Summer Internship Report

Data Collection for Additively Manufactured Ti-6Al-4V Specimens

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1 Ti-6Al-4V

1.1 Description

Ti-6Al-4V, commonly known as Ti64, is an alpha-beta titanium alloy with high specific strength and excellent corrosion resistance. It is one of the most commonly used titanium alloys and is applied in a wide range of applications where low density and excellent corrosion resistance are necessary.

1.2 Composition

It is made up of 6% aluminum (Al) and 4% vanadium (V), along with about 0.25% iron and 0.2% oxygen, with the remainder being titanium (Ti).Aluminum(Al) is an alpha-stabiliser whereas Vanadium(V) is a beta-stabiliser. Ti-6Al-4V titanium alloy commonly exists in alpha with hcp crystal structure and beta with bcc crystal structure.

1.3 Important Properties

- High Corrosion Resistance
- High Tensile Strength
- Biocompatibility
- Low Density
- Non-Magnetic
- High-heat Resistance

1.4 Applications

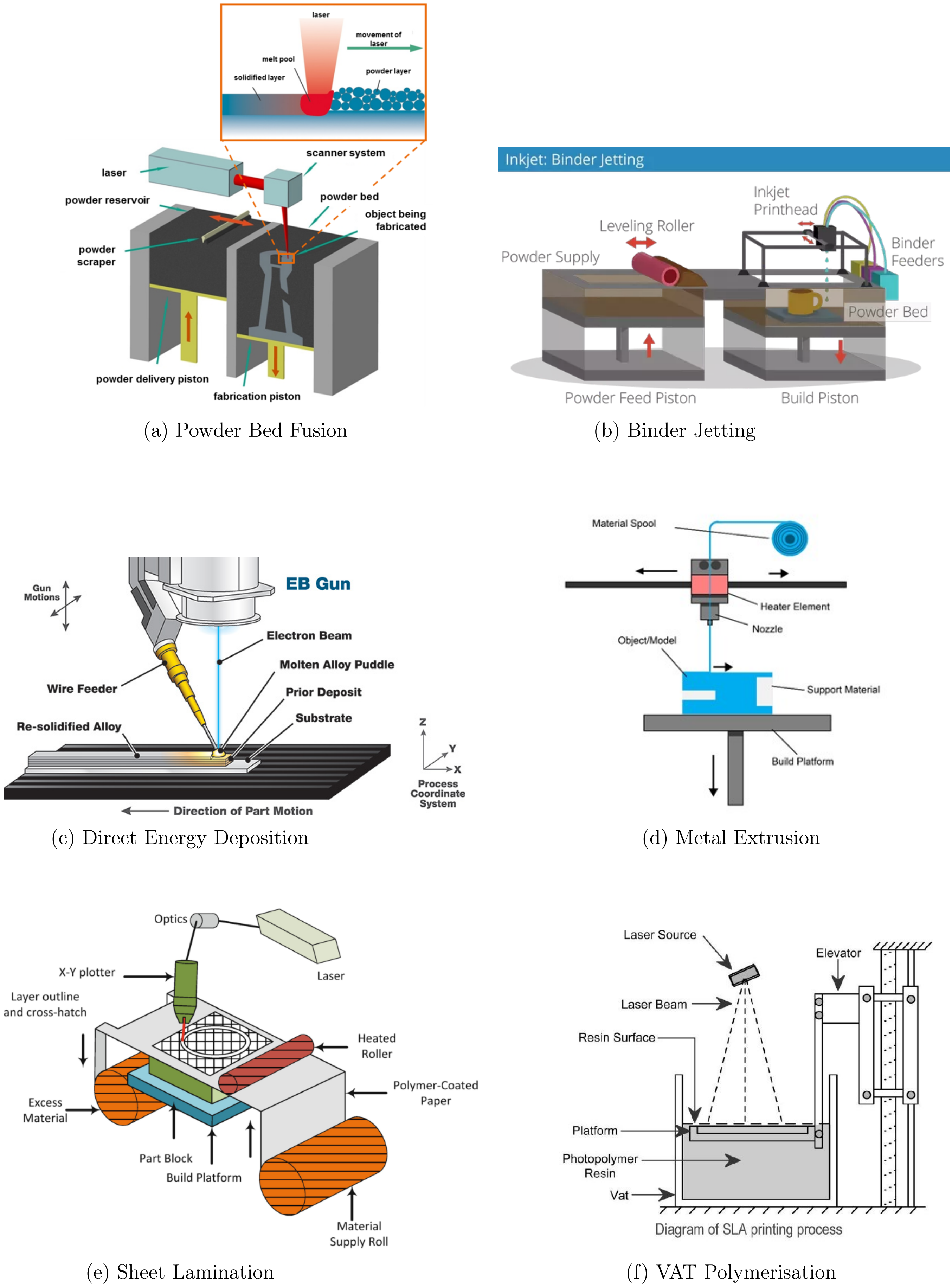
- Aerospace Industry
- Military Equipments
- Biomedical Implants
- Automobile Industry
- Marine Application
- Chemical Industry

