I.FAST

Innovation Fostering in Accelerator Science and Technology

Horizon 2020 Research Infrastructures GA n° 101004730

# DELIVERABLE REPORT

# Survey of AM applications and strategies for repairing components by AM

## DELIVERABLE: D10.2

| | |
|---|---|
| **Document identifier:** | IFAST-D10.2 |
| **Due date of deliverable:** | End of Month 24 (April 2023) |
| **Report release date:** | 30/04/2023 |
| **Work package:** | WP10: Advanced Accelerator Technologies |
| **Lead beneficiary:** | RTU |
| **Document status:** | Final |

## ABSTRACT

This report presents additive manufacturing (AM) applications and strategies for particle accelerator component repair, it is divided in three parts:

1) State-of-art analysis: where existing AM repair technologies have been reviewed. The concept of AM repair process and strategies is also introduced, with an emphasis that AM repair process differs from AM manufacturing process and has several key factors that must be recognized. Several examples are given of successful repair cases in other industries.
2) A qualitative study in form of a questionnaire covering information obtained directly from the particle accelerator community. It comprises community feedback and experiences on the usage of the AM technologies and AM repairs in this field. This includes also the list of potential accelerator components (parts), which are plausible candidates for the repairs using AM technologies.
3) An indicative case study of a tantalum electrode repair by AM. This study includes quantitative sample characterization before and after the repair process (morphological, chemical, and mechanical analysis) and overall data of relevant repair conditions.

I.FAST Consortium, 2023

For more information on IFAST, its partners and contributors please see https://ifast-project.eu/

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004730. IFAST began in May 2021 and will run for 4 years.

## Delivery Slip

| | Name | Partner | Date |
|---|---|---|---|
| **Authored by** | A. Ratkus, D. Krogere, T. Torims,<br>T. Romano, M. Vedani, F. Marquardt,<br>H. Lauer, F. Brukner, E. Lopez,<br>M. Weinmann, D. Obrados | RTU, PoliMi, Fraunhofer IWS, Taniobis, CIEMAT | 30/04/2023 |
| **Reviewed by** | M. Vretenar [on behalf of Steering Committee] | CERN | 30/04/2023 |
| **Approved by** | Steering Committee | | 30/04/2023 |

# TABLE OF CONTENTS

1 INTRODUCTION AND OBJECTIVE ........ 7
2 AM REPAIRS CONCEPT AND CURRENT AM REPAIR APPLICATION WITHIN THE ACCELERATORS ........ 8
2.1 AM REPAIR CONCEPT ........ 8
2.2 CURRENT AM REPAIR USAGE IN THE FIELD OF ACCELERATORS ........ 9
3 QUESTIONNAIRE ABOUT AM APPLICATIONS AND POTENTIAL DEVELOPMENTS ........ 10
3.1 RESULTS: EXISTING EXPERIENCE AND FUTURE PROGNOSIS FOR AM USE ........ 10
3.2 LIST OF POSSIBLE AM REPAIR OBJECTS ........ 11
*3.2.1 Cavities ........ 11*
*3.2.2 Targets ........ 12*
*3.2.3 Beam dumps ........ 14*
*3.2.4 Ion source electrodes ........ 14*
*3.2.5 Vacuum chambers ........ 15*
*3.2.6 Drives and mechanical parts ........ 15*
3.3 CONCLUSIONS ON CURRENT AM STATUS ON ACCELERATOR FIELD ........ 15
3.4 PARTICLE ACCELERATOR COMPONENT REQUIREMENTS ........ 16
4 AM REPAIR TECHNOLOGIES ........ 17
4.1 REPAIR TECHNOLOGIES ........ 17
*4.1.1 Powder bed fusion for repairs ........ 17*
*4.1.2 Directed energy deposition for repairs ........ 19*
*4.1.3 Cold spray for repairs ........ 22*
*4.1.4 Additive friction stir deposition for repairs ........ 23*
4.2 AM REPAIR CHALLENGES ........ 24
4.3 CONCLUSIONS AFTER AM REPAIR TECHNOLOGY STUDY ........ 24
5 POTENTIAL AM REPAIR STRATEGIES ........ 26
*5.1.1 AM repairs for damaged parts after failure ........ 26*
*5.1.2 AM repairs as part of maintenance ........ 26*
*5.1.3 AM repairs for manufacturing errors ........ 27*
*5.1.4 Remote and in-situ repairs ........ 27*
6 CASE STUDY – TA CATHODE REPAIR ........ 29
6.1 CASE STUDY OBJECT IDENTIFICATION ........ 29
6.2 ELECTRODE CHARACTERIZATION ........ 29
6.3 ELECTRODE REPAIR STRATEGIES ........ 31
6.4 CHOICE OF AM TECHNOLOGY, TESTING OF PARAMETERS AND STRATEGIES ........ 31
6.5 ELECTRODE REPAIR PROCESS AND RESULTS ........ 33
6.6 CONCLUSIONS ABOUT CASE STUDY ........ 38
7 CONCLUSIONS AND FUTURE PLANS ........ 40
8 REFERENCES ........ 42

# Executive summary

*The report presents results of a comprehensive study on additive manufacturing (AM) applications, technologies and strategies for particle accelerator component refurbishment and repairs. It is divided into several parts: Research on current AM repair usage in the accelerators, a study of AM repair technologies and strategies and a case study as a demonstrator application for accelerators.*

***Current use of AM repair technologies within the accelerator community**. Concept of AM repair process has been introduced, emphasising that AM repair process differs from AM manufacturing process and has several key factors that must be recognized; such as a need for a reverse engineering, handling of the damaged components, deformations, issues of alignment and tolerances, potential need for additional pre- and post-machining, surface contamination, and finally a new material layer bonding with the substrate.*

*Extensive and detailed research in publication servers and multiple general and specialised databases, revealed that there is no evidence of any identifiable case of AM repair within the accelerator realm. To validate this conclusion, a targeted questionnaire directed to the to the accelerator community at large was designed and performed.*

***A qualitative study** was aimed to collect existing experience and willingness to use AM technology for repairs as well as to identify potential accelerator repair objects. According to the results accelerator community is more optimistic towards production rather than repairs using AM – only 42.9% would consider AM for repairs and overwhelming 81% of respondents inclined towards component production. It is important to note, that 23.8% of respondents don't even consider using AM repairs technology as such. Naturally, a slightly pessimistic view towards AM repairs would also potentially get better with time and examples of applications. Nonetheless, **the accelerator community suggested several objects as potential demonstrators for repair, such as cavities, targets, beam dumps, electrodes, vacuum chambers and mechanical parts.** Unfortunately, almost none of the mentioned repair prospects are immediately possible without specific equipment. Therefore, further targeted studies in this direction will be needed to fully benefit from the large potential of the AM technology by the accelerator community.*

*Those **AM repair technologies**, which could plausibly be applied to the above mentioned repairs, have been reviewed and successful repair cases in other industries are presented. It is clear that not all AM technologies can, should and would be used for the repairs. Only Directed Energy Deposition, Powder Bed Fusion, cold spray AM and Additive Friction Stir processes are currently used by similar industries for component repair. One can conclude that the most promising technology is Direct Energy Deposition (DED), due to its flexibility and capability to repair large-size and complex components. The DED technology has been used in different applications in several industries and it can use either powder or wire as feedstock material.*

***AM repair strategies.** Several ways in which accelerator community can benefit from the implementation of AM repairs have been suggested. It appears that repairs can be implemented according to the following strategies:*

*1) **Reactive Repair**: react only after failure is present - large repair costs, potential that repairs are not feasible anymore and potentially large downtime;*

*2) **Repair as part of maintenance**: react before failure - less downtimes, probability of relatively higher costs and need for monitoring capabilities;*

*3) **Repair to rectify the manufacturing errors**: applicable for large and costly structure repairs, on case-by-case basis, has potential issue with reachability as well as step-by-step approach will be eventually required;*

*4) **Remote and in-situ repairs**: AM equipment installed on robot arms and perform repairs in-situ and directly in the environment where damaged part(s) is located, with minimal dismantling required. Potential approach can be applied for large structures (with transporting issues) and in hostile environments, e.g., accelerator tunnels.*

*It can be concluded that none of the aforementioned strategies are providing a silver bullet or a quick solution for the complex accelerator component repairs, especially those with the high requirements of accuracy, tolerances or positioning. A step-by-step approach is necessary to demonstrate AM repair feasibility since all cases are different. This approach should begin with testing on external objects without reachability issues, using standardized equipment to exclude uncertainties. Feasibility can then be demonstrated on simplified objects, followed by targeted research and development of the required experimental equipment.*

***Case study:** electrodes made of tantalum (an exotic and expensive material with high melting temperature – close to 3000℃) have been repaired by AM. The case study includes sample characterization before and after the repair process (morphological, chemical, and mechanical analysis) and quantitative data outlining repair conditions.*

*After analysis of all available AM repair technologies, two of them have been recommended for tantalum electrode repair – powder and wire directed energy deposition. Two repair approaches were distinguished: full electrode head restoration (cutting off and printing a new head) and partial repair (crater filling). The best values of the process parameters were found, and the feasibility of the repair strategies was tested.*

*The case study includes sample characterization before and after the repair process (morphological, chemical, and mechanical analysis) and quantitative data about repair conditions.*

*It was successfully demonstrated that the tantalum electrodes can be repaired by both wire and powder direct energy deposition technology. In both cases, eroded craters were filled to form a dome-shaped surface, demonstrating the applicability of the selected technologies and strategies to the repair of a particle accelerator component.*

***Conclusions.** AM repair technologies have the potential to refurbish the geometry of accelerator components, although an experimental-based step-by-step approach and functional tests are necessary to ensure successful results, particularly for closed structures such as accelerator cavities. This research provides initial information to the accelerator community, which could open up new avenues for more sustainable practices through the use of AM repair technologies. Additionally, this* *research may guide the AM industry in recognizing further developments needed for AM repair technology equipment to become more applicable for accelerator repairs.*

# 1 Introduction and Objective

The term additive manufacturing (AM) is often used synonymously with 3D printing and refers to a collection of technologies where materials are selectively accumulated to build, grow of an object layer-by-layer until a three-dimensional object conforms to its digital model [1]. AM technologies have been implemented mostly for component manufacturing. However, a layer-by-layer approach has been applicable for component repairs as well [2].

The main focus of task 10.3 research, which is reported in this deliverable, is on AM repair technologies only (not AM technologies for object manufacturing), indicating state-of-the-art approaches and successful implications in other industries which might offer a roadmap for the particle accelerator community.

Another important term in this report is particle accelerator, which is a machine that accelerates elementary particles, such as electrons or protons, to very high energies. In other words, particle accelerators produce beams of charged particles that can be used for a variety of research, medical and industrial purposes. Despite particle accelerator wide range of applications and high level of maturity and success, innovation is needed to identify and develop new sustainable accelerator technologies capable of reaching the performance required by particle physicists at an acceptable impact on society and environment [3].

All accelerator components – starting from the beginning of the beam in particle source, including components along the way as colling circuits, vacuum systems, and power sources, ending in beam dumps – all are within scope of this research.

The particle accelerator industry potentially could benefit from AM in several ways as this approach is very flexible, suitable for automation and suited for multi-material micro and macro in-situ repairs. Especially for components that are made from exotic materials, have complex manufacturing procedures, are in hostile environments or are generally prone to develop local defects.

Therefore, the objective for task 10.3 is to understand the current status of AM repair usage in the field of accelerators, to list possible AM repair applications for accelerators, as well as AM repair strategies and technologies for repairing accelerator parts, and demonstrate AM repair for accelerator components.

# 2 AM repairs concept and current AM repair application within the accelerators

In this chapter the concept of AM repair process is introduced, with an emphasis that AM repair process differs from AM manufacturing process and has several key factors that must be recognized. As well as will cover information on the current AM repair status within the field of accelerators.

## 2.1 AM REPAIR CONCEPT

AM repairs are the process where a new material layer is directly printed on the base material, which has sustained some damages and lost features. At the basic level AM repair process have some similarities with the welding repair process, which is commonly used to improve, update, and rework parts so that they equal or exceed the usefulness of the original part. Both processes can be used to fill holes, cracks, and dents in the surface. However, AM repair exceeds those applications as the near net shape feature can be restored directly on the damaged part. For example, a few damaged teeth of a gear can be restored and machined so that the part is again usable (Fig. 1). It is obvious that this approach is more sustainable and environmentally friendly than rebuilding ex-novo the full part.

*Fig. 1 Additive repair process of broken gear teeth: broken gear teeth, additive repair process and finished machined part (left to right) [2]*

It must be noted that in any case, component repair by AM is a more complicated process than component production by AM. Main reasons being:

- Some form of reverse engineering data is required to determine which part of the component is damaged and what geometry describes needed repair. As an example, if some defect needs to be repaired, precise information about defect location, its size and depth, etc. is needed.
- The damaged component may not match its theoretical model (new component) well at all, even in areas that are not considered a defect. Therefore, it becomes mathematically complicated to determine what the damaged volume is. In this case, the 3D scanning technique can be useful.
- Alignment of the physical component in the additive system (the machine that is doing the repair) should match with the coordinate system in the part's data in the software. If not, then the carefully determined repair geometry may not be placed correctly [4].

- Usually, some preliminary machining is needed before the repair operation to remove surface contamination and damage from surface, otherwise bonding problems between the substrate and the newly added material may occur.
- Post-machining is almost always needed, if part has critical tolerances and specification for high surface finish – which are the well-known downfalls of AM technology.
- Bonding between the base material and new material layer can be a problematic area in repairs especially if the new material layer differs from the substrate, when it is intended to improve the characteristics of the component by adding a new material layer with a different functionality to the substrate.

