ADVANCING ADDITIVE REPAIR: AUTOMATED FEASIBILITY TOOL DEVELOPMENT

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***ABSTRACT**: The transition toward circular and sustainable manufacturing operations presents a pressing challenge for the industry. Components with surface damage are often deemed non-reworkable due to high costs of remanufacturing, compared to replacement by new. Emerging technologies, such as Additive and Hybrid Manufacturing – now reaching satisfactory technology readiness levels (TRL 6 to 8) – are increasingly adopted to repair damaged parts, particularly in the aerospace and tooling sectors. Despite their technical viability, determining the feasibility of additive repair, remains a complex decision-making task, as economical, technical and environmental aspects need to be evaluated. The below work aims to address this challenge by developing a guideline and proposing an automated decision-making framework. A Python-based repair feasibility tool is introduced, capable of analysing diverse data inputs to define repair strategies and support sustainable decisions.*

***KEYWORDS**: repair, directed energy deposition, high-speed directed energy deposition, feasibility, automation*

1 INTRODUCTION

Additive Manufacturing (AM), the layer-by-layer fabrication of geometries is revolutionizing engineering domains starting from product design, manufacturing and maintenance, repair and overhaul (MRO). With promising research findings demonstrating the technology's capability to deposit layers on existing geometries for various metal material applications (Xu, et.al, 2023), (Xiao, et.al, 2023), (Zhang et.al, 2023) and with the significant efforts of the industry focusing on qualifying and standardizing this technology, it is increasingly applied in the aerospace and tooling industries to remanufacture, upgrade and repair components deemed as non-reworkable. (Ferreira, et.al, 2023), (Koruba et.al, 2023), (Aprilia et.al, 2022)

However, mechanical component repair is a complex operation, and AM doesn't always provide the best solution. The feasibility analysis is still a challenging process, as multiple aspects need to be aligned, such as component-specific requirements, damage evaluation, technological limitations, economic and environmental aspects, meaning that multiple departments need to align to make a decision in favour or against additive repair. Figure 1 summarizes these aspects.

The objective of the below work is to untangle these aspects of the AM repair feasibility analysis and propose a way to automate the decision making.

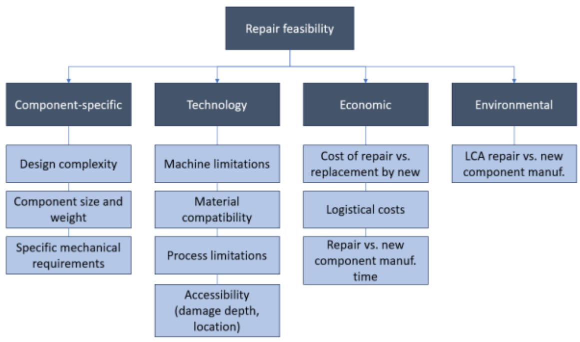


Fig. 1 Repair feasibility aspects

The proposed concept, by allowing data exchange between different departments, aims to realize a common language within which geometrical, technological, economic and environmental aspects can be evaluated and the decision-making process accelerated.

When referring to the technology aspects, a distinction and precision need to be made, as according to the ISO 52920:2023 standard, there are seven types of AM technologies: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. As the below work aims to analyse metallic repair applications, powder bed fusion (PBF) and directed energy deposition (DED) techniques stay most relevant.

Even if PBF presents increased accuracy depositing thinner material layers, compared to DED, it is too limited in overall dimensions. Components to be repaired with PBF, need to be loaded in PBF machines, placed in the powder bed, (see Figure 2) which limits the repair scope. Successful repair by PBF of burner components was demonstrated by Andersson et.al (Andersson, et.al, 2016), however, as Sato (Sato, et.al, 2022) also highlights, the PBF technology presents challenges of the repair process planning, component alignment and tool path execution without support structures as well as with monitoring methods. (Sato, 2022)

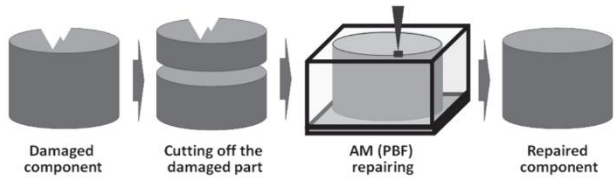


Fig. 2 PBF repair (Sato, 2022)

