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EXTENDING COMPONENT LIFE THROUGH HYBRID ADDITIVE MANUFACTURING: ENVIRONMENTAL ASSESSMENT OF A REMANUFACTURED VALVE COMPONENT

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Abstract: *This study evaluates the environmental benefits of extending the life of industrial parts through hybrid additive manufacturing instead of full replacement. A case study involved modifying an LF2 carbon steel ball valve flange using Laser Directed Energy Deposition (LDED) with recycled 316L stainless steel powder. The process included CNC milling, metal deposition, and precision machining. Non-destructive and pressure tests confirmed the mechanical integrity and performance of the remanufactured component. A Life Cycle Assessment compared this approach with conventional replacement, showing significant reductions in raw material use, energy consumption, and* CO_2 *emissions. The results highlight hybrid manufacturing as a sustainable solution aligned with circular economy goals, promoting reuse and minimizing environmental impact without compromising functionality.*

Key words: *Hybrid Additive Manufacturing, Laser Directed Energy Deposition (LDED), Remanufacturing, Circular Economy, Life Cycle Assessment (LCA), Recycled Metal Powder, Industrial Component Repair.*

1. INTRODUCTION

In industrial pipeline systems, components such as pressure valves often require modification to meet new connection standards during system upgrades or reconfigurations. Traditionally, adapting a part involves manufacturing entirely new assemblies, which is time-consuming, resource-intensive, and wasteful, particularly when the rest of the parts remains fully functional. This challenge is common in sectors such as energy or chemical where system integration is routine.

Remanufacturing offers a sustainable alternative by restoring used components to a condition that meets or exceeds their original standards, thus extending product life through responsible life cycle design. Compared to recycling, remanufacturing is more resource-efficient, as it retains the functional value of durable components rather than downcycling them to raw materials [1]. This approach significantly reduces material consumption, shortens lead times, and supports circular economy objectives by maintaining the value of critical parts over multiple use cycles [2], [3] .

Remanufacturing methods include both conventional and advanced approaches. Traditional techniques such as welding and machining remain in use but often lack precision, efficiency, and flexibility. In contrast, additive manufacturing enables accurate, automated repairs with strong metallurgical bonding, minimal material waste, and short lead time. These features make it a suitable solution for sustainable, high-performance component restoration aligned with circular economy principles [4][5].

Among additive manufacturing approaches, Directed Energy Deposition (DED) has gained particular attention for its ability to selectively add material to damaged regions, making it highly effective for repairing high-value components and reducing maintenance downtime [6].

DED uses focused energy sources, such as lasers, electron beams, plasma or electric arcs, to melt feedstock metal and deposit it layer by layer onto a substrate, enabling rebuilding of complex geometries [7].

Numerous studies have demonstrated the effectiveness of Laser Directed Energy Deposition (LDED) for restoring high-performance components across various industries. For instance, Richter et al. demonstrated successful mechanical restoration of Ti-6242 titanium blisk blades in aerospace applications using laser cladding, achieving enhanced tensile and fatigue strength [8].

Xiao and Huang improved surface accuracy in aero- engine blade repair through adaptive abrasive belt grinding post-processing [9]. Zhu et al. showed that laser cladding using H13 steel powder on 45 steel gears enhanced hardness and wear resistance, although with a reduction in tensile strength [10].

Wet al. used hot wire laser cladding to repair FV520B stainless steel, resulting in clad layers with mechanical properties comparable to or better than the original substrate [11]. Similarly, Song et al. reported strong metallurgical bonding and defect-free microstructures in repaired carbon steel grooves [12].

Although the technical feasibility of LDED is well established, quantitative data on its environmental performance remain limited. Life Cycle Assessment (LCA) offers a standardized methodology for evaluating environmental impacts across all stages of a product's life cycle, from raw material extraction to end-of-life. Governed by ISO 14040 and ISO 14044, LCA enables the identification of environmental hotspots and supports the comparison of alternative solutions to guide more sustainable design and manufacturing decisions [13].

