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INDUSTRIAL IMPLEMENTATION OF HYBRID MANUFACTURING FOR REPAIR

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Abstract: *The shift towards circular, sustainable fabrication is becoming an urgent challenge for the manufacturing industry. As relatively new technologies, such as additive and hybrid manufacturing gain more trust of the industry, the repair possibilities also get a new extension. Components deemed as non-reworkable or too expensive to repair with specialized personnel and technology, can be brought back to their original geometries and initial or even enhanced mechanical characteristics, within hours, instead of days, using the hybrid repair approach. The increasing number of research projects developed for various materials and industries, such as aerospace, automotive, tooling, underline its potential to reduce time, cost of repair, and extend the lifetime of components. Even if the results are promising, companies still doubt the reliability of the process, as the technology readiness level is not yet explored for this approach. To respond to the industrial reluctance, this article aims to highlight the latest capabilities and challenges of hybrid repair, followed by the definition of a roadmap of implementation, extended with an industrial case study from the semiconductor equipment industry.*

Key words: *hybrid manufacturing, additive manufacturing, repair, sustainability, direct energy deposition*

1. INTRODUCTION

Hybrid manufacturing by its definition means the combination of two or more different technologies in one system, to overcome the shortcomings of the individual processes and take advantage of their individual benefits, resulting in a "1+1=3 effect", which indicates the efficiency of the machining process. It is the combination of different energy sources, shaping methods, operations or tools in a single setup. [1]

Widespread hybridization methodology is the integration of directed energy deposition (DED) and CNC machining (milling) into one setup. The DED process as the ASTM/ISO standard defines, is "an additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited". [2] The laser beam melts the target surface, generates a small molten pool of the base material, therefore it creates a metallurgical bonding, instead of adhesive or mechanical. The metal powder delivered through the nozzle is absorbed into the molten pool and becomes part of the existing object. This fusion ensures the metallurgical bonding of the additively manufactured (AM) layers and the substrate.

Hybrid manufacturing appeared as a response to the industrial needs of shortening time-to-market, cutting production costs of complex geometry components. The repair applications reduce material waste, eliminate the returns, keeping the parts in the field for extended lifetimes.

Even if the results are promising, companies still react with reluctance, when it comes to integrate hybrid repair into their re-use strategies. This article, with the initial literature review, workflow development and repair example, aims to bridge the gap between the research findings and industrial needs.

The literature review focuses on hybrid repair findings, highlighting the quality evaluation and validation methods as well. As an outcome, the workflow proposal includes a feasibility study of the repair approach and the implementation steps. The industrial example from a leading semiconductor equipment manufacturer is proof of the study's feasibility.

2. HYBRID REPAIR CAPABILITIES, CHALLENGES

2.1 Repair capabilities, research outcomes

Target components for the hybrid repair are the high-value and high-performance parts identified in aerospace, automotive and tooling industries. DED, in comparison with other AM processes, allows a higher level of flexibility, with multi-axis deposition capabilities. It typically doesn't require support structures, therefore no post-processing to remove them or any non-metallic or bonding agent, new geometries are built directly on the target surface. Both powder or wire material from steels (tool / stainless steel) to Ni-based alloys or reactives (Ti, Al, Mg) can be deposited with full integrity and density. Metal powders can be mixed during the process, to create new alloys or to functionally grade materials, apply coating for part property enhancement or to form multi-material structures. [3]

Fig. 1. (left) DED freeform design, without support structures, (right) DED multi-material structures, own pictures from Formnext Frankfurt, 2022

According to the research of A.Saboori, to achieve good quality of the rebuilt areas, metal powder with spherical particles of 50-200 μm are recommended. The laser type plays an important role in the remanufacturing quality as well, for instance, according to the research, CO_2 lasers are suitable for thick layers (measured in mm) of regular geometry, while Nd-YAG laser is recommended for layer thicknesses under 1 mm. [4]

For increased process precision, Wang et. al uses dual-beam laser for Ni-based superalloy part repair. The first laser beam melts the target area around the crack, the second laser deposits the material in the cavity. This research shows that cracks of 0.1-0.3 mm can be successfully repaired through the DED process. [5]