On the other hand, in the DED process the metal powder is injected into the focused beam of a high-power laser in a controlled atmosphere. The laser beam melts the target surface, generates a small molten pool of the base material, and the deposited powder becomes part of the existing geometry, bonding metallurgically. (see Figure 3)

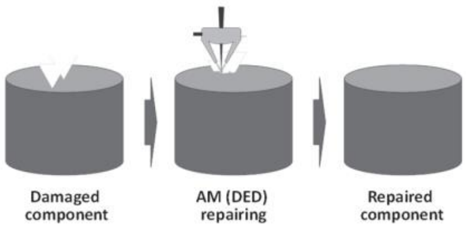


Fig. 3 Simplified representation of DED repair (Sato, 2022)

DED's great advantage is its flexibility, as DED deposition heads can be integrated in existing CNC machines or on robotic arms, therefore from small, precision items (Ko, 2023) to large (meter-scale) components can also be retrofitted. (Ramlab, 2024)

By now, DED became a general term, referring to multiple DED technology types, depending on the energy source and feedstock type used. Figure 4 presents an overview of different DED technology types. Understanding the limitations and capabilities of each technology type is essential when defining a DED repair strategy. For example, wire-arc AM (WAAM) and wire-laser AM (WLAM) technologies stand out with deposition rates of kilograms of material per hour, in detriment of the deposition accuracy and increased heat input in the base material. Laser metal deposition (LMD) and especially high-speed laser metal deposition (EHLA) technologies deposit layer thicknesses starting from 30-50 µm (Ko, 2023) up to 1-2 mm, (Dezaki, 2022) increasing accuracy significantly, but reducing deposition rates.

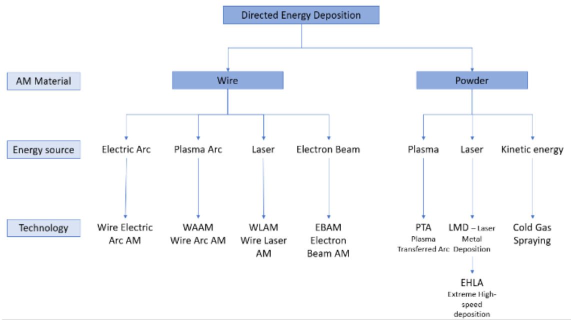


Fig. 4 DED technology types – overview

2 REPAIR FEASIBILITY TOOL DEVELOPMENT

To address the complexity of deciding whether a damaged component is suitable for additive repair, a dedicated feasibility tool was developed. The tool aims to automate the evaluation process by combining geometric analysis, machine and material validation, and user-friendly reporting. Python was selected as the development language due to its strong libraries for 3D data processing, visualization, and interface design.

The tool architecture integrates two main modules: a computational core for mesh processing and a graphical user interface (GUI). The core module performs geometry alignment, mesh validation, Boolean operations to extract misalignments, and quantitative analysis such as bounding box generation and aspect ratio calculation. The GUI guides users through uploading CAD files, inputting component dimensions, weight and material data, visualizing results interactively, and exporting feasibility reports in PDF and damage areas in STL formats.

This modular approach supports easy updates of machine build volumes, material libraries, and validation criteria as new data becomes available. Furthermore, the concept can be expanded with additional features such as cost modelling and environmental impact assessment, and integrated with existing enterprise systems like SAP or life cycle assessment (LCA) tools for broader industrial application.

2.1 Data requirements and preparation

Reliable input data is fundamental for the tool's feasibility analysis. The first step of developing a repair process is to identify the damaged areas by comparing original CAD models with the 3D scan of the damaged component.

The tool supports common neutral 3D formats such as STL, STEP, and IGES. It requires the mesh to meet quality standards, ensuring watertightness, non-manifold integrity, and consistent triangle orientation. Invalid meshes can be corrected using established mesh-repair libraries before analysis.

Machine and material data are consolidated in libraries prepared from an extensive review of OEM datasheets and validated process parameters. These include build envelope dimensions, maximum load capacity, and the range of compatible materials. By checking user inputs against this library, the tool automatically verifies whether the component's weight, size, and material meet the necessary conditions for DED/EHLA repair.

Material properties were fed into the tool based on validated parameter sets and industrial standards, covering commonly used metals (Dezaki, 2022), such as SS316L (Oh, 2019), Nickel-based alloys (IN718) (Bambach, 2024), Titanium (grade 5) (Saboori, 2017), and AlSi10Mg (Kiani, 2020).

