Value Chain of the Spheroidisation of Metal with particular emphasis on Titanium: A literature Review

Tsepo.M. Dube[1*]; Andre F van der Merwe[2]; Stephen Matope[3]& Hertzog Bissett[4]

[*1] Department of Industrial Engineering, University of Stellenbosch, South Africa,tseposmdubes@gmai.com

[2] Department of Industrial Engineering, University of Stellenbosch, South Africa,andrevdm@sun.ac.za

[3] Department of Industrial Engineering, University of Stellenbosch, South Africa,smatope@sun.ac.za

[4] Research and Development, South African Nuclear Energy Corporation, South Africa, hertzog.bissett@necsa.co.za

ABSTRACT

Titanium is an abundant resource on earth and the issue with extracting it from the ground is that the processes are expensive. For additive manufacturing Titanium powder needs to be reused and one of the processes of reconditioning of titanium powder is spheroidizing. The review also included understanding how value chain analysis has been conducted in South Africa in the past five years for bench marking purposes. The literature review analyses how far research has gone in terms of value chain analysis for spheroidisation process. Similar research papers have been analyzed from the past for bench marking purposes.

Keywords
Spheroidizing, Metal powder and Additive manufacturing

1 INTRODUCTION

Titanium is an abundant resource, but the issue is that the processing of the metal is expensive, especially in the additive manufacturing industry. Titanium has a high strength to weight ratio and is suited for aircraft and automotive industry however it is costly to extract from the ground and must be used with caution. For additive manufacturing, titanium powder needs to be reused, and one process of reconditioning of titanium powder is plasma spheroidisation. Reconditioning titanium minimizes the need to extract titanium thus reducing costs and saves the environment. The paper reviews various techniques used to obtained spherical powders and evaluate how they contribute to the value chain of additive manufacturing. Literature available covers the value chain from extraction of titanium to the printing of the titanium product. Studies that focus on the technique used to obtain spherical titanium powder needs to be done as it can improve the value chain of additive manufacturing and currently literature is limited on spheroidisation value chain studies. The review highlighted the various powder treatment techniques reviewed their strengths and weaknesses through a systematic review. The study also seeks to identify the gaps in spheroidisation that can help in the development of the spheroidisation process.

Literature available covers the value chain from extraction to the final titanium product. There is need to cover the research gaps in the spheroidisation of the Ti6Al4V and a literature review will help identify the gaps. Since there are few publications that focus on spheroidisation of titanium, the research was broadened to covered spheroidisation of other materials as there would be little data to analyze and evaluate. Similar research needs to be studied to give build a bases in which the research can start. A systematic literature review was done to identify the extent to which the value chain analysis of the spheroidisation of Ti6Al4V was done. It was discovered that the value chain analysis for spheroidisation for has not been done extensively.

2 Methodology

Purpose of the research

1. Identify the trends in terms of Titanium powder recycling worldwide.
2. Find out how much ground has been covered in the value chain of Ti6Al4V powder production and identify the gaps.
3. Find out how much ground has been covered in the value chain of the spheroidisation of Ti6Al4V powder.

The first stage of the research was to select the database for the research. Scopus was selected for the study because of its availability and has a wide range of journals and materials. Scopus was also selected because of the time frame available for the research and location from which the research was conducted SCOPUS was the viable option. The search was mainly a document search, searching within topics, abstracts and keywords.

The next stage was to identify key words for the titanium value chain topic. The search terms used were "Titanium" OR "Titanium Powder" AND "value chain". Upon discovering that a similar research was done by (Roux, van der Lingen and Botha, 2019), the search was further refined to include "spheroidisation" or "spheroidise" with the intent to find out the extent to which spheroidisation has advanced worldwide. The research is based on titanium thus the search was refined to include "Titanium" OR "Titanium Powder" with the purpose of finding out the trends in titanium spheroidisation. Few articles were found that include titanium spheroidisation. The research identified gaps in spheroidisation of titanium powder and discovered that there was little done on value chain analysis of the spheroidisation of this metal. A further search was done but this time limiting the search South Africa and from 2016 to 2020 to find out how South Africa performs value chain analysis has been performed in South Africa. The research was split into three. The reason was to find out the trends in similar research areas before narrowing down to titanium.

Table 1: Search Terms and Topics

Topic	Search term	Filters	Number of Hits	Relevant Papers
Titanium Value Chain	"Titanium" OR "Titanium Powder" AND "value chain"	None	17	3
Spheroidisation	Spheroidisation OR Spheroidizing	2016 - 2021	145	45
Titanium Spheroidisation	"spheroidisation" or "spheroidise" AND Powder	None	15	7

Table 1 shows the search results from Scopus together with their filters.