To overcome the concerns regarding mechanical characteristics of the repaired components after the DED remanufacturing, the following comparison of mechanical properties of as-built and as-repaired Inconel 625 alloys was made by A. Saboori [4]:

Table 1

Mechanical properties – comparison between annealed, DED as-build and DED repaired [4]

Process	UTS (MPa) – ultimate tensile strength	YS (MPa) – yield strength	E (%) – elongation
Annealed bar	841	403	30
DED as-build	815	487	69
DED repair	793	482	56

For in depth analysis, the concept of dividing the different layers of a DED-repaired component developed by Zhu et al.,[6] who investigated the repair of a nickel-iron alloy mould using DED enables for detailed property mapping. They divided the layers into base metal, HAZ (heat affected zone) and deposited layers and confirmed that super-cooling degree affects the quality of the deposited layers, transforming them from irregular to regular ones from the bottom to the surface of deposited layers.

When compared to traditional welding, DED repair of gray cast iron parts results in 21.5 times smaller sized HAZ, leading to increased elongation rates (62% on average), as well as in significantly better hardness measured from the top surface to base metal, according to the study of Yu et al. [7]

DED allows for multi material structures, which is a good practice for repair as well, wide-spread applications being in steel-Copper, steel-Aluminium, steel-Nickel and steel-Titanium. In the research conducted by Onuike et.al. [8] the consistency and quality of Ti-6Al-4V/Inconel718, Ti-6Al-4V/stainless steel and Inconel718/copper material combination were monitored in cross-sectional samples. Cladding CPM 9V on H13 tool steel was demonstrated to increase roughness, hardness and wear resistance of the base H13 tool steel material, as it has excellent hot working properties and high-quality surface roughness at high temperatures, shows the research of Kattire et al. [9] During the DED process, compressive residual stresses resulted, which are beneficial when the surface is exposed to cyclic thermomechanical loads.

In the research of J.D.Hamilton [10] damaged cast iron, a difficult to repair material was completed with 316L stainless steel, a weldable and widely available material. The experiments conclude that repaired structures do require post-processing to enhance fatigue life, due to the presence of tensile residual stresses. Utilizing a combination of low-dilution process parameters, preheating, and annealing effectively reduces the extent of brittle microstructures and solidification fractures in the vicinity of the repair. This results in the restoration of cast iron tensile strength and an increase in elongation. Porosity formation is contingent upon thermal conditions, with higher-dilution parameters accelerating gas formation, pore coalescence, and entrapment within the solidifying melt pool.

H.Rajaei et.al investigated the microstructural and tribological evaluation of brake disc refurbishing using Fe-Based coating via DED [11] and highlights the impact of using buffer layers in the repair process. Gray cast iron is a widely used casting material, due to its low cost of manufacture, good castability and good tribological and mechanical qualities, therefore preferred in the fabrication of brake discs. The already developed metal spraying method (thin layers of WC-Co or WC-FeCrAlY) is not cost effective, therefore laser deposition of Fe-based coatings via the DED process was considered for rebuilding geometry. The gray cast iron contains a high level of carbon, therefore it's difficult to coat, as hot cracking appears due to the thermal stresses and carbide precipitation at the interface of the molten pool, this is why the usage of buffer layers of stainless steel (AISI415) is justified. In this research, low-chromium steel and soft martensitic Cr-Mo-Ni stainless steel powder were used for the buffer layers. The study compares the coating efficiency with and without using buffer layers. Without any buffer layer, the coating is not well bonded on the gray cast iron surface, cracks are visible, while the stainless-steel layers result in defect-free adhesion areas. An only 0.55 mm thin buffer layer leads to the possibility of crack-free deposition of 3.55 mm thick, F55 outer layers. The ductile stainless-steel ensures the accommodation of strains created by the thermal cycle resulting from DED and its low carbon content balances the excess of carbon diffusion from the gray cast iron layers. This results in the extreme benefit that there are no carbon formations on the coating-substrate interface, reducing the brittleness as well and preventing the formation of cracks. To reduce the surface roughness to 0.25 μm, mechanical polishing was applied. The hardness tests result in a 700 HV hardness, which is significantly better compared to the original hardness of the brakes. The tribological tests conclude the enhancement of friction and wear coefficients.