2.2 Boundary conditions

The feasibility tool uses defined boundary conditions to determine whether a repair is practical. These conditions address both the physical limitations of DED/EHLA systems and the characteristics of the component under investigation.

Machine and deposition head specifications, such as stand-off distance, maximum working angles of the deposition head, head geometry, clearance and configuration, material feed direction or the distance between the deposition nozzle and the workpiece, help determine whether the identified damaged areas can be repaired. Figure 5 showcases inaccessibility challenges due to maximum working angle limitation and edge accessibility.

The depth of the damage is another critical value. For the feasibility check an aspect ratio definition is introduced:

$$R = \frac{Z}{\max(X, Y)} \quad (1)$$

where X, Y, Z represent the size of damage propagation in these three directions respectively.

Identifying and computing these dimensions is possible with Python, by creating a boundary box around the extracted damaged areas, and calculating on the X, Y, Z dimension of the bounding box.

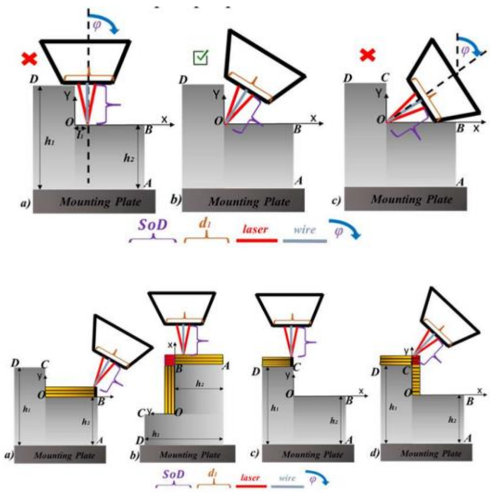


Fig. 5 Tool inaccesbility examples (Porevopoulos, 2024)

The bounding box is defined by the min and max coordinates of the component along the X, Y, Z axes. For a component C, the bounding box can be mathematically represented as:

$$Bounding\ box = \{\min(C_x), \max(C_x), \min(C_y), \max(C_y), \min(C_z), \max(C_z)\} \quad (2)$$

where Cx, Cy, Cz represent the X, Y, Z coordinates of the vertices of the component, respectively. It is the smallest axis-aligned rectangular box that encloses the component. This is useful for simplifying the geometry and performing high-level analysis of the component's shape, as the damaged areas are freeform cavities.

For low aspect ratios (R < 1), the repair region is wider than it is tall, meaning material can be deposited in wider, more stable layers. This minimizes thermal gradients, allows for better layer adherence, and generally results in more uniform deposition with fewer thermal stresses.

For moderate aspect ratios (R ≈ 1–2), there's a balance between the vertical build-up and the horizontal footprint, and while the deposition process may require more careful heat management and layer bonding control, it remains feasible for many repair applications, especially for localized damage.

For high aspect ratios (R > 2), the challenges become more significant. At these ratios, controlling thermal gradients and ensuring the deposition remains stable without excessive material sagging or pooling becomes increasingly difficult. Special deposition strategies, such as slow scanning speeds or more frequent re-orienting of the part, may be needed to manage these challenges. At these aspect ratios, geometry preparation by pre-milling is mandatory, as otherwise the deep cracks are not accessible by the deposition head.

Other internal channels of less than 100 mm internal diameter can not be processed by available powder feeding nozzles.

3 TOOL CONSTRUCTION AND TESTING

3.1 Tool construction

The tool leverages several computational libraries to handle 3D data processing, 3D visualization and graphical user interfaces. The GUI, shown on Figure 6, guides the user in an intuitive way to input 3D data to be computed and component specific data for validation.

The tool can handle 3D formats to analyse misaligning areas, by overlapping the original 3D model with the 3D model of the damaged component and, performing Boolean operations, compares and extracts the misalignments (the damaged areas) between the two files. The analyse geometry feature of the tool computes quantitative attributes of the extracted areas, creating bounding boxes around them to measure their propagation in X, Y, Z directions, to calculate the aspect ratio of the damaged areas and decide whether from geometry perspective, a DED repair is feasible. The tool also validates user inputs for component weight, dimensions and materials and combines the outputs to define the repair feasibility.

For the tool to stay relevant, it needs to support updates with actualized data. As the technology evolves rapidly, build volumes of different machines and the library of possible materials can be extended. This is a matter of expanding and continuously redefining the boundary conditions and acceptance criteria within the tool architecture.

