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Life Cycle Assessment of Metal Part Repair Using Directed Energy Deposition

A Comparison Between Arc- and Laser-Based Methods

Department of Mechanical and Materials Engineering

Bachelor’s thesis

Author:

Jaakko Hörkkö

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Author: Jaakko Hörkkö
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Supervisor(s): Prof. Oskar Karlström, M.Sc. Erik Haapa
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This bachelor’s thesis investigates the environmental performance of metal part repair using Directed Energy Deposition (DED), focusing on a comparison between arc-based (DED-Arc) and laser-based (DED-LB) methods. The analysis is based on a process-phase life cycle assessment (LCA), using energy consumption, material efficiency, and shielding gas use as key indicators. A real-world case involving the DED-LB repair of a hydraulic cylinder rod is used as a reference, with the DED-Arc scenario modeled using literature-based data under comparable conditions. The thesis also outlines the main process steps involved in DED-based repair, including surface preparation, material deposition, and post-processing, providing technical context for the environmental assessment. The findings indicate that the laser-based method resulted in significantly lower energy consumption and material losses compared to the arc-based alternative, primarily due to reduced overbuild and post-processing requirements. However, DED-LB also required substantially more shielding gas. The study highlights that environmental advantages depend strongly on part geometry, deposition volume, and process planning. While DED-LB demonstrated higher resource efficiency in the case studied, the results are not universally generalizable. The thesis underscores the importance of context-specific process selection in sustainable repair operations and encourages the integration of simplified LCA tools into industrial decision-making, while also recognizing their inherent limitations.

Key words: Directed Energy Deposition, DED-Arc, DED-LB, additive repair, life cycle assessment, material efficiency, energy consumption, shielding gas, DED, LCA, sustainable manufacturing

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1 Introduction

Additive manufacturing (AM) is increasingly shaping the way industrial components are produced, maintained, and repaired. While originally developed for prototyping, AM has evolved into a robust technology capable of fabricating complex metal parts with high material efficiency and design flexibility. One particularly impactful application of AM lies in the repair of worn or damaged components, where targeted material deposition can reduce waste and extend the useful life of critical parts.

Among the various AM techniques, Directed Energy Deposition (DED) offers a promising framework for metal part restoration. DED processes build up material layer by layer using a concentrated energy source to fuse material onto the substrate. Multiple DED variants exist, differing in their energy sources and feedstock forms. In this thesis, two commonly applied methods are examined: laser-based DED (DED-LB), which uses powder feedstock and a high-powered laser, and arc-based DED (DED-Arc), which utilizes wire feedstock and an electric arc.

The comparison focuses on the environmental performance of these two processes in a real-world application. The analysis is grounded in life cycle assessment (LCA) principles and evaluates key differences between the two methods.

1.1 Background, Motivation and Scope

Many industrial components are exposed to heavy wear throughout their service life, especially in demanding applications such as mining, energy, and transportation. Traditionally, worn parts are either discarded or repaired using conventional welding techniques, which may be limited in terms of geometric precision, material control, and automation. As sustainability goals become more central in manufacturing and maintenance, there is growing interest in more efficient, controlled, and material-saving repair solutions.

DED-based repair enables targeted material addition with precise control over geometry and deposition volume. These features make it well-suited for extending the lifetime of complex components while reducing waste and raw material demand [1]. It has also been recognized as a promising enabler of circular manufacturing, particularly in the refurbishment of worn or obsolete parts, where complete replacement would require significantly more material and energy [2]. However, DED is also relatively energy-intensive, and its environmental performance depends strongly on process planning, feedstock efficiency, and post-processing.

This thesis addresses that gap by focusing specifically on repair-oriented LCA in an industrial setting. Earlier work emphasized the need for case-specific modelling to understand the actual trade-offs involved in DED-based repair [3].

The study compares the environmental performance of two DED-based repair methods: DED-LB and DED-Arc. The analysis focuses on the process phase and uses selected LCA indicators to evaluate energy consumption, material efficiency, and shielding gas use. The comparison is based on a real-world repair case involving a hydraulic cylinder rod. The study excludes upstream material production, downstream impacts, and economic or mechanical performance considerations. The aim is to provide insight into how these two repair processes differ environmentally, supporting more informed decision-making in industrial maintenance.

1.2 Structure of the Thesis

This thesis follows a hybrid approach: real-world process data from an industrial operator is combined with literature-based estimates to compare the environmental performance of two DED methods. The mixed approach reflects the reality of industrial comparisons, where process data is not always equally available for all technologies and materials. By combining operator-supplied and literature-based data, the study enables a balanced assessment of the environmental implications of DED-LB and DED-Arc.

The remainder of the thesis is structured as follows. Chapter 2 presents an overview of DED technologies in the context of repair, with attention to both arc- and laser-based variants. Chapter 3 introduces the principles of life cycle assessment and explains how LCA can be applied and interpreted to compare manufacturing processes, and outlines key methodological limitations relevant to DED-based repair.

Chapter 4 forms the analytical core of the study, presenting a case-based analysis of a DED-LB repair and a comparative environmental estimate for DED-Arc. The environmental impact of both processes is assessed using selected LCA indicators. Finally, Chapter 5 summarizes the main findings, discusses the implications and limitations, and outlines directions for future work.

2 DED in Repair Applications

Directed Energy Deposition (DED) is a class of additive manufacturing (AM) technologies that enables the repair of metal components by building material directly onto damaged areas. DED is formally classified under ISO/ASTM 52900:2021, the standard for additive manufacturing terminology. In this thesis, the focus is placed on two commonly applied DED variants: arc-based DED (DED-Arc) and laser-based DED (DED-LB) [4,5]. These techniques are particularly suited for repair operations due to their ability to deposit material precisely where needed and minimize material waste.

