Environmental Impact Assessment of Titanium Swarf Cleaning Methods

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Abstract. This paper evaluates the environmental impacts of chemical based and CryoClean swarf cleaning techniques through a comprehensive Life Cycle Assessment (LCA) aimed at identifying sustainable practices for recycling titanium swarf in additive manufacturing processes. Employing ISO 14040 and 14044 standards, the study focuses on a functional unit of cleaning 100 gr of titanium swarf, enabling direct comparison of environmental footprints across these methods. Data for the inventory analysis includes specific inputs such as energy consumption, water use, and chemicals, alongside outputs like emissions and waste generation, with supplemental secondary data sourced from Ecoinvent. The impact assessment utilizes the ReCiPe methodology, concentrating on key environmental indicators such as Global Warming Potential (GWP) and Acidification Potential (AP). The findings reveal distinct environmental trade-offs between the chemical based and CryoClean methods. Chemical-based cleaning, while effective at removing contaminants, often involves the use of hazardous substances that can lead to significant ecological impacts. In contrast, CryoClean, which utilizes liquid nitrogen to freeze and remove impurities, shows a lower environmental impact across several categories but may require higher energy inputs. By estimating the specific environmental impacts of the selected swarf cleaning techniques, the study contributes valuable insights towards optimizing material recovery and advancing circular economy principles in industrial manufacturing. The paper aims to guide industry stakeholders toward adopting more environmentally sustainable practices that align with the transition to greener manufacturing processes.

Keywords: Titanium Swarf, Life Cycle Assessment, Sustainability.

1 Introduction

The manufacturing of titanium and high-performance alloys is of high importance in industries, such as aerospace, automotive, and medical applications, where high thermal and mechanical material properties are crucial. These materials, known for their high strength-to-weight ratios and corrosion resistance, have significant environmental burdens due to their intensive production and processing methods [1]. Specifically, traditional machining processes generate great volumes of swarf fine metallic filings or shavings that are often discarded. Yet, recognizing this swarf as a valuable resource is critical, as its effective recovery and reuse are pivotal for advancing sustainable manufacturing practices [2].

Traditional swarf recycling, which involves melting and reforming, is well established, but energy-intensive, significantly increasing the environmental footprint due to high energy demands and greenhouse gas emissions [3]. Newer, less energy-intensive recycling methods integrate swarf directly into production cycles using additive manufacturing, reducing waste and dependence on environmentally disruptive virgin material extraction [4,5].

However, the integration of swarf into manufacturing faces challenges, particularly in ensuring the cleanliness of recycled materials. Effective removal of contaminants such as cutting fluids and metal particles is critical to maintain product quality, necessitating robust swarf cleaning technologies [6,7].

Advanced techniques like dry machining, Minimum Quantity Lubrication (MQL), and cryogenic machining minimize initial contamination [8]. Although sodium carbonate is a safer cleaning alternative, it is less effective than more harmful chemicals like acetone, which poses significant environmental risks [9,10]. Dhiman et al. (2022) describe a resource-intensive combined chemical and thermal cleaning process [11]. Synron GmbH's CryoClean process uses liquid nitrogen, providing a greener option, though its impacts need careful evaluation [12].

The literature reveals a critical gap in the comprehensive analysis of swarf cleaning technologies' environmental impacts, with most studies focusing primarily on either technical efficacy or isolated environmental parameters [13,14]. This study aims to fill that gap by providing a holistic analysis that considers both environmental impacts and cleaning efficacy to determine the most sustainable practices for industry adoption [15-17]. By doing so, the study will offer an overall understanding of the trade-offs involved in various swarf cleaning techniques and their alignment with broader sustainability objectives, such as reducing the dependency on primary resource extraction and minimizing industrial waste [18,19]. This approach is crucial, as it addresses the need for integrated solutions that optimize both environmental and production efficiency, which is essential for sustainable industrial practices [20,21].

This research critically explores several swarf cleaning processes using a life cycle assessment (LCA) methodology to evaluate their environmental impact. The assessment investigates multiple impact factors, including Global Warming Potential (GWP), Cumulative Energy Demand (CED), and ecotoxicity, employing the Recipe method of impact assessment. The aim of this research is to determine the best sustainable swarf cleaning solutions that correspond to circular economy principles and resource efficiency. The goal is to give actionable insights that aid industry stakeholders in adopting techniques that not only improve material recovery and reuse but also greatly reduce the environmental impacts associated with the manufacture of high-performance materials.

2 Methodology

This study employs a structured approach to evaluate the environmental impacts of different swarf cleaning techniques through a comprehensive Life Cycle Assessment (LCA). The methodology is designed to provide a holistic view of the environmental implications associated with each cleaning technique and to identify the most sustainable options for industrial adoption.