## 2.2 CURRENT AM REPAIR USAGE IN THE FIELD OF ACCELERATORS

The survey has been done to clarify current AM repair usage within the field of accelerators. For mentioned following databases were used: ScienceDirect, Scopus, Springer, Web of science, CERN document service, The Joint Accelerator Conferences Website (JACoW) and GoogleScholar. Search within these databases was done with main keywords: repair, refurbishment, maintenance, additive, manufacturing, 3D printing, accelerator.

After previously mentioned literature survey it stands out that AM applications for component manufacturing in particle accelerator field have already been studied [5]. However, it appears that for now the application of AM technology for accelerator part repair is practically non-existent, in contrast to automotive and aerospace industries, which have already adopted AM repairs in an effort to improve their product sustainability.

As investigations have shown that there are no references in literature or any publications on the topic of AM repair in the particle accelerator field, a questionnaire aimed at the particle accelerator community was launched in order to understand the reasons behind it, to identify potential knowledge gaps and potentially to collect information on the existing use AM techniques in the repairs of particle accelerator components that are not published. In addition, the authors survey potential objects for the following case/experimental study on which to demonstrate the advantages and disadvantages of the use of AM approaches in their production and refurbishment.

# 3 Questionnaire about AM applications and potential developments

In order to collect information on the existing use of AM techniques in the production and repairs of particle accelerator components, task 10.3 partners reached out to the particle accelerator R&D community with a questionnaire. In addition, authors seek out potential candidate component objects on which to demonstrate the advantages and disadvantages of the use of AM approaches in their production and refurbishment.

The questionnaire has been created and conducted on GoogleForms platform, distributed and circulated by weekly I.FAST project newsletter on 22.03.2022 to 290 project members from 49 participating organisations and 32 associated partners within 14 countries [6]. Further distribution of questionnaire by task leaders and coordinators has been encouraged but cannot be realistically followed.

The questionnaire was active for 3 months, after this time only 21 responses were received resulting in no more than 7.2% response rate (out of an assumed 290 mailing list members). Where the activity highlights how disinterested the particle accelerator community is in this topic at the moment or doesn`t want to share their expertise in AM applications.

## 3.1 RESULTS: EXISTING EXPERIENCE AND FUTURE PROGNOSIS FOR AM USE

To get an overall idea of how widespread AM technology is in general – AM for component manufacturing, and repairs in any industrial application, within the accelerator community. Respondents were given a choice of three answers: they have had previous experience, they don't have had any previous experience and they don't have experience but have heard of AM use in other institutions. Out of all responses, only 9.5% of people haven't previously heard about or had any experience with AM (Fig. 2). This might lead to think, that most of accelerator community has information about AM.

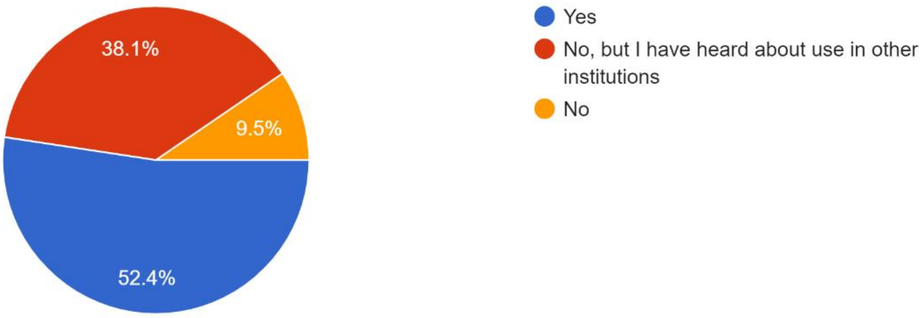
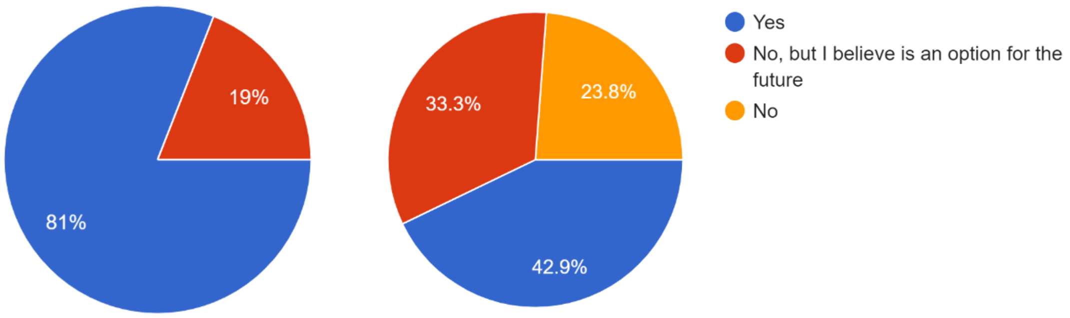


*Fig. 2 Particle accelerator community experience with AM*

To discover accelerator community`s current and future intentions on repairs with AM. Respondents were asked "Would you consider to use of AM for accelerator component production/ repairs?" with given three choices: they would now consider AM for accelerator component repair, they would not and they would consider it in future.



**AM for production** **AM for repairs**

*Fig. 3 Particle accelerator community consideration of using AM for component production and repairs*

Results show that accelerator community is less optimistic about repairs than just production by AM – only 42.9% would consider AM for repairs at this moment (in comparison with 81% of AM for component production) (Fig. 3) – this points out that the repair process is an unknown principle to the community, they haven't evidence of successful examples or they truly don't believe in AM suitability for repairs. An interesting point – if no one definitely declined AM use for part manufacturing in previous question, then 23.8% don't even consider repairs for future use.

Possible AM repair applications for accelerators have been sought in the survey and listed in the following chapter.

## 3.2 LIST OF POSSIBLE AM REPAIR OBJECTS

Respondents, who would now or in the future consider AM for accelerator part repair (in this case – 16 respondents) were asked additional question, to elaborate on their thoughts about what parts might benefit from AM repairs. Respondents were expected to provide examples of parts that could be potentially repaired by AM. Several interesting objects were named: cavities, targets, beam dumps, ion source electrodes, vacuum chambers and drive and mechanical parts; which have been investigated in the following subchapters.

### 3.2.1 Cavities

To accelerate particles, the accelerators are fitted with metallic chambers containing an electromagnetic field known as cavities (Fig. 4). Charged particles injected into this field receive an electrical impulse that accelerates them [7].

The most critical part of a cavity and especially a superconducting cavity is the surface. This comes from the fact that the current flows with nearly no losses. Any contamination on the surface will give rise to extra heat and will drastically increase the losses. Due to the low thermal capacity at low temperatures even a minute heat source may provoke a large increase in temperature and superconductivity may be destroyed [8].

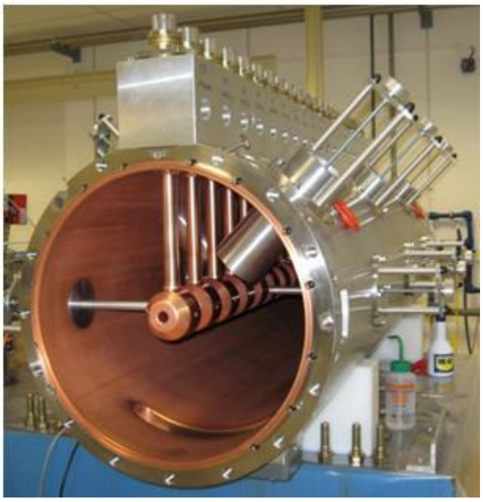


*Fig. 4 Drift Tube Linac accelerating structure [9]*

**Possible defects**. The surface of the cavity could be defective in several ways: from welding process or from surface coating process. Surface coating is now done by several technologies, including, vapor deposition, liquid tin dipping, multilayer sputtering, mechanical plating, electron beam evaporation, bronze processing, and electrodeposition [10].

Electropolishing is presently the preferred route for preparing the final cavity interior surface. A particular problem that electropolishing cannot address is the removal of pits near the equator welds. It is not clear at present whether pits are a result of conditions resident in the material, flaws of the material preparation prior to welding, flaws in the welding process itself, flaws in the polishing process, or a combination of these. The application of AM techniques could possibly even out the surface pits, although this is not yet researched.

Another problem arising from welding process is the burn-through – burning holes in the material if welding is done incorrectly. This is usually repaired by solid material plugs and additional welding, but could be potentially done with AM methods.

**Conclusions about possible AM repairs:** possible repair of coating defects, welding seams or welding process defects potentially can be done. Requires high surface finish, no inclusions and no impurities, which might be challenging with most AM methods where targeted research are needed. Defected area's reachability can be one of the main issues.

### 3.2.2 Targets

In a particle accelerators targets are used for research and medical applications. In research accelerators, this collision generates various types of particles and radiation, which is registered by various detectors. Targets can be solid bodies or liquid circulation systems.

Target materials are chosen based on three key characteristics: the types and abundances of rare isotopes produced; the rate at which they diffuse out of the target; and the beam power they can withstand without melting or decomposing. The three most frequently used proton-beam target materials are uranium carbide, silicon carbide, and tantalum; others include tantalum carbide, tantalum, nickel oxide, niobium, zirconium carbide and titanium carbide [11].

Target can be used only for a limited time, then it needs to be replaced and used target is stored in radiation isolated chamber. Lower-energy interactions can have long-term, negative impacts on a target, building up heat energy inside it. As the target material rises in temperature, it becomes more vulnerable to cracking. Expanding warm areas hammer against cool areas, creating waves of energy that destabilize its structure. Some of the collisions in a high-energy beam can also create lightweight elements such as hydrogen or helium. These gases build up over time, creating bubbles and making the target less resistant to damage. A proton from the beam can even knock off an entire atom, disrupting the target's crystal structure and causing it to lose durability [12].

In the case of liquid target (Fig. 5) (which is very commonly mercury) the beams bombard the target; pressure waves are generated in mercury by thermally shocked heat deposition. Cavitation is induced through the pressure wave propagation in mercury and erodes the vessel inner surface contacting with mercury, i.e. pitting damage. The eroded vessel wall is damaged by cyclic fatigue because pulsed beams strike the target repeatedly as seen in Fig. 6 [13]. Due to the service environment and elevated level of radiation, the materials used to construct the target module experience radiation and high-cycle fatigue damage. Consequently, the target module has a limited-service life and must be periodically removed and replaced, to avoid mercury leaks from targets.  The target module is replaceable exclusively by remote handling equipment [14].

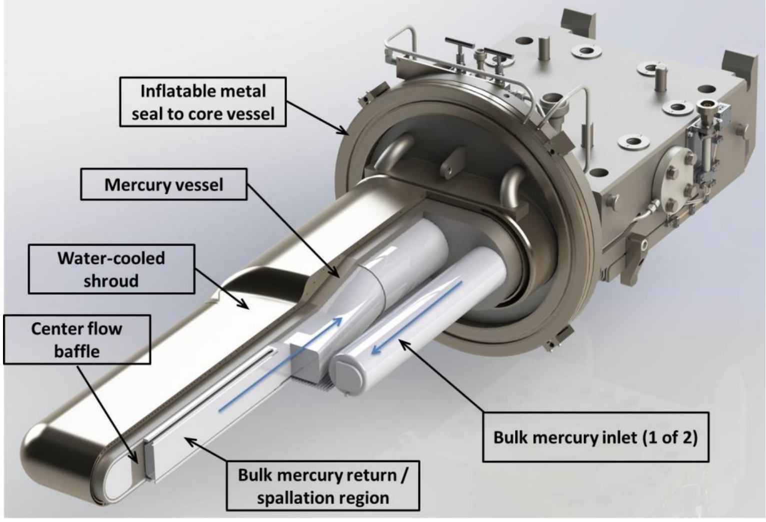


*Fig. 5 Structure on liquid mercury target [14]*

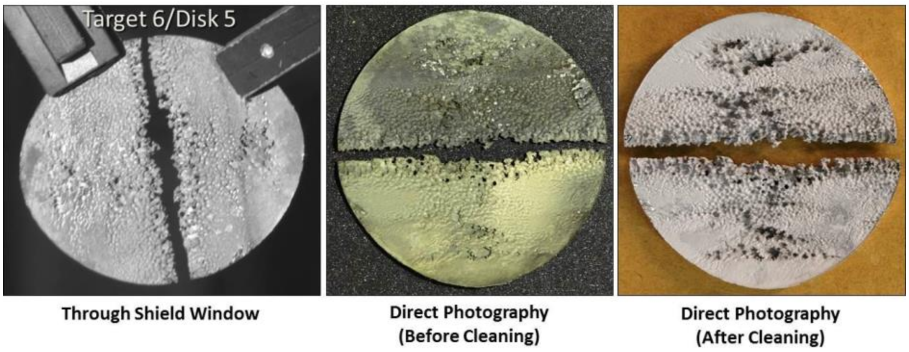


*Fig. 6 Target inner wall damage due to mercury cavitation and fatigue [14]*

**Conclusions about possible AM repairs**: targets sustain deep damage into the bulk of material (Fig. 6), therefore repair should be executed before crustal damages as a maintenance. However, AM repairs are not possible to implement for fine-tuned targets with thin multiple-layer structures.

### 3.2.3 Beam dumps

The purpose of a charged-particle beam dump is to safely absorb a beam of charged particles such as electrons, protons, nuclei, or ions. This is necessary when, for example, a particle accelerator has to be shut down or the beam has lost its properties and needs to be disposed before a new one is created.

Beam dumps can range from small solid metal blocks, to intricately designed assemblies to massive building like structures as the one used by CERN for the Super Proton Synchrotron, which consists of graphite, molybdenum, and tungsten surrounded by concrete, marble, and cast-iron shielding.

Beam dumps mainly sustain damage because of the heat created, since the energies of the beams to be absorbed can run into the megajoules range. For example, radiation damage from proton irradiation exhibits specific features due to the retention of hydrogen in the metal, such as hydride formation, embrittlement and nucleation and growth of hydrogen bubbles as seen in Fig. 7.

