METAL ADDITIVE MANUFACTURING OF BLENDED ELEMENTAL Ti-6Al-4V POWDERS

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ABSTRACT

South Africa primarily produces titanium raw material as a TiO_2 rich slag of which most is exported, without further value addition to the mineral. Therefore, powder development becomes a significant aspect of research with possibilities of growth within the titanium metal industry in South Africa. Commercially pure titanium has been successfully blended in conventional powder metallurgy processing, but the use of blended elemental powder to produce Ti-6Al-4V powder for metal additive manufacturing alloy parts has not been demonstrated yet. The objective of this study is to determine the feasibility of using blended elemental Ti-6Al-4V powder for use in a powder bed additive manufacturing (AM) system. In this paper a literature review and proposed methodology are presented and the expected outcomes are discussed.

1. INTRODUCTION

South Africa is the second largest producer of titanium raw material in the world. However, the country primarily produces titanium raw material as a TiO_2 rich slag without further value addition to the mineral. In recent years researchers at the CSIR has developed a technology to directly produce commercially pure (CP) Ti powder from $TiCl_4$ as feedstock. Therefore, titanium metal powder development and application is a significant aspect of research with potential impact on growth of the titanium industry in South Africa.

CP Ti has been successfully blended with Al and V to produce Ti-6Al-4V in conventional powder metallurgy processing and in additive manufacturing processes, such as the laser solid forming (LSF) and laser engineered net-shaping (LENS) [1,2,3], but the use of blended elemental powder in powder bed fusion (PBF) processes to produce Ti-6Al-4V powder for metal additive manufacturing (MAM) alloy parts, has not been demonstrated yet. Consequently, a study was launched to determine the feasibility of using blended elemental Ti, Al and V powders for use in a selective laser melting (SLM) system. Since experimental results were not available by the time of publication, this paper focuses only on the literature review, proposed methodology and expected outcomes.

2. ADDITIVE MANUFACTURING

2.1 Selective laser melting

SLM technology is an additive manufacturing (AM) technique which is applied to build objects layer-by-layer from 3D CAD model, instead of removing material through subtractive methods such as machining. The essential operation in selective laser melting is the laser beam scanning over the surface of a thin powder layer previously deposited on a substrate to fuse powder particles together. The forming process proceeds along the scanning direction of the laser beam. Each cross-section (layer) of the part is sequentially filled with elongated lines (tracks) of molten powder. One of the variations of the SLM technology is known as Direct Metal Laser Sintering (DMLS) [4].

SLM has already had positive impact on manufacturing industries such as aerospace, medical implants and devices, automotive, sports equipment, marine applications and more. Complex parts, small and light components with complex geometric features such as hollows, thin walls and undercuts, are now possible to be made with SLM [4]. In Figure 1 a pelvic implant of a 15 year old cancer patient that was made through the SLM process is shown.

SLM uses materials such as aluminium, stainless steel, titanium and more. DMLS allows for multiple components such as fasteners and mountings to be made at once. This reduces waste of time and resources.

Figure 1: Pelvic implant of a 15 year old cancer patient [5]

2.2 The direct metal laser sintering process

The DMLS process is shown schematically in Figure 2. The DMLS process starts by drafting the desired component in a three-dimensional CAD file. Subsequently the three dimensional CAD component is sliced into two-dimensional layers [6].

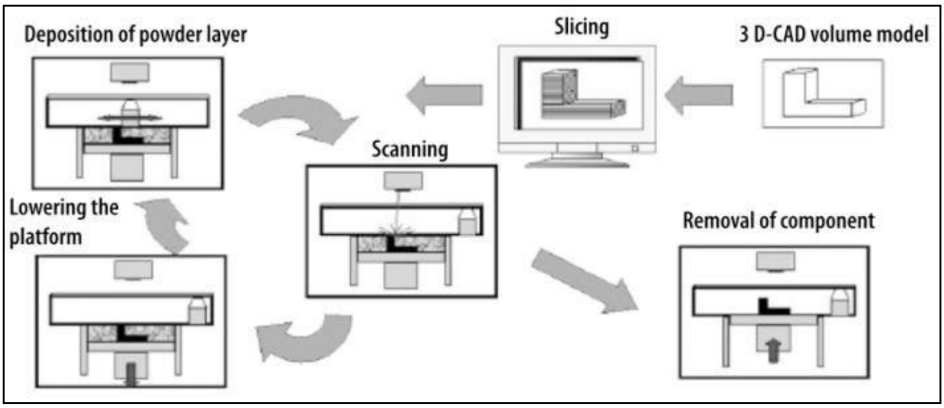

Figure 2: Illustration of the DMLS process [7].