For the evaluation of swarf cleaning techniques, various methods including chemical baths, ultrasonic cleaning, and CryoClean were examined. The selection of CryoClean and chemical-based cleaning methods for this study was driven by their contrasting approaches offering insights into both traditional and progressive environmental management practices.

Chemical-based cleaning, using agents like sodium carbonate, acetone, and white spirits, has been traditionally favored for its high degreasing efficiency. However, concerns over the environmental and health impacts of volatile organic compounds (VOCs) such as acetone necessitate careful consideration, as listed in Table 1 below [9,10]. On the other hand, the CryoClean method stands out for its minimal chemical waste production and reduced health hazards, listed also in Table 1 below. This method uses liquid nitrogen to freeze and remove contaminants, presenting a significant reduction in chemical usage and thus a lower overall environmental footprint [12].

Table 1. Swarf Cleaning Methods.

Journal	Materials Research	Cleaner Production	Materials, MDPI	-	-
Chemicals Used	Sodium carbonate	Detergent, Acetone	Spiridane D25	None	None
Cleaning Efficiency	83.5%	Not specified	96.2% oil removal	> 95%	98.8%
Throughput	2.5 hrs/batch	3.5 hrs/batch	3 hrs/batch	Not available	10t swarf/hr
Remarks	Degreasing only	Magnetic sep., heat treatment	Degreasing only	Crushing, magnetic sep.	Degreasing, no sep.
Maturity Level	Lab-based	Lab-based	Lab-based	Industrial	Industrial ready
Reference	Wang et al., 2022	Dhiman et al., 2022	Żelazny et al., 2020	Rotajet	Synron CryoClean

The LCA in this study adheres to ISO 14040 and 14044 standards, focusing on energy use, resource consumption, emissions, and waste generation across each cleaning process. We assess a 'cleaning of 100 gr of titanium (Ti-6Al-4V) swarf' as our functional unit to standardize results across various LCA techniques.

Environmental impacts are evaluated using the ReCiPe methodology with impact categories including on global warming, human carcinogenic toxicity freshwater toxicity, marine toxicity, and human non-carcinogenic toxicity. The use of SimaPro software integrates impacts into one assessment, making it easier to compare different swarf cleaning techniques.

3 Swarf Cleaning Processes

3.1 Process Maps

In additive manufacturing (AM) processes, swarf cleaning is an essential step to prepare the swarf for reuse by removing all impurities. This study specifically focuses on two cleaning methods: CryoClean and chemical-based cleaning, which is a more traditional methmethod, as proposed by Dhiman et al. More specifically, CryoClean method utilizes liquid nitrogen to freeze and separate impurities from the swarf. The process map in Fig. 1 indicates the flow of liquid nitrogen, the speed of the drum where freezing occurs, and subsequent magnetic separation to ensure thorough cleaning. The efficiency of impurity removal is influenced by the rate of liquid nitrogen flow and the drum speed.

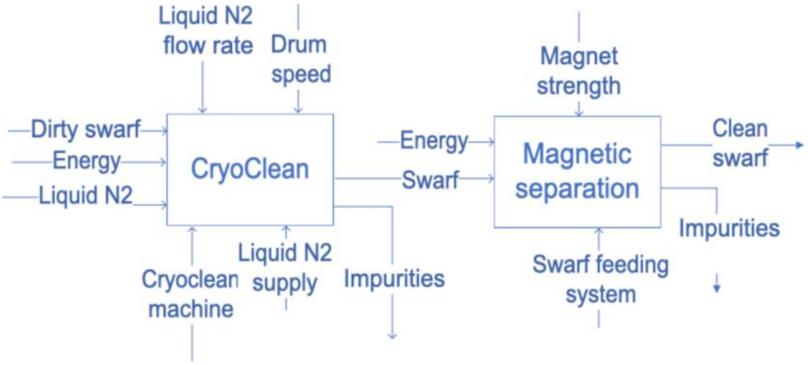

Fig. 1. CryoClean process map.

Chemical based cleaning process involves multiple stages including washing with solvents such as acetone, and ultrasonic bathing to agitate and remove finer particles, followed by drying and sieving. The effectiveness of this method depends on solvent concentration, ultrasonic frequency, and drying temperature. A subsequent magnetic separation step, similar to that added to the CryoClean process, ensures the removal of any ferrous materials as shown in Fig. 2 below.