2 Additive Manufacturing

Additive manufacturing uses Computer-Aided-Design (CAD) software or 3D object scanners to direct hardware to deposit material, layer upon layer, in precise geometric shapes. As its name implies, additive manufacturing adds material to create an object. By contrast, when we create an object by traditional means, it is often necessary to remove material through milling, machining, carving, shaping or other means.

There are different varieties of Additive Manufacturing:

- **Powder Bed Fusion(PBF):** In PBF, a powdered material is selectively fused using thermal energy, typically in the form of a laser or electron beam, layer by layer on a powder bed
- **Binder Jetting:** The binder jetting process uses two materials; a powder-based material and a binder. The binder acts as an adhesive between powder layers. The binder is usually in liquid form and the build material in powder form. A print head moves horizontally along the x and y axes of the machine and deposits alternating layers of the build material and the binding material. After each layer, the object being printed is lowered on its build platform
- **Direct Energy Deposition(DED):** DED employs laser or electron beam as an energy source to melt and direct the powder/wire and deposit it directly on CAD controlled path on substrate
- **Material Extrusion:** Material is drawn through a nozzle, where it is heated and is then deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited.
- **Sheet Lamination:** Sheet lamination is an additive manufacturing (AM) methodology where thin sheets of material (usually supplied via a system of feed rollers) are bonded together layer-by-layer to form a single piece that is cut into a 3D object.
- **VAT Polymerisation:** Vat polymerisation uses a vat of liquid photopolymer resin, out of which the model is constructed layer by layer. An ultraviolet (UV) light is used to cure or harden the resin where required, whilst a platform moves the object being made downwards after each new layer is cured.



(a) Powder Bed Fusion

(b) Binder Jetting

(c) Direct Energy Deposition

(d) Metal Extrusion

(e) Sheet Lamination

(f) VAT Polymerisation

Figure 1: Different varieties of AM.

3 Data Collection

After going through more than 50 research papers, I collected approximately 250 datasets. Among them, approximately 120 datasets had Microstructure Images available with them, which will be used for the Computational purposes later on.

3.1 Parameters

Following are the paramters that I came across while collecting the data:

- Machine Parameters
  1. Preheating Temperature
  2. Maximum Beam Power
  3. Beam Spot Size
  4. Scan Speed
  5. Layer Thickness
- Post-Processing Parameters
  1. Type of Treatment
  2. Temperature
  3. Time
- Fatigue Test Parameters
  1. Max Stress
  2. R-ratio
  3. Roughness
  4. Test Frequency
  5. Stress Concentration Factor
  6. Stress Amplitude
  7. Fatigue Life

3.2 Sample Dataset

- *Yellow Colored Samples:* These are the specimens whose **Microstructures were available.**
- *White Colored Samples:* These are the specimens whose **Microstructures were not available.**

