



Prifysgol Cymru
Y Drindod Dewi Sant
University of Wales
Trinity Saint David

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Extraction, processing, and failure mechanisms of titanium and its alloys:
Causes and Avoidance of Failures and Defects with a focus on Additive
Manufacturing

Tharish Ravin Ranjit (2208284)

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Abstract

This study investigates the challenges and solutions related to the 3D printing of titanium components through the direct metal laser sintering (DMLS) process. Despite the advantages of layer-by-layer fusion of fine metal, the fatigue life of 3D-printed parts is found to be inferior to conventionally machined components due to the presence of small voids and cracks, causing stress concentrations and premature failure. Z-axis defects and overhangs are identified as major imperfections that can be prevented by implementing rigorous design, monitoring the DMLS machine, and using support structures. Additionally, the effect of crystal structure on the physical properties of 3D printed components is explored, highlighting the potential of grain structure manipulation to alter properties. In summary, further research and optimisation are required to improve the fatigue life of 3D-printed titanium components and their suitability for specialised small-batch applications.

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1. Introduction

Titanium has distinct qualities that make it appealing for various technical applications. It has a high strength-to-weight ratio, excellent corrosion resistance, good biocompatibility, and can withstand high temperatures. On the other hand, titanium has certain downsides, including high cost, limited wear resistance, and difficulty in manufacturing. As a result, titanium is frequently alloyed with other elements to increase its performance and broaden its uses (Ahmed, Sahari, Ishak, & Khidhir, 2014). An alloy is a material formed by the fusion or electro-deposition of two or more elements (metals or nonmetals). Titanium alloys have exceptional properties and are created by combining elements such as aluminium, molybdenum, niobium, vanadium, zirconium, and many others to create alloys such as Ti-6Al-4V and Ti-24Nb-4Zr-8Sn, among others (Yang, Hao, & Shujun, 2011). There are three structural types of titanium alloys: alpha, alpha-beta, and beta (AZO MATERIALS, 2004).

Alpha alloys are composed of Hexagonal Close-Packed alpha phase and have low strength but high creep resistance and thermal stability. A major class of alpha alloys is the unalloyed CP titanium family of alloys that differ by the amount of oxygen and iron in each alloy (Froes & Whittaker, 2022). They contain only neutral alloying elements or alpha stabilisers (such as aluminium, oxygen or nitrogen) and are not heat-treatable. They are suitable for applications requiring high corrosion resistance and moderate strength at temperatures up to about 550 °C (Hamweendo & Botef, 2019). Examples of alpha alloys include Ti-5Al-2Sn-ELI and Ti-8Al-1Mo-1V (Talent Titanium, 2023). Near-alpha alloys contain a small amount of bcc beta phase and have higher strength and toughness than alpha alloys. They are alloyed with 1–2% of beta stabilisers such as molybdenum, silicon, or vanadium in addition to alpha stabilisers. Heat treatment can boost their strength by precipitation, hardening the beta phase. They are appropriate for high-temperature applications requiring great strength and creep resistance. An example of a near-alpha alloy is Ti-6Al-2Sn-4Zr-2Mo (Rickard Specialty Metals, 2023).

Alpha-beta titanium alloys have high tensile strength, fatigue strength, creep resistance and good hot formability (Elahinia, Hashemi, Tabesh, & Bhaduri, 2012). The amount of beta-phase stabiliser elements such as molybdenum, silicon tungsten, tantalum, and vanadium increases the amount of beta-phase in the metal matrix (Hamweendo & Botef, 2019). Ti-6Al-4V and Ti-6Al-7Nb are two examples of alpha-beta alloys (Material Properties, 2020), with Ti-6Al-4V comprising about half of all titanium alloys produced.

Beta alloys offer the best strength and formability of any titanium alloy since they are primarily bcc beta phase. They comprise beta stabilisers (such as molybdenum, vanadium, niobium, tantalum, or chromium) and include very few alpha stabilisers or neutral elements (Bieler, Trevino, & Zeng, 2005). They can be heat treated by solution treatment and ageing or thermomechanical treatment to obtain high strength and ductility by beta precipitation hardening or the production of metastable phases such as omega or martensite. Beta titanium alloys are entirely biocompatible and have a strength to modulus of elasticity ratios nearly double those of 18–8 austenitic stainless steel (Sidambe, 2012). They are appropriate for low-temperature applications requiring excellent strength and formability. Ti-15V-3Cr-3Al-3Sn and Ti-10V-2Fe-3Al are two beta alloys (Ballor, Li, Prima, Boehlert, & Devaraj, 2022).

Titanium alloys have been widely employed in aerospace, biomedical, military, and other industries because of their exceptional qualities. These alloys find application in various fields, including aviation engine components, orthopaedic implants, armour plates, golf clubs, and mobile phones. This study examines the material failure of titanium and its alloys, along with the current issues and prospects in this sector, with a particular focus on additive manufacturing. The paper comprises five main sections: extraction, processing, fabrication, common defects with improvement methods, and conclusion. The extraction and processing of titanium and its alloys are known to be complex, and subsequent machining and fabrication require specific techniques. Despite their renowned mechanical and corrosion-resistant properties, titanium and its alloys have limitations in specific environments, and defects can be introduced during processing and fabrication. This work identifies these factors and discusses how they are addressed in practice, particularly in the context of additive manufacturing.

1.1. Aim

This scientific report aims to critically examine the causes, effects, and mechanisms of fracture, fatigue, and creep, as well as the environmental degradation of titanium and its alloys, focusing on additive manufacturing.