A substrate is placed on the platform of the DMLS machine and a thin layer of powder is applied on top of the substrate by a wiper blade. The laser then scans across the powder layer and it fuses the powder at the exact points identified by the CAD file on the computer for that specific layer. The substrate is lowered once the layer is solidified and the next layer is built on top of the previous layer. This process is repeated until the last layer of the component is completed. The platform moves up to lift the three-dimensional part out of the powder bed. Once the part is out, the excess powder is brushed into the used powder container.

The substrate with the part still attached to it is heat treated to relieve residual stresses. Subsequently, the supports on angled sections or overhangs and other areas that attach the part to the substrate are broken off or machined off. Some surfaces of the part can be machined to improve surface finish and the part can be heat treated to improve strength.

Characteristics of the produced DMLS object such as porosity, microstructure and mechanical properties are influenced by the parameters selected for the DMLS process. Parameters such as layer thickness, as well as powder particle size and shape, are important for deposition of the powder layer. Laser power and temperature, spot size, scanning speed of the laser and the deposition time, determine the effectiveness and success of the process and the quality of the part produced. The DMLS parameters can be categorised into three different sections [4].

Machine based input parameters

- Laser: Wavelength, spot size, power density and beam profile;
- Atmosphere: airflow, ionising energy;
- Substrate: roughness, chemical composition and temperature.

Material based input parameters

- Chemical Composition;
- Optical Properties;
- Physical properties (particle size, powder morphology, density);
- Mechanical properties.

Process input parameters

- Laser power;
- Scanning speed;
- Powder layer thickness;
- Design and build strategy – scanning strategy, supports and orientation.

2.2.1 Machine based input parameters

A DMLS machine has three main areas of interest when considering machine based input parameters: the laser or heat source, the atmosphere in which the process takes place and the substrate or base on which the objects are manufactured. Absorption of the energy from the laser beam causes the powder particles to melt. These molten particles form the molten pool. The wavelength directly affects the percentage radiation absorbed and depends on the specific material. Laser spot size, mode and beam intensity profile define input energy density. The build atmosphere and material of the substrate also influence the quality of parts produced by DMLS. Materials such as Ti-6Al-4V need to be produced in an argon atmosphere to eliminate the formation of oxides. The formation of oxides negatively affects the mechanical properties of the produced DMLS parts [4].

2.2.2 Material based input parameters

Powder properties directly influence the deposition of powder onto the substrate and the formation of the molten pool. The distribution of powder is primarily affected by properties such as powder size and morphology of powder particles [6]. Particle shape or powder morphology refers to the shape of the individual powder particles. The shape of powder particles determines how the particles position themselves or pack together. A powder with spherical particles has a higher random packing density than more irregular shaped particles.

In the DMLS process particle shape is an important factor in creating an optimal layer thickness for fully dense objects. Spherical particles are preferred for the DMLS process as they flow easily to form a homogenous powder layer and have higher packing density, which is beneficial for molten pool formation. Particle shape also has an influence on powder layer formation and the absorptivity of the powder bed. The larger the absorptivity the more energy from the laser beam will be absorbed by the powder bed.