This study investigates a sustainable alternative to full component replacement by employing hybrid additive manufacturing. LDED with recycled 316L stainless steel powder is applied to remanufacture an existing carbon steel valve flange.

The environmental performance of this approach is assessed through a comparative LCA, evaluating two scenarios: hybrid remanufacturing and the conventional production of a new flange using virgin LF2 carbon steel.

The objective is to quantify the potential environmental benefits of LDED-based remanufacturing and to demonstrate its viability as a circular and resource-efficient solution for industrial applications.

2. MATERIALS AND METHODS

2.1 Hybrid Additive Manufacturing

For deposition of the modified geometry, recycled 316L powder with a PSD of -150+45 µm provided by f3nice, Italy was utilized. The printability of the recycled powder was evaluated by printing cubic specimens of 35× 35 ×30 mm using optimized parameters for the same virgin material. Depositions were performed using a LASERTEC 65 3D system (DMG MORI, Germany), equipped with a coaxial nozzle and a 2400 W infrared (IR) fiber laser featuring a top-hat intensity profile and a 3 mm spot size at a 13 mm stand-off distance.

A laser power of 2000 W with a scanning speed of 1000 mm/min, powder flow of 12 g/min, hatch distance of 1.5 mm and layer thickness of 0.9 mm was applied for the depositions. A zig zag scanning strategy was employed with 90-degree rotation between successive layers. Argon Grade 5 (99.999% purity) was used as both the shielding and carrier gas, at flow rate of 5 L/min.

Following the deposition, the samples were sectioned via electrical discharge machining (EDM) and prepared for metallographic examination according to standard procedures.

Density of the specimens were evaluated using Archimedes method. Microhardness testing was carried out on polished cross-sections using a Vickers indenter (HM-200, Mitutoyo, Japan) with a test load of 200 g (HV0.2) and a dwell time of 10 seconds.

The deposition of the final geometry was performed using the abovementioned parameters.

The part program preparations for the subtractive and additive operations were performed using Siemens NX.

The dimensions of the modified geometry were measured using 3D scanning technology (CREAFORM MetraSCAN 3D, Canada) both after the deposition and final turning of the part.

2.2 Non-Destructive Tests (NDTs)

Following the LDED process, the modified flange underwent a comprehensive inspection and validation protocol to assess its structural integrity and operational readiness. A series of non-destructive tests were conducted to evaluate the structural integrity and quality of the remanufactured valve flange.

Dye Penetrant Testing (PT) was performed to detect surface-breaking discontinuities in the deposited regions. The test involved the use of a Velnet Solnet solvent cleaner, the red visible penetrant Rotvel Avio B, and the developer Rotrivel U (C.G.M., Italy).

Ultrasonic Testing (UT) was carried out to identify any internal flaws or lack of fusion within the deposited material. The inspection was performed using a USM 3S ultrasonic flaw detector (Krautkramer, Germany). A B4S probe with a nominal frequency of 4 MHz and a 24 mm crystal dimension at a 0° refraction angle (SN 57746 52994) was employed during the testing.

2.3 Life Cycle Assessment Analysis

To evaluate the environmental benefits of the hybrid AM approach compared to conventional part substitution, a comparative LCA was conducted. The analysis was performed using SimaPro software (version 10.1.0.4) in combination with the Ecoinvent 3 database for life cycle inventory data.

The functional unit was defined as one fully functional ball valve flange restored to operational condition, ensuring comparability between scenarios. The system boundaries were defined as cradle-to-gate for both scenarios. For the hybrid process, this included CNC milling, LDED deposition using recycled metal powder, post-processing, and quality testing. On the other hand, for the conventional approach, it included raw material extraction, rolling, rough machining, and finishing.