1.2. Objectives

- To discuss Titanium extraction and Titanium alloy processing, machining, and fabrication.
- To comprehensively examine the underlying causes and mechanisms of fracture, fatigue, and creep in titanium alloys.
- To critically analyse the effects of environmental degradation on titanium alloys and identify the fundamental mechanisms involved.
- To develop a comprehensive understanding of the factors that influence titanium alloys' behaviour under varying stress and environmental exposure conditions.

2. Extraction and Processing

This section of the report evaluates the extraction of titanium and two chemical processing methods using Sodium and Magnesium on TiCl_4 . Figure 2-1 by the Department of Metallurgical Engineering at the University of Utah and the United States Army Research Laboratory shows the thermochemical reduction routes for Ti metal production using various reductants. Their review (Zhigang, et al., 2018) details the history, current day, and future advancements in the powder metallurgy of titanium. Following the chemical-based processing, titanium powder manufacturing is discussed.

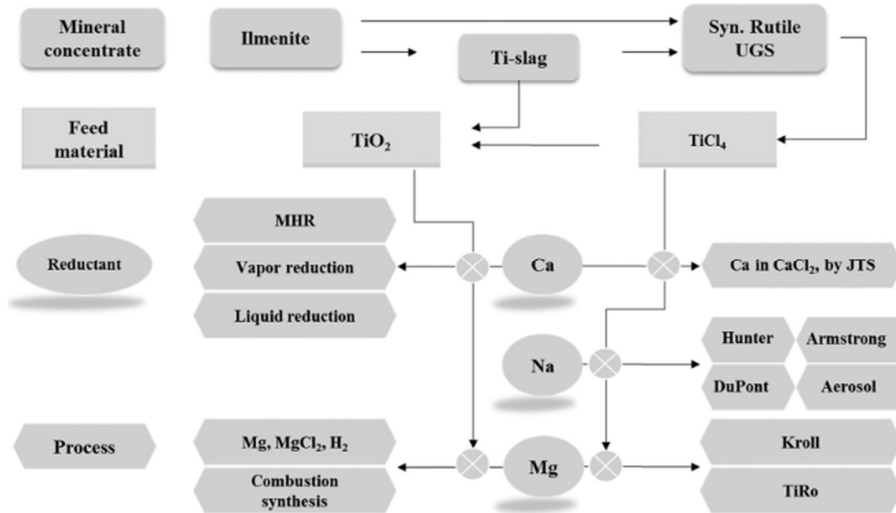


Figure 2-1: Thermochemical reduction routes for Ti metal production using various reductants (Zhigang, et al., 2018)

2.1. The Kroll Process – Mg Reductant

The Kroll process is the predominant method used to recover titanium from its ore, rutile - TiO_2 or titanium concentrates. There are two steps to the procedure. Rutile (TiO_2) is mixed with carbon and chlorine at 1273 K in the first phase to remove the oxygen from the titanium to produce titanium tetrachloride (TiCl_4). To generate titanium, TiCl_4 is reduced using either magnesium or sodium in the second stage (Seagle, 2019). These procedures are required because titanium cannot be recovered by reducing the ore using carbon as a cheap reducing agent like with iron. If heated with carbon, titanium forms a carbide, TiC , producing an unwanted, very brittle impure metal (Clark, 2020).

Due to high temperatures and reactive chemicals that might introduce impurities into the metal, this method does not yield extremely pure titanium metal. Oxygen, nitrogen, carbon, iron, and other metals are common impurities in titanium metal generated via the Kroll method. Titanium's good mechanical characteristics as a structural material are attained by closely limiting impurity levels and adding alloying elements (Advanced Refractory Metals, 2020). Certain impurities can impact characteristics such as strength, ductility, hardness, and fatigue resistance. While various research has been conducted to investigate the impact of small amounts of these impurities on the characteristics of titanium and its alloys, a thorough knowledge of their individual and combined effects are unknown (Michaud, 2021). Small amounts of oxygen reduce the ductility of titanium (Chong, et al., 2020). Nitrogen can make titanium metal brittle and prone to breaking. Due to the presence of transformed beta in the structure Ti-Fe alloys are stronger than binary titanium alloys incorporating oxygen, nitrogen, or carbon at equal hardness levels (Michaud, 2021).

2.2. Armstrong Process – Na Reductant

The Armstrong Process is a metal halide reduction process for titanium powder production, which involves the injection of titanium tetrachloride gas into a stream of liquid sodium metal, resulting in the formation of titanium metal and sodium chloride. The Armstrong process generates powder particles with distinctive features and a reduced bulk density. Post-processing treatments are used to improve the tap density and particle size distribution (Hamweendo & Botef, 2019). The process can also produce homogeneous, pre-alloyed Ti-6Al-4V powder by introducing other metal chlorides into the reaction stream (Araci, Mangabhai, & Akhtar, 2015). Figure 2-2 illustrates a scanning electron microscope image of a powder particle having a distinctive, coral-like morphology with microporosity (Wei, Yamamoto, & Peter, 2010).