Particle shape and particle size distribution also affects powder flowability. Powder flowability is the ability of powder to flow in a desired manner in a specific piece of equipment. It is important to have good powder flowability when depositing a thin powder layer, because it ensure a layer with consistent thickness. Powder particle size and size distribution have a major influence on the flowability and quality of manufactured parts. Powder with particle size in the range of (0.1-5μm) tends to agglomerate in clusters and prevent uniform recoating during AM, while larger particles in the range of (90-120μm) reduce the maximum layer packing density [8]. A mixture of small and large particle sizes was recommended by German and Park [9], since such particle sizes would permit the smaller particles to percolate through the larger particles and suitably fill the voids to achieve higher parking density. But if the fine powder particle size is ≤5μm, the agglomeration effect of fine particles would nullify their positive effect of filling up the voids between larger particles [8].

Inaccurate selection of powder particle size can cause in situ segregation due to the mechanical re-coater pushing coarser particles away from the bed, which would result in production of exceptionally heterogeneous parts. Generally, fine powders with wide powder particle size distribution produce parts with higher fractional density [10]. Liu et al. investigated the effect of powder particle size on the mechanical properties of as-built DMLS samples and found that metallic powders with higher particle size distribution have higher flowability and ultimate tensile strength [11]. An optimal powder layer thickness has to be selected for employed powders. When considering the particle size, the maximum diameter of the particles should be less than the laser spot size [4].

2.2.3 Process input parameters

Low scanning speed tends to form distortions and irregularities while excessively high scanning speed tends to form drops (balling effect). High scanning speed promotes low cooling rates and therefore results in a coarser microstructure. Higher laser power and slower scanning speed promote the formation of finer microstructures [9]. Close control of the amount of heat in the melt pool is required. High temperatures in the melt pool can lead to oxidation. Oxygen is detrimental to the ductility of Ti-6Al-4V through forming an interstitial solid solution with titanium at high temperatures [11]. The stability of the single track formation is not only dependent on the laser power, scanning speed and layer thickness but also the substrate material, physical properties and morphology of the material

The difference in heat expansion rates of the different metals causes internal stresses to develop in the intermetallic zone. Metals with different melting points, using the same heat source will mean that the metal with the lower melting point will be molten before the other metal gets molten. One metal melts first and causes uneven heat flow and non-uniform dilution in the molten pool. When the melt pool solidifies the metal with a higher melting point is already solid at the time the metal with the lower melting point is still partially liquid or it is still in a mushy state [12].

The difference in thermal conductivity produces different heating and cooling rates. The metal with higher conductivity will tend to draw heat away from the melt pool. Differences in conductivity may result in uneven heat flow and prevent complete fusion of the low conductivity metal. Uneven flow affects solidification and can lead to distortions. The difference in melting points will cause the metal with the lower melting point to separate out in the course of cooling and solidification, and increases the risk of crack formation in the low melting point metal. One way to reduce this effect is to use high energy density, high heating and cooling rates [12].

3. Ti-6Al-4V

Ti-6Al-4V is the most widely used titanium alloy. It is an alpha-beta alloy containing 6 wt% Al and 4 wt% V and is known for its high mechanical strength to weight ratio, outstanding corrosion resistant properties and biocompatibility. This alloy is widely used in a range of industries which require high levels of reliable performance. It is used in industries such as aerospace, automotive, chemical plant, power generation, oil and gas extraction, sports and medical applications. Table 1 shows the physical properties of wrought titanium, aluminium, and vanadium.

Table 1. Physical properties of wrought titanium, aluminium, and vanadium [13]

Property	Titanium	Aluminium	Vanadium
Melting point(˚C)	1668	660	1910
Thermal Expansion (µm/m.K) @ 25 ˚C	8.6	23.1	8.4
Thermal Conductivity (m.K)	21.9	237	30.7

From Table 1 it can be seen that the melting point of Al is much lower than the other two metals V and Ti, and that will have an impact on the process of alloying of the powder. The behaviour during the cooling and heating of these three different elemental metal powders with their different thermal expansion and thermal conductivity properties will also play a role during the SLM process.

3.1 Microstructural differences of Ti-6Al-4V fabricated through different processes

Figure 3 shows the microstructures of Electron Beam Melting (EBM), Selective Laser Melting (SLM), wrought and cast specimens of Ti-6Al-4V.