*Fig. 7 A 40 cm diameter tungsten beam dump from SARAF accelerator damaged after several minutes of irradiation by 4 MeV protons at a current of 6×10 15 protons/sec [15]*

**Conclusions about possible AM repairs:** beam dumps sustain damage deep into material. Needs special equipment and technique. As with beam dumps, large material removal before repairs is potentially needed. Most beam dumps remain radioactive for a long time – remote or in-situ repair is the only possibility if any are needed.

### 3.2.4 Ion source electrodes

An ion source is a device that creates atomic and molecular ions. There are many types of ion sources classified by ion type created or by ion creation method. Due to working mechanisms of ion sources – removing material to create a beam of particles, their lifetime is limited, to be more specific electrode (filament, sacrificial material) lifetime is limited and it needs periodical replaced.

In specific cases electrodes are made out of expensive and exotic materials (tungsten, tantalum) therefore disposing of used electrodes is neither economically sound nor environmental friendly.

For example, Penning Ionization gauge ion source cathodes are replaced regularly, because when the cyclotron operates, the cathodes are subjected to the impact of plasma back-accelerated ions. After a variable running time an erosion crater appears at the surface of the cathodes.

**Conclusions about possible AM repairs:** usually, electrodes are disposable items, but knowing that exotic materials are used for electrode production, AM repair could be an innovative application, economic and a more environmentally friendly approach.

### 3.2.5 Vacuum chambers

Most beam enclosing structures must maintain vacuum for beam to maintain its quality and not dissipate due to collision with air molecules. Magnet insulation chambers also must maintain a vacuum, although not as high as beam vacuum.

Components that must hold vacuum but have developed cracks and leaks are potential candidates for AM repair. Most vacuum chamber failures occur on weld seams or in places with inclusion in the raw material. Potential solution - spray metal (most likely aluminium or copper) on a chamber on which a leak developed. This could significantly increase the vacuum chamber lifetime and/or reduce the cost for the remanufacturing. CERN vacuum group is today using a varnish that is sensitive to radiation and also not ultra-high vacuum compatible. A full metal solution would be clearly an asset**.**

**Conclusions about possible AM repairs:** repairing cracks or holes in leaking vacuum chambers is a very perspective case for AM repairs, as most vacuum chambers do not need high geometrical tolerances and surface roughness. But due to high-quality requirements for porosity and inclusions, designated research in this application area would be needed because they are present with most AM methods.

### 3.2.6 Drives and mechanical parts

All kinds of mechanical parts that are subject to wear and tear are logical choices for repair operations. Although not every broken gear or worn shaft must be repaired – usually only economically justified pats. For example, legacy parts and custom-made components, parts from expensive and exotic materials, large and very complex parts also parts of a large assembly, that is not easily disassembled. Economic factors excluded, part repair is always more sustainable and environmentally friendly.

**Conclusions about possible AM repairs:** mechanical parts that wear in time, could be repaired if economically justified. However, there are not many wear and tear parts in accelerators.

## 3.3 CONCLUSIONS ON CURRENT AM STATUS ON ACCELERATOR FIELD

After extended survey that included and targeted questionary to accelerator community it stands out that AM technology applications for accelerator repair is not yet applied. Different situation is in automotive, energy and aerospace industries, where AM repair technologies have been adopted in order to improve their product sustainability.

The main conclusions of the questionary are that the accelerator community is not enthusiastic about AM repairs in general, according to the survey response only 42.9% would consider using AM technologies for repairs at the moment. However, respondents gave a decent number of suggested accelerator components for AM repair applications. Unfortunately, almost none of the mentioned repair prospects are immediately possible without individual study and major parts without specific equipment (due to reachability issues). However, several mentioned objects, like cathodes, cavities and vacuum chambers can show great potential by using AM repair technologies. That led to collect accelerator requirements within the following chapter (Table 1), which should be considered in AM repair applications.

By summing up: according to initial research that consisted of current AM repair status investigation, and extended research with the survey, feasible AM repair technologies should be collected by showing AM repair options to the accelerator community. Also, it was noted that probably positive examples are missing as evidence for accelerators, therefore AM repair technology should be demonstrated as a case study by using the accelerator components. The research is  in progress and continuation is done in the following report.

## 3.4 PARTICLE ACCELERATOR COMPONENT REQUIREMENTS

Particle accelerators are complex, with tight tolerances, fine-tuned machines, where component production and especially repairs pose many engineering challenges for supporting technologies. Major physical constraints are described in Table 1.

*Table 1 Physical properties affecting particle accelerator components*

| Requirement | Value | Unit | Source | Significance for components |
|---|---|---|---|---|
| Vacuum | $< 10^{-12}$ | mbar | [16]<br>[17] | No pores, no contamination, no defects, structural integrity. |
| Voltage | < 120 – 330 | kV | [18]<br>[19] | No internal defects, low surface roughness, no surface damages. |
| Magnetic field | <16.5 | T | [20] | Correct choice of magnetic/ nonmagnetic materials, shielding |
| Temperature | 1.9 – 2273 | K | [20] | Choice of material. |
| Radiation | <10 000 | Gy per year | [21] | Choice of material, part location and shielding |
| Frequency | 3 – 12 000 | MHz | [22] | Very low surface roughness |
| Electrical conductivity | $5.8 \cdot 10^{7}$ | $\Omega^{-1} \cdot cm^{-1}$ | [23] | Pure materials, dense structures, no surface contamination, low roughness |

Of course, not all aforementioned specifications applies to every single one of accelerator components all the time – they might vary from case to case, but the specific requirements have been mentioned for holding vacuum, high voltage, wide temperature range, radiation etc. It could be concluded that the strict and unusual demands of component properties could be one of the reasons why AM is not very widespread in accelerator community and should be considered in further developments.

# 4 AM repair technologies

This chapter is dedicated to the investigation of which AM technologies have the potential to be used in particle accelerator component repair, including a short analysis of dominant metal AM technologies. Several examples are given of successful repair cases in other industries. In order to maintain focus and narrow down the subject, the main emphasis has been on metal AM technologies as most of the particle accelerator components are made of metallic materials.

## 4.1 REPAIR TECHNOLOGIES

A variety of technologies, equipment, and materials are used in the repair of parts via AM. Each method and machine have advantages and drawbacks – characteristics such as speed, costs, versatility, manufactured part geometrical limitations and tolerances, as well as mechanical properties and visual appearance.

There are several technologies that are already now used in component repair – directed energy deposition, powder bed fusion, cold spray AM and additive friction stir deposition. Examples of successful repair cases have been reported in the next sections.

### 4.1.1 Powder bed fusion for repairs

Powder bed fusion is the most well-known AM technology for metal part production. In this process, a powder bed is created by raking powder across the work area. The energy source (electron beam or laser beam) is programmed to deliver energy to the surface of the bed melting or sintering the powder into the desired shape. Additional powder is raked across the work area and the process is repeated to create a solid three-dimensional component by many layers. In the end, the part is removed from the powder, cleaned from residual powder, and post-processed [24] .

Research has been done using this method by Zghair [25] who introduces an additive repair design approach, with focus on Laser Powder Bed Fusion (LPBF) technique, and investigates mechanical properties and the bonding force between the damaged components and the added repaired volume, whilst introducing several distinctive repair strategies for powder bed fusion process (Fig. 8).

There is also research in accelerator field, but it is not described as repair, although the concept is almost the same. There is a two-part component called beam dump. To perform its functions, the beam dump should have a front portion, facing the beam, composed of bulk dense copper to effectively stop the incoming protons, and a second back portion where the cooling system acts to cool down the front. In this case the back portion cooling channels are printed with LPBF on top of solid copper disc (Fig. 9) [26].

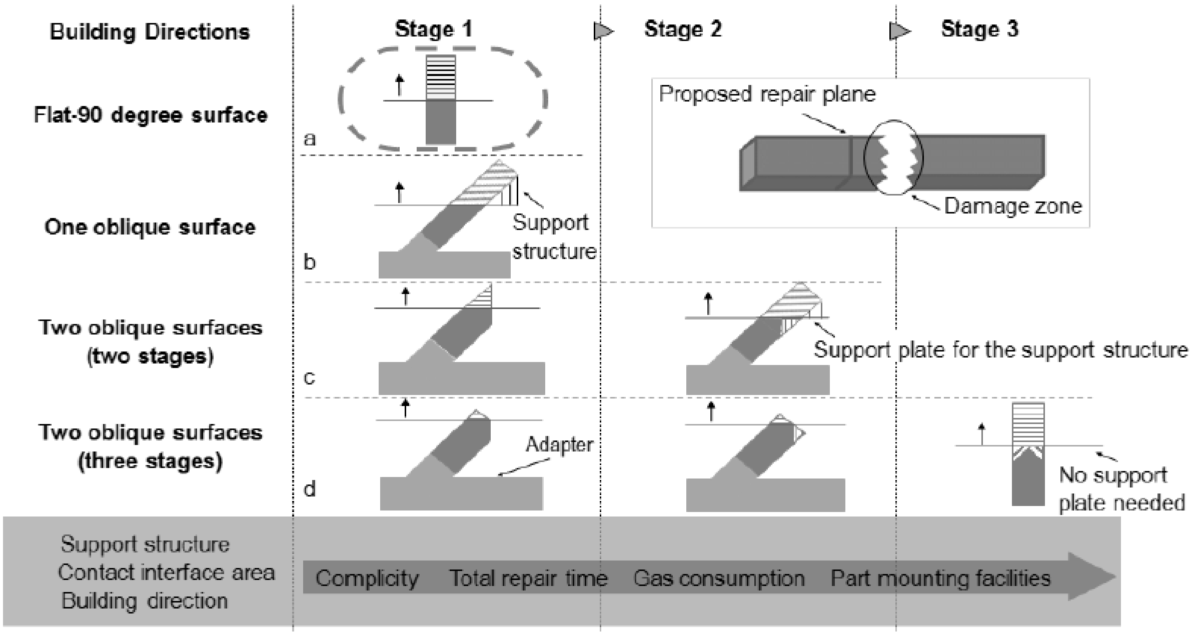


*Fig. 8 Powder bed fusion repair process, building directions and planes. a) Flat surface, one building stage. b) One oblique surface, one building stage. c) Two oblique surfaces, two building stages. d) Two oblique surfaces, two building stages [25]*

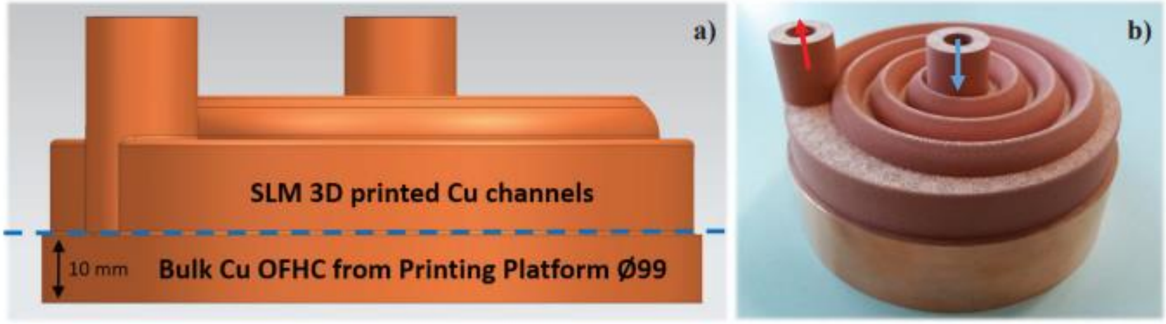


*Fig. 9 Side view of the CAD design and manufactured cooling channels on top of copper disc (as an example: the new part is manufactured on top of an existing object by creating a mono structure, that demonstrates repair feasibility and possibilities by using LPBF) [26]*

Similar work done by Smelov [27] on possibility of restoring blades while repairing gas turbine engines parts by LPBF (Fig. 10). Based on this, Siemens Energy (Germany) is announcing a new digital repair chain using “Hybrid” LPBF that makes it possible to add new features to gas turbine blades [28].