Both DED-Arc and DED-LB systems share a modular structure comprising a deposition head with wire or powder feedstock input, motion control such as a robotic arm or gantry system, a shielding gas supply to prevent oxidation, and a system controller to coordinate deposition parameters. This general configuration enables flexible use in a variety of repair tasks, while the energy source, electric arc or laser beam, introduces notable differences in process behavior and application suitability [6,7].

In DED-Arc, a metal wire is melted using an electric arc, and the molten material is deposited layer by layer onto the damaged area. In this process, the surface of the substrate also partially melts, enabling a metallurgical bond between the deposited and original material. The process is compatible with conventional welding equipment, resulting in lower investment costs and easier system integration. Additionally, DED-Arc is characterized by high deposition rates, making it particularly efficient and cost-effective in the repair of large-scale components [8,9].

DED-LB, on the other hand, uses a high-power laser to melt the feedstock, which may consist of wire or powder, depending on the application. Similar to DED-Arc, the laser also causes localized melting of the substrate, ensuring strong bonding. This energy source enables better control over the melt pool, leading to improved surface quality, narrower heat-affected zones, and higher geometric precision. Consequently, DED-LB is often preferred in repairs that require tighter dimensional tolerances and reduced thermal distortion [7,10,11].

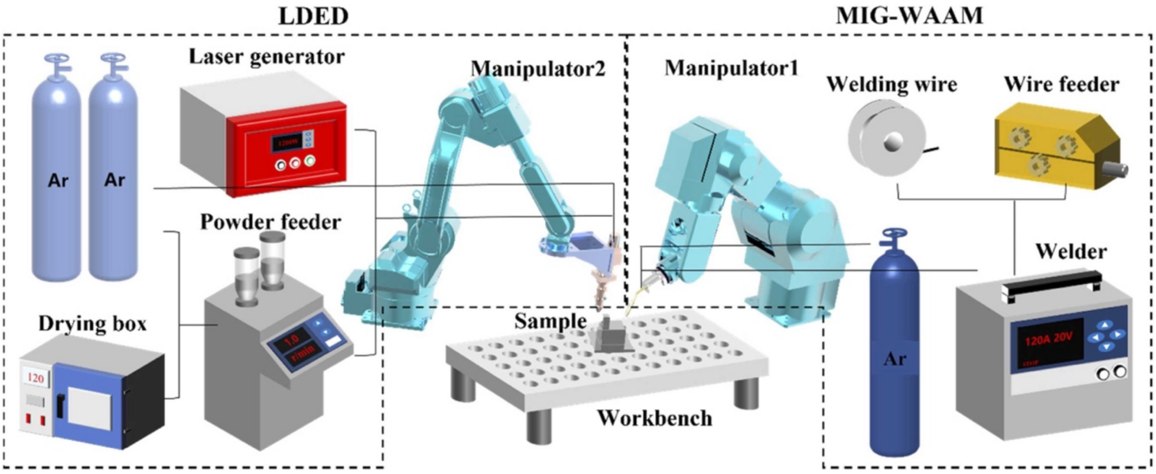

Figure 1. Schematic setup of DED-LB on the left and MIG-WAAM (Metal Inert Gas- Wire Arc Additive manufacturing, a form of arc-based DED) on the right. The illustration is adapted from [10].

Figure 1 provides a schematic comparison of the two DED system configurations examined in this thesis: DED-LB and DED-Arc. The figure highlights typical system components, allowing for a visual comparison of how the two methods differ in terms of equipment setup and operational principles.

2.1 Repair Process Using DED

The repair process using DED technologies follows a structured sequence of phases that apply to both DED-Arc and DED-LB. While these methods differ in their heat sources and process characteristics, they share a similar overall workflow. Typically, the process consists of surface preparation, geometric scanning and modelling, toolpath generation, material deposition, and post-processing [11,12].

The following subsections examine each of these process phases in more detail. Method-specific differences between DED-Arc and DED-LB are noted where relevant.

2.1.1 Pre-Processing and Surface Preparation

The repair process using DED technologies begins with accurately removing damaged areas and preparing a clean and geometrically defined substrate. This step is essential in both DED-Arc and DED-LB methods to ensure a stable foundation for material deposition and proper metallurgical bonding between the base and deposited layers.

In DED-Arc, mechanical methods such as grinding and machining are typically employed to remove worn material and define a regular repair area [8]. The same general approach applies to DED-LB, although the geometry of the repair region may be adapted based on the laser process requirements and access constraints [11].

After surface preparation, the component's geometry is captured using 3D scanning techniques. This process results in a point cloud representation of the surface, which must be digitally processed before repair planning [12]. As part of this processing, noise and outliers caused by scanning artifacts are removed, missing surface data is reconstructed, and the damaged area is digitally segmented from the intact regions. The cleaned and segmented point cloud is then aligned with reference geometry and converted into a mesh model, which serves as the basis for toolpath generation [12].

In the case of DED-LB, the demands for geometric precision are typically higher due to the smaller melt pool and finer energy control of the laser. As a result, the scanning resolution and point cloud accuracy may need to be higher to ensure optimal deposition outcomes [11]. Furthermore, DED-LB systems may incorporate automated routines for data processing and repair volume extraction, streamlining the workflow prior to deposition [13].

In both processes, physical surface cleaning is also required to remove oxides, oil, or other contaminants that could affect the bonding quality. This step is crucial for ensuring proper fusion between the deposited material and the base substrate [8].