The life cycle inventory (LCI) was based on a combination of primary data (e.g., energy use, material input, and processing time collected during the experimental remanufacturing) and secondary data (sourced from Ecoinvent 3). End-of-life phases were excluded from the system boundaries as they are assumed to be identical and negligible in both scenarios. To ensure model consistency, key assumptions were adopted. In particular, for the hybrid additive manufacturing scenario, the metal powder used in the LDED process was assumed to be sourced from recycled stainless-steel scrap, reflecting actual practices by f3nice.

3. RESULTS

3.1 Machining and Remanufacturing of valve flange

A relative density of 99.9% was obtained in the samples printed by LDED. No lack of fusion or gas porosities were detected in the microstructure, implying the suitability of selected process parameters. The microhardness of the as-built part was 191 ± 4 HV0.2. This is slightly higher than the value for cold rolled annealed 316L stainless steel plates, i.e. 170HV, and is mainly attributed to higher cooling rates resulting in finer grains.

The initial phase of the geometrical modification process involved material removal to prepare the substrate for subsequent deposition. The workpiece coordinate system (WCS) was established through precision probing to ensure accurate alignment with the machine coordinate system. Material removal initiated with the machining of the existing flange using an end mill, followed by face milling to achieve the nominal height required for the modified component. To ensure a clean interface for deposition and minimizing risk of interfacial defects, the component was cleaned using compressed air to remove debris and wiped with ethanol to remove surface contaminants. Subsequently, LDED was employed to fabricate a new flange. The deposition process utilized the previously specified process parameters, with the scanning strategy adapted to a rotary scan to accommodate the component's geometry. During the process, approximately 350 g of material was deposited, with a powder efficiency of 85%. After, a 3D scanning procedure was conducted to verify that sufficient excess material was present for the final machining operation.

The deposited flange was then machined to its nominal dimensions via turning. Fig. 1 illustrates the sequential execution of the aforementioned procedures:

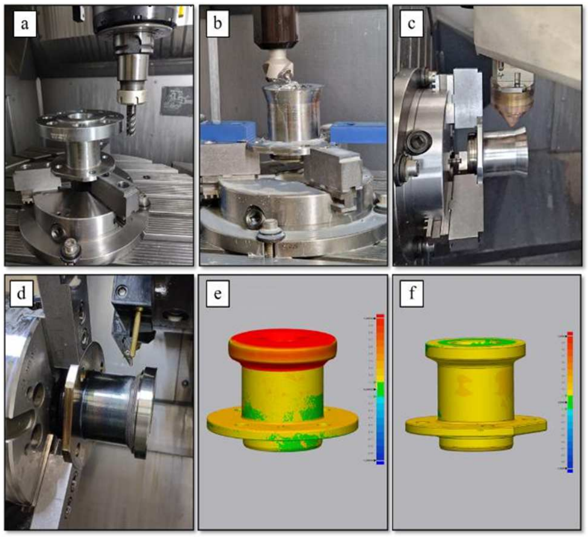

Fig. 1. Different steps from milling to deposition and final part after functional change

3.2 NDTs on the valve flange

Dimensional verification confirmed that the modified flange geometry conformed to the specified tolerances, ensuring compatibility with the required flange interface. Dye penetrant testing revealed no evidence of surface defects such as cracks or porosity in the deposited regions. Ultrasonic testing confirmed the absence of internal discontinuities, including lack of fusion and subsurface porosity, indicating sound metallurgical bonding throughout the deposited material. These results are summarized in Fig. 2, which illustrates the successful outcomes of the dye penetrant and ultrasonic inspections:

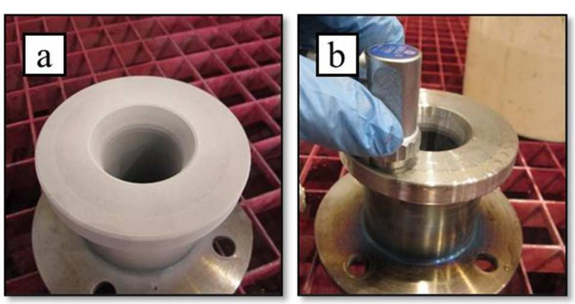

Fig. 2. Ball valve flange quality assessment via dye penetrant (a) and ultrasonic inspections (b).

