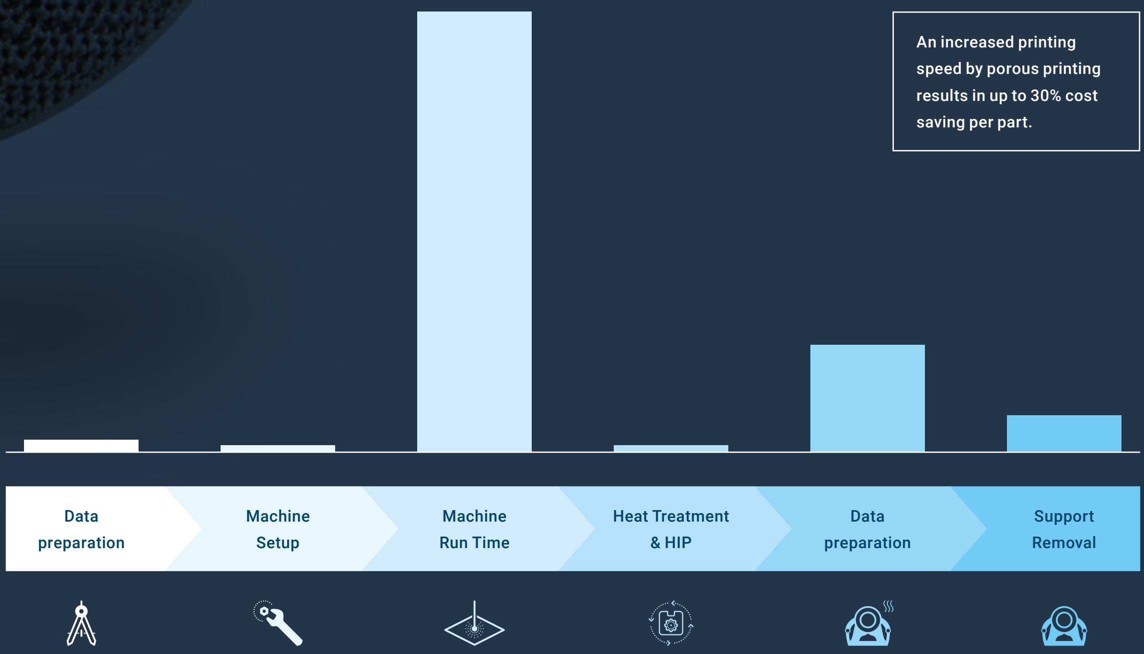
Goal of optimized HIP treatment

Densify material and close porosity by diffusion bonding.

Excursion: Porous printing

When looking at conventional metal parts from casting, plate or sintered material a certain amount of residual porosity is always present. Either the amount is non-critical for the required performance or the parts are densified via HIP treatment.