1	Material	Process	Preheating (°C)	Maximum Beam Power(W)	Beam Spot (µm)	Scan Speed (m/s)	Layer Thicknes s(µm)	Treatment	Temperature (in °C)	Time (in h)	Max Stress(MPa)	R-ratio	Roughness (µm)	Test Frequency (Hz)	Stress Concentration Factor	Stress Amplitude (MPa)	Mean Fatigue Life(cycles)	Microstructure/Surface Morphology/Fracture Surface Image(ID)	Reference
2	Ti-6Al-4V	SLM						As-built	-	-	1080	-1		40		600	2.7X10^4	102-Microstructure	https://www.researchgate.net
3	Ti-6Al-4V	SLM						Heat Treatme	800	2	1040	-1		40		600	9.3X10^4	103-Microstructure	https://www.researchgate.net
4	Ti-6Al-4V	SLM						Heat Treatme	1050	2	945	-1		40		600	2.9X10^5	104-Microstructure	https://www.researchgate.net
5	Ti-6Al-4V	SLM						HIP	920	2	1005	-1		40		600	2X10^6	105-Microstructure	https://www.researchgate.net
6																			
7	Ti-6Al-4V	SLM		200		0.2	50	Machined(X-	-	-	240	-0.2	10.5		1		1.98448X10^8	106(a)-Micrstructure 106	https://www.sciencedirect.cor
8	Ti-6Al-4V	SLM		200		0.2	50	Machined(Y-	-	-	170	-0.2	10.5		1		1.97780X10^8	106(a)-Micrstructure 107	https://www.sciencedirect.cor
9	Ti-6Al-4V	SLM		200		0.2	50	Machined(Z-	-	-	100	-0.2	10.5		1		1.94080X10^8	106(a)-Micrstructure 108	https://www.sciencedirect.cor
10	Ti-6Al-4V	SLM		200		0.2	50	As-built(X-dir	-	-		-0.2	194.1		1			106(a)-Micrstructure 109	https://www.sciencedirect.cor
11	Ti-6Al-4V	SLM		200		0.2	50	As-built(Y-dir	-	-		-0.2	187.7		1			106(a)-Micrstructure 110	https://www.sciencedirect.cor
12	Ti-6Al-4V	SLM		200		0.2	50	As-built(Z-dir	-	-		-0.2	220.3		1			106(a)-Micrstructure 111	https://www.sciencedirect.cor
13																			

Figure 2: Data Collected

*Sample Microstructure and Fracture Surface Images of a specimen is presented below. (**Note:** The Microstructure image is taken before the fatigue test.)*