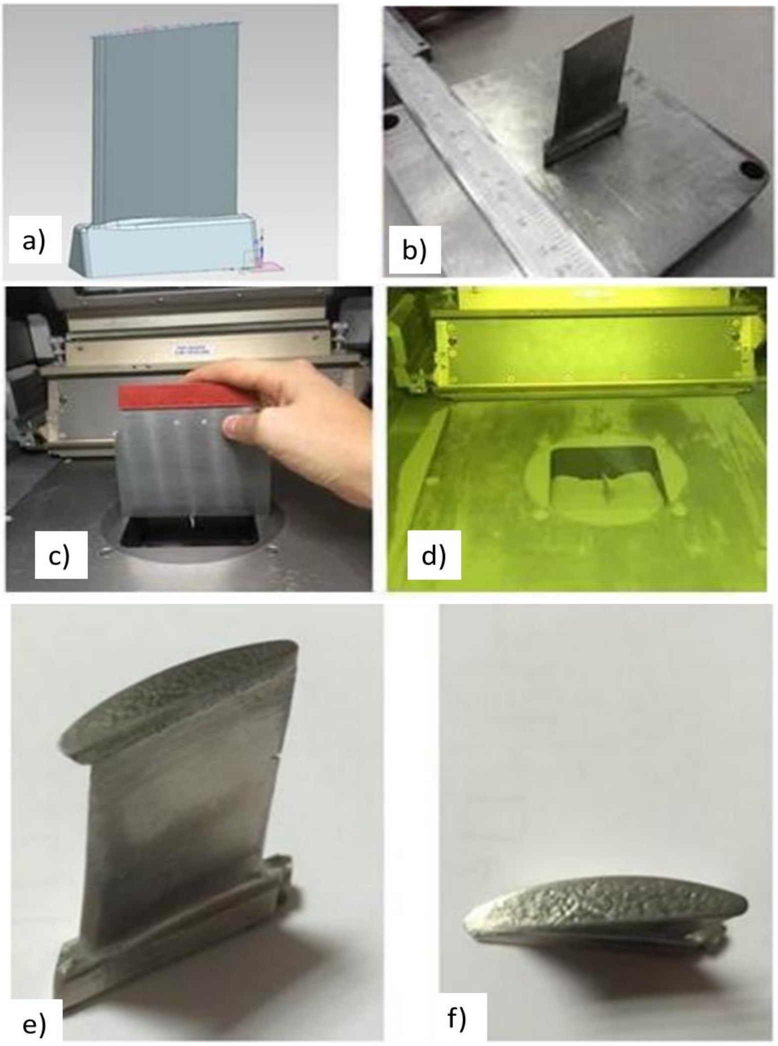


*Fig. 10 Gas turbine engine blade repair by selective laser melting. a) model of damaged blade b) welding part to build plate c) lowering blade into powder bed d) pre-filling powder bed with powder e) and f) repaired parts [27]*

The main limitation of PBF repair technology is that the build surface needs to be flat and parallel to the build platform (in the plane with x-y axis). Otherwise, the first layer of powder thickness will not be uniform and will lead to severe build defects. The common method to do this is to fix the repairable component to build platform, then grind the top of the repairable part parallel to the built platform bottom plane, lower all these fixtures in the powder bed, and rake powder across fixture until it is all covered. Due to this, there is no possibility to incorporate support structures for upcoming builds if needed, as now there is only the possibility to build upwards and support only on powder that limits overhangs (max 45 deg.). It is now evident why this method is not one of the favourites in part repairs.

### 4.1.2 Directed energy deposition for repairs

Directed energy deposition (DED) is a group of AM processes that add material alongside the heat input simultaneously. The heat input can either be a laser, electron beam, or plasma arc. The material feedstock is either metal powder or wire [29]. In both systems, build material is conveyed through a nozzle onto the build surface. A laser beam is used to melt build material and base material (or previous layer) to obtain monolith structure and cerate the desired shape. This process is repeated to create a solid three-dimensional component layer by layer [24].

There is some promising research in railway industry – restoration of worn rails by laser powder deposition (Fig. 11) [30]. Where the deposition zone contained a total of six deposition layers. There were visible signs of microcracks in the first layer near the rail-deposition interface. Micropores also were detectable in all the layers. The overall evaluation indicated that this is a promising rail repair technique. However, to achieve a perfectly repaired rail, the microcracks and micropores that developed must be minimized or eliminated. Preheating before repair process and isolating the rail substrate during heat treatment are suggested solutions that will require further studies in the future [30].

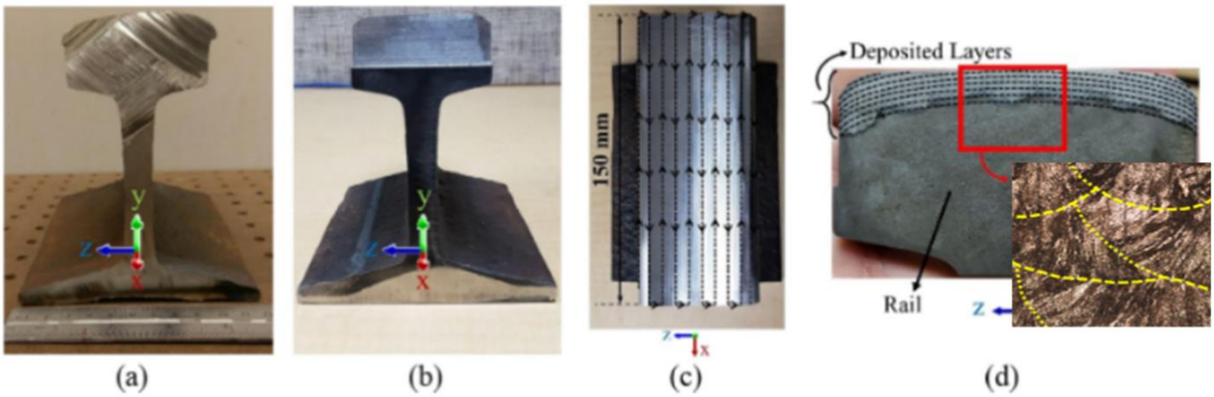


*Fig. 11 Rail repair by DED a) Worn rail; (b) repaired rail, front view; (c) repaired rail, upper view, showing the longitudinal tool path; (d) a thin slice from the repaired rail [30]*

Other research of laser powder deposition for repairing the surface defects of spline shaft to improve wear resistance, shows how composite coatings were fabricated on the spline shaft surface by laser cladding with TiC reinforced Ni based powder (Fig. 12) [31]. A very notable detail must be noted from this work – after AM processes the finished surface was obtained by grinding process.

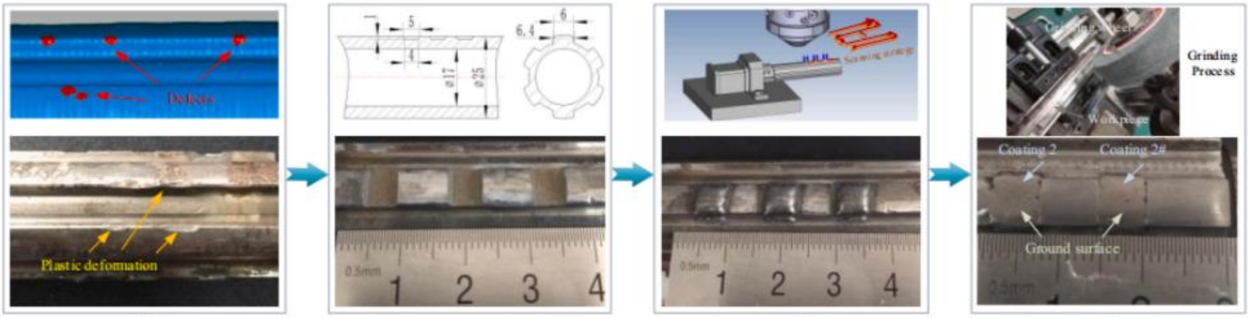


*Fig. 12 Repair of spline shaft by laser cladding [31]*

A procedure to repair a mold insert for use in the casting of aluminum cylinder heads for internal combustion engines by wire arc AM deposition technology and subtractive processed on single machine has been developed and analyzed in recent research (Fig. 13) [32]. Overall, at the end of the first life of the mold insert, the results highlighted that the AM repair-based approach could allow potential savings and offer environmental benefits, compared with the mold insert being machined from a massive workpiece. It must be noted that in this repair, very extensive machining operations were conducted after AM to obtain specified surface roughness and geometric accuracy.

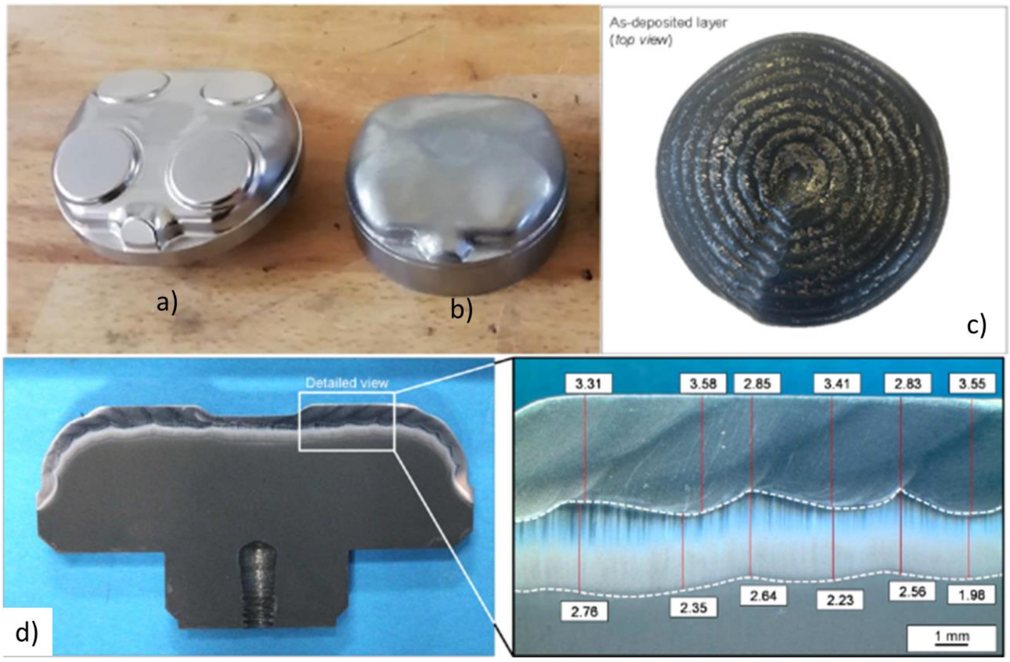


*Fig. 13 Wire Arc AM for mold repair. a) original component b) component with damaged faces removed c) component with added metal layer d) cross section after AM process [32]*

The research about DED technology shows there are many possible issues and defects due to thermal influence and technology properties. Common defects for all DED systems are [33]:

- Poor surface finish;
- Porosity, cracks, non-metallic inclusions and incomplete fusion;
- Lack of geometrical accuracy;

For now, DED is the most popular AM technology for part repairs. The key benefits of DED over other techniques are:

- It creates a stronger bond between base and added material;
- less restrictions on the repairable component sizes than with PBF;
- repair equipment has multi axis movement;
- In-situ repair opportunities.

The benefits of the stronger bond are obvious. A multi axis and in-situ repairs means that repair can be made of many angles and is not restricted to one plane. The downside of the technology is that the structure to be renovated will be of relatively simple construction and will require surface post-processing.

### 4.1.3 Cold spray for repairs

Cold spray additive manufacturing (CSAM) is a derivation of cold spraying – one of thermal spraying methods which are a class of surface coating technologies. CSAM uses heated high-pressure inert gas to accelerate metal powders through a nozzle above the critical velocity for deposition onto a substrate. Upon impact particles deform, creating high strains and localized plasticization of the material so that a combination of both mechanical interlocking and metallurgical bonding can be achieved thus creating a 3D component [34].

A comprehensive review of cold spray AM has been published by Yin [35], with several examples of cold spray repair applications (Fig. 14 and Fig. 15).

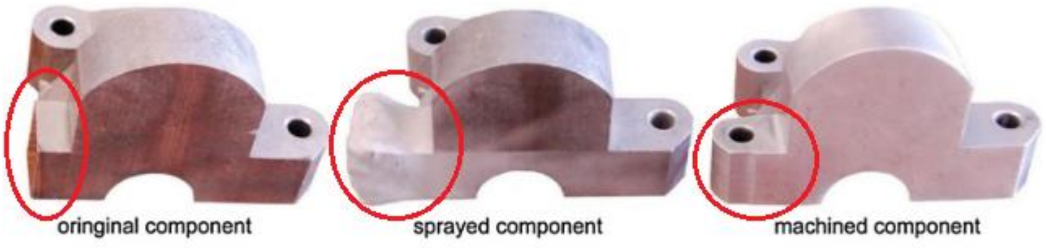


*Fig. 14 Cold spray AM repair process of bearing cap [35]*

*Fig. 15 Cold spray AM repair process of flange – damaged part, part after spraying, part after machining [36]*

In cold spraying used for repairs, there are concerns about bonding forces (delamination is very common with cold spraying), work hardening and higher residual stress in the deposit due to increased plastic deformation of the particles. Research shows that residual stress in the deposits can be released through post-spray annealing. Additionally, deposits normally have worse mechanical properties – as lower ductility, lower electrical conductivity, and lower thermal conductivity when compared to bulk materials or fusion-based AM. Defects such as micro-pores and inter-particle boundaries are commonly found in deposits. These defects are caused by insufficient particle plastic deformation and poor inter-particle bonding during deposition [35].

Similar to other restoration techniques, the feedstock for CSAM cannot be deposited on the damaged component directly because of the complex surface topography, and the potential for the contaminated surface of the damaged area to compromise bond strength. Pre-machining on the damaged zone is necessary to reconstruct the damaged surface. Surface treatment is then conducted on the reconstructed surface with milling, grinding, or grit-blasting to prepare a clean and level surface which is suitable for CSAM. As well post machining is also required as CSAM is struggling to produce sharp edges, perfectly flat surfaces and high tolerance geometries [35].

### 4.1.4 Additive friction stir deposition for repairs

Additive friction stir deposition (AFSD) process is an emerging solid-state technique which works on principles of AM and friction stir engineering. AFSD enables near-net shaping with the help of site-specific deposition. It involves a hollow non-consumable rotating tool through which raw material in the form of powder or solid rod is fed. The fed material inside the hollow tool rotates with the tool shoulder. As the tool/fed material meets the substrate, frictional heat generates. The temperature of fed material increases resulting in its yielding and extrusion in the space between substrate and tool head.

One niche application of AFSD is the structural repair of components for the aerospace and defence industries, in which load-bearing components may suffer from corrosion, wear, or other damages. Griffiths et al. [37] explored the through-hole and groove filling of AA7075 plates and showed that AFSD was effective at filling the entire volume (Fig. 16).

