Environmental Impact Assessment of Reconditioning Titanium Alloy Powder

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Abstract. The environmental impact was assessed for the spheroidisation process to compare its advantages versus mining titanium from the ground. Energy consumption was used to compare the environmental impact. With the introduction of spheroidisation at Necsa, there was a need to investigate the environmental impact of the process. The environmental impact of plasma spheroidisation making use of the 15 kW Tekna plasma system was investigated. Environmental impact assessment is part of a bigger study to investigate the holistic impact of the spheroidisation of titanium powder at Necsa. The study was carried out using ASTM standards, ensuring that the results from the experiments are acceptable. The primary focus of the paper was the 15-kW spheroidisation system. The energy consumption of the reconditioning of titanium alloys was compared to conventionally producing titanium. The role spheroidisation plays in the additive manufacturing lifecycle was also assessed. This life cycle assessment also included the other processes in additive manufacturing to give an overview of how the spheroidisation process can fit in and improve the additive manufacturing value stream.

1 Introduction

For selective laser melting the powder used must have spherical particles [1]. The powder's high density and flowability, which are desired properties for metal selective laser melting, is facilitated by the spherical particle shapes [2]. A minimal amount of oxygen, hydrogen, and nitrogen must also be present in the metal [3]. As a result of these impurities, titanium will become hard and brittle, which may lead to cracks [4]. These contaminants are a by-product of the selective laser melting and atomization process exposing the material to air [5]. Spheroidization can assist in transforming a particle's irregular shape into a spherical shape [6].

Plasma, which can be produced in a variety of ways, is where spheroidization occurs. According to the analysis of the literature, TEKNA is one of the leading industry players in plasma generation [7]. A partially ionized gas called plasma that has ions, electrons, atoms, and molecules in it [7]. Thermal plasma typically has a temperature of more than 10,000K. They are produced either at normal pressure or in a soft vacuum. Depending on the material being treated, an inert environment or occasionally an oxidizing atmosphere is provided. The thermal plasma that is available includes high frequency induction plasma discharges and direct current arcs [7].

The main aspects investigated were the energy consumption. At Necsa, the Tekna 15kw system is used. It was found that different particles sizes require different amounts of energy and material. In the research the particle sizes ranged from 50µm -200µm. The aim is to meet the minimum requirement for additive manufacturing while utilising as few resources as possible for the benefit of the environments.

There is little literature on the environmental impact of the spheroidisation process however there is more literature available on the additive manufacturing process which is related to spheroidisation. Several of the studies on metal additive manufacturing's environmental sustainability are comparison studies between traditional and additive manufacturing [8] [9] [10] [11]. Several studies have shown that additive manufacturing reduces material waste when measured against traditional manufacturing methods[12] [13] [14].

The more energy a process consumes, the more resources are required to generate the energy required to keep it running. Much of the energy is derived from organic resources, which are difficult to replenish and consequently cause long-term environmental damage [15]. The spheroidisation processes must be included in the AM value stream to obtain a comprehensive picture of AM energy usage, which many studies hardly accomplish on their own. Material extraction and material refinement are two procedures that also influence AM value chain and are discussed in the article [16]. The study focus is spheroidisation and does not include logistics and indirect environmental impacts like transportation. The material consumption of the process is included in the study to a lesser extent, however there is literature that covers material consumption within AM [17] [18] [19].

2 Methodology

The aim was to find out the energy consumption per kilogram of titanium required to spheroidise the powder and compare it to conventional production of titanium. This then led to an evaluation on potential energy saving. The study was only limited to the activities that were directly linked to the research and development at Necsa.

Two process parameters were used for spheroidisation, one employing plasma powder with an 11-kW power and the other with a 12-kW power. The two process parameters used for the experiment are shown in Table 1. There were 50 grams of powder used for each setup. After spheroidization, the powder was also weighed to check for powder loss. The 12-kW settings produced better-quality, more spherically balanced powder, making them ideal for outstanding powder. The 11-kW settings were more environmentally friendly. The 11 kW settings also produced powered which was still acceptable for selective laser melting the powder size distribution used for the experiments was 50 µm -200 µm. After the spheroidisation process the sample were weighted and analysed to ensure that they met the quality standards required for selective laser melting.

Table 1: Process parameters for Spheroidising Titanium with the 15-kW Tekna System

Power Settings	Amount of powder used	Helium flow rate	Argon	Helium flow rate
12-kW	50g	Litres per minute	32 litres/minute	1 kg /hr
11-kW	50g	0 litres/minute	52 litres/minute	0.9 kg/hr

After the spheroidisation process it was observed that there was powder loss, which was considered to calculate the energy. For the 12-kW power setting there was a powder loss of 12.5 grams and for the 11-kW setting the powder loss was 5 grams. These losses were taken into consideration for the calculation of energy consumption. +The second part of the research was also to develop a life cycle assessment for spheroidisation value stream. The life cycle assessment aims to find out the resource utilization of spheroidisation in relation to AM. When the assessment is done, improvements can be done to improve the AM chain.