As the damage causes are of various types, such as cracks, corrosion, damage caused by thermal cycles, contact with other components, the geometry preparation differs.

In case of surface damage, grooves, notches, tip damage, geometry preparation includes a machining and cleaning step. Machining ensures the accessibility for the deposition head. Several examples can be found for blade repair, where trailing edge cracking is a common failure. The crack surrounding is machined in a V or U shape for tool accessibility, after extracting the points and optimizing the contour in the damaged area. [12]

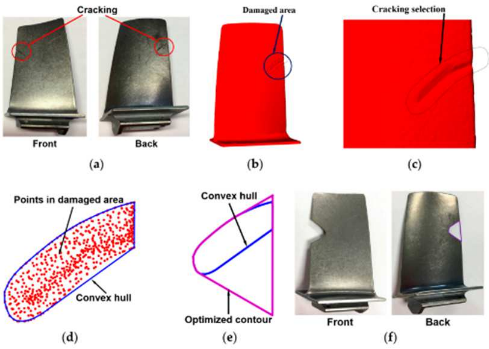


Fig. 2. Geometry preparation for DED repair [12]

In other cases, the direct deposition is targeted on the "as-is" damaged surface. It is possible after effecting a 3D scan of the damaged area, determination of the cavity volume, by overlapping the scan results with the original geometry, CAD&STEP model creation for that cavity, ended by the actual execution of the created toolpath for filling the cavity. The main problem in this process occurs at the detection and determination of the material volume that needs to be deposited in the cavity of the damaged component, as the result of the 3D scanning is a point- cloud, instead of a solid model, which is required for further analysis and manipulation in CAM. [13]

Perini comes with a software solution (DUOADD) that bridges the gap between the result of the 3D scanning and CAM, translating the point-cloud into a solid STEP model. The cavity volume results from the comparison between the original model and the 3D scan of the damaged model. After a series of experiments, it turned out, that overlapping and comparing two meshes, based on Boolean operations does not lead to a continuous model. For this reason, the two meshes are discretized using octrees. As Perini states, with octrees it is possible to obtain denser data structures where needed. The result is a dense set of nodes that firmly represent the damage and that needs to be exported as a step file. The conversion of nodes into a solid STEP file is possible via Visualization Toolkit (VTK) and Open CASCADE (OCC) libraries, embedded in DUOADD. Another advantage of DUOADD is that the solid model created is already aligned with the original model's coordinate system, meaning that during the tool path creation process, the filling material volume is already placed precisely in the cavity of the worn part.

Overall, the main steps in executing a hybrid repair are identified as follows: surface preparation and 3D scanning of the damaged component, determination of cavity volume, CAD&STEP model creation, tool path creation (additive CAM), execution of DED and machining operations. [13]

2.2. Repair challenges

Hybrid manufacturing combines at least two different types of technologies, therefore defects occur from double the reason, as compared to traditional manufacturing. Machining parameters from both the additive and subtractive operation can cause damage, as well as the thermal or mechanical effects between the operations. [14,15] The following overview aims to map the possible anomalies:

Fig. 3. Anomaly classification in hybrid repair [14,15]

2.3. Repair quality evaluation and qualification methods

One of the biggest challenges for additive manufacturing is the qualification of the processes and components, to ensure the integrity of the applications. The ISO/ASTM 52920 standard, released in 2022 specifies "the requirements, which are independent of the material and manufacturing method used, for part manufacturers using additive manufacturing techniques". [16] As a general approach, the standard is applicable for all additive manufacturing processes defined in ISO/ASTM 52900, and for quality insurance the ISO 9001 (ISO9001:2015 - Quality management systems – Requirements) standards are recommended. The evaluation of additively / hybrid additively repaired components can be classified into non-destructive and destructive methods. A successful execution of the deposition cycle, filling the cavity of the damaged surface does not automatically mean the repair is successful, as micro-cracks, pores in the transition area might appear and influence the microstructure and mechanical properties of the repaired component.