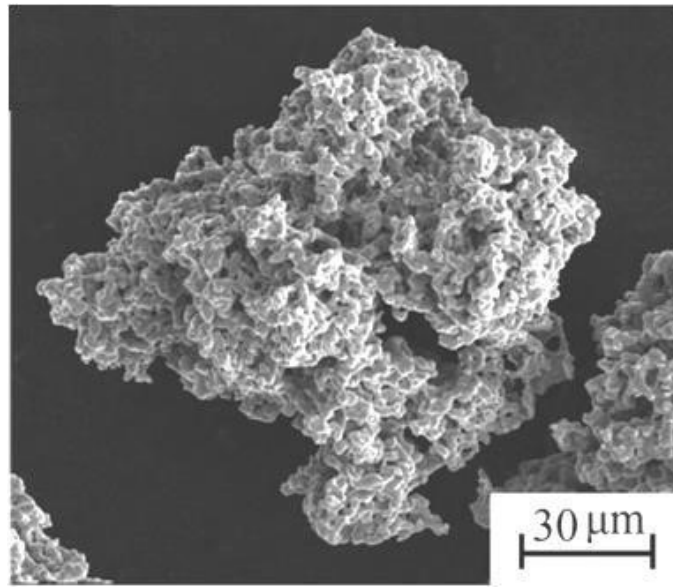


Figure 2-2: SEM micrographs of CP-Ti produced by Armstrong process (Zhigang, et al., 2018)

2.3. Processing – Spherical Ti powder

To begin the process of 3D printing parts and elements using Ti6Al4V, the alloy must first be obtained in powder form. Most commercially accessible titanium powders are manufactured from Ti sponge, Ti ingot, Ti mill products, or Ti waste metals (Zhigang, et al., 2018).

Spherical titanium (Ti) powder is in great demand for additive manufacturing (AM) processes such as selective laser or electron beam sintering. Spherical powders are also required for Ti alloy metal injection moulding (MIM). This powder has advantages such as high purity, good sphericity, low oxygen content, suitable particle size and low cost. Different methods have been developed to produce this powder from various sources of Ti metal, such as gas atomisation (GA), plasma rotating electrode process (PREP), plasma atomisation (PA), plasma spheroidization (PS) and dewetting spheroidization. Each method has strengths and weaknesses regarding sphericity, size distribution, oxygen content, production cost and process complexity. Table 2-1 compares these methods.

Table 2-1: Comparison of Powder Production Methods of Titanium Alloys for Additive Manufacturing

Method	Description	Advantages	Disadvantages	Source
Gas Atomisation (GA)	Uses inert gas to atomise molten Ti alloy into fine droplets that solidify into spherical particles	Good sphericity, narrow size distribution, easily controlled composition	Satellite balls, hollow balls, high gas consumption, high production cost	(Pei, Zhigang, Ying, & Yang, 2017)
Plasma Rotating Electrode Process (PREP)	Uses a rotating electrode that is melted by a plasma torch and ejected by centrifugal force into spherical particles	Good sphericity, easily controlled composition	Coarse particle size, low yield of a fine powder, high equipment requirements	(Jin, Dashun, Geng, Ming, & Shaolon, 2022)
Plasma Atomization (PA)	Uses a plasma torch to melt Ti alloy and atomise it into spherical particles	High sphericity, low oxygen content, narrow size distribution	High energy consumption, high production cost	(General Electric, 2023)
Plasma Spheroidization (PS)	Uses a radio frequency (RF) plasma to heat and melt commercial hydride-dehydride Ti alloy powder and form spherical particles	High sphericity, narrow size distribution, good flowability	High oxygen content, need for deoxidation using calcium	(Jing, Zhenhua, Yongchun, & Jilin, 2020)
Dewetting Spheroidization	Uses an intermediate alloy to coat Ti alloy powder and then heat it to form spherical particles by dewetting mechanism. The intermediate alloy is then removed by the dealloying process	Good sphericity, low oxygen content, low cost	Complex process, need for further purification	(Jin, Dashun, Geng, Ming, & Shaolon, 2022)

3. Fabrication – DMLS

Direct metal laser sintering (DMLS) is a widely used 3D printing technology for titanium. Figure 3-1 shows a DMLS machine, and Figure 3-2 shows a laser used to fuse/weld fine metal powder layer by layer, thereby creating a three-dimensional object.



Figure 3-1: DMLS Machine



Figure 3-2: Powder welding (AMFG, 2019)

The DMLS 3D printing process, as shown in Figure 3-3, consists of the following steps. A recoater arm first spreads a thin metal powder coating on a build platform. Then, using the 3D model data, a carbon dioxide laser scans the cross-section of the component and melts the powder. The build platform is lowered by one layer of thickness, and a fresh layer of powder is applied over the previous one. This procedure is repeated until the component is finished. Figures 3-4 and 3-5 show the machine used and the process of powder removal. Finally, the part is separated from the build surface, and support structures are cut off. Figure 3-6 from the Wales Centre for Advanced Batch Manufacture (CBM) shows a build plate post-part removal. Once removed, the part may undergo additional post-processing steps such as heat treatment, surface finishing, or polishing.