The main aspect investigated was the energy consumption, which was to be compared to mining titanium. A comparison of reconditioning titanium to mining titanium was carried out. The powder produced had to meet the requirements for selective laser melting for the study to be valid. **Table 2** shows the powder requirements for additive manufacturing. These requirements were used to determine if the powder is similar to virgin powder.

Table 2: Powder Requirements for AM powder

Property	Standard
Flowability	50 grams should be flow through a standard hale flow meter in less than 30 seconds
Powder density	99.9%
Powder size	50 µm -200 µm
Powder shape (spherical)	80% of the powder should be spherical
Chemical composition oxygen	0.01%
Hydrogen	0.002%
Nitrogen	0.02
Elemental (composition)	6% aluminium and 4 % vanadium must be maintained

The ISO 9001 standard was used to run the spheroidisation system. To verify that the environmental impact assessment was performed on powder that conformed to selective laser melting requirements the standards in **Table 3** were used to test the powder.

Table 3: Standard Test Methods for assessing AM powder Quality

Standard for testing	What the standard means
9001	Quality Management System—Requirements
B311	Test Method for Density of Powder Metallurgy (PM) Materials Containing Less Than Two Percent Porosity
B213	Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel.
B214	Test Method for Sieve Analysis of Metal Powders
B964	Test Methods for Flow Rate of Metal Powders Using the Carney Funnel
E1409	Test Method for Determination of Oxygen and Nitrogen in Titanium and Titanium Alloys by Inert Gas Fusion.

2.1 Benefits of Spheroidisation in the Life Cycle of Ti6Al4V

The spheroidisation has some benefits as it can reduce the need to extract more titanium by recycling the titanium. Extracting titanium is highly expensive, thus saving the amount required. The benefits of spheroidisation can be elaborated by explaining the negative effects of mining titanium which reconditioning powder minimises.

2.2 Effect of Mining Titanium

The reason for discussing the negative effects of titanium mining is that the research is an environmental impact assessment and thus there is need to know what the long-term effects of mining titanium are.

To get a kilogram of titanium from its ore, the amount of energy required is 900 - 940 MJ (250,000 to 261,000 watt-hours) [20], which is high compared to the amount used to spheroidise the titanium. Energy sources utilised to process titanium are usually non-renewable and thus can be harmful to the environment.

2.2.1 Resource utilisation in Spheroidisation

Spheroidisation is beneficial to the environment as it uses less energy than mining the titanium. At Necsa experiments were carried out to find out the amount of energy which would be needed to spheroidise 1000 grams of powder. The time to spheroidise the powder and the power needed to run the system were recorded. The energy required to spheroidise Ti6Al4V is 17.53 kWh/kg. The total energy required to spheroidise is given by Equation 1

$$Energy = Power \times time = 17.53kJ \times 3600s = 63108\ kJ \tag{1}$$

63108 kJ is required to spheroidise 1 kg of Ti6Al4V. This value will vary with powder size. and does not take into consideration the powder required to run the Tekna system.

From the experimental runs from Necsa the running time require to spheroidise 50 grams of powder was 9 minutes and thus to spheroidise 1 kilogram it would be multiplied by 20 to give 90 minutes. When running the spheroidisation system at 12-kW plasma power the power needed to run the machine is 27-kW which is derived from the machine specifications. If the machine is allowed to spheroidise 1000 grams of powder, then the required power is given by

$$Energy = power \times time = 27kW \times 4800 = 129600\ kJ \tag{2}$$

The 129.2 is the value derived from the Tekna system while the 63.108 MJ is derived from an average value derived from past records at Necsa. When considering that the powder loss during the spheroidisation process then more energy is required to spheroidise the powder. When Spheroidising at 12-kW the powder loss was 250 grams for every 1000 grams. The energy required to produce 1000 grams of Ti6Al4 V will be given by:

$$\frac{1}{0.75} = 129600kJ = 172{,}8\ MJ/kg \tag{3}$$

It is worth noting that this value is for the 15 kW Tekna system. The energy consumption may vary in different spheroidisation machines.

3 Conventional Production of Titanium Vs Spheroidisation

From research and investigations at Necsa, spheroidisation of powder uses less energy per unit mass. It is beneficial to invest more in recycling titanium powder as it is better than extracting titanium. Compared to conventional production of titanium, spheroidisation can bring about more savings. Table 4 shows the energy variance of titanium production and reconditioning.

Table 4: Reconditioning 1 kg of titanium Energy Consumption

	Energy	Time
Conventional Production	900MJ [20]	Varies from 2 days to 14 days depending on logistics
Reconditioning used Titanium Powder	172.8 MJ	1 hour
Difference	727.2MJ	14 days

4 Spheroidisation in the Lifecycle of Additive Manufacturing

Spheroidisation in additive manufacturing is critical for additive manufacturing to be effective. The additive manufacturing industry is growing; however, efforts need to be made to ensure its sustainability. In the whole value chain of additive manufacturing, reconditioning by spheroidisation is a factor that can improve additive manufacturing industry by reducing waste in the whole process.

4.1.1 How Spheroidisation is Beneficial to the Environment

Spheroidisation benefits the environment through

- Energy savings
- Material saving

In SLM 90% of the material is not used and after some time the material is not usable. Reconditioning can prolong the titanium life span in the process chain. The life cycle of titanium in the AM value stream is described to give an overview of how spheroidisation can fit in to improve AM.