As the study of M.P.Masterton enumerates, non-destructive methods such as thermography, acoustic emission testing, ultrasounds, dye penetration, hyperspectral imaging don't provide enough details for accurate evaluation. CT scanning proves to be the most accurate out of the non-destructive methods. [17]

As AI and machine learning technologies evolve, CT scan results can be analyzed in depth by these tools. An algorithmic characterization of the resultant CT-scan is developed by M.P.Masterton et.al. [17] The developed algorithm identifies the particle cluster boundaries within cross sectional images and classifies them comparing to a circular cross-section. Based on the attachment profiles of partially attached particles and the data gathered from the effect of post-processing, the degree of confidence to which a particle will be attached after a cleaning regime, can be determined with the algorithm.

In the majority of repair projects mechanical testing is performed for substantial results. In the study conducted on pure copper motor commutator repair by laser powder deposition, microscopies were compared to understand the influence of different laser intensity, feed rate and scan rate on layer thickness and wettability. The microhardness, wear resistance and electrical conductivity were also evaluated. [18]

M.Liu et.al, in the repair of steel panel dies and molds for automotive industry, evaluates the Fe- and Ni-based cladding on steel based on thermal expansion coefficient, melting points, wettability and cracks of the laser cladding layers, as well as temperature and stress field, elastic modulus ad dilution ratio. In this study elements for machinability evaluation are also given: thermal expansion coefficient, max. length of cracks, wear mass loss, roughness of machined surfaces, tool damage rate. [19] The investigation of P.Kahhal highlights the importance of performance testing, by tensile, impact and fatigue testing. [20] The required tests depend also on specific part requirements.

3. THE HYBRID REPAIR ROADMAP

Hybrid repair is beneficial for preventive maintenance, restoration, and decentralized repair. It can be implemented for regenerating geometries, creating replacement parts, but also in direct repair, at the immediate proximity of the defect. From manufacturing point of view, hybrid repair enables more flexibility, reduces tooling needs, helps optimize designs. However, the large-scale implementation of hybrid repair is not a straightforward process. Organizations need to consider different technological, ecological, logistical, and economical aspects, when shifting to this new way of working. The set of opportunities and limitations need to be defined, as well as a detailed product portfolio evaluation, a testing and validation process. In the following the article walks through the most important aspects and a logical workflow when considering hybrid repair on large-scale.

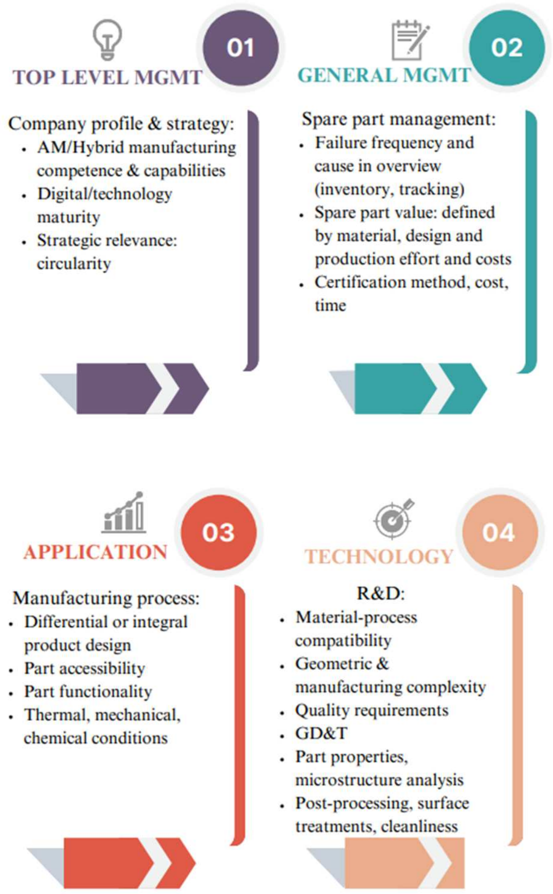


Fig.4. Implementation aspects for large-scale implementation

For the case study an implementation roadmap was developed for a leading company from the semiconductor equipment manufacturer industry. The company deals with a large number of scrapped components, and most of those components are manufactured at specialized supplier.