2.1.1 Value Chain Analysis

In many production processes there are multiple activities that take place in order to produce a product and get the product to the final user (Rawlins, De Lange and Fraser, 2018). The value adding activities are the activities that are necessary to produce the product. The process of identifying and categorizing these activities is termed the value chain analysis (Popescu and Brasov, 2015).

2.2 Brief Review for titanium

For the search term “Titanium” OR “Titanium Powder” AND “value chain”. From the initial search it was discovered that the value chain was done for titanium metal from a South African perspective by. For additive manufacturing much of the research is focused on the value chain at the end product and from extraction of titanium. From the 17 papers from the first search only six are closely related to the research. Two of the papers talk about the complete value chain from extraction from the ground to the processing of the metal powder. Four of the papers talk about the value chain in the additive manufacturing industry. (Wilkinson, 2007), has covered the value chain of powder production. From the data one of the papers extensively talk about the manufacturing of additive manufacturing powder or spheroidisation. Since the value chain of titanium was covered, a further search was done to find out how far the value chain of spheroidisation of titanium has been done.

2.3 Trends in Spheroidisation

There are various methods to attain spheroidisation. Most of the spheroidisation search results yielded unrelated topics which include spheroidisation of solid metal during heat treatment which were not relevant for the research (Abosbaia *et al.*, 2011). The search terms had to be refined to be ((spheroidisation OR spheroidise) AND powder) in order to get an over view of the literature available for spheroidisation. Over the last decade additive manufacturing has been commercialized especially for metals. The need to reuse powder is apparent as most powders are expensive to produce and reusing them after processing makes economic sense. After multiple cycles in selective laser sintering the metal powder loses its desired qualities and will need to be reconditioned. Figure 1 shows the publication trends for metal powder spheroidisation and from the graphite also shows increase in research for spheroidisation over the past ten years. For titanium the search was further refined to find out how much of the work is titanium based and the search yielded 145 results, but 45 where chosen to be analyzed. The other 100 publications mentioned spheroidisation in passing and were not related to the research directly.

From Figure 2, China had the highest number of publications of which related to spheroidisation with 17 publications. The studies in China include radio frequency induction and pulsed electron beam irradiation. The studies in China also dominated in the past five years. Russian Federation has 16 publications relevant to spheroidisation of metals. The United States of America has a total of 5 publications directly related to spheroidisation. In South Africa spheroidisation is a fairly new technology and a lot of work is currently being done to improve the process. Necsa is leading in the research in terms of spheroidisation.

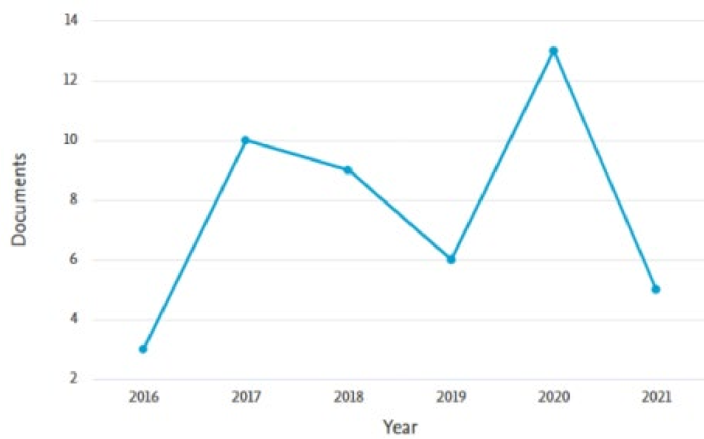

Figure 1: Publications by Year for Spheroidisation

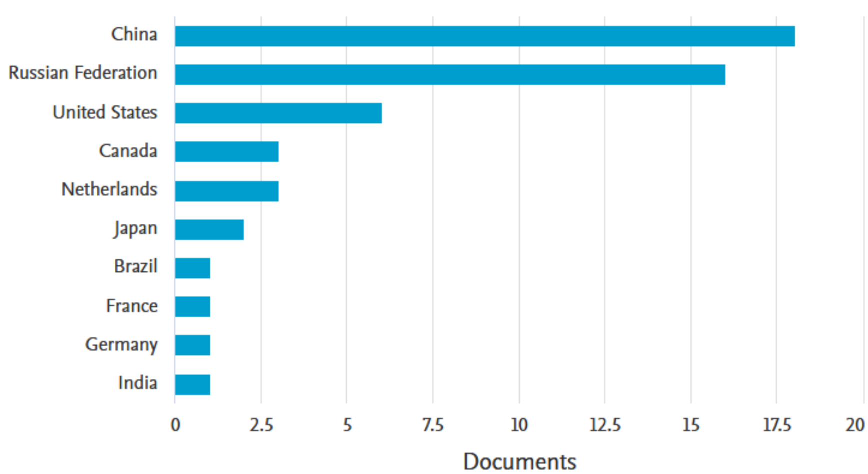

Figure 2: Spheroidisation trends by country

Table 2: Publications by journals

Journal	Number Of Publications
Materials Today Proceedings	3
International Journal Of Refractory Metals And Hard Materials	2
Material Design	2
Materials Letters	2
Tsvetnye Metally	2