Distribution of production cost for standard hip implant in LB-PBF

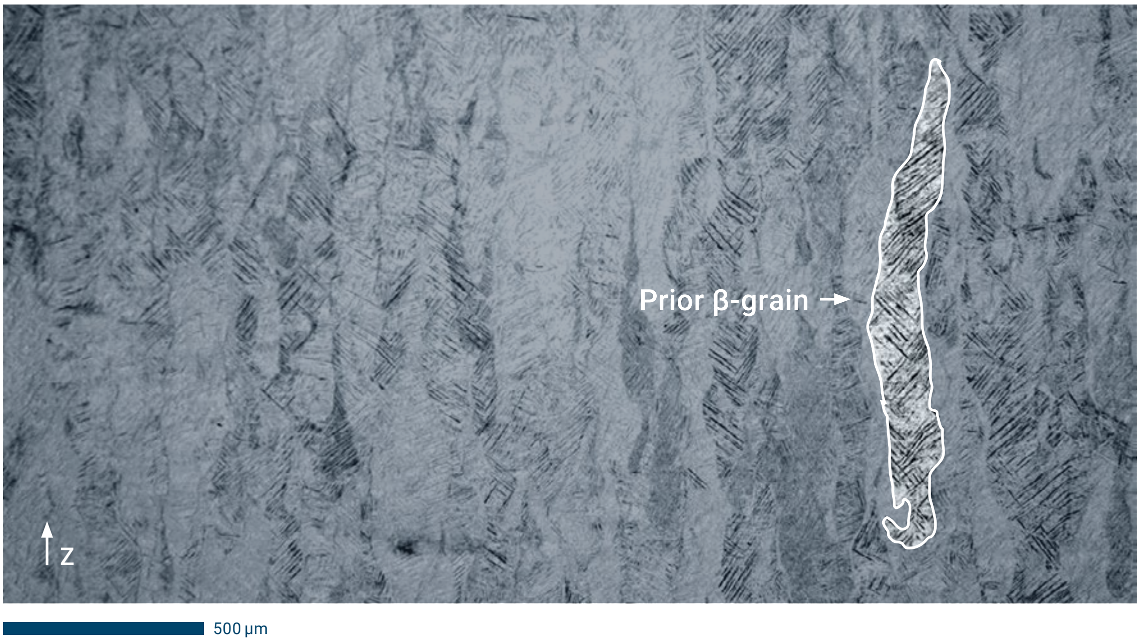


Since many applications do not require a density of 99,5 % and higher, first AM users deliberately print their metal parts with 3 % or more porosity. The reason to do so is purely economical. When increasing print speed through increased layer thickness or faster exposure times, typically the porosity of the resulting material increases as well. Because the machine run time is the largest driver of production costs, ignoring development and QA costs, an increase in print speed reduces the overall production costs significantly. The effect is often so great that an additional post HIP treatment to "repair" the deliberately porous print is more than covered if a high density is required.

Goal of optimized HIP treatment
Reduce overall production cost per part.

Anisotropy in direct AM technologies

The microstructure of all direct AM technologies based on welding principles such as powder bed fusion, powder deposition or wire arc are characterized by epitaxial columnar grain growth. The grain growth in building direction occurs due to the primarily and directed heat dissipation into the solidified lower layers of the part during production. Consequently the columnar grain solidifies from the parent grain at the bottom of the melt pool in a preferred crystallographic orientation upwards. In Powder Bed Fusion technologies the grain can grow across multiple dozen layers.



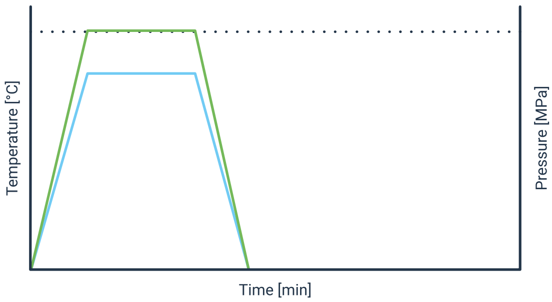
The crystallographic orientation of the α-phase in as-build AM parts is closely related to the prior parent grain β-phase. This typically results in a strong texture of the material. Meaning most of the α-lamella have the same crystallographic orientation resulting in an anisotropic behavior of the material. The magnitude of texture in the material is driven by the thermal conditions during solidification more precisely the ratio between thermal gradient and solidification ratio. With the thermal gradient determining the solidification orientation.

Goal of optimized HIP treatment
Reduce or annihilate anisotropic material properties.

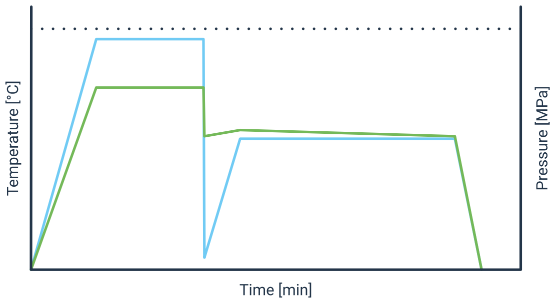
Optimized HIP cycles

To achieve the AM specific optimized material performance four HIP treatments have been defined. One low and one high temperature treatment as well as two treatments above β-transus temperature. To reach full densification at low temperatures the pressure has to be adapted accordingly. Resulting in high pressure at low temperature treatment and vice versa.