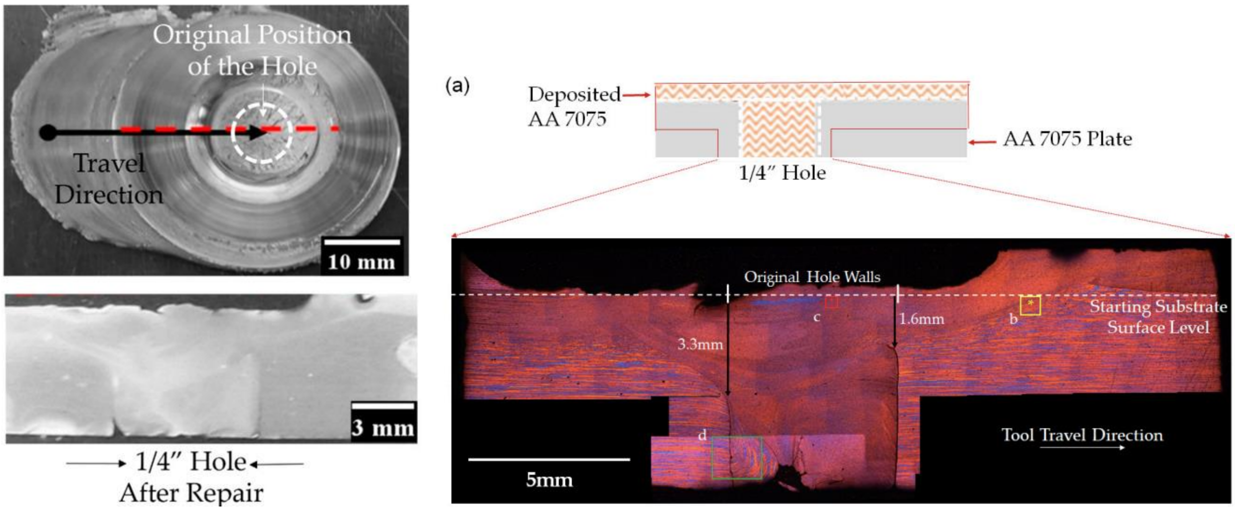


*Fig. 16 Friction stir AM repair for 1/4`` hole [37]*

Sufficient mixing was observed between the deposited material and the sidewall of the feature; as a result, the interface was indiscernible with a gradual change in microstructure. In that preliminary investigation, no optimization strategy was employed for process parameters and the scanning path, and inadequate repair quality was sometimes observed in deeper portions of the filling. In the on-going work by the same group of authors, such defects are shown to be largely eliminated by improving the repair strategy, e.g., by tuning the tool head rotation rate and dwell time. The repaired aluminium plates (after removing the excess deposited material from AFSD) exhibit decent static and fatigue performance [38].

The downsides for friction stir repairs are that the repaired structure can be very simple, the repair will require surface machining and mechanical forces are involved in the process where a repaired object can be damaged. All mentioned leads to conclude that AFSD is not the best choice for accelerator applications.

## 4.2 AM REPAIR CHALLENGES

AM repair challenges that are known within AM and have been noted after the survey from the accelerator community as well, are concerned with part properties – porosity, surface roughness, grain structure (Fig. 17), density, mechanical strength. All the aforementioned challenges are well known in AM applications and therefore are being researched intensely in all industries.

Right now, AM technologies like LPDF, state of art reached 99.99% or really close to that, dense structures in multiple applications, however, knowing that the AM is a complex, dynamic and metallurgical process there would be present some minor internal imperfections and especially surface roughness as it is shown in (Fig. 17). As can be seen most of the defects are on the surfaces or close to it (Fig. 17 c)) and that is an area where AM technologies should focus on. Nevertheless, on the market are available several technologies (for example from Rösler) that can make post-processing for rough AM-built structure.

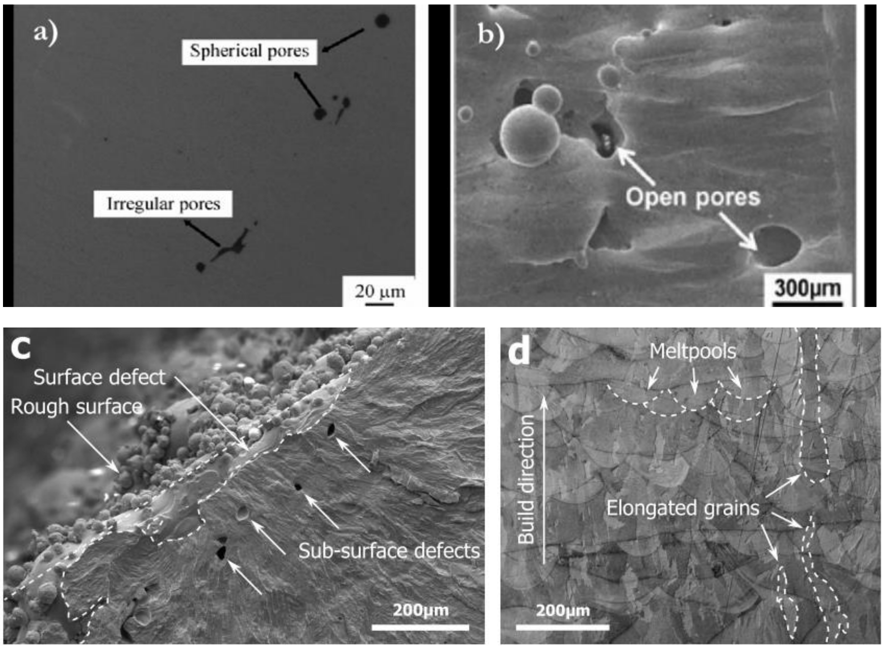


*Fig. 17 Typical defects of the Selective Laser Melting parts: a) spherical and irregular porosity, b) open porosity [39] c) surface defects and d) grain structure [40]*

The specific problem that particularly stands out for AM repair is the accessibility issue – repairing parts, especially in accelerators are closed structures, like cavities. Where without specially designed equipment it would be hard to reach the damaged areas. The same, reachability issue would be present for local post-processing, and machining that are applied after AM repair. However, those challenges can be minimized step by step, beginning with testing AM repairs for easily reachable areas by testing the feasibility and then improving reachability by modifying equipment.

## 4.3 CONCLUSIONS AFTER AM REPAIR TECHNOLOGY STUDY

It can be concluded that not all AM technologies can be used for repairs. Only DED, PBF, CSAM and AFSD processes are now used in industries for component repair. It must be noted that in any case component repair by AM is a more complicated process than component production by AM.

The main reasons are the need for some reverse engineering, theoretical and real part dimension comparison to construct geometry that will need to be added. Additionally, the component must be reliably and precisely placed in the machine that will do the repairs – so that added geometry aligns with existing geometry. Usually, some pre- and post-machining is needed – this makes AM repair process more of a hybrid type process. DED is the favourite and is used in the majority of cases due to versatility and equipment availability.

The AM repair process is a special case for the particle accelerator industry as accelerator components operate in specific work environments: ultra-high vacuum, high voltage, extremely low temperatures etc. (requirements are included in Table 1.) This calls for low porosity, good mechanical properties, high tolerances and excellent surface finish for parts that routinely need to be made from exotic materials of the highest purity. Those all are possible reasons why in particle accelerators AM is now used mainly in proof-of-concept component manufacturing and not yet in repairs. Although in some specifics accelerator industry is similar to others - aviation, aerospace, nuclear energy etc. industries.

After elaborate research, a decision was made to focus on a specific case study as a demonstrator for the accelerator community, to show and suggest that AM repairs can be successfully applied. The case study is described in a further section of the report.

Also, seeing that there are no straightforward AM repair applications for accelerator components like in other industries, potential repair strategies will be demonstrated in the following chapter.

# 5 Potential AM repair strategies

From a wider point of view, AM repair is not only a technology that can refurbish performance of the damaged objects, but also it can be used in several strategical ways. AM repair can be used not only to refurbish worn, damaged parts, but also as regular maintenance, and repair manufacturing errors and remote and in-situ repair. Following those mentioned strategies are described.

### 5.1.1 AM repairs for damaged parts after failure

Applying repair activities after failure means the component is out of order or its performance are reduced. According to Fig. 18 it would be reactive action. This approach is widely used however, repair costs can be the highest and by applying AM technologies most efforts would be needed due to the extra material amount to be added. As well there is the risk that after failure the damaged object gets additional defects (usually issues with mechanical parts). In any case, there are two ways in which AM repair can be done: cover with a new material layer just a damaged area, like pits, holes or cracks or re-built the complete part of the damaged object.

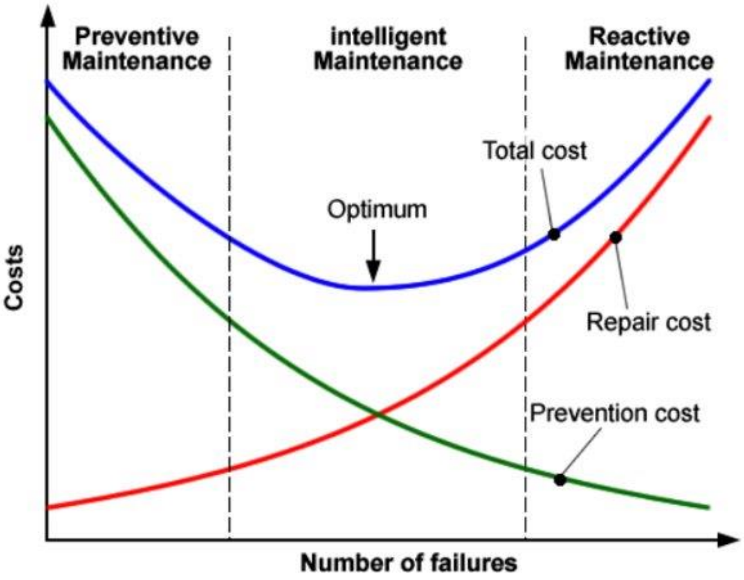


*Fig. 18 Maintenance costs versus number of failures in manufacturing*[1] *[41]*

When the issue has been noticed with some components only after the breakdown, we are not reducing or preventing the risk of downtime. Therefore, maintenance or preventive would be preferable for large operating systems.

### 5.1.2 AM repairs as part of maintenance

Maintenance operations are essential to modern manufacturing systems in terms of minimizing unplanned downtime, assuring product quality, reducing customer dissatisfaction, and maintaining advantages and competitiveness edge in the market. It has a long history that manufacturers struggle to find balanced maintenance strategies without significantly compromising system reliability or

---

[1] doi.org/10.3390/en7042595

productivity [42]. Costs and down time in Fig. 18 highlight the importance of maintenance. As it can be seen, there is a potential case for AM repairs to lower the repair cost in the reactive maintenance approach.

There are several successful examples in other industries, that could lead to the AM repair revolution in particle accelerator field. For example, AM technology has made it possible to eliminate environmentally polluting supply chain activities in the tooling industry and to repair and remanufacture valuable tools and dies. There is broad consensus on the potential applications of AM technologies for repairing and manufacturing parts in the aerospace industry. There are many studies on the capability of this technology for designing parts in this industry; repairing and manufacturing parts for turbo engines; in the spare part supply chain, amongst others [43].

### 5.1.3 AM repairs for manufacturing errors

Particle accelerator components are often large, geometrically complex parts from exotic materials – making them expensive to manufacture. It is obvious, that any mistake in manufacturing process, that could lead to scrapping the part is also very expensive. But it could be remedied with AM repair applications.

Manufacturing errors in particle accelerator parts that can potentially be repaired by using AM technologies are:

- Surface and coating defects;
- Welding errors: pores, burn-throughs;
- Error in geometry or dimensions.

Due to possible reachability issues, thin coating and other accelerator technology requirements, step by step approach should be applied. In this approach AM repair feasibility testing would be needed on beginning for external objects without reachability issues and by using standardized equipment. Following with targeted research experimental and equipment development activities increase AM repair feasibility where for example cavities repairs can be done.

### 5.1.4 Remote and in-situ repairs

All computer-controlled processes have always had a great potential for remote operations, AM is no exception – remote repairs could possibly solve the problem that some accelerator parts are harmful to people due to radioactivity, temperature, magnetic fields etc. Custom made repair equipment could be potentially used in solving accessibility problems as most accelerator parts are shielded from outside world, because of the already mentioned reason, that they are harmful to people. But robots and other equipment can be adapted for that. Thanks to the large reach and several degrees of freedom of robotic units, even highly complex components measuring several meters could be repaired simply and inexpensively with the precision and speed of industrially available robots with AM equipment mounted on them (Fig. 19) [44]. As a future option is to use previously mentioned systems: robot arms, AM equipment etc. and mount in areas where the damaged object is and do repair in-situ, with minimal dismantling operation. In-situ approach also can be applicable for a hostile environment.

*Fig. 19 AM setup with KUKA shelf-mounted robots [44]*

At the beginning of 2022 a collection of organizations from Germany (BTC and Fraunhofer ILT) and Canada (National Research Council of Canada, McGill University and Braintoy) set up a new consortium to automate the process of repairing parts using AM and artificial intelligence. The project, named Artificial Intelligence Enhancement of Process Sensing for Adaptive Laser AM (AI-SLAM), aims to develop advanced AI-based software to automatically run Directed Energy Deposition (DED) 3D printers. Used in conjunction with Fraunhofer's LMD technology (a form of DED), the software will algorithmically manage the printing process to more effectively repair of irregular surfaces on damaged components – all without the need for human input [45]. Results from their research could provide valuable results also for particle accelerator community.

In the conclusion, in most of the applications and strategies there won't be quick solutions by just implementing AM repair, there step-by-step approach is necessary to demonstrate AM repair feasibility because all cases can be different. This step-by-step approach should begin with AM repair testing on external objects that do not have reachability issues where standardized equipment can be used and different uncertainties can be excluded. Following by demonstrating the feasibility on the simplified object, targeted research and experimental and equipment development can be gradually developed.

# 6 Case study – Ta cathode repair

This chapter summarizes an in-depth, detailed examination of a particular case within a real-world application in particle accelerator – repair of tantalum electrode. Case study includes quantitative sample characterization before and after repair process (morphological, chemical, and mechanical analysis) and quantitative data about repair conditions, to demonstrate and verify particle accelerator component repair by AM as a future solution for part sustainability improvement and life cycle extending. Overall aim is to present AM technology to particle accelerator community as tried, tested, reliable and dependable procedure for part refurbishment.