For the time of development, build volumes and material libraries of 20 OEMs were analysed and the boundary conditions were defined based on the investigation, accepting only the materials, for which sufficient process parameter data is available and validated. As a general rule defined by the ASTM F3413 – 2019 DED guideline, almost all weldable alloys, in wire or powder feedstock form, are compatible with DED. However, for some, high reflectivity materials like Tungsten or Molybdenum, further process development is needed. The maturity of processing those specific materials is still low, and therefore they are not included in the feasibility tool.

In preparation for the tool building process, available material and machine data was centralized in Excel files to create a library. After the data preparation and curation, a combination of decision-making methods was implemented to analyse the repair feasibility.

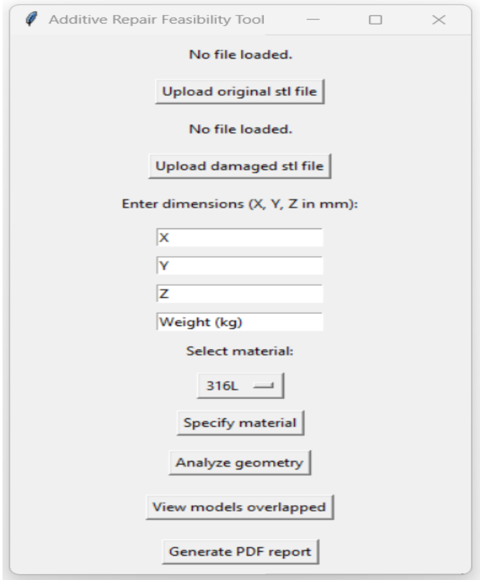


Fig. 6. Feasibility tool GUI

The tool has the functionality to save a report of the decisions in .pdf format, and to save the extracted damaged areas in .STL format, for the ease of further handling (such as CAM toolpath planning for performing the repair operation).

Adding further aspects, such as a cost model and sustainability impact of the DED/EHLA additive repair, would make the tool more complex, but at the same time more impactful in the automated decision making. The concept of this tool can be commercialized and integrated in existing SAP, TeamCenter, life cycle assessment tools (Simapro, Gabi Sphera, OpenLCA), to directly extract relevant data for the analysis and process it for accelerated guidance and decision making.

3.2 The tool's recommendations

Based on the boundary conditions defined in chapter 2, the tool is trained to output recommendations based on the analysed input data. The simplified recommendation logic is shown on Figure 7.

Component overall dimension and weight determines whether the part can be loaded in an inert DED system and therefore processed by EHLA as well, or solely on robotic systems, which limits the repair method to DED. The component's initial thickness also plays a crucial role in the feasibility analysis. As of now, thicknesses less than 25 mm can only be processed by EHLA, not also by DED, due to the increased heat input in the substrate, resulting in significant warping.

Based on the damage type and location, the tool can assess the required deposition rate and layer thickness and therefore advise on deploying EHLA for fine structures or conventional DED for high deposition rates.

Specifying the material type will output either the recommendation to further develop process parameters or a parameter set defined by literature review.

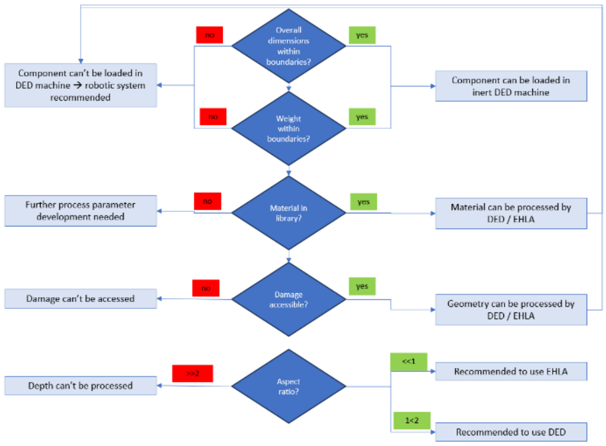


Fig. 7 Simplified scheme of recommendations

The damage's aspect ratio, its propagation analysis helps in defining the deposition strategy. In case of multiple damages identified with different damage aspect ratios, the tool will take into account if there is at least one aspect ratio outside of boundaries and will recommend no feasibility of the additive repair.