From Table 2 the Material Today Proceedings have published the most journals with regards to spheroidisation. International Journal of refractory metal and hard materials, Material Design, Materials Letters and Tsvetnye Metally has the highest publications, but the publications are still few with regards to spheroidisation. Thirty-five other journals have one publication each showing that there is still a need to explore spheroidisation.

2.4 Spheroidisation Methods

For additive manufacturing the desired metal particles need to be spherical in shape (Ahmed *et al.*, 2020). The spherical particle will give the powder high density and flowability which is a desired quality for additive manufacturing metal (Hao *et al.*, 2019). The metal will also need to have minimum oxygen, hydrogen and nitrogen content. These impurities will then cause the titanium to be brittle and hard which can result in cracks. These impurities are a result of exposure to air during selective laser melting and atomization process. Spheroidisation can help in bringing irregular shaped particle to spherical shapes. Reducing the impurities is also another aim of spheroidisation (Murray *et al.*, 2019). Spheroidisation takes place in plasma which can be generated in various ways. From the literature review TEKNA is one of the dominating specialists in plasma generation. Plasma is a partially ionized gas, containing ions, electrons, atoms and molecules. The temperature of thermal plasma is usually above 10,000K. They are generated at atmospheric pressure or under soft vacuum conditions. An inert atmosphere is provided and in some cases oxidizing atmosphere depending on the material processed. Direct Current arcs and high frequency induction plasma discharges are examples of the thermal plasma that are available.

2.4.1 Radio Frequency induction Plasma Spheroidisation

In order to generate an induction plasma electrical energy is passed through discharge medium through a magnetic coupling. When a radio frequency current is passed through a coil and oscillating magnetic field is generated which will then be coupled to a partially ionized gas flowing within discharge cavity as shown in Figure 3. This will generate ohmic heating which will sustain the induction plasma (Tong *et al.*, 2015).

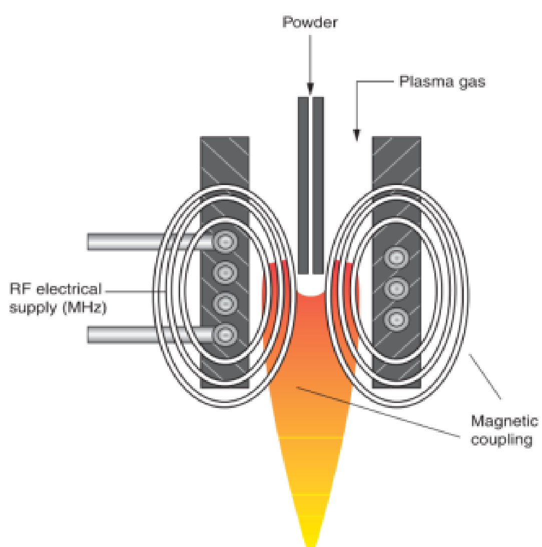

Figure 3: Radio Frequency Plasma Spheroidisation Process (Kolaric, Hubrich and Addinall, 2017)

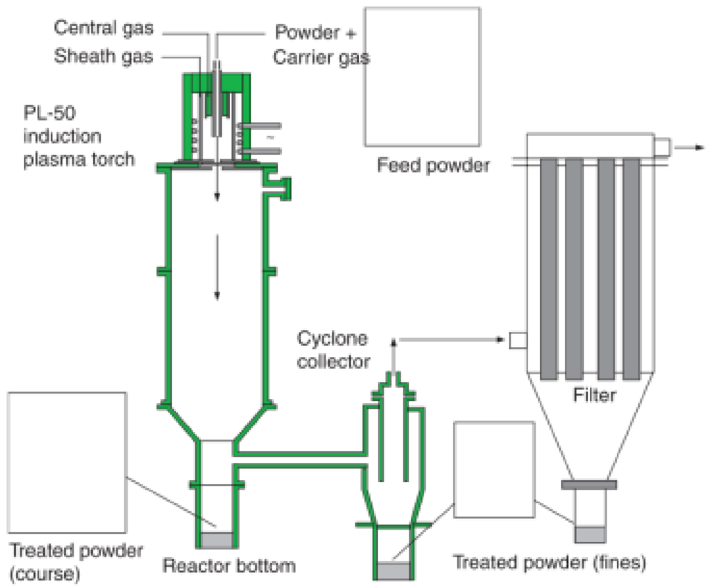

Figure 4: Process Flow Diagram for Radio frequency (Kolaric, Hubrich and Addinall, 2017)