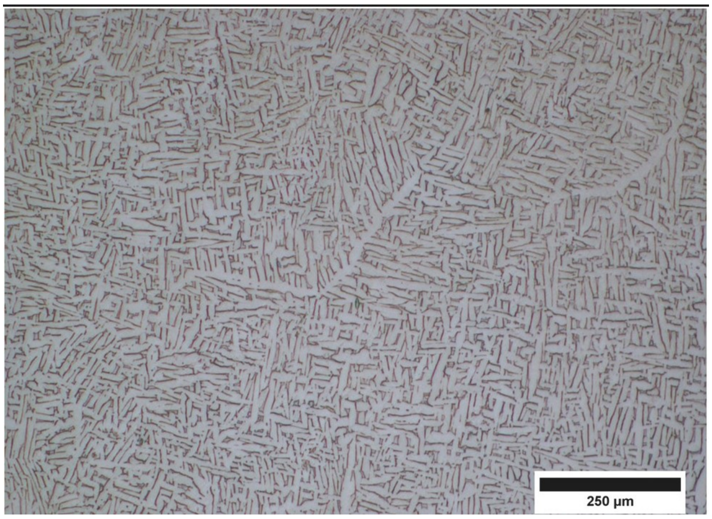


Figure 3: Microstructure

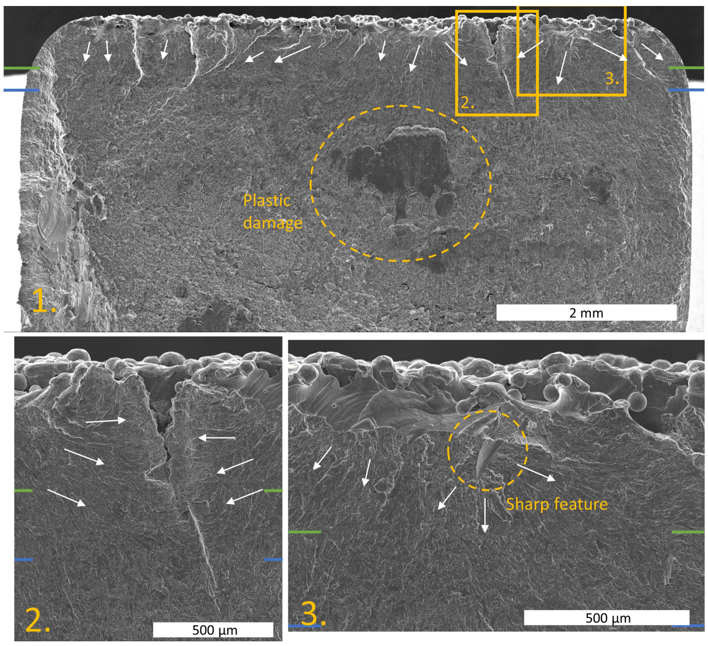


Figure 4: Fracture Surface

4 Learning Outcomes

Finally, after going through so many research papers, I concluded the following points:

- **General Dependence**
  - *High tensile residual stresses, surface roughness, microstructure and porosity* are expected to be the key contributors to the low fatigue strength of the additively manufactured Ti64 specimens.
  - The microstructure of Ti64 can exist in different forms such as bi-modal, equiaxed, lamellar α and β, and martensitic α' structures. All these microstructures can result in different fatigue properties.
  - The effect of *build orientation* on fatigue performance is significant.
  - *Grain size* and *ductility* also have a relatively small effect on the fatigue behavior.
- **Effect of different AM processes**
  - The thermal conditions of DED and SLM processes result in α' martensitic microstructure and high tensile stresses while the high build temperature involved in the EBM process leads to an $\alpha + \beta$ lamellar microstructure free from residual stresses.
  - α' martensites in DED and SLM manufactured Ti64 are responsible for the lower crack thresholds but higher fatigue limits as compared to EBM, wrought, forged and heat treated Ti6Al4V.
  - Relatively thick layers in EBM cause the "stairstep effect" and larger particle size powders adhering to the surface lead to higher surface roughness. Thus the fatigue life of EBM Ti64 is lower than SLM or DED-manufactured Ti64.
  - SLM-produced Ti64 samples have higher tensile strength than EBM-produced samples. Whereas EBM-produced samples have higher ductility.
- **Different types of defects**
  - One of the internal defects found in EB-PBF is *Lack-of-Fusion (LOF)* type defects. LOF defects are created due to the failure of the molten metal to fuse with the previously built layer. This can happen due to local under-melting or melt pool dynamic effects.
  - The influence of *pores* on the fatigue strength is significantly larger than the influence of the microstructure.

- *Stress concentrations* at defects significantly reduce the fatigue strength.
- Under tension–compression crack initiation shows less influence on fatigue life compared to tension–tension loading.
- Pores within the samples have a drastic effect on the fatigue behaviour of Ti64 in the *High Cycle Frequency*(HCF) regime. A significant extension of the crack initiation phase can be achieved only by reducing the porosity. This leads to a significant improvement of fatigue strength, which can match the values reported for conventionally processed Ti64.

- **Different Techniques for increasing fatigue life**
  - *HIP treatment* on samples not only reduced *porosity* but also significantly decreased *residual stresses*. The amount of β -Ti was increased slightly as compared to the as-built material due to the Temperature-Time-Profile of the *HIP* process.
  - The main influencing factor on crack growth behaviour is *residual stress*.
  - Some research deduced that improving the *surface condition* was far more important than closing internal defects for enhancing the fatigue performance of additively manufactured Ti64.
  - *Peening*, which is another post-processing technique, induces compressive surface residual stresses which enhance fatigue performance.
  - Other post-processing techniques like *Milling, Electropolishing, Chemical Etching, Blasting and Machining* can also increase the fatigue life of Ti64 to a good extent.

END OF THE REPORT