3.3 Tool testing and validation

For 3D visualization, the tool evaluated both VTK and PyVista libraries. VTK offers robust capabilities for complex data manipulation and rendering but requires extensive coding effort. PyVista, as a higher-level Python interface built on VTK, provides similar functionality with a simpler, more intuitive workflow for mesh analysis and visualization. (see Figure 8) After testing, PyVista was selected for its ease of use and efficient integration into the tool's geometry processing tasks.

Once the visualization method was selected and tested, the component overlap was implemented in the code. For that, the goal was to align the two uploaded models in the same coordinate system, having the same point of origin.

Extracting the misaligning areas between the two analysed STL files relies on Mesh Boolean operations. The Boolean operation is one of the

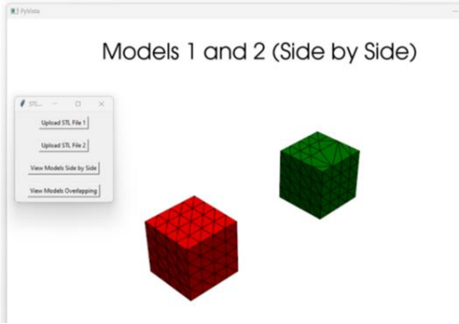
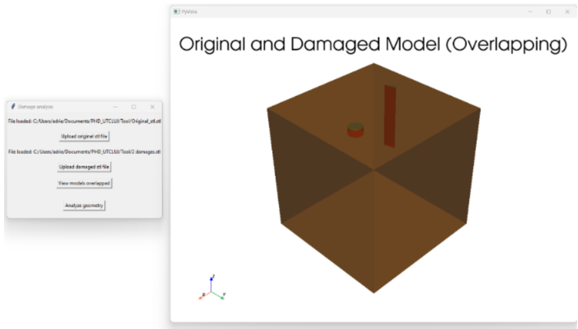


Fig. 8 3D visualization with PyVista

fundamental operations for 3D data handling. With Boolean Difference, the misalignments were extracted and handled for aspect ratio calculation.

Identifying multiple damages (shown on Figure 9, 10 and 11) and computing them separately needed to be done by connected components analysis, which is a fundamental technique in topology and graph theory used to classify disconnected parts of a graph or, in this case, a



mesh.

Fig. 9 Handling multiple damages

By adding this algorithm in the source code, the tool does not only split the extracted misalignments, but it is also capable of exploring the damage propagation, it adds efficiency to the analysis and at the same time allows for more sophisticated mesh analysis. (Python documentation, 2024)

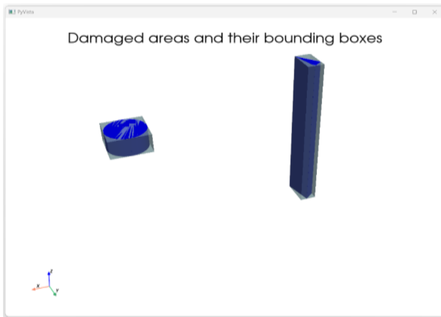


Fig. 10 Extracted damaged areas and their boundary boxes

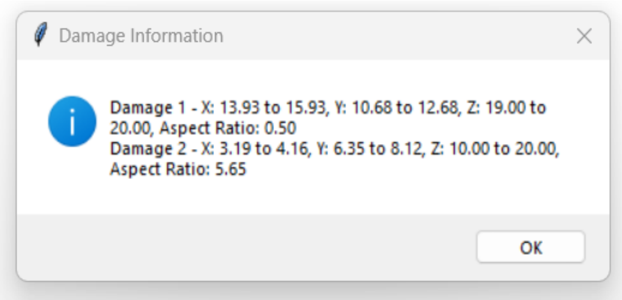


Fig. 11 Damage analysis output

The outputs of the user input data validation, as well as the geometry analysis are concluded in a PDF summary. The generated conclusion sheet is useful for further refinement of the feasibility tool.

4 CONCLUDING REMARKS

The developed repair feasibility tool provides a practical, automated framework for evaluating whether additive (DED or EHLA) repair is suitable for a damaged component. By combining mesh analysis, validated machine and material libraries, and an intuitive interface, the tool reduces decision time, supports data-driven maintenance planning, and contributes to circular manufacturing goals.

Future work will focus on integrating cost and environmental impact models as well as refining the boundary conditions and recommendations for multi-aspect analysis. Connecting the tool with enterprise and lifecycle analysis systems, will further enhance its value for industry adoption.

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