Figure 4 shows the spheroidisation process flow. One the purposes of the plasma are to provide a flexible environment. This environment will provide for chemical synthesis and can either be reducing, oxidizing or inert atmosphere. The individual particles are heated and melted before being fed into the plasma. The droplets become spherical and are cooled under free fall. The fall is controlled depending on the material, powder density and particle size to ensure that the particles have sufficient time to solidify before reaching the base of the primary chamber (Boulos, 2004). The powders in plasma gas are recovered by cyclone or filter arrangements downstream the primary reactor. Conduction and convection are the primary heat methods that occur from the plasma to the particle surface. Heat is lost through radiation from the particle surface to the vapor cloud around. Heating of the metal particle with higher melting temperatures becomes difficult for larger particle size and diameters (Zi *et al.*, 2018).

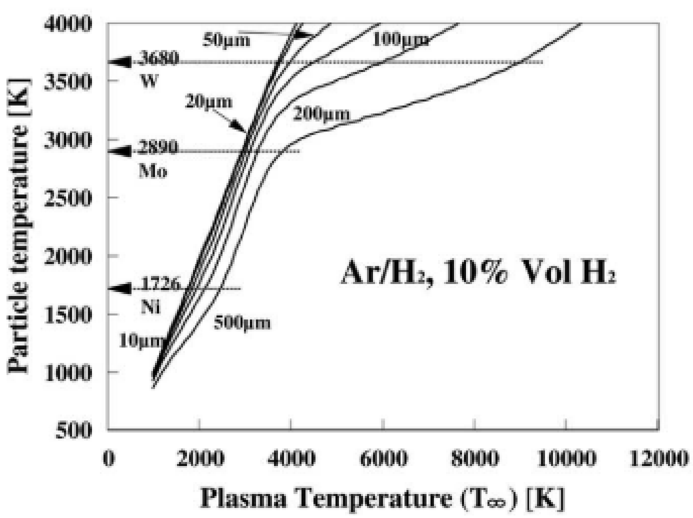

Figure 5: Equilibrium particle temperatures as a function of material, size and the plasma temperature, at 1 atmosphere pressure of Ar/H_2 plasma, with additional 10% vol concentration of H_2 (Kolaric, Hubrich and Addinall, 2017)

Figure 5 shows plasma temperatures needed for melting particles of various melting point and various particle diameters based on energy balance between conductive heat transfer between the plasma and particle surface and energy loss through radiation. The calculations that the graph is based on assumes a mixture of hydrogen and argon maintained at atmospheric pressure. For refractory materials the plasma temperature must be significantly greater than the temperature of the material for in-flight melting to take place (Boulos, 2004). At Necsa the process is used to reshape used titanium powder by re-melting the irregular shaped powders at high temperatures through thermal plasma at 3000K to 10000K then quenching them rapidly at (approx. 106 K/s). Direct current (DC) arc plasma torches and radio frequency (RF) inductively coupled discharges are typically used for the spheroidisation process. RF induction is the preferred method for the spheroidisation process. There is lower possibility of contamination during the RF induction process due to the longer residence times in the plasma. The contamination is caused by the electrode erosion which is low in RF induction (Bissett and Walt, 2017).

2.4.2 Pulsed electron beam irradiation

A magnetic field is produced by a solenoid, of which a pulsed voltage of 5 kV is applied to the anode and Penning discharge is initiated. The Penning discharge will reach a current of 150-170 A after 50µs. A plasma column is then formed near the anode. An accelerating voltage of 40 kV is applied to the cathode after delay time of 10-30µs. The concentration of the electric field will reach 400 kV/cm causing an explosive emission (Murray *et al.*, 2019). Dense plasma clouds appear and emit electrons. The electrons are accelerated and a beam is formed through the applied voltage concentrated in a double layer between the cathode plasma and the anode plasma. The beam is transmitted through the anode plasma to a collector cathode. The energy is uniform and the pulse time typically 3µs. The powder exposed to the irradiation becomes spherically shaped.

2.4.3 Microwave plasma reactor

Microwave plasmas are an alternative that can spheroidise powders and studies have been carried out on iron in South Africa. The two main approaches of generating plasmas are:

- Applying microwave radiation to an electrode to produce an electric field and perpendicular magnetic field. These fields will generate a capacitive-coupled microwave plasma at the tip of the electrode (Williams *et al.*, 2019).
- Or applying microwave radiation into a resonant structure filled with a neutral gas. The energy from the standing wave is transferred to the gas and the electric field and magnetic field to produce and sustain the plasma (Niedzielski *et al.*, 2015; Williams *et al.*, 2019).