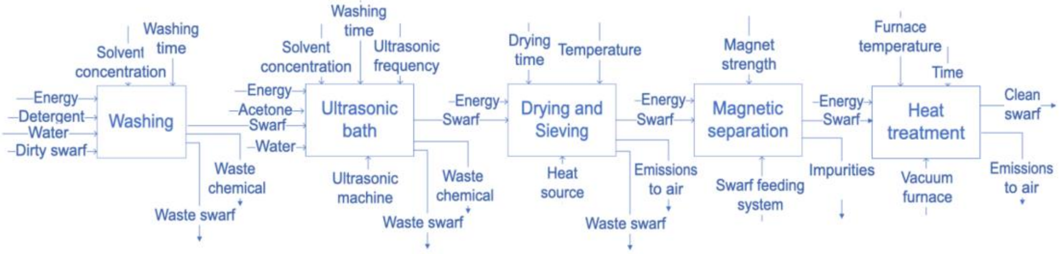

Fig. 2. Chemical based cleaning process map.

To ensure more accurate comparison, magnetic separation was integrated into both cleaning processes. This additional step is crucial for achieving high purity in the recycled swarf, making it suitable for high-quality additive manufacturing applications. The integrated approach in both methods highlights the detailed steps required to optimize swarf cleanliness and sustainability in industrial recycling operations.

3.2 Inventory Analysis

In the lifecycle assessment of swarf cleaning processes, it is crucial to identify and quantify the inputs and outputs at all manufacturing stages. This assessment involves not only direct measurements but also estimates derived from standard characterisation factors. These factors include Material Utilization Factor, Energy Intensity, and CO2 footprint, which are sourced from databases such as Granta EduPack 2024, Ecoinvent, or existing literature.

To accurately calculate the environmental impacts associated with each stage of the swarf cleaning processes depicted in the process maps, the following equations were employed:

$$\text{Input Material Mass} = \text{Mass Produced} \times \text{Material Utilization Factor} \quad (1)$$

$$\text{Consumed} = \text{Mass Produced} \times \text{Energy Intensity Factor} \quad (2)$$

$$\text{Equivalent CO2 Emission} = \text{Mass Produced} \times \text{CO2 Intensity Factor} \quad (3)$$

The input and output data for both processes are showcased in Tables 2 and 3 below.

Table 2. CryoClean process inventory data.

	Input Data	**Value**	**Output Data**	**Value**
Degreasing	Energy (MJ)	0.0014	Clean swarf (kg)	0.103
	Liquid N2 (kg)	0.0155		
	Swarf (kg)	0.103		
Magnetic Separation	Energy (MJ)	0.082	Clean swarf (kg)	0.1
	Swarf (kg)	0.103	Waste swarf (kg)	0.003

Table 3. Chemical based cleaning process inventory data.

	Input Data	**Value**	**Output Data**	**Value**
Washing	Energy (MJ)	0.11	Clean swarf (kg)	0.107
	Detergent (kg)	0.05	Waste swarf (kg)	0.001
	Water (l)	0.54		
	Swarf (kg)	0.108		
Ultrasonic bath	Energy (MJ)	0.32	Clean swarf (kg)	0.106
	Acetone (l)	0.216	Waste swarf (kg)	0.001
	Swarf (kg)	0.107		

Heat drying and sieving	Energy (MJ)	0.54	Clean swarf (kg)	0.104
	Swarf (kg)	0.106	Waste swarf (kg)	0.002
Magnetic separation	Energy (MJ)	0.09	Clean swarf (kg)	0.1
	Swarf (kg)	0.103	Waste swarf (kg)	0.003
Heat treatment	Energy (MJ)	2.16	Clean swarf (kg)	0.1

4 Results

The environmental impacts of CryoClean and chemical-based cleaning were evaluated using the ReCiPe method through SimaPro 9 software, incorporating inventory data on energy, detergent, and liquid nitrogen usage. The chemical-based process utilized Linear Alkylbenzene Sulphonate from the Ecoinvent database to reflect detergent use, chosen for its industrial ubiquity [22].

The comparison of the five most impactful categories was done using Recipe midpoint as shown in Fig. 3 below. The endpoint results are shown in Fig 4 below. The midpoint analysis focused on global warming, human carcinogenic toxicity freshwater toxicity, marine toxicity, and human non-carcinogenic toxicity. In addition, the endpoint analysis considered broader impacts on human health, ecosystems, and resource use.