Pre-processing is, therefore, both a physical and digital preparation step that lays the foundation for reliable and geometrically accurate repair. Physically, it ensures that the substrate is sound and clean. Digitally, it provides an accurate 3D model that precisely guides the deposition process.

2.1.2 Material Deposition with DED

The core of the DED-based repair process is the controlled deposition of new material onto the prepared surface. In both DED-Arc and DED-LB, this is layer by layer, following a predefined toolpath that reflects the geometry of the damaged area. The deposition toolpath is typically generated during the digital planning stage, where strategies such as raster or zig-zag patterns are selected to ensure uniform coverage and stable bonding [7,12].

In DED-Arc, deposition follows a continuous toolpath based on the geometry of the damaged area. Higher deposition rates typically characterize arc-based systems, but they also introduce more heat into the part, which can affect dimensional accuracy and induce residual stresses [9].

To manage these effects, delays are introduced between layer depositions to allow partial cooling, which helps reduce distortion and thermal accumulation [14].

In DED-LB, the laser energy generates a localized melt pool on the substrate, enabling precise material deposition. The high energy density of the laser results in a small melt pool and a narrow heat-affected zone, which reduces thermal distortion and contributes to finer grain structures and a strong metallurgical bond between the deposited and base material [4,11]. The process is more sensitive to deviations in feedstock positioning and surface geometry, which is why higher scanning resolution and more precise toolpath planning are often required [13].

In both methods, the deposition process is influenced by a set of interdependent parameters, including feed rate, energy input, and movement speed. These parameters are carefully tuned depending on the part geometry, material, and repair objectives. It is important to note that optimal settings are highly case-specific and cannot be generalized without context [7,9].

Shielding gas is also applied during deposition in both DED-Arc and DED-LB to protect the molten pool from oxidation and other atmospheric contamination. Maintaining a stable and defect-free deposition environment is critical for achieving strong metallurgical bonding and ensuring the functional integrity of the repaired part [15].

While DED-Arc and DED-LB differ in precision and heat input, both require a tightly controlled deposition stage to ensure dimensional accuracy, material integrity, and overall structural performance.

2.1.3 Post-processing

After the deposition stage, post-processing is applied to restore the dimensional accuracy, surface quality, and mechanical performance of the repaired part. While DED-LB often achieves a geometry close to the final shape due to its high deposition precision, DED-Arc typically involves the addition of excess material. This allows for subsequent machining to refine the surface and ensure that the part meets the required tolerances and functional properties.

In DED-Arc applications, thermal characteristics such as slower solidification rates and lower temperature gradients result in larger molten pools and broader heat-affected zones compared to DED-LB methods [10]. These factors can lead to coarser microstructures and increased residual stresses, particularly in critical repair contexts [12]. Further steps, such as postdeposition machining and heat treatments, are often essential to eliminate built-up stress and to improve both geometric accuracy and structural integrity [12]. In some implementations, in-situ hot rolling has also been applied during or immediately after deposition to reduce residual stresses, refine microstructure, and increase hardness, potentially minimizing the need for separate heat treatment [16].

Due to its more localized energy input and narrower melt pool, DED-LB generally produces smoother surfaces and more consistent bead geometries. This can reduce the extent of post-processing required, although fine machining or polishing is still typically applied to meet functional tolerances, particularly in precision applications [11]. The minimized heat-affected zone in laser-based processes also lowers the need for thermal treatments aimed at stress relief, especially when appropriate process parameters have been used during deposition [7].

2.1.4 Comparison Summary of DED-Arc and DED-LB Process Characteristics

Table 1 provides a side-by-side overview of the main process steps involved in DED-Arc and DED-LB repair workflows. The table highlights the most significant differences between the two methods in terms of their process characteristics.

Table 1. Overview of Process Characteristics: DED-Arc and DED-LB

Process Step	**DED-Arc**	**DED-LB**
Surface preparation	Mechanical methods (grinding, machining)	Like DED-Arc, but may be adapted for laser accessibility
Geometric scanning & modelling	Standard scanning and point cloud processing	Higher resolution often required; more precise segmentation
Toolpath generation	Standard slicing; less sensitive to micro-variation	More accurate path planning needed; sensitive to deviations
Material deposition	Arc melts wire; high depositions rate, more heat input	Laser melts wire/powder; smaller melt pool, more precise
Thermal control during deposition	Intentional cooling delays between layers to reduce heat accumulation and distortion	Less thermal input; better thermal stability
Post-processing	Machining often required; larger heat-affected zones, sometimes hot rolling	Less post-processing, smoother surface, minor finishing only, heat treatment rarely required

As shown in Table 1, both DED-Arc and DED-LB follow the same overall process structure but differ in how each stage is executed. DED-Arc emphasizes robustness and deposition efficiency, using standard scanning and path planning methods, but it generates more heat and often requires heavier post-processing. In contrast, DED-LB achieves greater precision and smoother surfaces through high-resolution scanning and finer thermal control, reducing finishing needs but demanding higher accuracy in earlier stages.

2.2 Strengths and Challenges in Repair Context

Arc- and laser-based DED methods offer distinct advantages and notable challenges when used for repairing metal components. Both technologies enable the restoration of worn or damaged parts by selectively adding material only where needed, reducing the amount of waste compared to conventional manufacturing methods. This localized deposition also extends component life and avoids complete replacement, which is especially valuable in high-cost or large-scale applications [8,11].