The microwave generator typically operates at 2.45GH to produce a wave that will travel through a cable. The wave is focused by tuning systems which sits in the centers of the cavity. A gas flows through the outer portion of the torch and the plasma is produces by Telsa coil. Typically, a 2.45 GHz microwave generator (magnetron) produces a wave that travels through a cable and is focused via a tuning system where a torch sits in the centre of a cavity (Laar *et al.*, 2015). This torch has a carrier gas flowing through the outer portion of the torch (sometimes tangentially, other times not) and the plasma is started (or ignited) via a Tesla coil or a piece of copper wire. Analyte is introduced into the centre of the plasma by a nebulizer or ETV system.

- The torches that can be used are
- Beennakker cavity,
- microwave plasma torch,
- And the capacitively coupled microwave plasma.

The carrier gas is air, nitrogen, helium and argon. Helium and argon are easiest to ionize. South Africa company NECSA has also done work using Microwave plasma on iron and silicon carbide in argon and highlighted that there is more work to be done though it shows great potential for use in industrial applications (Van Laar *et al.*, 2016; (Laar *et al.*, 2015).At the moment the process still needs further development and is still under research.

2.4.4 Plasma rotating electrode process

Another method to produce spherical powder is using plasma rotating electrode process where a plasma arc melts the end of a rotating metal rod in a confined chamber (Chen *et al.*, 2018). The metal is ejected from the rod by centrifugal forces solidifying into spherical particles in the process. The particles produced are uniform and contain minimum impurities because of the inert gas environment. Figure 6 illustrates the plasma rotating electrode process (Yin *et al.*, 2017).

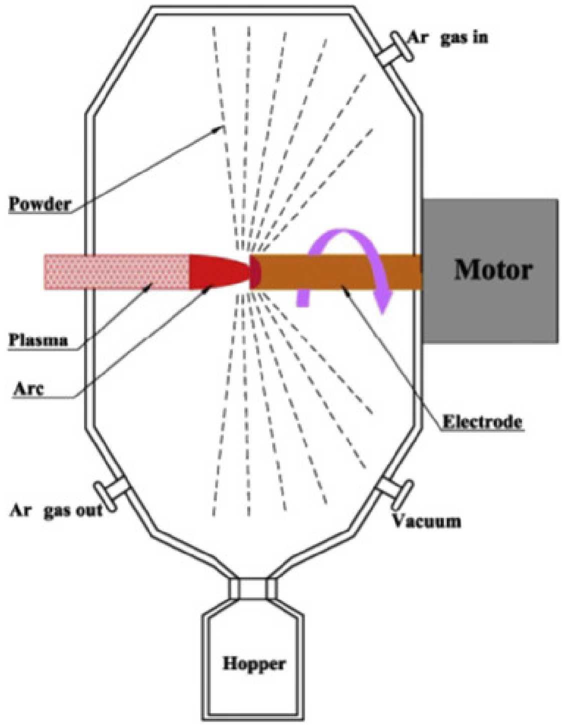

Figure 6: Plasma rotating electrode process (Yin *et al.*, 2017)

The plasma rotating electrode process can produce powder of high spherical powder content and low porosity. The process produces products of high purity levels with low contamination (Sun *et al.*, 2017); (Fang *et al.*, 2018); (Stallard and Airey, 1989). The process requires consumes a lot of energy when the electrode rotates at high speeds (Cui *et al.*, 2020). When at low rotational speed, process is not efficient. The process is costly and has a low yield for fine powder (Nie *et al.*, 2020);(Chen *et al.*, 2018). The challenge is producing consistent powder size distribution and fine powder due to the fact that high rotational speeds are needed and thus high levels of power are required. This makes the process expensive and needs further refining to be applicable in industry that aims to make profit (Cui *et al.*, 2020).

2.4.5 Plasma atomization

In plasma atomization a plasma arc is utilized as a high enthalpy heat source which will melt and spray molten metal wire, producing titanium powder that has a very high purity round shape (Baskoro, Supriadi and Dharmanto, 2019). Plasma atomization may not be suited for reconditioning as it manufactures atoms from solid metal.

2.4.6 Centrifugal Plasma Atomization

Centrifugal Atomization plasma is a melting process of the feed material and uses a rotating container to produce a centrifugal force which improves the more rounded powder form in the crystallization stage (Baskoro, Supriadi and Dharmanto, 2019).