## 6.1 CASE STUDY OBJECT IDENTIFICATION

A suitable repair object has been found within I.FAST project WP12.3 “Design of Internal RF Ion Source for Cyclotrons”. The specific component that has been used in this experimental study is the tantalum cathode of Internal Cold cathode Penning Ionization Gauge (PIG) ion source of the Advanced Molecular Image Technologies (AMIT) superconducting cyclotron.

When the cyclotron operates, the cathodes are subjected to the impact of plasma back-accelerated ions. After a variable running time an erosion crater appears at the surface of the electrodes. This delays the thermionic emission and reduces the current density of the produced beam [46]. When a large amount of material is removed, the ion source cannot be turned on and the cathodes need to be replaced or, as this research demonstrates, repaired.

Used and unused tantalum electrodes (Fig. 20) are supplied by El Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT) in Spain where the cyclotron is developed.

*Fig. 20 Unused and used tantalum electrodes*

## 6.2 ELECTRODE CHARACTERIZATION

Before repair activities, electrode characterization has been carried out in Politecnico di Milano by following methods: 3D laser scanning, Scanning Electron Microscopy (SEM) coupled with energy dispersive spectroscopy (EDS), microstructure investigation and hardness. Sample characterization revealed that after use electrodes have been damaged by several mechanisms. Electrode surface morphology shows signs of remelting and sputtering, also some cracks have been observed (Fig. 21).

Electrode surface spectroscopy reveals surface contamination by various particles – organic and inorganic (Fig. 22). 3D scanned models show severe deformation of material – deviation from form is up to 2/3 of electrode thickness (Fig. 23). Grain microstructure analysis reveals extreme grain growth at the tip of electrodes – in some cases single grain structure dominates the whole damaged area (Fig. 24). Consequently, undesirable mechanical properties of material at the tip (for example large hardness) will make it difficult to machine samples.

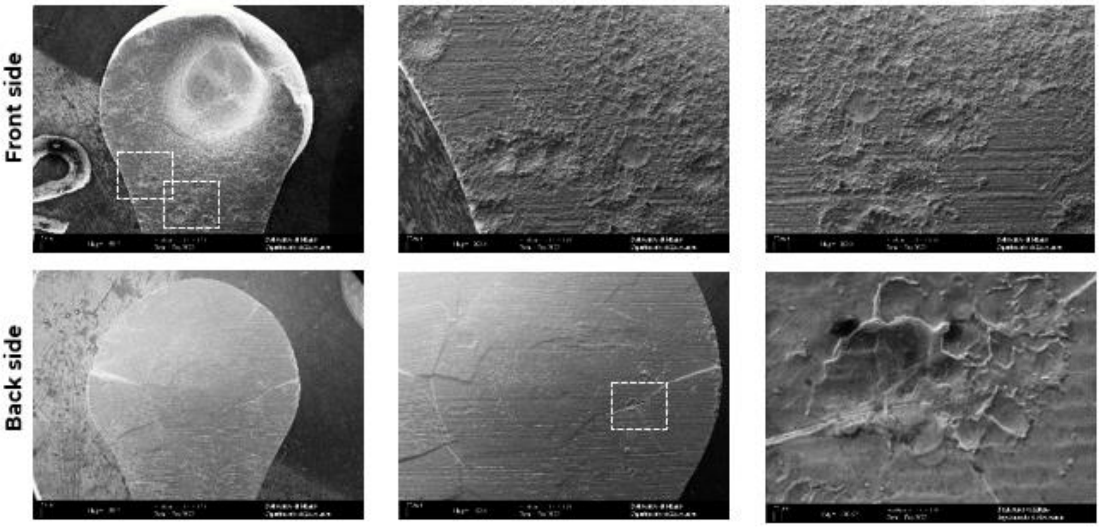


*Fig. 21 Electrode surface morphology by SEM*

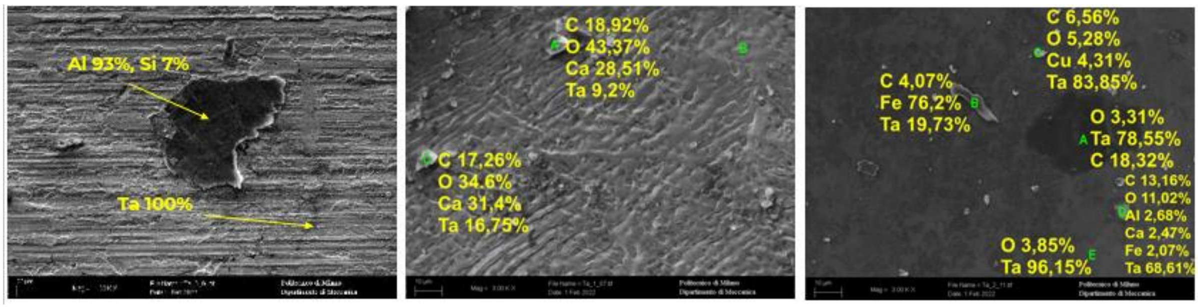


*Fig. 22 EDS results of electrode surface*

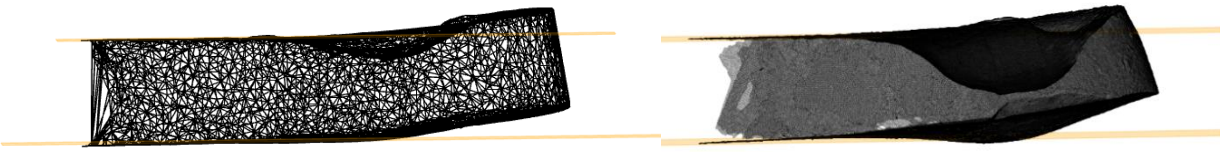


*Fig. 23 Electrode shape deformation 3D scan*

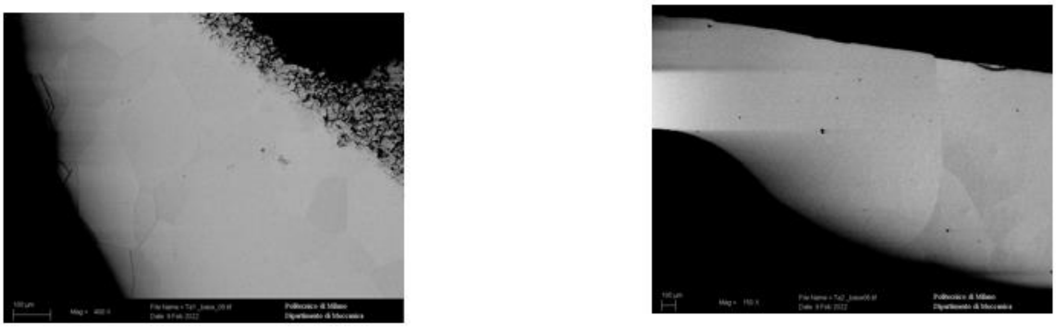


*Fig. 24 Electrode microstructure*

## 6.3 ELECTRODE REPAIR STRATEGIES

There are several possible ways to restore functionality of a damaged electrode. At the first glance, the easiest way is to cut off damaged part of electrode (the head) and print a new one in place. Another possible way would be to eliminate main damages – fill erosion craters (partially rebuild electrode head). Many more approaches could be devised including hybrid manufacturing elements, but these are more complicated and are left for future experiments.

## 6.4 CHOICE OF AM TECHNOLOGY, TESTING OF PARAMETERS AND STRATEGIES

Theoretically several technologies could be used for electrode repair (directed energy deposition, cold spray AM, powder bed fusion and additive friction stir processes). But realistically only direct energy deposition (DED) can be used with small components and has multi axis movement needed for non-flat surfaces. More specifically laser cladding of two types – powder and wire. Another reason, why specifically these technologies are used is machine availability and offered technological expertise of I.FAST project partners Fraunhofer IWS.

Preliminary tests on tantalum test pieces have been carried out to ascertain the feasibility of previously described strategies and to determine best possible process parameters.

Wire process was carried out using COAXwire mini laser deposition head developed at Fraunhofer IWS (Dresden). The machine was equipped with a TRUMPF TruDisk 1000 laser with 1064 nm wavelength and fed with a pure tantalum wire with a diameter of 0.5 mm.

Two different repair strategies were tested in process testing: single layer and multilayer. The first approach consisted in depositing material inside the erosion craters in single layer to restore the original electrode morphology. Single dots, tracks, and domes consisting of multiple concentric rings were deposited on tantalum test pieces (Fig. 25) varying the main process parameters.

The powder-based repair process was performed using a COAX14 annular gap nozzle and a Laserline LDF laser with 1080 nm wavelength. The feedstock material was the AMtrinsic® 99.9% pure tantalum powder supplied by Taniobis, having spherical morphology and 10-63 µm particle size. Initial parameter test results can be seen in Fig. 26

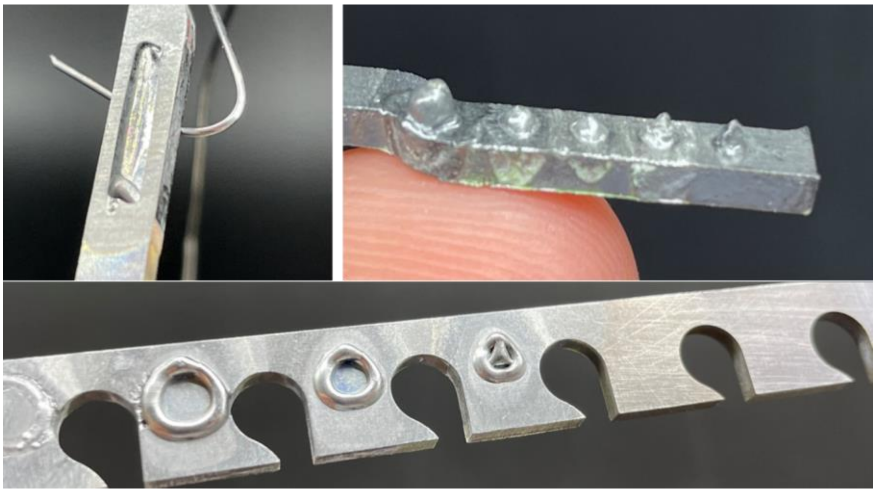


*Fig. 25 Different test shapes manufactured by wire DED*

*Fig. 26 Different test shapes manufactured by powder DED*

During the tests several samples were cut and their grain structure observed. For wire process, results showed distinct oxidation layer in all samples and also small uniform porosity in deposited area with several large inclusions on deposition boundary. Grain size differs from sample to sample, but no single-grain structures were observed, therefore hardness is estimated in range, which would allow for mechanical material removal in later stages. Metallographic analysis of powder samples showed distinct lack of fusion – explained by that samples cannot be preheated by laser in this process because laser is turned on after the powder flow has already been established. Different from wire process, here there was no uniform porosity – only some large inclusions and individual pores. Grains in this process were also bigger than in wire process.

The second strategy was to cut off the damaged portion of the electrodes (i.e., the head) and print a new one in place, which would ask for several layers to be printed on top of each other with parameters shown in Table 2. Multilayer tests were conducted with powder-based DED using the parameters optimised from the previous trials. However, after depositing the first ten layers, the material begun to flow and the desired geometry could not be achieved (Fig. 27).

*Table 2 Process parameters used in multilayer powder-based*

| **Parameter** | **Value** |
|---|---|
| Laser power (W) | 1200 |
| Powder feed rate (g $s^{-1}$) | 2.55 |
| Carrier gas flow rate (l $min^{-1}$) | 6 |
| Deposition speed (mm $min^{-1}$) | 300 |
| Layer thickness (mm) | 0.3 |
| Cooling time between layers (s) | 30 |

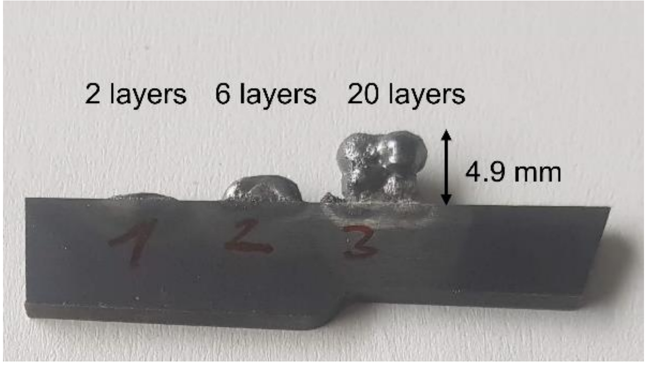


*Fig. 27 Multilayer deposit made by powder DED*

Neither an interlayer cooling time of 30 s nor keeping the interlayer temperature below 250 °C could prevent this phenomenon. Because of these unpromising results, this approach was discarded.

## 6.5 ELECTRODE REPAIR PROCESS AND RESULTS

Damaged tantalum electrodes were repaired by DED using feedstocks in wire and powder form. Three representative tantalum electrodes with varying extent of damage were refurbished with each DED technique using best process parameters from previous tests.

As regards the wire-based process, the repair strategy providing the most reliable and repeatable results was to simply fill the erosion craters with a single dot of material. The volume of deposited material depends on the duration of the deposition process. Therefore, a deposition time of 0.2 s was used to refurbish the electrode with the smallest crater. The deposition time was prolonged to 0.4 s and 0.6 s for the electrodes with medium and large crater size, respectively (Fig. 28) (used parameters in Table 3).