3.3 LCA

The resulting environmental impacts were modeled and analyzed to determine the relative advantages of hybrid remanufacturing in terms of reduced resource consumption and emissions, in alignment with circular economy principles.

The LCA results demonstrate a clear environmental advantage of hybrid AM over conventional substitution across all eight impact categories defined by the EPD (2018) method. The comparison considers the entire process chain, from raw material acquisition and transportation to machining and finishing, for both scenarios. Detailed contribution analyses were performed for both the conventional and hybrid manufacturing routes.

In the conventional substitution scenario (Fig. 3), the highest environmental burdens are consistently associated with steel production, which contributes approximately 71% of the total impact in the global warming category and around 85% in abiotic depletion of elements. Steel production is also the dominant contributor across all other impact categories.

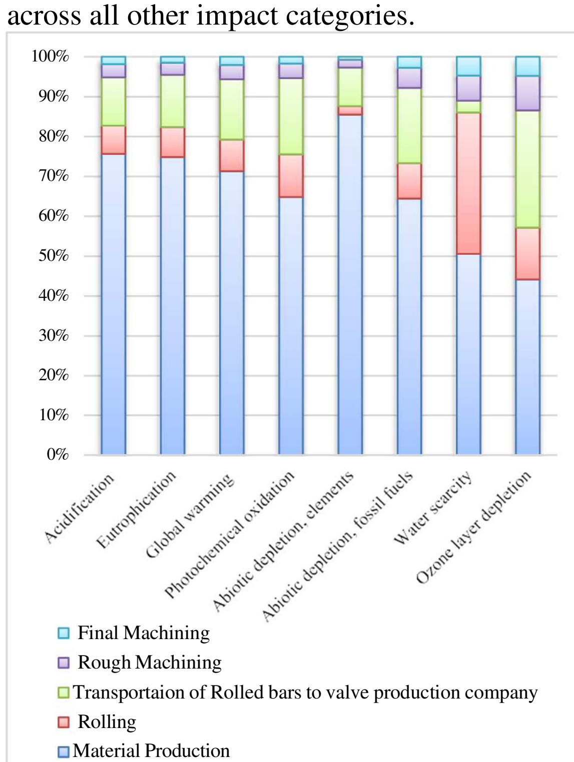

Fig. 3. Relative contribution of process steps to environmental impact categories for Conventional Substitution scenario

In the hybrid additive manufacturing scenario (Fig. 4), the LDED process emerges as the primary contributor to environmental impact. It accounts for 68% of the global warming potential, 84% of the water scarcity impact, and approximately 66% of abiotic depletion of elements.

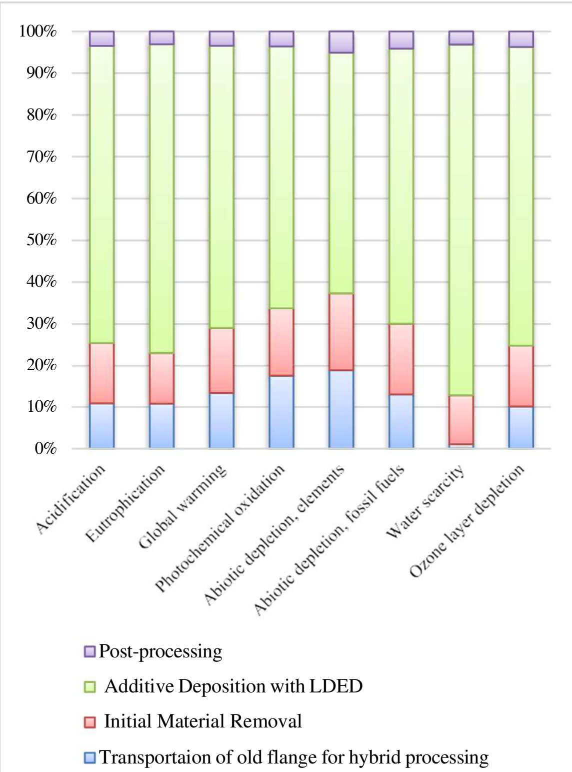

Fig. 4. Relative contribution of process steps to environmental impact categories for Hybrid AM scenario