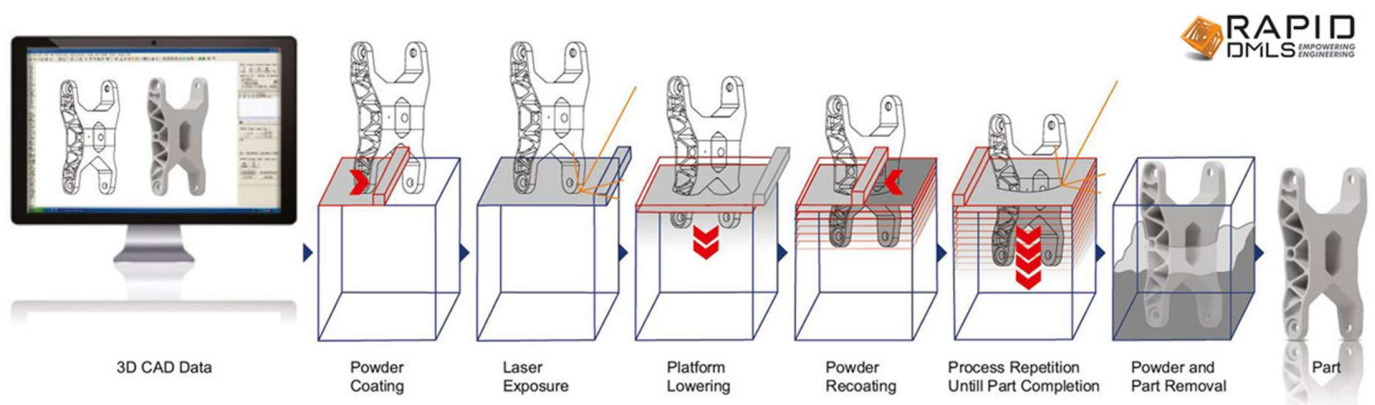


Figure 3-3: DMLS 3D printing process (RAPID DMLS, 2023)



Figure 3-4: Part cleaning machine



Figure 3-5: Part cleaning



Figure 3-6: Post part removal build plate

4. Defects and Solutions

Currently, 3D printed parts are prevented from being utilised in specialised small batch applications due to poor fatigue life. Figure 4-1 shows an SN curve comparing machined (Benedetti, Cazzolli, Fontanari, & Leoni, 2016) and 3D-printed titanium (Janecek, et al., 2015). 3D printed parts fail much soon and under less load than conventionally machined components, thus restricting the use of additively manufactured parts. This report section discusses the causes of crack growth and possible remedies for metal 3D-printed components.

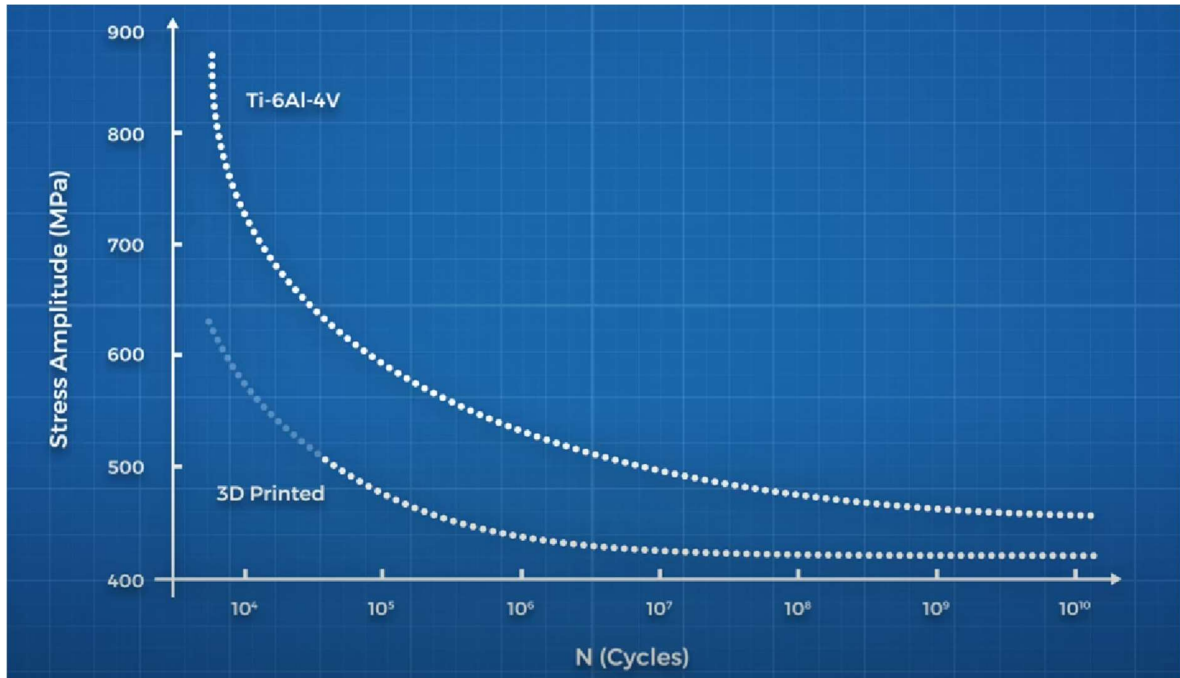


Figure 4-1: SN Curve of Machined and 3D printed Titanium (Real Engineering, 2019)

4.1. Imperfections

Small voids or imperfections cause stress concentrations, leading to high local stress and increasing crack growth. 3D printed materials tend to have many imperfections.

4.1.1. Z-Axis Defects

DMLS machines are known to be prone to Z-axis defects, which are caused by the layering process. While this technology excels at controlling fine details on the X and Y axes, the vertical movement of the layers is less refined. A rigorous design approach combined with continuous monitoring of the DMLS machine during printing might help prevent such concerns. If abnormalities are discovered, it is best to interrupt the printing process and make the required corrections (Jalili, 2022).

4.1.2. Overhangs

Printing overhangs is another source of imperfection. Figure 4-2a shows a scrapped 3D-printed component made by the Wales Centre for Advanced Batch Manufacture (CBM). Figures 4-2b and 4-2c show failed overhangs. The bridging in focus in b has broken while c has completed with major drooping noticed on both. An angled print section is shown in Figure 4-2d. The angular sections are accurately produced, while sections without support are imperfect.