2.5 Powder Characterization

From the papers reviewed it was noted that the quality of the powder can be classified to flowability, morphology, particle size packing density and shape. The spheroidisation processes aims to give the powder ideal physical properties and they are described in this section.

2.5.1 Flowabilty

The powder must easily flow when layered in powder bed for sintering. The flowability will depend on the particle shape and morphology (Powell *et al.*, 2020). Flowability is lost during sintering due to the high temperature of the process which causes particles to change structure. The flowability is affected by particle size and particle size distribution.

2.5.2 Particle size distribution

Particle size is critical in determining the layer thickness of the printed part that can be achieved. Powder of wider range of particle size provides higher powder bed density, generates parts of higher density with low laser energy intensity, and generates smoother side surface finishing parts (Powell *et al.*, 2020). Powder of narrower range of particle size provides better flowability, generates parts with higher UTS and larger hardness. Laser diffraction is an established technique for determining the particle size distribution of metal powders (ASTM B822) and works by measuring the angular variation of light scattered as a laser beam passes through a dispersion of the metal powder (Markusson, 2017).

2.5.3 Particle Shape

Spherical shaped particles are preferred as they pack more efficiently than non- spherical particles and they spread efficiently and give uniform powder bed density. They also flow more easily than non-spherical shapes giving better final product (Ahmed *et al.*, 2020). The particle shape can change surface area per unit mass which can influence how well the powder sinters together (Markusson, 2017).

2.5.4 Non-metallic elements

Hydrogen, carbon, oxygen, sulphur and nitrogen can influence the physical properties of metallic materials. Oxygen is found in *used* Ti6Al4V powder and can also be introduced to the titanium during the production process (Sun, Aindow and Hebert, 2017). Oxygen can have a significant effect on the hardness and toughness of titanium alloys, even in small amounts (Merkushev *et al.*, 2017). The non-metallic elements affect different metals differently.

2.6 Spheroidisation of Titanium

Titanium and its alloys received the most attention in spheroidisation with 15 publications of the 46 in the search focusing on titanium spheroidisation. Radio frequency Plasma spheroidisation has more publications than other spheroidisation techniques. Plasma atomization and rotating plasma atomization receive attention and these techniques are usually used to create metal powders from scratch. Pulsed electron beam irradiation, Plasma rotating electrode process and Microwave plasma reactor are some of the spheroidisation techniques that have been found in publications but do not receive as much attention as Radio frequency plasma spheroidisation. The increase in titanium publications reflects on the increase the demand in recycled titanium because of its high buy to fly ratio.

Research has confirms that spheroidisation can improve the economic viability of additive manufacturing hence more research is starting to focus on spheroidisation. Of all the publications on spheroidisation of titanium one is from South Africa under NECSA. (Bissett and Walt, 2017) published a paper highlighting the recent developments at NECSA on the addition of the TEKNA system for spheroidisation of Ti6Al4V. The system has been proven through experimentation to be capable of producing highly spherical titanium powder from irregular shaped powder particles.

2.7 Discussion

In additive manufacturing many of the materials are expensive to produce and thus reusing the material is critical. As material continues to be reused it degrades and needs to be spheroidised to minimize wastage. Wasted material can impact on the financial sustainability of additive manufacturing (Powell *et al.*, 2020). Spheroidisation is still being developed and the value chain for spheroidisation needs to be developed and improved. Various plasma spheroidisation methods are being developed worldwide with the TEKNA system leading the industry. The economic viability of spheroidisation also needs to be developed for spheroidisation to be accepted in industry. A lot of the research is ongoing for spheroidisation and there is still room for improvement. The spheroidisation process chain in general needs to be developed in South Africa and there is little literature available that can be used and thus benchmarking against international researchers will be of importance.

Many of the papers available discuss the technical aspects of spheroidisation however there is a gap in the research that covers the economic aspects of spheroidisation. Most of the research covers the experimental aspects that improve the end product of spheroidisation which is metal powder. As discussed the qualities discussed are powder flowability, chemical composition particle size and powder morphology. More needs to be done on the economic aspects of the spheroidisation. The environmental sustainability of the process is still yet to be proven as there are few publications of the environmental sustainability are available. If the spheroidisation is to be accepted in industry the process must prove itself to be economically and environmentally sustainable. Within the supply chain of additive manufacturing spheroidisation also still needs to prove it can contribute to the profitability through its ability to recycle additive manufacturing material.

South Africa is rapidly growing in the area of additive manufacturing and there is need to develop a value chain and an economic analysis of the processes that will add value for additive manufacturing.