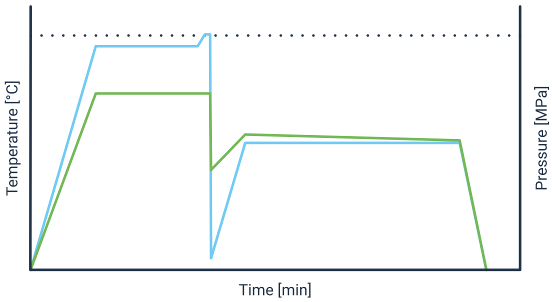
Low temperature treatment

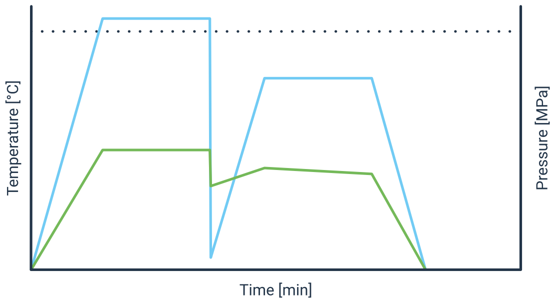


High temperature treatment



β-transus treatments





— Temperature · · · β-transus — Pressure

Outlook to Vol. 7 PART 2

AMPOWER Insights Vol. 7 **PART 2** will show resulting material properties for LB-, EB-PBF & BJT after optimized HIP treatments. The material performance as well as part cost will be evaluated. Depending on the desired result, e.g. highest possible fatigue strength or isotropic material properties, different combinations of AM technology and HIP treatment will be presented.

1

Porosity

The foremost goal of all HIP treatments is to close critical porosity to achieve the highest possible material performance. Micrographs and µCT analysis will show remaining pore size and amount.

2

Microstructure

Micrographs of the as build and resulting microstructure are compared to tensile and fatigue strength. The α-lamella width and texture of the different technology and HIP treatment combinations is evaluated.

3

Tensile strength

The mechanical properties will be evaluated in 22 different combinations of technology and HIP treatment to give a comprehensive picture on resulting tensile strength, remaining porosity and anisotropy.

4

Fatigue performance

The analysis of the fatigue performance will focus on optimizing the fatigue strength and evaluating the scatter and failure probability resulting from possible insufficient diffusion bonding of pores.

5

Part cost

Part cost will be shown considering the complete production route and the effect of purposely porous printing on the overall part cost will be evaluated.

About the authors

Dr.-Ing. Maximilian Munsch

Maximilian is a professional user of Additive Manufacturing since 2007. In his first affiliations he acquired extensive knowledge in Laser and Electron Beam Powder Bed Fusion for medical applications. He was responsible for the installation and qualification of AM production lines, today turning out over EUR 10 million in revenues, and supported multiple implant manufacturers, among others, setting up a qualified LB and EB-PBF production for regulated applications.

Matthias Schmidt-Lehr

Matthias successfully led multiple projects in Additive Manufacturing with focus on business case and strategic development for AM users as well as system and material supplier. With a history in management consulting he has a wide experience in business development, strategy development and communication. At AMPOWER he led multiple projects concerning DED, BJT and Metal FDM as well as a wide range of polymer AM technologies.

Dr.-Ing. Eric Wycisk

Since 2008 Eric successfully supports OEMs from aerospace, medical and automotive to identify Additive Manufacturing applications and implement production capacities in their regulated environments. With a background in topology optimization, titanium alloys and fatigue he is focused on achieving the maximum part performance with the right AM technology.

Missed out on our previous issues?

Download **AMPOWER Insights Vol. 1-6** at
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Find market numbers and technology insights in the new AMPOWER Report

The AMPOWER Report provides the most detailed and comprehensive analysis of the state of the metal AM industry and its projected growth. Additionally, the report provides a deep dive into metal Additive Manufacturing technologies. The AMPOWER Report captures the current state of the metal AM industry and additionally provides a 5-year outlook based on expectations of supplieres as well as users in this highly dynamic market environment.

Read the full report today:

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