A key strength of DED-Arc is its high material deposition rate and compatibility with conventional welding equipment, enabling cost-effective restoration of large industrial components[8]. Furthermore, using wire as feedstock simplifies material handling and provides relatively high material utilization rates. These attributes make DED-Arc well-suited for heavy repair tasks in the energy, marine, and construction sectors [17]. However, the process also presents technical challenges: high heat input can lead to residual stresses and shape distortion, and the resulting surface quality often necessitates post-processing to meet dimensional requirements [15,18].

DED-LB, by contrast, offers precise control over energy input and melt pool size, resulting in narrower heat-affected zones and improved surface quality. This makes it especially suitable for repairs that demand tight tolerances, minimal distortion, and refined microstructures [11]. The smaller melt pool also reduces thermal loading on the part, which is advantageous when dealing with thin-walled geometrically complex components [7].

However, DED-LB is not without limitations. The process is more sensitive to feedstock positioning, surface irregularities, and alignment precision. In addition, laser-based systems typically involve higher equipment costs and more complex control requirements, which may limit their accessibility in certain industrial settings. Furthermore, DED-LB typically incurs higher operational costs compared to DED-Arc, partly due to the use of powder feedstock in DED-LB, which is more expensive and less efficiently utilized than the wire feedstock predominantly employed in DED-Arc [10]. Maintaining consistent quality also demands high-resolution scanning and precise toolpath generation, adding to the overall complexity of the repair workflow [9].

Beyond these system-level challenges, DED-LB processes can also suffer from microstructural heterogeneity, porosity, and residual stresses, particularly in materials such as stainless steel. In stainless steels, the combination of high thermal gradients, dynamic melt pool behaviour, and rapid solidification during deposition leads to heterogeneous microstructures. This includes features such as epitaxial columnar grain growth, grain coarsening at increasing build heights, and variations in microhardness. These effects are closely tied to the thermal gradients and solidification rates inherent in DED-LB, contributing to forming porosity, residual stresses, and localized mechanical property variations [19].

In summary, DED-Arc and DED-LB offer complementary strengths for industrial repair: the former excels in throughput and robustness, while the latter provides superior precision and surface quality. Selecting the appropriate method depends on the specific requirements of the repair task, such as part geometry, material sensitivity, and functional performance expectations.

3 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a methodology used to evaluate the environmental impacts associated with all stages of a product's life, from raw material extraction and processing to manufacturing, use, and end-of-life. The method provides a quantitative basis for comparing the sustainability of different processes and products across their entire life cycles. It is particularly valuable in industrial applications, where decisions about material use, process selection, and end-of-life strategies significantly influence environmental performance [20].

Two international standards, ISO 14040 and ISO 14044, define the framework for conducting LCA. ISO 14040 provides the overall principles and structure, while ISO 14044 outlines specific requirements and guidelines for implementation. Together, they define four main phases of an LCA Study: goal and scope, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation. These phases ensure methodological consistency and transparency in assessing environmental burdens [21]. However, methodological challenges, such as data availability, allocation rules, and system boundary choices, can significantly impact the outcomes and comparability of LCA studies.

In LCA of DED-based repair, several environmental impact categories are commonly evaluated to capture the environmental performance across the full product lifecycle. The most widely assessed category is the Global Warming Potential (GWP), which quantifies greenhouse gas emissions in kilograms of carbon dioxide equivalents (kg CO_2-eq) [20]. Another important metric is the Cumulative Energy Demand (CED), which measures the total amount of primary energy consumed throughout the product lifecycle, typically expressed in megajoules (MJ) [20]. The selection of the functional unit is crucial in LCA studies, as it defines the basis for the comparison. Typical functional units include "per kilogram of deposited material" or "per finished component", providing a consistent framework for evaluating environmental impacts across manufacturing or repair processes [22].

As the manufacturing sector seeks to reduce its environmental footprint, LCA has become a widely accepted decision-supporting tool. It has been particularly useful in evaluating additive manufacturing (AM) technologies, where claimed benefits such as reduced material waste and energy consumption require systematic validation. The relevance of LCA is further emphasized when AM is applied not for new part production but for repair, where environmental savings may be even more pronounced due to avoided raw material extraction and reduced manufacturing demand [20].

3.1 DED-Based Repair through the Lens of Life Cycle Assessment

DED technologies, particularly DED-Arc and DED-LB variants, have gained increasing attention in metal part repair due to their potential for material efficiency and process customization. LCA offers a structured method to evaluate their environmental performance, especially in comparison to conventional manufacturing or full part replacement. Applying LCA to repair contexts helps to reveal whether DED-based approaches result in meaningful environmental savings over the full product lifecycle [20].

LCA studies on DED have demonstrated reduced material waste compared to subtractive methods [23]. Since DED processes typically rely on adding only the needed volume, the process avoids the extensive removal, which is typically necessary in conventional Computer Numerical Control (CNC) machining. In particular, DED-arc can result in lower life cycle impacts in use cases where geometric complexity is limited and material volumes are high [23].

The type of feedstock used in DED processes can also significantly influence material efficiency and environmental impact. DED-Arc primarily utilizes wire feedstock, which generally results in high material utilization during deposition, although additional material loss occurs during post-processing operations. In contrast, DED-LB often employs powder feedstock, where inefficiencies such as overspray and powder recovery losses can lead to much greater raw material consumption. These differences highlight the importance of considering feedstock characteristics when assessing the overall life cycle performance of DED-based repair methods [3,24].

Some assessments have applied multi-criteria decision analysis (MCDA) to evaluate DED-based methods in industrial repair contexts, taking into account not only environmental indicators but also cost, time, and quality aspects. This broader perspective highlights practical trade-offs often encountered in real-world applications [25].