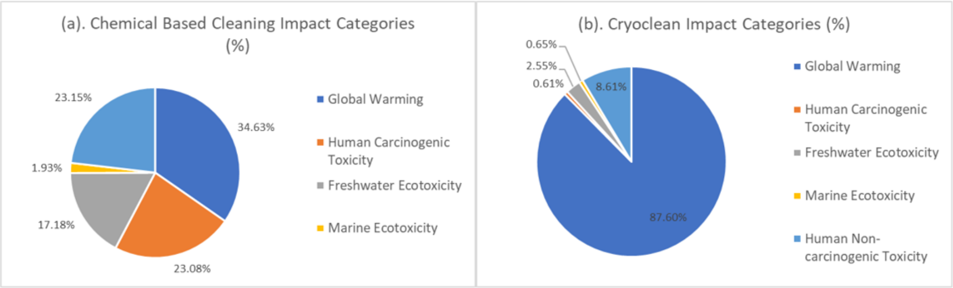

Fig. 4. Most impactful categories for cryoclean process (a). and chemical based cleaning process (b).

This figure presents the most impactful categories for both CryoClean and chemical-based cleaning processes. In the chemical-based process (a), Global Warming is the most significant impact, constituting 34.63% of the total, followed by Human Carcinogenic Toxicity and Freshwater Ecotoxicity. In contrast, the CryoClean process (b) is predominantly impacted by Global Warming, accounting for 87.60% of the total impact, indicating a more focused environmental footprint.

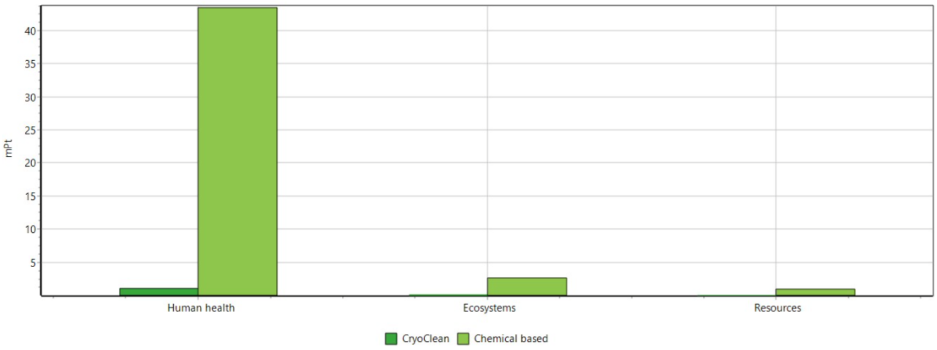

Fig.4. Endpoint results for swarf cleaning processes.

The endpoint results for the swarf cleaning processes illustrate that the chemical-based method has a substantial impact across human health, ecosystems, and resource categories. Notably, human health is the most affected area, highlighting the need for more environmentally considerate alternatives.

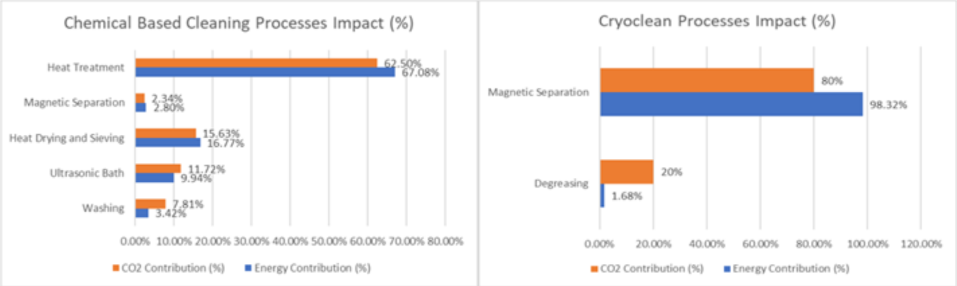

Fig. 5. CO2 and energy contribution of each process step for the selected swarf cleaning methods.

Details the CO2 and energy contribution of each process step for both CryoClean and chemical-based methods. For the chemical-based cleaning, heat treatment dominates the contributions, consuming 67% of the total energy but disproportionately contributing only 41% to the Global Warming Potential. Conversely, the CryoClean process shows that magnetic separation alone accounts for 80% of energy use but has a comparably lower CO2 impact.

5 Conclusion

This study critically evaluated the environmental impacts of two swarf cleaning techniques, CryoClean and chemical-based cleaning, utilizing the ReCiPe method using SimaPro 9. The findings highlight significant differences in their environmental footprints, highlighting the potential of CryoClean as a more sustainable option due to its minimal chemical usage and lower overall environmental impact. On the other hand, the chemical-based process, while effective, demonstrated a considerably higher global warming potential, particularly from acetone use, which despite its high cleaning efficacy, poses substantial environmental and health risks.

Future efforts will integrate these cleaning technologies into sustainable additive manufacturing processes, focusing on optimizing efficiency and reducing ecological impacts. Further research will validate these methods in industrial applications and explore alternatives to minimize the need for intensive swarf cleaning, aiming to reduce the overall environmental footprint of manufacturing.

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Life-cycle assessment of titanium swarf cleaning methods

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