*Table 3 Process parameters for wire-based DED repair*

| Parameter | Electrode | | |
|---|---|---|---|
| | W1 | W2 | W3 |
| Laser power (W) | 1000 | 1000 | 1000 |
| Wire feed rate (mm $s^{-1}$) | 50 (start/end speed)<br>20 (normal speed) | 50 (start/end speed)<br>20 (normal speed) | 50 (start/end speed)<br>20 (normal speed) |
| Shielding gas pressure (bar) | 2.5 | 2.5 | 2.5 |
| Preheating time (s) | 1 | 1 | 1 |
| Deposition time (s) | 0.2 | 0.4 | 0.6 |

*Fig. 28 Damaged electrodes (top) and repaired electrodes(bottom) using wire DED*

As regards the powder-based process, the repair strategy  was to deposit three concentric rings inside the erosion crater, starting from the inner circle. The radius of the external circle was selected depending on the size of the damaged zone. A special case with the most damaged electrode: the deep crater was partially filled by depositing two dots of material before building the concentric circles (Fig. 29).

*Table 4 Process parameters for powder-based DED repair*

| Parameter | Electrode | | |
|---|---|---|---|
| | P1 | P2 | P3 |
| Laser power (W) | 800 | 800 | 800 |
| Powder feed rate (g $s^{-1}$) | 2 | 2 | 2 |
| Carrier gas flow rate (l $min^{-1}$) | 6 | 6 | 6 |
| Shielding gas flow rate (l $min^{-1}$) | 12 | 12 | 12 |
| Deposition speed (mm $min^{-1}$) | 400 (inner circle)<br>600 (middle circle)<br>600 (external circle) | 400 (inner circle)<br>600 (middle circle)<br>600 (external circle) | 400 (inner circle)<br>600 (middle circle)<br>600 (external circle) |
| Circle radius (mm) | 0.4 (inner circle)<br>0.9 (middle circle)<br>1.5 (external circle) | 0.4 (inner circle)<br>0.9 (middle circle)<br>1.2 (external circle) | 0.4 (inner circle)<br>0.9 (middle circle)<br>1.2 (external circle) |
| Deposition time for dots (s) | - | - | 0.5 |

*Fig. 29 Damaged electrodes (top) and repaired electrodes(bottom) using powder DED*

After repair, one of each set of electrodes was again characterized. A Zeiss Sigma 500 FE-SEM coupled with EDS was used for microstructural and chemical characterization. Electron back-scattered diffraction (EBSD) was also performed to study grain size and orientation in the deposits. Finally, microhardness tests were conducted to estimate the mechanical properties of the repaired electrodes compared with the original ones.

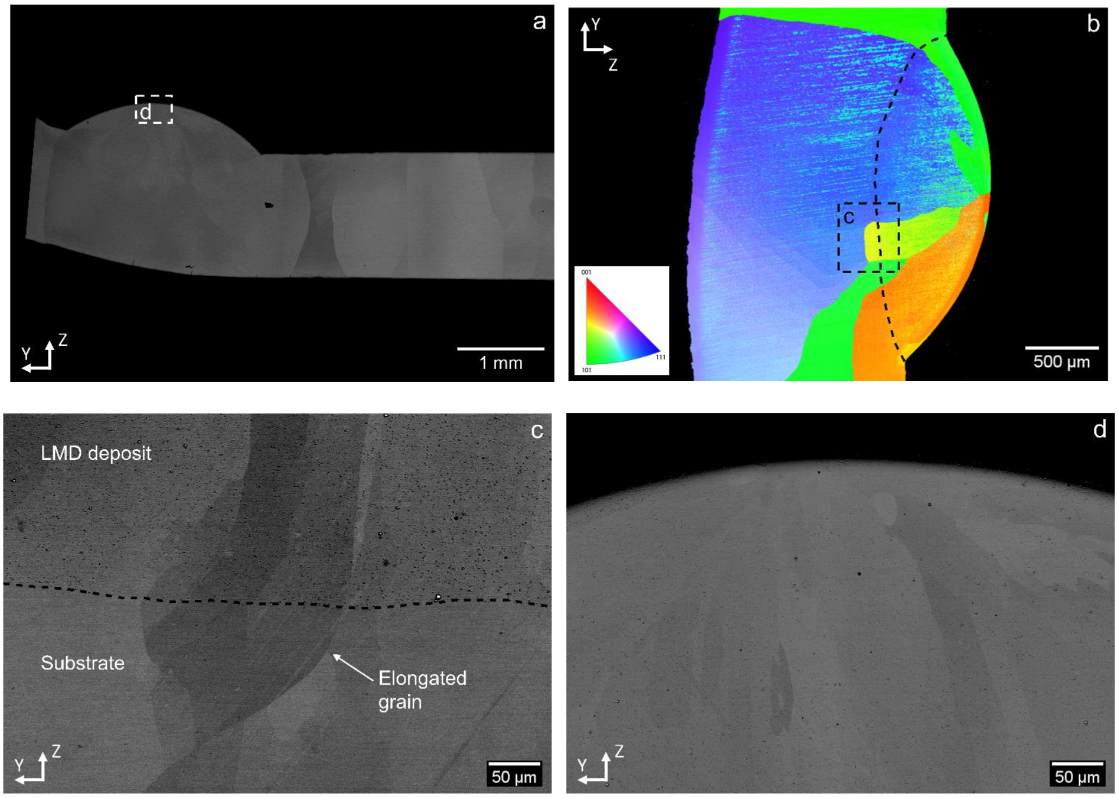


*Fig. 30 (a, c-d) SEM and (b) EBSD images of the electrode W2 repaired by wire-based DED.*

The EBSD image in Fig. 30 shows that the electrode repaired by powder process (deposit highlighted by the dotted line) is composed of few large grains having the same crystallographic orientations as the grains of the substrate. In the repair process, the high thermal energy provided by the laser partially melted the base material. Then, the grains grew epitaxially from this remelted layer, as also evidenced by the elongated grain penetrating the substrate beyond the interface with the DED deposit. Only few dispersed pores smaller than 10 µm in diameter were observed. In addition, there are no distinct signs of oxidised layers. This indicates that the shielding gas effectively protected the material against oxidation during the repair process.

Fig. 31 shows the cross-section of electrode repaired with the powder-based process. The deposit comprises of equiaxed grains with random orientation and average size of about 52 µm. Compared to the wire-based process, the substrate could not be preheated in powder-based DED because the laser could only be turned on after establishing the powder flow. Therefore, the deposited material underwent rapid cooling in contact with the cold substrate, resulting in the fine grain structure observed. Fine oxide particles are found in the grain boundary regions, while extremely fine oxide particles (with diameter lower than 300 nm) are dispersed in the grain core regions. These oxides may be endogenous defects stemming from the native oxide layer that covers the surface of the initial powder material or may be due to instabilities in the shielding gas flow during the repair process. A 60 µm thick oxide layer also covers the external surface of the deposited dome.

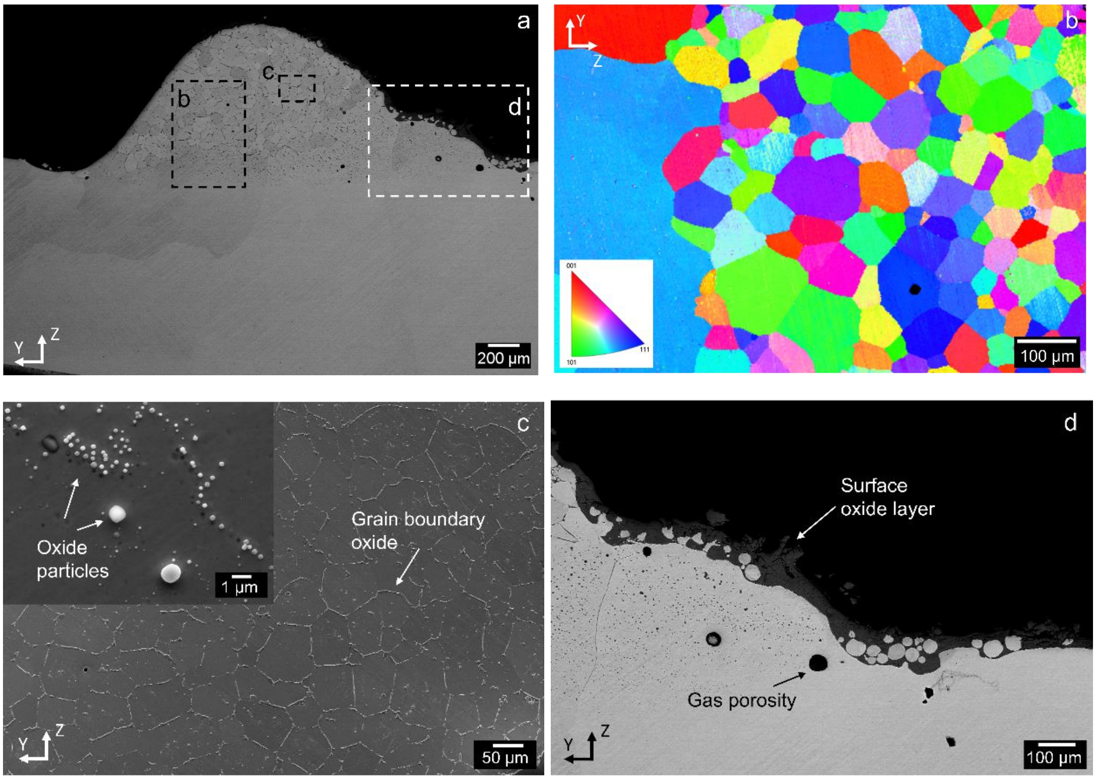


*Fig. 31 (a-b,d) SEM and (c) EBSD images of the electrode P2 repaired by powder-based DED.*

As discussed previously, a similar oxide layer was not observed on the material deposited by the wire-based process. The presence of the oxide layer on the specimens repaired with the powder-based process can be attributed to the higher reactivity of the tantalum powder compared to the wire, due to its higher surface area. Relatively large round pores are located at the interface between the substrate and the deposited dome. These defects can be classified as gas-induced porosity.

The hardness profiles measured along the body of the electrodes showed a progressively increasing trend from about 100 $HV_{0.5}$ at the base of the cathodes, which is in line with the typical hardness of annealed tantalum, to over 700 $HV_{0.5}$ in the regions near the head, as shown in Fig. 32a. This effect can be attributed to the entrapment of large amounts of hydrogen in the cathode head region, which is simultaneously exposed to ion bombardment and to the pure hydrogen atmosphere employed in the cyclotron, and to the formation of ion-irradiation-induced defects like sessile dislocation loops.

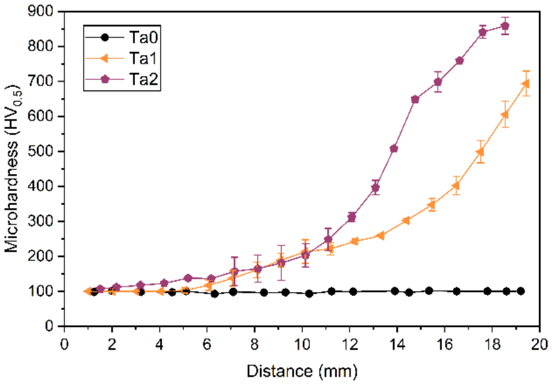


*Fig. 32 Microhardness measured along the body of the tantalum cathodes. The error bars represent the standard deviation over three measurements.*

## 6.6 CONCLUSIONS ABOUT CASE STUDY

The damage mechanisms experienced by pure tantalum cathodes in the AMIT superconducting cyclotron were investigated, followed by testing of various repair strategies utilizing direct energy deposition with high-purity tantalum wire and powder feedstocks. The wire and powder-based processes both proved effective in restoring the cathodes to their required geometry for use in the cyclotron. Overall, the main findings of this case study can be summarized as follows:

(1) During operation in the cyclotron, the region of the cathodes that is subjected to ion impingement reaches extremely high temperatures leading to localised melting and abnormal grain growth. In addition, a significant increase in hardness (from about 100 $HV_{0.5}$ to more than 665 $HV_{0.5}$), was observed moving along the body of the cathodes from the base region to the head. This was attributed to the entrapment of large amounts of hydrogen in the cathode head region, which is simultaneously exposed to ion bombardment and to the pure hydrogen atmosphere employed in the cyclotron, and to the formation of ion-irradiation-induced defects..

(2) The wire-based repair consisted in depositing single dots of material inside the erosion craters at the head of the damaged electrodes. Laser preheating of the substrate eliminated the interface porosity and improved the interface dilution. Epitaxial grain growth occurred from the remelted layer on the substrate surface. The large columnar grains that typically develop in additively manufactured tantalum were not observed because edge effects were dominant in the solidification process.

(3) Two different repair strategies were tested using the powder feedstock. The strategy involving cutting off the damaged head of the cathodes and printing a new one in place was not pursued because an acceptable geometrical accuracy could not be achieved in multilayer build-up tests due to material flowing after the deposition of the first ten layers. The other approach was to deposit concentric rings to fill the erosion crater at the head of the damaged electrodes. Both dissolved oxygen and fine oxide particles presumably resulting from instabilities of the shielding gas were observed. In addition, a 60 µm thick oxide layer was found on the surface of the deposited dome. The effect of these oxide scales on the performance of the repaired electrodes compared to the original parts still needs to be evaluated by testing under service conditions.

In conclusion, in both partial electrode head refurbishment strategies with wire and powder direct energy deposition technology the electrode craters were filled to form a dome shaped surface. This demonstrates the applicability of the selected technologies and strategies for the repair of a particle accelerator component.