The EBM microstructure has a coarse grain structure with prominent acicular α plates and dark or black β-phase areas separating the α-phase grains. The SLM microstructure shows a mix of α-phase and α-martensite with some twinning in the α-phase. This fabrication method produces more rapid cooling than EBM and results in transformation to α-martensite. The SLM, EBM and wrought specimens all have much finer α-β lamellar structures than the lamellar structure in the cast specimen [13].

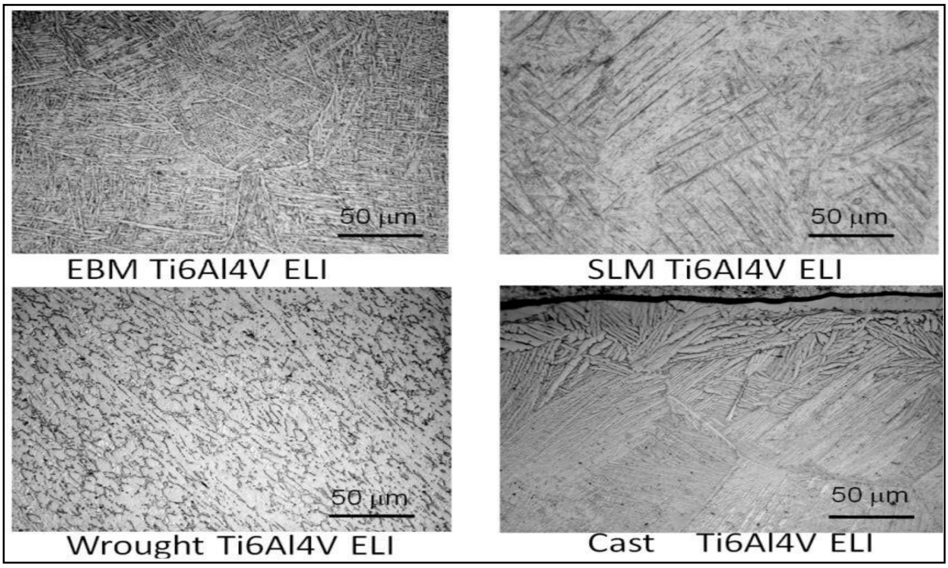

Figure 3: Typical microstructure of (a) an EBM specimen; (b) an SLM specimen; (c) a wrought specimen and (d) a cast Ti-6Al-4V (ELI) specimen [13].

4.THERMODYNAMIC ENTHALPY OF MIXING

The thermodynamic enthalpy of mixing is expected to significantly influence the powder mixing process and the homogeneity of the alloy [14]. The mixing enthalpy of an alloy can be negative or it can be positive. A negative mixing enthalpy results in an exothermic reaction, whereby additional heat is supplied to the melt pool during the mixing of the elemental powders, aiding in homogenization of the resulting deposit. A positive enthalpy of mixing results in an endothermic reaction, whereby heat is extracted from the melt pool, making mixing and homogenization of the powder more difficult. The mixing enthalpy of Ti-6Al-4V is calculated to be –11.35 kJ/mol [14] and therefore a homogeneous microstructure and rapid solidification is expected.

The crystal growth direction is strongly affected by the direction of the heat flow. Since the intermixing of Ti-6Al-4V in the molten pool is exothermic, it is appropriate to consider that the liberated heat may lead to changes of the heat flow direction in the local area ahead of the solid/liquid interface [15]. When the next layer is built, the disturbance of the heat flow can interrupt the epitaxial growth of the columnar grains along the building direction and promote nucleation and growth of the new grains ahead of the solid/liquid interface, thus resulting in the formation of irregular equiaxed grains at low laser powers.

An increase in laser power weakens the relative effect of the heat disturbance and beta Ti columnar grains are formed and grow epitaxially. It is also inferred that increasing the laser power further will cause the grain morphologies to change from columnar grains to equiaxed grains again and this calls for critical control of the laser power at high temperatures [15].

In SLM, where the laser beam scans over the surface of a thin powder layer previously deposited on a substrate, the enthalpy of mixing and the direction of the heat flow is expected to have a similar impact as that observed for the laser solid forming (LSF) process [15].