First step of the project is the identification of the relevant, high-value components which are deemed as non-reworkable. For that the SAP Resource System is used, and scrapped components are classified using different filters. Relevant for hybrid repair are the surface damages, cracks, broken features of high-value components. To define "high-value", the following comparison is made:

$$C_{hybrid\ repair} < C_{scrapping} + C_{new} \quad (1)$$

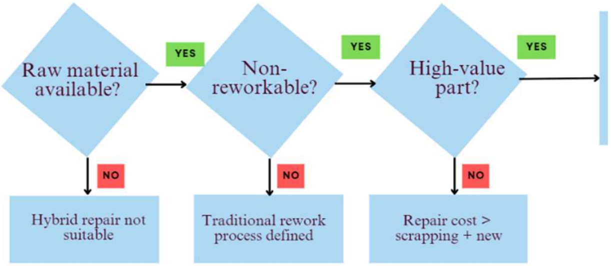
$C_{hybrid\ repair}$ involves the following steps, therefore costs:

- 3D scan of the geometry
- Cleaning and fixing in hybrid machine
- Toolpath creation
- Set-up in the hybrid machine
- Actual repair execution: cost of metal powder, tooling
- Post-processing costs (surface treatment / milling)

$C_{new}, C_{scrappping}$ refer to the costs of manufacturing a new component and the cost of scrapping the worn-out one.

Once the appropriate components identified, a supplier and technology investigation and review are performed. Supplier must fulfill the requirements specified by the company, in form of an internal standard. The standard classifies components into different complexity levels, each level having the specific requirements of cleanliness, tolerance, strength.

The following decision tree defines all necessary steps for the implementation process:



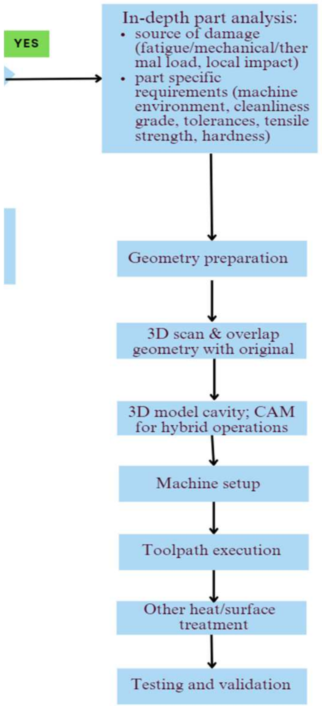


Fig. 5. Decision tree of hybrid repair implementation

4. CASE STUDY

Following the above-mentioned aspects, a high-value component was identified at a leading semiconductor equipment manufacturer. The presented complex component is fabricated by selected laser melting; therefore, this case study highlights the versatility of the hybrid repair approach.

During the de-powdering process, hairline cracks of 0,05 mm width (on average) appeared in critical areas of the component. Due to this imperfection, the component was rejected, as it must satisfy highest manufacturing standards.

For the repair feasibility, first, the material was analyzed. The component is made of Titanium Grade 2, widely used in industrial applications, due to its good ductility and corrosion resistance, as well as low density, serving as good choice for lightweight parts. The deposition of Titanium Grade 2 powder is with Argon shielding gas. As the material is commercially available and, in this case, the same powder as the base material, a cost comparison was performed in the following step.

As C_{new} is significantly high, the cost estimations justify the cost efficiency of the repair approach.

Fig. 6. Titanium Grade 5 component with hairline crack

Once the additive process performed, the most critical part is repair evaluation and qualification. Out of the available non-destructive testing methods, X-ray CT scanning is chosen. It is the most accessible and compatible non-destructive inspection method.

In the CT scan a small cluster of porosities is visible on the surface, which does not affect the functionality of the component.