The overall comparison between the two scenarios highlights the environmental advantages of hybrid additive manufacturing over conventional substitution. The results are based on midpoint indicators from the EPD 2018 method, applied to a consistent functional unit. As illustrated in Fig. 5, the hybrid route results in substantial reductions in environmental impact. Notably, global warming potential is reduced by 89%, and abiotic depletion of elements by 95%. Other impact categories, such as acidification, eutrophication, and photochemical oxidation, also show reductions of nearly 90%, while water scarcity and ozone layer depletion are lowered by 73% and 71% respectively.

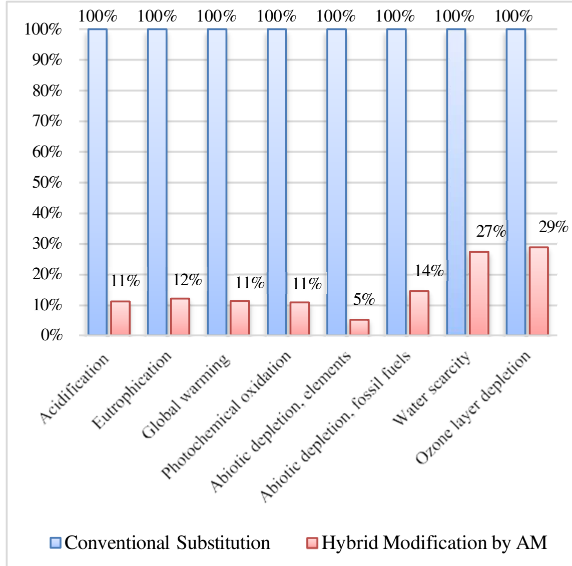

Fig. 5. Environmental impact comparison between Hybrid and Conventional scenarios

4. CONCLUSIONS

This study demonstrates the technical and environmental viability of using Laser Directed Energy Deposition for the functional modification of pressure-retaining components. The remanufactured valve flange achieved full functional equivalence with a conventionally manufactured part, as confirmed by dimensional checks, non-destructive evaluations, and functional performance tests. The LCA further highlights the sustainability benefits of the hybrid approach, showing significant reductions in global warming potential, abiotic resource depletion, and water scarcity compared to conventional substitution. These findings support the integration of LDED into remanufacturing workflows as a reliable and resource-efficient solution aligned with circular economy principles.

5. ACKNOWLEDGEMENTS

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Prelungirea duratei de viață a componentelor prin fabricație aditivă hibridă: Evaluarea de mediu a unei componente de robinet remanufacturate

Rezumat: Acest studiu evaluează beneficiile de mediu ale extinderii duratei de viață a pieselor industriale prin fabricație aditivă hibridă, în locul înlocuirii complete. Un studiu de caz a vizat modificarea unei flanșe de robinet sferic din oțel carbon LF2, utilizând Depunere Directă de Energie Laser (LDED) cu pulbere reciclată de oțel inoxidabil 316L. Procesul a inclus frezare CNC, depunere de metal și prelucrare de precizie. Testele nedistructive și de presiune au confirmat integritatea mecanică și performanța componentei remanufacturate. O evaluare a ciclului de viață a comparat această abordare cu înlocuirea convențională, evidențiind reduceri semnificative în utilizarea materiilor prime, consumul de energie și emisiile de CO_2. Rezultatele subliniază fabricația hibridă ca o soluție sustenabilă, aliniată cu obiectivele economiei circulare, promovând reutilizarea și reducerea impactului asupra mediului fără a compromite funcționalitatea.

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