# 7 Conclusions and future plans

The main conclusions of the "Survey of AM applications and strategies for repairing components by AM" are that particle accelerator technologies have high standards and requirements, due to a very specific work environments, for example – high vacuum, high voltage, extremely low temperatures etc. This calls for low porosity, good mechanical properties, high tolerances and excellent surface finish for parts that routinely need to be made from exotic materials of the highest purity. Those requirements can be challenging for AM repair technologies, mainly due to surface roughness and undesirable internal defects. However, several specific accelerator requirements are very similar to those of other domains – vacuum requirements are similar to aerospace, radiation effects to the nuclear energy industry etc. There are several technologies that are already now used in component repair – directed energy deposition, powder bed fusion, cold spray AM and additive friction stir deposition. Other fields as aerospace and automotive have already implemented AM repairs, yet in particle accelerators AM today is being used only for component manufacturing.

The main conclusions of the qualitative study in form of a questionnaire addressed to the particle accelerator community are that the accelerator community is not yet enthusiastic about AM repairs, according to the survey response rate. However, the possibilities of this technology have been acknowledged as 3/4 of the respondents would consider AM for part production but less than 1/2 for repairs. This fact is supported by all the examples of AM parts in the particle accelerator industry reported in previous chapters and by the fact that demonstrator for AM repairs was hard to find. One can assume that the slightly pessimistic view of AM repairs would also get better with time and examples of applications and successful examples.

During case study research, it has been demonstrated that particle accelerator components, in this case, tantalum (exotic and expensive material with very high melting temperature) electrodes can be repaired by directed energy deposition technology using both wire and powder laser melting methods. The electrode erosion craters were filled to form a dome-shaped surface, demonstrating the applicability of the selected technologies and strategies to the repair of particle accelerator components by demonstrating that tantalum electrodes geometry can be refurbished. As a next step, the repaired electrodes should be tested in the AMIT cyclotron at CIEMAT in further research to evaluate their performance after repair and validate the adopted repaired strategies.

Several strategies for implementing AM repairs in the accelerator community have been suggested, including reactive repairs, repairs as part of maintenance, repairs to solve manufacturing errors, and remote or in-situ repairs using robot-mounted AM equipment. Quick solutions through implementing AM repair are unlikely for most applications and strategies, and a step-by-step approach is necessary to demonstrate feasibility due to each unique case. Testing on external objects without reachability issues and using standardized equipment is recommended to exclude uncertainties.

In conclusion, AM repair technologies can be used for accelerator components to refurbish components' geometry, however, there experimental-based step-by-step approach and functional tests would be needed, especially to reach successful results for closed structures like accelerator cavities. Finally, with this research initial information was presented to the accelerator community that can open more perspectives on how to be more sustainable by using AM repair technologies. On other hand, by this research AM industry can recognise what further developments are needed for AM repair technological equipment to become more useful for accelerator repairs.

# 8 References

[1] “Additive Manufacturing Glossary,” [Online]. Available: https://www.sme.org/technologies/additive-manufacturing-glossary/ . [Accessed 11. 02. 2022].

[2] V. Listek, “Restoring Industrial Components with Directed Energy Deposition Saves Time and Costs,” [Online]. Available: https://3dprint.com/238130/restoring-industrial-components-with-directed-energy-deposition-saves-time-and-costs/. [Accessed 15. 03. 2022].

[3] “About I.FAST,” [Online]. Available: https://ifast-project.eu/about. [Accessed 08. 06. 2022].

[4] T. E. Sparks, “A framework for a successful additive repair system,” *Missouri University of Science and Technology.Doctoral Dissertations.,* 2020.

[5] “Additive manufacturing opens up new prospects at CERN,” [Online]. Available: https://home.cern/news/news/engineering/additive-manufacturing-opens-new-prospects-cern. [Accessed 10. 03. 2022].

[6] “Project I.FAST Participants,” [Online]. Available: https://ifast-project.eu/participants. [Accessed 04. 04. 2022].

[7] “Accelerating: Radiofrequency cavities,” [Online]. Available: https://home.cern/science/engineering/accelerating-radiofrequency-cavities. [Accessed 11. 08. 2022].

[8] W. Weingarten, “Superconducting cavities — basics,” CERN, [Online]. Available: https://cds.cern.ch/record/308015/files/p167.pdf.

[9] A. Degiovanni, “Accelerating Structures,” in *CAS-CERN Accelerator School: Accelerators for Medical Applications*, Vösendorf, 2015.

[10] S. Posen and D. L. Hall, “Nb3Sn superconducting radiofrequency cavities: fabrication, results, properties, and prospects,” *Superconductor Science and Technology,* vol. 30, no. 3, 2017.

[11] “targets and ion sources,” [Online]. Available: https://fiveyearplan.triumf.ca/teams-tools/targets-and-ion-sources/. [Accessed 21. 08. 2022].

[12] S. Lawhun, “Aiming at a target: the science of particle production,” [Online]. Available: https://news.fnal.gov/2018/04/aiming-at-a-target-the-science-of-particle-production/#:~:text=In%20a%20fixed%2Dtarget%20experiment,the%20target%20in%20all%20directions.. [Accessed 28. 08. 2022].

[13] M. Futakawa and N. Tanaka, “Cavitation in High-power Pulsed Spallation Neutron Sources,” *Konsoryu,* vol. 24, no. 2, pp. 138-145, 2010.

[14] S. Kaminskas, S. Chae and H. Jiang, “High power mercury target design exploration using Isight,” [Online]. Available: https://www.3ds.com/fileadmin/PRODUCTS-SERVICES/SIMULIA/Resources-center/PDF/2018-SAoE-High_power_mercury_target_design_exploration_using_Isight.pdf. [Accessed 09. 08. 2022].

[15] I. G. Segev, E. Yahel, I. Silverman and G. Makov, “Blister formation at subcritical doses in tungsten irradiated by MeV protons,” *Journal of Nuclear Materials,* vol. 496, 2017.

[16] A. Krämer, “Vacuum Requirements for GSI and FAIR.Accelerator Seminar.,” [Online]. Available: https://indico.gsi.de/event/11845/attachments/34356/45054/Praesentation_Andreas_Kraemer.pdf. [Accessed 13. 02. 2022].

[17] M. Baylac, F. Gerigk, E. B. Mora and F. Caspers, “Conceptual design of the SPL II: A high-power superconducting H- linac at CERN,” CERN, Geneva, 2006.

[18] M. Moisieienko, O. Bezditko, I. Karnaukhov, A. Mytsykov and A. Zelinsky, “electron gun for 100 mev / 100 kw linear accelerator of electrons as the driver of nuclear subcritical assembly neutrons source,” in *29th International Linear Accelerator Conference*, Beijing, 2018.

[19] M.Omeich, “RF Power Linac,” [Online]. Available: https://indico.ijclab.in2p3.fr/event/3442/contributions/9037/attachments/8316/9787/rf_power_linac.pdf. [Accessed 13. 02. 2022].

[20] C. Pralavorio, “A demonstrator magnet produces a record magnet field,” 2020. [Online]. Available: https://home.cern/news/news/accelerators/demonstrator-magnet-produces-record-magnet-field. [Accessed 13. 02. 2022].

[21] “Ionizing radiation.Taking a closer look at LHC.,” [Online]. Available: https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.ionizing_radiation. [Accessed 13. 02. 2022].

[22] S. Atieh, G. Favre and S. Mathot, “Manufacturing & Assembly for Vacuum Technology,” [Online]. Available: https://indico.cern.ch/event/565314/contributions/2285867/attachments/1474132/2288161/CAS_Vacuum_2017-EN-MME_Mathot_3.pdf. [Accessed 30. 03. 2022].

[23] W. Weingarten, “Superconducting cavities — basics,” [Online]. Available: https://cds.cern.ch/record/308015/files/p167.pdf. [Accessed 30. 03. 2022].

[24] W. E. Frazier, “Metal Additive Manufacturing: A Review,” *Journal of Materials Engineering and Performance,* vol. 23, p. 1917–1928, 2014.

[25] Y. A. Zghair and R. Lachmayer, “case study to repair aluminium base components, additive repair design approach: case study to repair aluminium base,” in *21st International Conference On Engineering Design*, Vancouver, 2017.

[26] M. Sinico, G. Cogo, M. Benettoni and I. Calliari, “Influence of Powder Particle Size Distribution on the printability of Pure Copper for Selective Laser Melting,” in *Solid Freeform Fabrication Symposium 2019 - An Additive Manufacturing Conference*, Austin, 2019.

[27] V. G. Smelov, A. V. Sotov and A. V. Agapovichev, “Research on the possibility of restoring blades while repairing gas turbine engines parts by selective laser melting,” in *International Seminar on Interdisciplinary Problems in Additive Technologies*, Tomsk, 2015.

[28] “Additive Manufacturing Enables Advanced Blade Tip Repair and Upgrade,” [Online]. Available: https://press.siemens-energy.com/global/en/news/additive-manufacturing-enables-advanced-blade-tip-repair-and-upgrade. [Accessed 07. 03. 2022].

[29] *ISO/ASTM 52900:2021 Additive manufacturing — General principles — Fundamentals and vocabulary*, Geneva: ISO/ASTM international, 2021.

[30] E. Mortazavian, Z. Wang and H. Teng, “Effect of heat treatment on microstructure and hardness of a worn rail repaired using laser powder deposition,” *International Journal of Transportation Science and Technology*, 2021.

[31] L. Chen, Y. Zhao, X. Chen, T. Yu and P. Xu, “Repair of spline shaft by laser-cladding coarse TiC reinforced Ni-based coating: Process, microstructure and properties,” *Ceramics International*, vol. 47, no. 21, pp. 30113-30128, 2021.

[32] P. C.Priarone, G. Campatelli, A. R.Catalano and F. Baffa, “Life-cycle energy and carbon saving potential of Wire Arc Additive Manufacturing for the repair of mold inserts,” *CIRP Journal of Manufacturing Science and Technology*, vol. 35, pp. 943-958, 2021.

[33] R. Leach and S. Carmignato, Precision Metal Additive Manufacturing, Boca Raton: CRC Press, 2020.

[34] C. A. Widener, O. C. Ozdemir and M. Carter, “Structural repair using cold spray technology for enhanced sustainability of high value assets,” *Procedia Manufacturing*, vol. 21, p. 361–368, 2018.

[35] S. Yin, P. Cavaliere, B. Aldwell and R. Jenkins, “Cold spray additive manufacturing and repair: Fundamentals and applications,” *Additive Manufacturing*, vol. 21, pp. 628-650, 2018.

[36] “Cold Spray - SST™ Equipment & Supplies,” [Online]. Available: https://www.cntrline.com/products/cold-spray-sst-equipment-supplies. [Accessed 25. 03. 2022].

[37] R. J. Griffiths, D. T. Petersen, D. Garcia and H. Z. Yu, “Additive Friction Stir-Enabled Solid-State Additive Manufacturing for the Repair of 7075 Aluminum Alloy,” *Applied sciences*, vol. 9, no. 17, p. 3486, 2019.

[38] H. Z. Yu and R. S. Mishra, “Additive friction stir deposition: a deformation processing route to metal additive manufacturing,” *Materials Research Letters*, vol. 9, no. 2, pp. 71-83, 2021.

[39] P. Karimi, “SLM additive manufacturing of Alloy 718 Effect of process parameters on microstructure and properties,” University of Waterloo, 2016.

[40] K. Solberg and F. Berto, “What is going on with fatigue of additively manufactured metals?,” *Material Design & Processing Communications*, vol. 1, no. 5, 2019.

[41] Tchakoua, R. Wamkeue, . M. Ouhrouche, F. Slaoui-Hasnaoui, T. . A. Tameghe and G. Ekemb, “Wind Turbine Condition Monitoring: State-of-the-Art Review, New Trends, and Future Challenges,” *Energies*, vol. 7, no. 4, pp. 2595-2630, 2014.

[42] J. Lee, J. Ni, J. Singh, B. Jiang, M. Azamfar and J. Feng, “Intelligent Maintenance Systems and Predictive Manufacturing,” *Journal of Manufacturing Science and Engineering*, vol. 142, 2020.

[43] L. Portoles, O. Jorda, L. Jorda, A. Uriondo, M. Esperon-Miguez and S. Perinpanayagam, “A Novel Qualification Procedure to Manufacture and Repair Aerospace Parts with Electron Beam Melting,” *Journal of Manufacturing Systems*, vol. 41, pp. 65-75, 2016.

[44] “Additive manufacturing and industrial 3D printing,” [Online]. Available: https://www.kuka.com/en-ch/products/process-technologies/3d-printing. [Accessed 5. 8. 2022].

[45] “More productive coating and repair with Artificial Intelligence,” [Online]. Available: https://www.ilt.fraunhofer.de/en/press/press-releases/2022/01-27-research-project-ai-slam.html. [Accessed 2. 8. 2022].

[46] P. Calvo, D. Obradors, R. Varela, I. Podadera, C. Oliver, A. Estévez, M. Domínguez, C. Vázquez, F. Toral, L. García-Tabarés and J. Pérez, “Experimental characterization of the internal ion source for the AMIT compact cyclotron,” *Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip.*, vol. 1025, 2022.

[47] J. Byrd, “RF Cavities and Linacs,” [Online]. Available: https://uspas.fnal.gov/materials/14UNM/RF_Structures.pdf. [Accessed 14. 08. 2022].

Annex: Glossary

| **Acronym** | **Definition** |
|---|---|
| 3D | three dimensional |
| AFSD | additive friction stir deposition |
| AM | additive manufacturing |
| AMIT | Advanced Molecular Image Technologies |
| CAD | computer aided design |
| CERN | Conseil Européen pour la Recherche Nucléaire |
| CIEMAT | El Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas |
| CNC | computer numerical control |
| CSAM | cold spray additive manufacturing |
| DED | directed energy deposition |
| EDS | energy dispersive spectroscopy |
| JACoW | the joint accelerator conferences website |
| LHC | large hadron collider |
| LPBF | laser powder bed fusion |
| PBF | powder bed fusion |
| PIG | penning ionization gauge |
| SEM | scanning electron microscopy |
| SLM | selective laser melting |
| | |
| | |
| | |