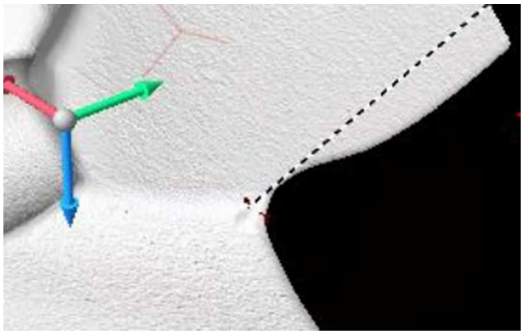


Fig.7. CT scan of rebuilt geometry, visible porosity in the filled area

Preferred and tangible evaluation methods include the reproduction of the performed repair process in form of samples, tensile bars, and their conventional mechanical testing.

A strategy consisting of the following steps was defined for this particular part repair evaluation:

- Standard ISO tensile bar fabrication by selective laser melting
- Replication of cracks in the middle of the tensile bars, by wire electrical discharge machining (wire-EDM), average kerf with of the cut being 0.25-0.30 mm [21]
- Cavity filling with the same laser parameters as for repair
- Mechanical testing of the repaired tensile bar for hardness, strength

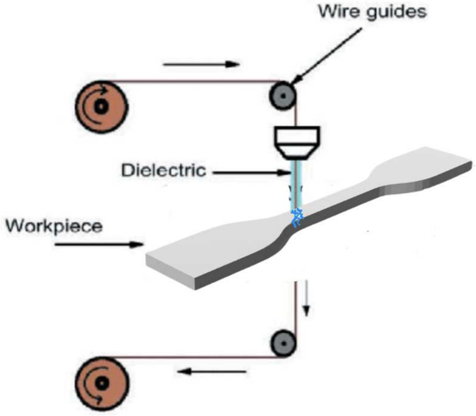


Fig.8. Crack introduction by wire EDM in ISO tensile bar for repair replication and evaluation

5. CONCLUSION

The hybrid repair approach is targeted on the high-value, complex geometry components from different industries, with the aim of repairing them in an efficient, economical, and sustainable way. It has numerous successful applications, but it also presents a lot of challenges in the large-scale implementation. Gaps in research go in multiple ways, such as the refinement of process parameters, the clear mapping of parameter influence on the process, the development of hybrid CAM programming, to incorporate all parameters and setups into one software solution, as well as process standardization, to boost the validation of hybrid repaired components. The industrial examples of hybrid repair are meant to accelerate the mapping process, their output being the parameter, process data, which can be used for standardization and automation in the future.

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Fabricația hibridă pentru reparații – implementare industrială

O provocare urgentă pentru producție este trecerea la fabricația circulară și durabilă Pe măsură ce tehnologiile relativ noi, cum ar fi fabricarea aditivă și hibridă, câștigă mai multă încredere din partea industriei, posibilitățile de reparații capătă, de asemenea, o nouă extindere. Componentele considerate nereparabile sau prea scumpe pentru a fi reparate cu personal și tehnologie specializată, pot fi readuse la geometria și caracteristicile mecanice inițiale sau chiar îmbunătățite, în câteva ore, în loc de câteva zile, cu ajutorul abordării hibride de reparare. Numărul din ce în ce mai mare de proiecte de cercetare dezvoltate pentru diverse materiale și industrii, cum ar fi industria aerospațială, industria automotive, cea a echipamentelor, subliniază potențialul său de a reduce timpul, costul reparațiilor și de a prelungi durata de viață a componentelor. Chiar dacă rezultatele sunt promițătoare, companiile se îndoiesc încă de fiabilitatea procesului, deoarece nivelul de pregătire tehnologică nu este încă definit pentru această abordare. Pentru a răspunde la această reticență, acest articol își propune să evidențieze cele mai recente rezultate, capacități și provocări ale reparației hibride, urmate de definirea modului in care reparația hibridă este implementată în serii mari de producție, și extinsă cu un studiu de caz din industria mașinilor unelte pentru semiconductori (microcipuri).

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