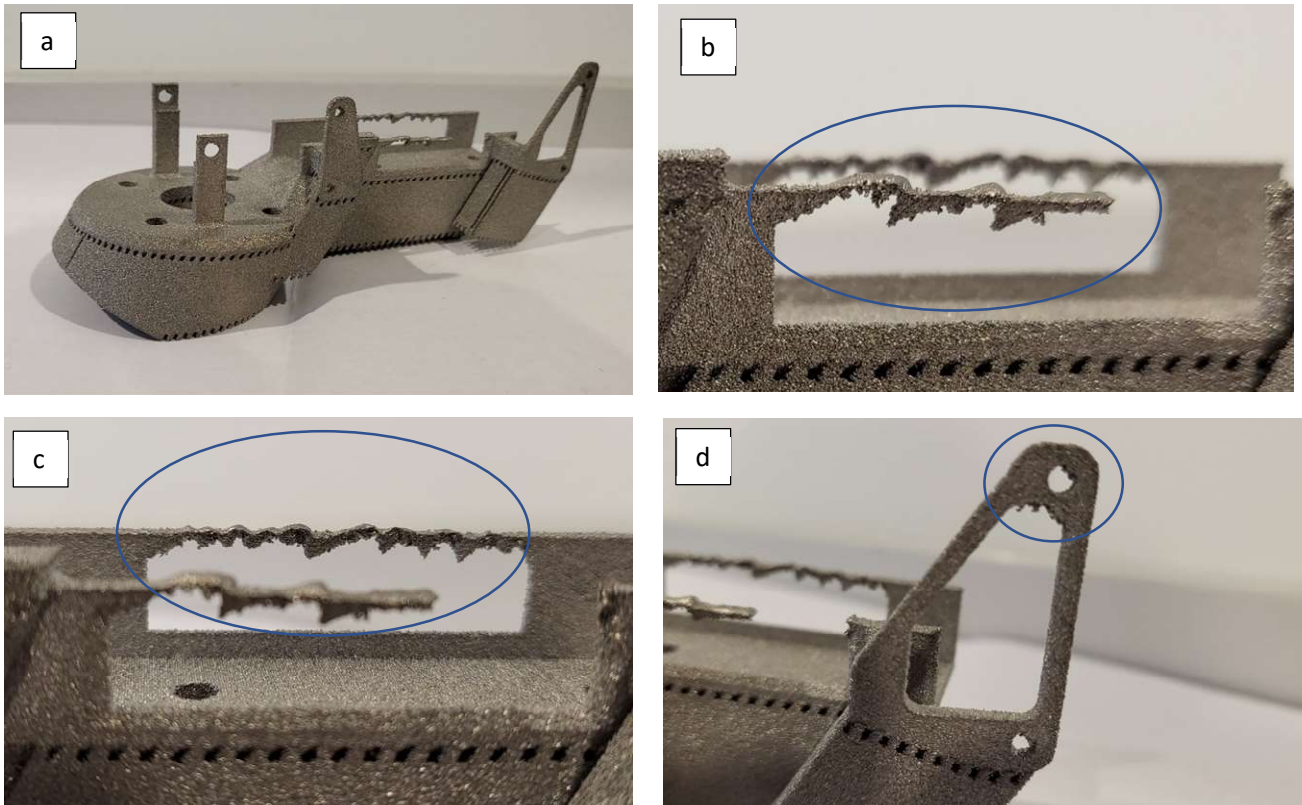


Figure 4-2: Wales Centre for Advanced Batch Manufacture (CBM) part

(Leung, Marussi, & Atwood, 2018) investigate defects and molten pool dynamics in laser additive manufacturing. High-speed synchrotron X-ray imaging revealed the underlying physical phenomena during the deposition of the first- and second-layer melt tracks. Figure 4-3 shows the first layer melt track deviating from the intended scan path as the solidified metal digs into the powder below. Impurities are highlighted within the melt track with lettering b to e. F highlights pores that formed at the end of scanning, and this would likely be a source of crack growth.

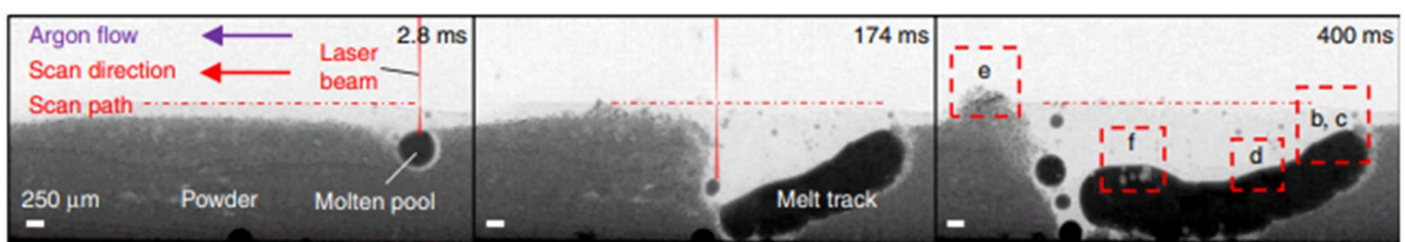


Figure 4-3: First Layer (Leung, Marussi, & Atwood, 2018)

Figure 4-4 shows the interaction of two melt tracks. Pore formation is significantly increased as gas is trapped in MT1 and the secondary molten pool. These microstructural defects and inaccuracies have led to the part defects in Figure 4-2. A method to mitigate these overhang errors is to use removable support structures. This will increase the amount of post-processing required and induce residual stresses. Hot isostatic processing closes pores and improves fatigue strength but not significantly enough to equal traditionally machined components (Antona & Mapelli, 2001). The University of Birmingham's School of Metallurgy and Materials found that closing practically all the porosity HIPing transformed the

martensitic structure into α and β phases. This resulted in decreased strength but a significant increase in ductility (Qiu, Adkins, & Attallah, 2013).