While most existing literature has focused on DED-Arc, the increasing adoption of DED-LB in precision repair applications highlights a need for further LCA investigations. Currently, comparisons between DED-Arc and DED-LB in literature remain scarce despite their differing energy profiles and equipment requirements. Extending the scope of LCAs to cover both technologies equally would provide more balanced insights for decision-making in industrial contexts.

3.2 Methodological Limitations in LCA of Repair Processes

Although LCA is a standardized tool, its application to repair processes, particularly those involving emerging technologies like DED, presents several methodological challenges that can influence the reliability and comparability of results.

One recurring issue in the literature is the lack of clarity and consistency in defining system boundaries. In several cases, it is not explicitly stated which life cycle stages are included in the assessment, forcing readers to infer this information from figures or result sections. This undermines comparability between studies and limits the interpretability of findings [26].

Another key limitation is data availability and transparency. Many studies rely on secondary data or generalized inventory databases but often fail to report which version of the database was used or which system model was applied. In some cases, key inputs, such as raw materials or energy flows, are insufficiently documented, and proxy data from unrelated contexts may be used without adequate justification or uncertainty assessment [26]. This lack of transparency hinders reproducibility and weakens the interpretative strength of comparative analyses [27].

The choice of functional unit is also critical in repair-oriented LCAs. Since repaired components are typically compared either to newly manufactured parts or to alternative repair methods, ensuring functional equivalence between the compared objects is essential. However, some studies fail to provide sufficient justification or clarity in their functional unit definitions, limiting the relevance and fairness of their comparisons [26].

Finally, many studies lack proper uncertainty analysis, despite ISO standards recommending its inclusion. Techniques such as sensitivity analysis or Monte Carlo simulations are rarely used, even though they are particularly important in early-stage or ex-ante assessments, where technological maturity is low and input data may be sparse or estimated [3]. These uncertainties are inherent in evaluating emerging technologies and must be acknowledged when interpreting LCA results.

Taken together, these methodological limitations underline the importance of cautious interpretation and transparent reporting in comparative LCA studies, especially when assessing repair-oriented applications of DED.

4 Case Study: LCA of a Repaired Metal Part

To complement the literature-based comparison of DED-Arc and DED-LB presented in the previous chapters, this section introduces a real-world example of a DED-LB repair process. The aim is to demonstrate how typical LCA metrics, such as energy consumption, material efficiency, and process inputs, can be examined in the context of actual industrial conditions.

The case focuses on the repair of a hydraulic cylinder rod using powder-based DED-LB performed by a Finnish industrial operator. The DED-LB process parameters and outcomes are based on direct communication with the company. Instead of conducting a full-scale LCA, the study applies a simplified but structured approach based on a realistic functional unit: the repair of one hydraulic cylinder rod.

To enable a fair comparison, it is assumed that both DED-LB and DED-Arc repair technologies are available within the same facility. This assumption allows the analysis to focus solely on the repair phase, covering direct emissions and resource use, while excluding upstream material production and downstream end-of-life impacts. This provides a coherent basis for comparing the environmental performance of the two processes under practical repair conditions.

Several inventory-related factors must be considered in both DED-LB and DED-Arc processes. These include not only direct energy consumption but also the use of auxiliary materials, material losses, and post-processing needs. For example, shielding gas is used not only to protect the molten pool but, in the case of DED-LB, also to transport powder feedstock, which can lead to higher gas consumption compared to wire-based systems [24].

Material utilization efficiency is another critical factor. It determines how much raw material is required and how much waste is generated. Lower utilization rates increase both material demand and waste output, which in turn elevate cumulative energy use and emissions. Additionally, post-processing operations such as machining and heat treatment add further energy consumption and material loss, increasing the environmental burden of the repair process [24,28]. Together, these factors define the environmental parameters that are explored further through a practical repair case in the following sections.

4.1 LCA of the Laser-Based Repair (DED-LB)

This section examines the environmental impact of a DED-LB repair process applied to a worn hydraulic cylinder rod. The component, made from S355 structural steel, was restored by a Finnish company using powder-based DED-LB with Stellite 21 as the coating material. The repair included pre-machining, laser deposition, and post-machining steps, resulting in an estimated threefold increase in service life compared to an uncoated new component.

Figure 2. A repaired hydraulic cylinder rod restored using DED-LB. The image shows a similar component type to the one analyzed in this case study (red arrow points to the part that has been worked on).

The majority of technical values and process parameters presented in this section are based on direct communication with the industrial service provider responsible for the repair. However, estimates for post-processing energy use are based on literature data due to the unavailability of measured values.

The laser deposition was performed using a 3.8 kW laser at a travel speed of 1500 mm per minute. The layer thickness was approximately 1.0 mm, with a vertical increment of 2 mm per rotation. Based on an estimated deposition area of 300 mm in diameter and 400 mm in length, the total deposition time was about 2.1 hours. The laser system had an electrical-to-optical efficiency of approximately 45 percent, and the overall material utilization rate was reported to be around 95 percent, indicating low powder waste. Argon was used both as a shielding gas and as a carrier for powder feedstock, with a flow rate of approximately 40 liters per minute throughout the process. An overview of the deposition parameters is presented in Table 2, while energy and gas consumption values are shown in Table 3.