2.8 Value chain of Titanium

For many production processes there are multiple activities that take place in order to produce a product and get the product to the final user. The value adding activities are the activities that are necessary to produce the product. The process of identifying and categorizing these activities is termed the value chain analysis (Popescu and Brasov, 2015). By identifying these activities the researcher can then eliminate the activities in a firm that are unnecessary and focus on activities that can improve the production process taking as a case study the reconditioning of used Ti6Al4V at NECSA. One of the concerns in the reconditioning of Ti6Al4V is measuring its economic sustainability in South Africa and a value chain would provide information on the sustainability.

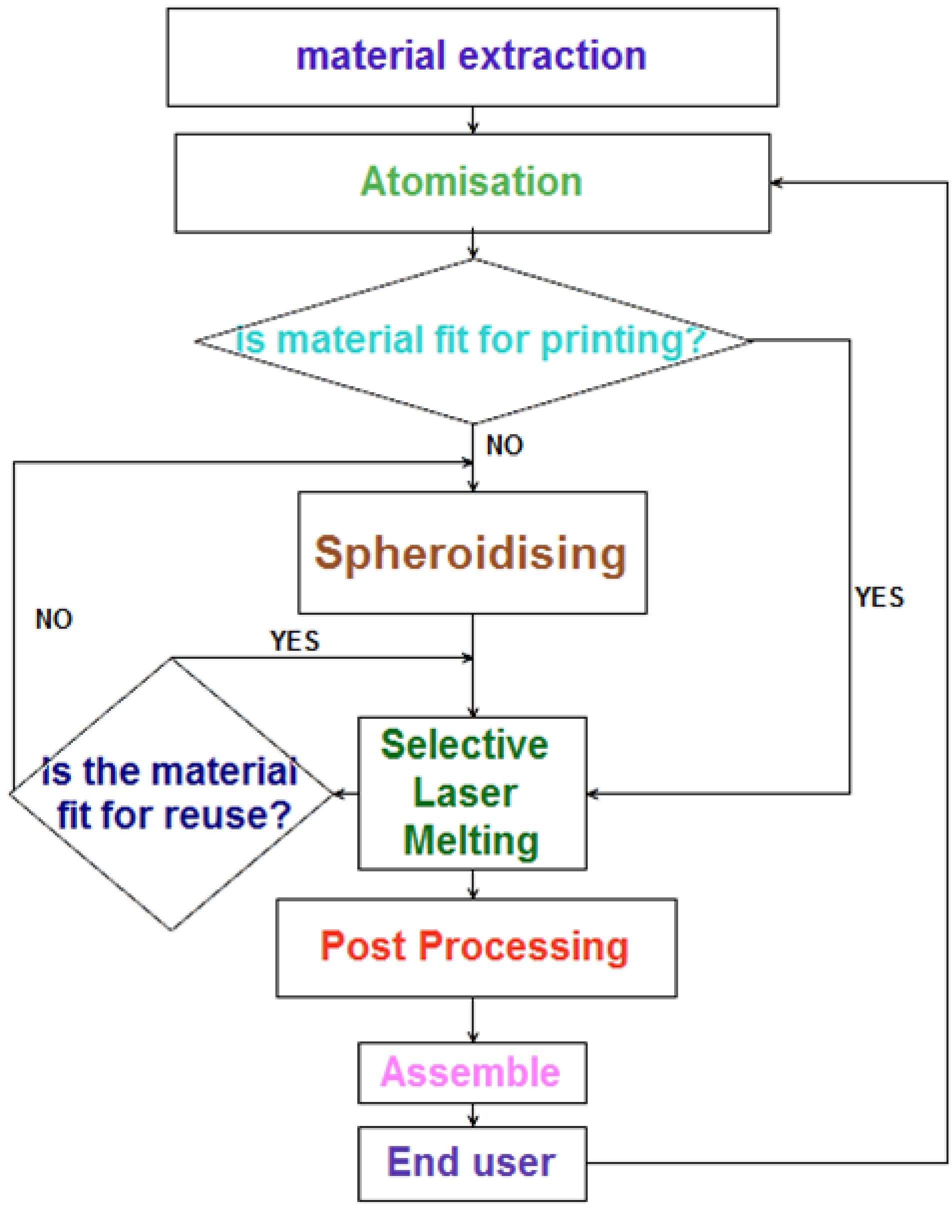

Figure 7: Life cycle of Titanium in additive manufacturing

Literature available covers the value chain from extraction to the final titanium product. Titanium starts off as ore which can be either $FeTiO_3$ ilmenite or rutile TiO_2. From the ore mining the titanium should then be removed from the ore through beneficiation. This process serves to remove iron from the ilmenite. Slag is formed from the smelting which is 80-90% TiO_2 (El-Sadek *et al.*, 2019). Through further purification rutile is produced which is 92 -95% TiO_2. Purity of the product depends on the specifications of the required product. After producing rutile from the beneficiation the fluidized bed chlorination process follows (Fan *et al.*, 2017). The Kroll process is another process that titanium goes through before final processing. From literature, many of the processes from the extraction of the ore to the processing of the metal have had value chain analysis done on them and much research covers extraction extensively (Fang *et al.*, 2018). In additive manufacturing there is still a long way to go particularly in the processing of the metal powder. Atomization and plasma spheroidisation are the two processes available for metal powder processing. The research will focus mainly on spheroidisation which is a reconditioning technique applied at Necsa. Figure 7 shows the lifecycle of titanium from extraction to end-user but with spheroidisation in the mix. Figure 7 mainly refers to the titanium powder.