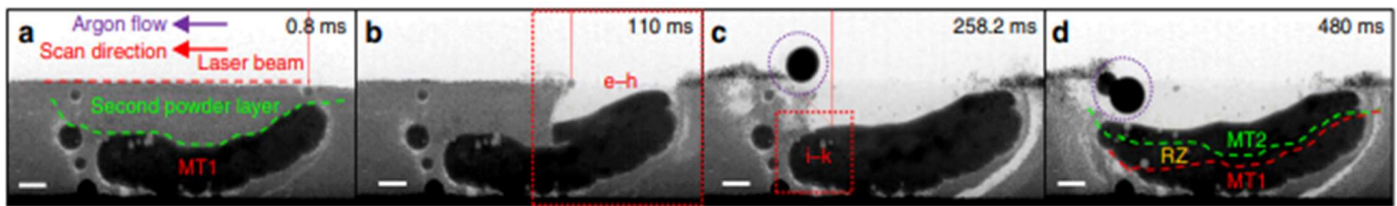


Figure 4-4: Second Layer (Leung, Marussi, & Atwood, 2018)

4.2. Crystal Structure

We have thousands of years of experience learning how production procedures impact the material qualities of the metals we employ, primarily via trial and error. Although the impact of how we heat and cool a metal on its crystal structure and characteristics are extensively documented, most of the techniques discovered do not immediately relate to additive manufacturing. This necessitates the development of unique methodologies for researching and optimising material characteristics.

3D printed materials tend to have long columnar grains that follow laser directionality, as seen in Figure 4-5 (Real Engineering, 2019). (Carter, Martin, Withers, & Attallah, 2014) claim that heat transmission away from the solidifying melt pool can be connected to the emergence of this bimodal grain structure. Via varying laser movement, the grain structure of a 3D-printed part can be manipulated, altering the physical properties of components. (Qiu, Adkins, & Attallah, 2013) noted anisotropy in ductility attributed primarily to differences in columnar grain orientation with respect to the tensile test direction.

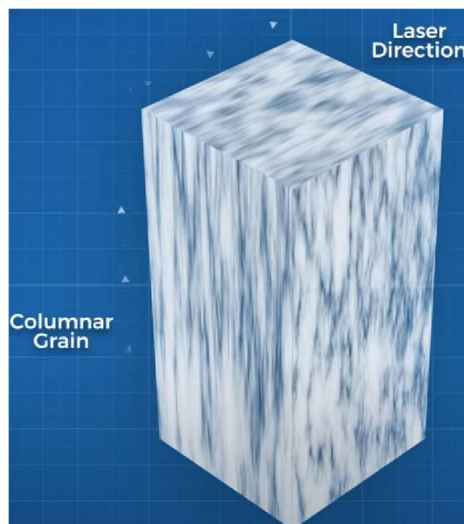


Figure 4-5: 3D Printed Grain Formation (Real Engineering, 2019)

Developed by Concept Laser, one of the most common scan strategies is the ‘islands’ scan strategy. Figure 4-6 shows the strategy; 5 mm islands are randomly scanned with islands sharing an edge perpendicular. The purpose of this method is to elevate residual stresses that result from uneven heating and cooling of the metal. (Carter, Martin, Withers, & Attallah,

2014) found that the island strategy produced fine grain boundaries between each island, illustrated in Figure 4-7, that had a high density of cracks.

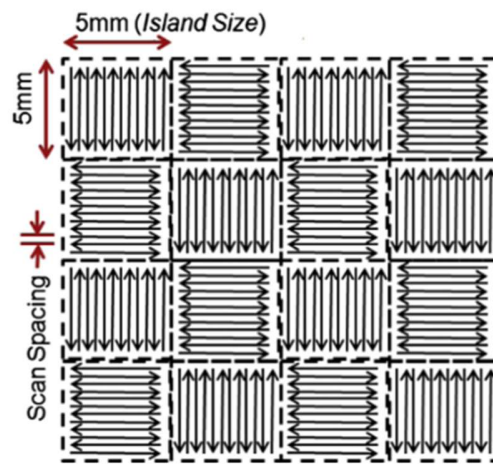


Figure 4-6: Island Scan Strategy (Carter, Martin, Withers, & Attallah, 2014)

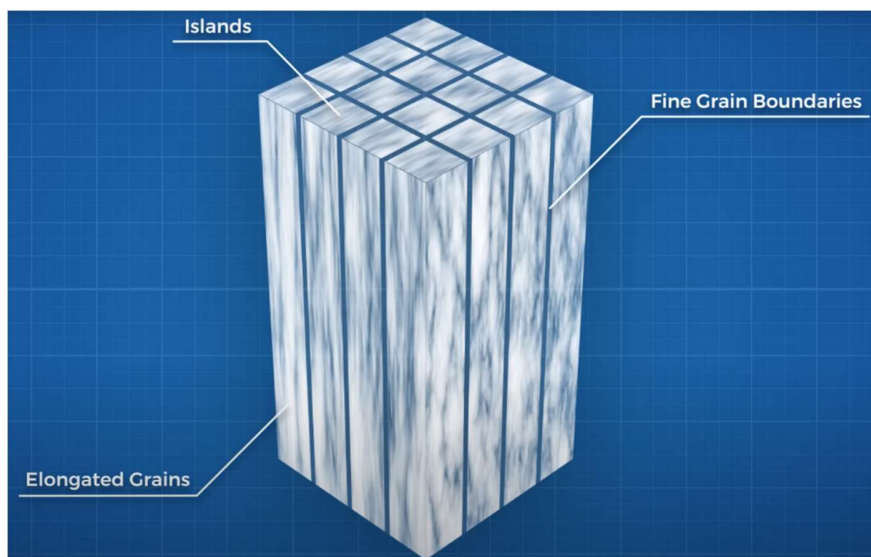


Figure 4-7: Illustration of island scan strategy grain structure (Real Engineering, 2019)

Researchers from Stellenbosch University in South Africa discuss the effects of various laser scan strategies on the deviation of hybrid parts (parts manufactured by SLM and milling). By using a modified helical scan strategy, known to reduce deformation and elevate residual stresses (Nickel, Barnett, & Prinz, 2001), warping and porosity were reduced (Hagedorn-Hansen, Bezuidenhout, Dimitrov, & Oosthuizen, 2017). Future research will investigate using machine learning and thermal cameras within the build chamber to optimise material characteristics (Real Engineering, 2019).