Energy consumption included the laser and auxiliary systems. The cooling system consumed about 9.5 kW and operated for approximately one-third of the total process time. In addition, pre-machining took approximately 1 hour, while post-machining, including grinding, required about 2 hours. The electricity consumption of the post-processing phase was estimated using a reference value of 2.24 kWh for removing 0.57 kg of steel (density 7.8 g/cm^3), corresponding to approximately 3.93 kWh/kg [23]. In this case, the deposited material was Stellite 21, a cobalt-chromium alloy with significantly lower machinability than steel. Experimental results for a similar alloy, Stellite 1, showed very low material removal rates and confirmed the alloy's poor machinability due to its hardness and thermal properties [29]. To account for this, a conservative +30% correction was applied to the energy intensity, resulting in 5.1 kWh/kg. Pre-machining energy was excluded, as the required operations are assumed to be identical for both DED-LB and DED-Arc cases. No heat treatment was needed, as the localized energy input and the coating's metallurgical properties did not require it.

Table 2. Material usage and losses in the DED-LB repair.

Category	**Value**
Component outer diameter (mm)	300
Deposition length (mm)	400
Deposition thickness before machining (mm)	1
Final deposition thickness after machining (mm)	0.5
Material density (g/cm^3)	8.33
Deposition volume before machining (cm^3)	377
Deposition mass before machining (kg)	3.14
Powder utilization efficiency (%)	95
Powder input required with 95% efficiency (kg)	3.3
Material lost in process (5%) (kg)	0.16
Material removed during final machining (kg)	1.57
Material remaining on component (kg)	1.57

The values in Table 2 illustrate how the efficiency of the process affects overall resource use. Approximately 3.14 kg of Stellite 21 was deposited onto the component surface. Due to final machining, only 1.57 kg remained on the part, almost exactly half (49.992%) of the deposited mass. This near-50% result, however, does not stem from the halved thickness, but rather from the underlying geometry. With a material utilization efficiency of 95%, the total powder input needed was 3.3 kg, meaning that 0.16 kg of powder was lost in the deposition phase of the process. These values emphasize the significance of machining losses even in high-efficiency deposition systems.

Table 3. Estimated energy consumption and gas usage during DED-LB repair

Category	**Value**
Laser power (kW)	3.8
Laser operating time (h)	2.1
Laser energy consumption (kWh)	7.98
Cooling system power (kW)	9.5
Cooling system operating time (h)	0.7
Cooling energy consumption (kWh)	6.65
Post-processing energy (kWh)	8.0
Total energy consumption (kWh)	22.63
Shielding/carrier gas flow rate (L/min)	40
Total process time (min)	126
Total shielding/carrier gas used (L)	5040

Table 3 summarizes the energy and gas consumption for the laser-based repair phase. The post-processing energy estimate is based on the calculated removal of 1.57 kg of Stellite 21 using an adjusted energy intensity of 5.1 kWh/kg (as explained earlier). The laser and cooling system together consumed 14.63 kWh of energy, while post-processing added 8.0 kWh, resulting in a total energy use of 22.63 kWh. The process also required 5040 liters of argon gas. The high gas usage reflects the dual role of argon in DED-LB: both shielding the molten pool and transporting the powder feedstock. This auxiliary input is a relevant factor when comparing DED-LB to wire-based systems, where shielding gas consumption is typically lower.

4.2 LCA of the Arc-Based Repair (DED-Arc)

This section evaluates the environmental impact of the DED-Arc repair process applied to the same worn hydraulic cylinder rod examined in the previous section. The repair utilizes S355 structural steel wire and a welding arc as the heat source, with the intention of restoring the same target layer thickness and surface area as in the laser-based case.

All technical values and process parameters presented in this section are based on existing literature and adjusted to reflect the geometry and material used in the DED-LB example. The data focuses solely on the deposition and finishing phases, without including upstream material production impacts.

Based on literature covering the use of S355 steel wire in DED-Arc additive manufacturing, a deposition rate of 2 kg/h is adopted for this assessment [30]. This value reflects the theoretical deposition rate used in environmental modelling and does not include interlayer dwell time or idle phases of the equipment. The same source reports an energy consumption of 1.97 kWh per kilogram of deposited steel for the welding process itself. In addition, robotic movement and ventilation during deposition contribute 0.22 kWh/kg and 0.27 kWh/kg, respectively [30]. The total energy consumption is summarized later in Table 5.

To achieve a final coating thickness of 0.5 millimeters, a deposited layer of 2.5 mm is assumed. This results in a machining allowance of 2.0 mm, which is necessary due to the lower surface quality typical of DED-Arc processes and the challenging cylindrical geometry of the repaired component. While estimating the required overbuild is not straightforward, comparable cases in literature report machining allowances between 1.85 and 1.9 mm for DED-Arc fabricated structural steel components. In these studies, the entire surface required finishing due to surface waviness and dimensional deviations, and importantly, the geometries were flat surfaces [28]. Based on these findings and the increased surface complexity in the present case, a 2.0 mm allowance is considered appropriate. The corresponding mass estimates are presented in Table 4.

With a deposition area of 300 mm in diameter and 400 mm in length, and an assumed deposited thickness of 2.5 mm, the total deposited volume is estimated to be 947 cm^3. Using a material density of 7850 kilograms per cubic meter for S355, this corresponds to a deposited mass of approximately 7.44 kg.

Shielding gas is required throughout the process. For S355, a mixture of 82% argon and 18% carbon dioxide is typically used. In the selected sources, flow rates between 12 and 16 liters per minute have been reported, depending on deposition conditions. As the assumed deposition rate in this case is 2 kg/h, a flow rate of 12 liters per minute is used for consistency [28,30].