5. OPTIMIZING PROCESS PARAMETERS TO IMPROVE MATERIAL PROPERTIES

To achieve high mechanical strength and adequate fatigue behaviour, it is important to produce high density parts with optimal surface quality and to minimize defects through the optimization of process parameters. In this way a working window is obtained with a defined set of parameters where parts with high densities and low roughness are guaranteed [6].

In laser processes, the energy density, E, is a key factor: sufficient energy density is needed to melt powder particles of the layer being processed and of the previous layer to assure a complete joining between successive layers and to avoid lack of fusion and porosity, while excessive energy can cause evaporation of the material, thus creating defects and reducing material density.

To optimize parameters, it is common practice to manufacture simple geometries like cubes maintaining constant power and varying the scanning speed in each cube, for a given layer thickness and hatch spacing [6]. Thus, each cube is manufactured with different energy density. Subsequently, the cubes are characterized by determining interior density, sub-surface density and roughness, so as to identify the right energy density window and corresponding parameters.

6. METHODOLOGY

The approach and methodology proposed for this study is presented by the flow diagram in Figure 4.

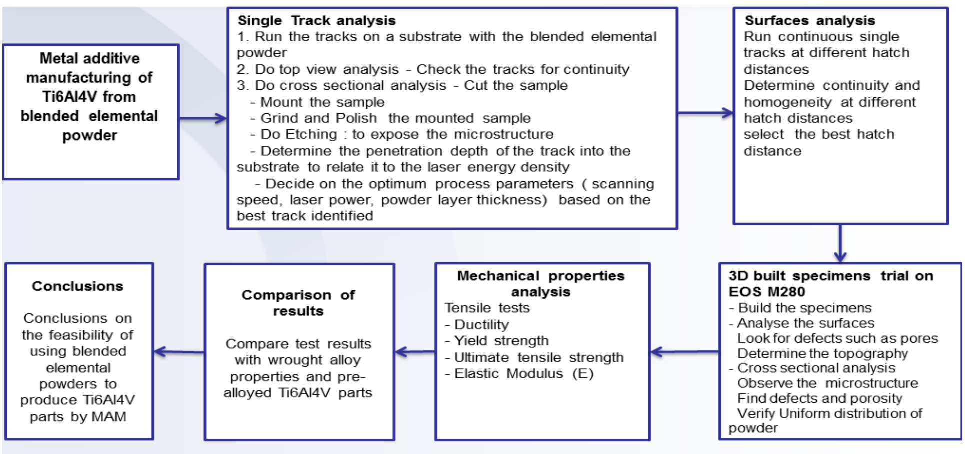

Figure 4: Flow diagram of the methodology adopted in this study

The first step will be to run single tracks on a substrate, using the blended elemental powder. From the single tracks the continuity of the tracks, the penetration depth of the track into the substrate to relate it to the laser energy density, and the microstructure of the tracks will be analyzed. This analysis will support decision making on selecting the optimum process parameters (scanning speed, laser power, powder layer thickness) based on the best track characteristics identified.

Once the optimum process parameters have been selected, continuous single tracks at different hatch distances will be built and surface analysis will be done to determine the continuity and homogeneity of the tracks for the different hatch distances. This will allow selection of the best hatch distance.

3D specimens will then be built on the EOS M280 DMLS machine. The surfaces and microstructures of the specimens will be analyzed, defects such as pores will be identified and the uniform distribution of the powder will be verified. Once that has been done successfully, the specimens will undergo tensile tests to determine the mechanical properties of the material.

The mechanical property results will be compared to the properties of the wrought alloy and pre-alloyed Ti-6Al-4V parts built through AM. Based on the outcome of the comparison, conclusions will be drawn regarding the feasibility of using blended elemental powders to produce Ti-6Al-4V parts by MAM.

7. CONCLUSION

From the literature and the characteristics of the SLM process it is anticipated that there is a real possibility of successfully blending elemental powders of appropriate particle size distribution to be used as feedstock for SLM processes that could produce Ti-6Al-4V parts with compositions and microstructures approaching those of parts built from pre-alloyed powders.

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