5. Conclusion

Despite the exceptional material property of titanium and its alloys, it has limitations. Many of these limitations are induced by the extraction, processing, machining, and fabrication of titanium-based parts. These processes induce defects that limit the application of titanium parts. This report focused on the additive manufacturing of titanium. Direct Metal Laser Sintering (DMLS) is a promising technology for 3D printing metal parts, mainly titanium, due to its ability to create highly precise complex geometries. However, some challenges associated with the technology must be addressed, particularly regarding the poor fatigue life of 3D printed components compared to conventionally machined components.

Defects in the 3D printed components, such as small voids or imperfections, can cause stress concentrations and increase crack growth. Z-axis defects and overhangs are two types of imperfections that are commonly observed in DMLS printed components. Rigorous design approaches, continuous monitoring of the printing process, and using removable supports can help prevent these concerns.

The crystal structure is another factor that affects the physical properties of 3D-printed metal parts. The long columnar grains that follow laser directionality in 3D printed parts can be manipulated by varying the laser movement, altering the physical properties of components. Research on optimising material characteristics and developing new methodologies for investigating the impact of production procedures on the crystal structure of metals is ongoing.

Further research and development are necessary to address the challenges associated with DMLS 3D printing technology, particularly regarding improving the fatigue life of 3D printed components. Nevertheless, the potential benefits of this technology, including the ability to create complex geometries and reduce material waste, make it a promising area for continued investigation and advancement.

6. References

- Janecek, M., Novy, F., Habcuba, P., Strasky, J., Trsko, L., Mhaede, M., & Wagner, L. (2015). *ACTA PHYSICA POLONICA A*, 497-502.
- Advanced Refractory Metals. (2020, April 22). *Physical Properties Of Titanium*. Retrieved from Refractory Metals and Alloys.
- Ahmed, M. Y., Sahari, K. S., Ishak, M., & Khidhir, B. A. (2014). Titanium and its Alloy. *Titanium and its Alloy*, 1351-1361.
- AMFG. (2019, June 18). *A Guide to 3D Printing With Titanium*. Retrieved from AMFG: <https://amfg.ai/2019/06/18/titanium-3d-printing-guide/>
- Antona, P. L., & Mapelli, C. (2001). Hot Isostatic Pressing (HIP): The State of the Art & Improvement on Two Steels. *Metallurgical Science and Technology* 19, 3-7.
- Araci, K., Mangabhai, D., & Akhtar, K. (2015). 9 - Production of titanium by the Armstrong Process. *Titanium Powder Metallurgy*, 149-162. Retrieved from <https://www.sciencedirect.com/science/article/pii/B9780128000540000095>
- AZO MATERIALS. (2004, August 17). *Titanium Alloys - Characterstics of Alpha, Alpha Beta and Beta Titanium Alloys*. Retrieved from AZO MATERIALS: <https://www.azom.com/article.aspx?ArticleID=2591>
- Ballor, J., Li, T., Prima, F., Boehlert, C. J., & Devaraj, A. (2022). A review of the metastable omega phase in beta titanium alloys: the phase transformation mechanisms and its effect on mechanical properties. *International Materials Reviews*, 26-45.
- Benedetti, M., Cazzolli, M., Fontanari, V., & Leoni, M. (2016). Fatigue limit of Ti6Al4V alloy produced by Selective Laser Sintering. *Procedia Structural Integrity*, 3158-3157.
- Bieler, T. R., Trevino, R. M., & Zeng, L. (2005). *Encyclopedia of Condensed Matter Physics*. (F. Bassani, Ed.) Michigan: Elsevier. Retrieved from <https://www.sciencedirect.com/science/article/pii/B0123694019005362>
- Carter, L. N., Martin, C., Withers, P. J., & Attallah, M. M. (2014). The influence of the laser scan strategy on grain structure and cracking behaviour in SLM powder-bed fabricated nickel superalloy. *Journal of Alloys and Compounds*, 338-347.
- Chong, Y., Poschmann, M., Zhang, R., Zhao, S., Hooshmand, M. S., Rothchild, E., . . . Minor, A. M. (2020). Mechanistic basis of oxygen sensitivity in titanium. *Science Advances*, 6. doi:10.1126/sciadv.abc4060
- Clark, J. (2020, August 22). *Chemistry of Titanium*. Retrieved from LibreTexts Chemistry: [https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Supplemental_Modules_and_Websites_\(Inorganic_Chemistry\)/Descriptive_Chemistry/Elements_Organized_by_Block/3_d-Block_Elements/Group_04%3A_Transition_Metals/Chemistry_of_Titanium](https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Supplemental_Modules_and_Websites_(Inorganic_Chemistry)/Descriptive_Chemistry/Elements_Organized_by_Block/3_d-Block_Elements/Group_04%3A_Transition_Metals/Chemistry_of_Titanium)
- Elahinia, M., Hashemi, M., Tabesh, M., & Bhaduri, S. (2012). Manufacturing and processing of NiTi implants: A review. *Progress in Materials Science*, 911-946.
- Froes, F. H., & Whittaker, M. (2022). Encyclopedia of Materials: Metals and Alloys α -Alloys. In *Encyclopedia of Materials: Metals and Alloys*.
- General Electric. (2023). *TITANIUM Ti-6Al-4V grade 5*. Retrieved from AP&C a GE Additive company: <https://www.advancedpowders.com/powders/titanium/ti-6al-4v-5>