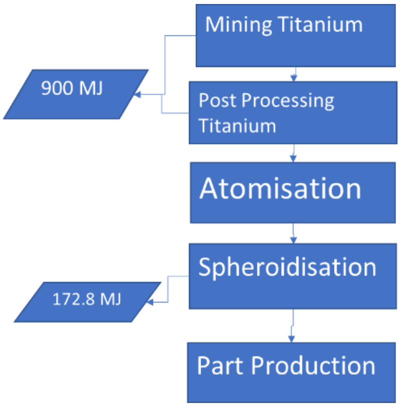

Figure 1: Process Chain for Titanium

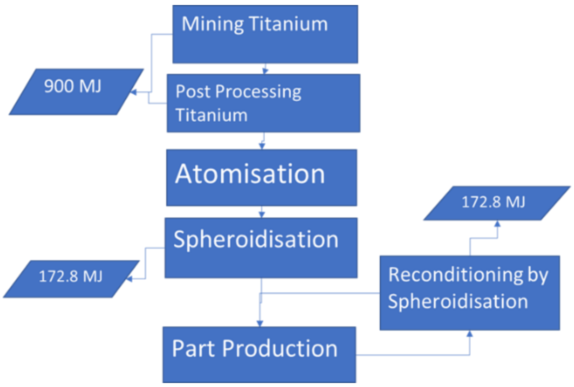

Figure 2*:* Process chain for titanium with Spheroidisation

Figure 1 shows the lifecycle highlighting the fact that some powder can end up disposed of eventually if it is not reconditioned. **Figure 2Error! Reference source not found.** shows the life cycle of titanium powder with reconditioning loop added to the process flow. Adding reconditioning in the additive manufacturing loop ensures that additive manufacturing is, more energy efficient.

4.1.2 Material Extraction

Spheroidisation reduces the material extraction which include mining and processing as used titanium is recycled. Extracting titanium is energy consuming, and methods to reduce the need to extract titanium need to be developed and perfected. [21].Titanium extraction is also expensive and can be damaging to the area in which it is mined [22].

4.1.3 Powder Production and processing

Spheroidisation and atomisation occur in the same level in the lifecycle. These processes occur after material extraction and processing. The first step is to atomise the powder then spheroidise. The atomisation turns a solid metal to powder then the spheroidisation focuses on turning the particles to spherical ones[23] [24]. The spheroidisation process can also recondition used powder form selective laser melting plants. This can serve in reduction of material consumption on a macro scale [25]. This also can save energy needed in extracting and mining more titanium from the ground. The energy savings made by reconditioning are 727.8MJ per kilogram as indicated in Table 4.

4.1.4 Processing

Selective laser melting is the main post processing method for titanium and there is much literature for SLM. The contribution of SLM in life cycle assessment has been assessed in past literature [14][26]. Aerospace is the most common application at this stage. The application in aerospace brings energy savings for aerospace since lighter parts can be made. Lighter parts in aerospace means savings in fuel for aerospace.

Additive manufacturing reduces tools required to make parts. Additive manufacturing used a single process to make a complex part unlike in conventional manufacturing which may require drilling, milling, and turning which make conventional manufacturing less energy efficiency [11]. Additive manufacturing produces less scrap as much of the material is left unprocessed which can be 90% of the material[27], [28]. Even through the unused material in AM can be reused it eventually loses its properties that make it suitable for the AM and thus reconditioning by spheroidisation is required to make it more suitable [24], [29]. The spheroidisation process can prolong the AM powder life span in the additive manufacturing process chain.

5 Discussion

Benefits of environmental impact assessment of reconditioning to the AM chain are

- The environmental impact assessment ensures friendly relationships with health and safety bodies.
- Reduction of carbon emissions at a larger scale
- Increase in customer satisfaction.

Before a business implement a process, they should highlight the potential impacts. This helps to ensure the business' integrity [29]. The assessments should highlight the positive impacts of spheroidisation in AM value stream and the environmental impact in the community. Knowing the current environmental impacts helps identify the areas of improvement. The reconditioning spheroidisation of AM materials makes the AM value stream more efficient. In addition to providing a more environmentally sustainable product, disruption to the supply chain is also increased through spheroidisation since AM is a disruptive technology [30] [31]. The emissions in the AM chain are also reduced since recycling reduces the need to extract titanium by mining, hence the titanium life span is prolonged.

Efforts in making spheroidisation more environmentally friendly will ensure that the process is accepted in industry.

6 Conclusions

The impact of the spheroidisation process was investigated focusing on its reduction in the energy consumption and material. The energy saving that are achieved by spheroidisation in the AM value stream were highlighted. The material savings were also highlighted. Material wastage is to be avoided as the extraction of material is harmful. The research also highlighted how the spheroidisation process fits into the additive manufacturing value stream. Overall spheroidisation of used titanium is beneficial to the environmental as it can reduce the need to mine titanium. The environmental sustainability of the spheroidisation needs to be known to prove that the process can be commercialised.

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