Material efficiency during deposition is high, with the welding stage estimated to achieve 99% utilization. Most material loss in this case results from post-processing rather than deposition itself [30]. Post-machining is assumed to involve 2.0 mm of material to reach the final surface. Pre-machining, as in the DED-LB case, is assumed to reduce the diameter by 1 mm. The associated energy demand for pre-machining is excluded from the analysis, as the operation is identical in both cases and thus does not affect the comparative results.

An overview of the deposition parameters is presented in Table 4, while energy and gas consumption values are shown in Table 5.

Table 4. Material usage and losses in the DED-Arc repair

Category	**Value**
Component outer diameter (mm)	300
Deposition length (mm)	400
Deposited layer thickness (mm)	2.5
Final layer thickness after machining (mm)	0.5
Material density (g/cm^3)	7.85
Deposited volume (cm^3)	947
Deposited mass before machining (kg)	7.44
Wire input required (kg)	7.51
Wire utilization efficiency (%)	99
Material lost in process (1%) (kg)	0.07
Material removed during final machining (kg)	5.96
Material remaining on component (kg)	1.48

Table 4 presents the calculated material use and losses associated with the DED-Arc process. A total of approximately 7.44 kg of S355 structural steel was deposited onto the surface of the pre-machined component. Following final machining, only 1.48 kg remained on the part, while 5.96 kg was removed. These values reflect the 2.0 mm machining allowance applied to achieve the final layer thickness of 0.5 mm. The deposited volume before machining was around 947 cm^3, reduced to 188 cm^3 after machining. With a wire utilization efficiency of 99%, the estimated material loss during deposition was only 0.07 kg. These results illustrate the substantial impact of post-processing on material efficiency in DED-Arc repair.

Table 5. Estimated energy consumption and shielding gas use in the DED-Arc repair

Category	**Value**
Welding energy (kWh)	14.66
Robotics energy (kWh)	1.64
Ventilation energy (kWh)	2.01
Post-processing energy (kWh)	23.42
Total energy consumption (kWh)	41.73
Shielding gas flow rate (L/min)	12
Total deposition time (min)	223
Total shielding gas used (L)	2678

Table 5 presents the estimated energy consumption and shielding gas use associated with the DED-Arc repair. The welding process consumed approximately 14.66 kWh, based on an energy intensity of 1.97 kWh per kilogram and deposited mass of 7.44 kg. Additional consumption came from robotic motion (0.22 kWh/kg x 7.44 kg = 1.64 kWh) and ventilation (0.27 kWh/kg x 7.44 kg = 2.01 kWh). Post-processing required 23.42 kWh, calculated from a removal of 5.96 kg of steel and an energy use of 3.93 kWh per kilogram [23]. Altogether, the process consumed approximately 41.73 kWh of electricity. A shielding gas flow rate of 12 liters per minute was maintained throughout the 223-minute deposition process, resulting in total gas usage of 2678 liters.

4.3 Comparison of DED-LB and DED-Arc

To assess the relative environmental performance of the two repair processes, this section compares the DED-LB and DED-Arc methods using a set of quantitative indicators. The comparison is based on the data presented in the previous sections and focuses on energy consumption, material efficiency, and shielding gas use. Both methods were applied to repair the same type of component, a worn hydraulic cylinder rod, using similar layer thickness and geometries. However, the process characteristics, feedstock material, and operational requirements of DED-LB and DED-Arc differ significantly. Table 6 summarizes the key findings, enabling a direct evaluation of each method's environmental trade-offs.

Table 6. Environmental comparison of DED-LB and DED-Arc repair processes

Parameter	**DED-LB**	**DED-Arc**
Total energy consumption (kWh)	22.63	41.73
Raw material input (kg)	3.3 (Stellite 21)	7.51 (S355)
Material deposited (kg)	3.14	7.44
Final material retained (kg)	1.57	1.48
Material loss (kg)	1.73	6.03
Overall material efficiency (%)	47.6	19.7
Deposition efficiency (%)	95	99
Shielding gas used (L)	5040 (argon only)	2678 (argon CO_2 mix)

The comparison shows that the DED-LB process performed more favorably in terms of total energy consumption, with approximately 19 kWh less required than in the DED-Arc process. This difference is primarily due to the larger volume of material deposited and subsequently removed during post-processing in the arc-based case. Although the deposition efficiency was slightly higher in DED-Arc, the need for overbuilding led to significantly higher post-processing energy use and material waste.

In terms of overall material efficiency, DED-LB achieved a retention rate of 47.6%, while only 19.7% of the deposited material in the DED-Arc case remained on the component after machining. This indicates that over 80% of the arc-deposited material was ultimately removed during finishing, highlighting a key drawback of the arc-based process when tight dimensional tolerances and a thin deposition layer are required. In absolute terms, the DED-LB process required approximately 3.3 kg of powder feedstock, resulting in a material loss of 1.73 kg. In contrast, the DED-Arc process consumed 7.51 kg of wire, of which 6.03 kg was lost, primarily due to overbuilding and subsequent machining.

The total volume of shielding gas consumed was higher in the DED-LB process (5040 liters) than in the DED-Arc (2678 liters). However, this difference is largely due to the design of the process setup: in DED-LB, argon serves both as a shielding gas and as a carrier for the powder feedstock. In contrast, DED-Arc uses shielding gas only, but the mixture contains carbon dioxide, which contributes directly to greenhouse gas emissions. The environmental relevance of gas usage is therefore primarily determined by the total amount consumed and the emission intensity of the gas, not by its specific role in the process.