- Hagedorn-Hansen, D., Bezuidenhout, M., Dimitrov, D., & Oosthuizen, G. (2017). THE EFFECTS OF SELECTIVE LASER MELTING SCAN STRATEGIES ON DEVIATION OF HYBRID PARTS. *South African Journal of Industrial Engineering*, 200-212.
- Hamweendo, A., & Botef, I. (2019, August 24). *Modern Production Methods for Titanium Alloys: A Review*. Retrieved from IntechOpen: <https://www.intechopen.com/chapters/68769>
- Jalili, A. (2022, February 05). *3D Printing Titanium, the Ultimate Guide*. Retrieved from The Additive Manufacturing: <https://theadditivemanufacturing.com/3d-printing-titanium-the-ultimate-guide/>
- Jin, Q., Dashun, D., Geng, W., Ming, S., & Shaolon, T. (2022). A method for the preparation of spherical titanium powder for additive manufacturing. *Powder Technology*, 411. Retrieved from <https://doi.org/10.1016/j.powtec.2022.117927>.
- Jing, L., Zhenhua, H., Yongchun, S., & Jilin, H. (2020). Fabrication of spherical Ti–6Al–4V powder for additive manufacturing by radio frequency plasma spheroidization and deoxidation using calcium. *Journal of Materials Research and Technology*, 9(6), 14792-14798. Retrieved from <https://www.sciencedirect.com/science/article/pii/S223878542031913X>
- Leung, C. L., Marussi, S., & Atwood, R. C. (2018). In situ X-ray imaging of defect and molten pool dynamics in laser additive manufacturing. *Nat Commun* 9,, 1355. Retrieved from <https://doi.org/10.1038/s41467-018-03734-7>
- Material Properties. (2020, November 16). *What are Titanium Alpha-Beta Alloys - Definition*. Retrieved from Material Properties: <https://material-properties.org/what-are-titanium-alpha-beta-alloys-definition/>
- Michaud, D. (2021, April 7). *How Impurities Affect Titanium Properties*. Retrieved from Metallurgist & Mineral Processing Engineer: <https://www.911metallurgist.com/how-impurities-affect-titanium-properties/>
- Nickel, A., Barnett, D., & Prinz, F. (2001). Thermal stresses and deposition patterns in layered. *Mater. Sci. Eng. A* 317(1–2), 59-64.
- Pei, S., Zhigang, Z. F., Ying, Z., & Yang, X. (2017). Review of the Methods for Production of Spherical Ti and Ti Alloy Powder. *The Journal of The Minerals, Metals & Materials Society*, 1853–1860. Retrieved from <https://doi.org/10.1007/s11837-017-2513-5>
- Qiu, C., Adkins, N. J., & Attallah, M. M. (2013). Microstructure and tensile properties of selectively laser-melted and of HIPed laser-melted Ti–6Al–4V. *Materials Science & Engineering A*, 230 - 239.
- RAPID DMLS. (2023). *Metal 3D Printing*. Retrieved from RAPID DMLS: <https://www.rapiddmls.com/metal-3d-printing/>
- Real Engineering. (2019, October 26). *The Material Science of Metal 3D Printing*. Retrieved from Youtube: <https://www.youtube.com/watch?v=fzBRYsiyxjI&t=762s>
- Rickard Specialty Metals. (2023). *TI-6AL-2SN-4ZR-2MO TITANIUM ALLOY*. Retrieved from Rickard Specialty Metals: <https://rickardmetals.com/products/titanium-alloy/ti-6al-2sn-4zr-2mo-titanium-alloy/>
- Seagle, S. R. (2019, May 17). *titanium processing*. Retrieved from Encyclopedia Britannica: <https://www.britannica.com/technology/titanium-processing>
- Sidambe, A. (2012). Biocompatibility of advanced manufactured titanium implants a review. *Materials*, 8168-8188.
- Talent Titanium. (2023). *TNTI*. Retrieved from Guide to Titanium: <https://www.tntitanium.com/titanium-grades.html>
- Tshephe, T. S. (2022). Additive manufacturing of titanium-based alloys- A review of methods. *Heliyon*, e09041. Retrieved from <https://doi.org/10.1016/j.heliyon.2022.e09041>

- Wei, C., Yamamoto, Y., & Peter, W. H. (2010). Investigation of pressing and sintering processes of CP-Ti powder made by Armstrong process. *Key Eng Mater*, 123-130.
- Yang, R., Hao, Y., & Shujun, L. (2011). Yang, R., Hao, Y., & Li, S. (2011). Development and Application of Low-Modulus Biomedical Titanium Alloy Ti2448. *Biomedical Engineering, Trends in Matertial Science*, 225-248.
- Zhigang, Z. F., Paramore, J. D., Sun, P., Chandran, K. R., Zhang, Y., Xia, Y., . . . Free, M. (2018). Powder metallurgy of titanium – past, present, and future. *International Materials Reviews*, 407-459.
doi:10.1080/09506608.2017.1366003