Little has been done on the viability of Ti6Al4V reconditioning and a complete value chain analysis is necessary because titanium is highly expensive, so every process must be evaluated for sustainability and techniques to make the process profitable need to be developed. The value chain for the reconditioning of titanium in South Africa is still under developed and steps need to be taken to develop it. Many of the studies available discuss atomization of metals which most of the powders produced after atomization still needs to be spheroidised. The spheroidisation process needs to be included in the life cycle of titanium metal and other metals in general especially with regards to additive manufacturing. The economic benefits of reconditioning metal are not yet documented and still need to be documented and published.

Atomization is usually the first step before spheroidisation. Atomization in many cases does not produce spherical powders and thus need additional processing. The various techniques to make powder are gas atomization, water atomization, plasma atomization and rotation cathode atomization. If the atomization produces spherical powders the need for spheroidisation is minimal and if the quality of the powder is not high there is little need for spheroidisation. However, in many applications of additive manufacturing, the materials are expensive and the applications are usually customized parts which require precision, thus most powders need to be high standard. The qualities that are important are morphology, powder density, particle size, flowability and chemical composition. In addition to refining powder from atomization process the spheroidisation can be used to recondition used powder from. This can bring about economic benefits of which many publications do not discuss in detail. More publications need to highlight in detail the economic benefits of spheroidisation in relation to reconditioning.

3 Conclusion

There is little literature that covers the value chain for spheroidisation and industry in general. A gap has been identified in the value chain in South Africa for titanium especially for titanium spheroidisation. From this research, value chain analysis needs to be done more thoroughly and systematically particularly in spheroidisation of titanium. There is also need to do an economic viability of the spheroidisation of Ti6Al4V. The study should have the goal of finding out if the spheroidisation is profitable and sustainable.

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Biography

André van der Merwe holds a Bachelors of Mechanical Engineering, a Masters of Industrial Engineering and a PhD Engineering on the topic of "Air suspension to reduce Human exposure to Vibration". He worked 18 years in industry as engineering manager in Africa and Europe. His subsequent 16 year academic career produced several conference and journal publications. He is a reviewer for several national and international peer-reviewed publications and conferences. He is often frustrated by academic thinking and seeks real world application for every research project he endeavours. He is currently at Stellenbosch University at the Industrial Engineering department in the field of Resource Efficiency Engineering Management. REEM research group focuses on Commercial Readiness Indicators for Industry 4.0, which includes Additive Manufacturing, Human-Machine interface and Food Security using Internet of Things. He is the current vise-chairman for RAPDASA, with a focus on skills development of technicians for the industry. For sport and leisure he is competitive in road cycling, mountain biking enjoys gardening, scuba diving, skiing, intensive olive farming, home automation and aquaponics.

Stephen Matope is an Associate Professor in the Department of Industrial Engineering, Stellenbosch University with over 16 years of lecturing industrial engineering related subjects at university level. His research interests are in advanced manufacturing covering additive manufacturing, manufacturing processes and manufacturing systems.

Tsepo Dube is an industrial engineering student studying a PhD at Stellenbosch University. Studied his first degree in industrial and manufacturing engineering at the National university of science and technology in Zimbabwe where also completed his master in industrial engineering. His research interests are in advanced materials and additive manufacturing.

Hertzog Bissett At the start of 2009 Hertzog joined Necsa (The South African Nuclear Energy Corporation) working in the Plasma Technology group obtaining knowledge in the use and operation of various plasma systems ("hot" and "cold" plasmas) and high temperature systems such as inductive coupling heating. Hertzog was also part of the Uranium Chemistry group at Necsa looking at various methods of uranium dissolution, extraction and purification. In 2012 Dr. Bissett obtained his Ph.D. degree also from the North-west University for the study "Membrane based separation of nitrogen, tetrafluoromethane and hexafluoropropylene". Currently, Dr. Bissett is part of the Nuclear Materials group within Applied Chemistry at Necsa working on various projects include the AMI-Nuclear Materials Development Network especially relating to spheroidisation.