To quantify the direct process phase emissions, the average electricity emission factor reported by Fingrid for the year 2024 [31], was applied. Since electricity is the primary energy input in both DED-based repair processes, this emission factor provides a practical and consistent basis for environmental comparison. Using the value of 33 gCO_2/kWh, the electricity-related emissions for the DED-LB process amount to approximately 0.75 kgCO_2eq, while the DED-Arc process results in 1.38 kgCO_2eq. These figures represent the most concrete and comparable environmental indicators within the defined system boundary of this study, and they reinforce the relative advantage of the laser-based method in terms of process-phase energy emissions.

It should be noted that the majority of greenhouse gas emissions associated with shielding gas and feedstock materials originate from their production and distribution rather than from the repair process itself [30]. These upstream impacts are excluded here due to the process-phase scope. Similarly, although material losses from post-processing are accounted for quantitatively, their end-of-life treatment, such as reuse or recycling, is typically not assessed in detail in existing studies. This limits the transparency of material-related burdens and introduces uncertainty to comparative conclusions.

Within this defined context, DED-LB showed lower electricity use and higher material efficiency, mainly due to reduced machining losses. However, these findings are specific to the studied component geometry, process planning assumptions, and the defined functional unit. In particular, the DED-Arc case is based on literature-derived estimates rather than measured process data, introducing additional uncertainty. Therefore, the results should be interpreted with caution and not generalized beyond this case without further validation.

5 Conclusions

This thesis has compared arc-based and laser-based DED repair processes through LCA that focused exclusively on the repair phase. The analysis revealed notable differences in energy consumption, material efficiency, and shielding gas use, providing insight into the environmental trade-offs between the two approaches. These results underline the importance of process selection in terms of sustainability and show how key parameters such as feedstock utilization rates or energy needs during deposition and post-processing can affect the resource efficiency of a repair process.

5.1 Summary of Key Findings

The results presented in Chapter 4 highlight several key differences between the two DED-based repair methods analyzed. The laser-based process demonstrated lower energy consumption and higher material efficiency, although this was accompanied by a significantly higher shielding gas usage relative to the arc-based process. These differences became evident within the process phase, where the precision and control of the laser system contributed to reduced waste and energy use.

That said, it is important to consider the context in which these results were obtained. The arc-based method was assessed in a repair case that involved a relatively small deposition area and modest material requirements. These conditions did not align with the typical strengths of arc-based deposition, which is generally better suited for large-scale repairs where its high deposition rate and excellent feedstock utilization can be fully leveraged, particularly in applications where high surface quality is not a primary requirement. In contrast, the laser-based method matched the repair task well due to its fine control, localized heat input, compatibility with smaller geometries, and the ability to produce smoother surface finishes that reduce the need for excessive overbuilding and post-processing. The results of this study, therefore, do not suggest that one method is inherently superior but rather illustrate how each process performs under specific constraints.

One specific observation in this study was the reported 95% powder utilization rate in the laser-based repair. This value stands out in comparison to values commonly cited in the literature for powder-based DED processes. For example, a recent study using an optimized annular nozzle with an inside-laser coaxial powder stream reported an average utilization rate of 83.2%, which was considered efficient under controlled laboratory conditions [32]. This comparison underlines the influence of process configuration, nozzle design, and operational parameters on material efficiency. It also suggests that the high efficiency observed in this case likely reflects the specific setup and optimization rather than a generalizable advantage of the laser-based method.

Taken together, the findings of this study reinforce the need for case-specific process selection. While the laser-based process demonstrated better performance in this particular repair scenario, the results cannot be automatically generalized to other use cases. Instead, they point to the broader understanding that process suitability in DED-based repair depends heavily on part geometry, deposition volume, and the characteristics of the equipment used. These same factors also determine which process is environmentally optimal, emphasizing that sustainability in additive repair must be evaluated in close connection with the technical and practical requirements of each case.

5.2 Implications for industry

For industrial actors considering the adoption of additive repair technologies, this study reinforces the importance of tailoring process choices to specific repair scenarios. Rather than defaulting to a single DED method, companies should evaluate factors such as repair volume, geometrical complexity, surface quality requirements, and operational constraints when selecting between arc- and laser-based deposition. These decisions are not only technical but also linked to broader sustainability goals, as process selection can significantly affect environmental burden.

From an implementation perspective, the study highlights the value of reliable process data and in-depth knowledge of system capabilities. Industrial stakeholders can benefit from integrating environmental assessments into early decision-making, such as simplified LCAs, which can support the selection of environmentally preferable repair strategies in different contexts. Furthermore, as additive repair technologies continue to evolve, there is growing potential for companies to enhance sustainability by optimizing deposition parameters, refining process control, and investing in methods that balance precision, speed, and efficiency.

5.3 Limitations and Future Research Directions

The scope of this thesis was intentionally limited to the repair phase of DED-based processes, excluding upstream and downstream life cycle stages. While this allowed for a focused comparison, it also narrows the applicability of the result to other life cycle contexts. Furthermore, the laser-based process assessment was based on a single real-world case, while the arc-based process relied on approximations from literature. These choices were appropriate for the scope of a bachelor's thesis, but they also introduce uncertainty and limit generalizability. In particular, the environmental burden related to shielding gas and material use mostly arises from their production and transportation rather than the deposition process itself.

Future research could address these limitations by incorporating more comprehensive LCA boundaries and multiple empirical cases, particularly for arc-based repair. Including additional environmental impact categories and exploring economic perspectives, such as life cycle costing, could further strengthen the decision-making relevance of future studies. Moreover, systematic comparisons between different DED configurations and repair applications would help develop more robust frameworks for evaluating additive repair from both environmental and practical viewpoints, especially when considering opportunities for material recycling and reuse of process-side waste.

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