PERSPECTIVES AND RECENT ACHIEVEMENTS ON ADDITIVE MANUFACTURING TECHNOLOGIES FOR ACCELERATORS*

T. Torims†, A. Ratkus, G. Pikurs, Riga Technical University, Riga, Latvia
M. Vedani, T. Romano, Politecnico di Milano, Italy
S. Gruber, E. Lopez, F. Marquardt, H. Lauer, Fraunhofer IWS, Dresden, Germany
M. Weinmann, Taniobis GmbH, Goslar, Germany
M.Vretenar, CERN, Geneva, Switzerland
D. Obrados, CIEMAT, Madrid, Spain
N. Delerue, IJCLab, Orsay, France

Abstract

This paper reports the exploratory studies on advanced accelerator technologies performed within the I.FAST (Innovation Fostering in Accelerator Science and Technology) EU project, and in particular the key results of the additive manufacturing Task 10.2 – "Additive Manufacturing – applications and potential developments" and Task 10.3 – "Repair of damaged accelerator components by AM technologies". This includes results of two surveys targeted to the accelerator community: a) on current additive manufacturing applications in accelerators and expected new developments, b) on current additive manufacturing repair technologies for accelerator and list of possible applications. The paper is outlining potential additive manufacturing applications in accelerators and overall strategies applicable to accelerator components repairs benefiting from additive manufacturing technology.

INTRODUCTION

Additive Manufacturing (AM) is a fast-evolving technology which is promptly becoming an integral part of the advanced technological portfolio available for the most demanding industrial applications. Still, within the particle accelerator community, AM is progressing at a slow pace, owing to traditionalism, lack of knowledge, and scepticism about the compliance with the stringent requirements. To raise AM awareness in our community, this paper summarizes the results of dedicated studies, which were carried-out within the accelerator community by I.FAST project [1] Tasks 10.2 and 10.3 [2]. The main objectives are: a) identification of the needs for coming developments, b) detection of technology barriers and challenges, as well as c) definition of future strategic directions. To this end, reliable information on the adoption of AM technologies by our community was crucial to map the current situation.

Thus, for the very first time, detailed surveys of AM applications in the accelerator field are provided, to describe potential opportunities and highlight the challenges yet to be faced.

POTENTIAL OF AM APPLICATIONS IN ACCELERATORS

In Task 10.2 "Additive Manufacturing – Survey of applications and potential developments" [3] accelerator community respondents were given a choice of three answers: a) they have had previous experience, b) they have not had any previous experience and c) they do not have experience but have heard of AM use in other institutions. Surprisingly, only 9.5% of respondents have not previously heard about or had any experience with AM (Fig1).

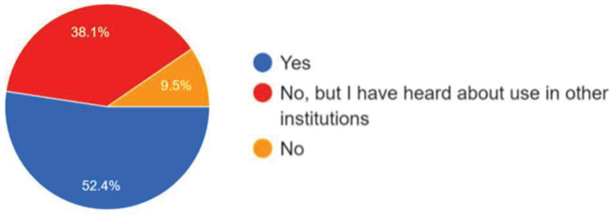

Figure 1: Particle accelerator community experience with AM.

This might lead to the assumption that most of accelerator community is well informed about AM. However, it is worth considering that the questionnaire was circulated through the IFAST project newsletter to 290 project members from 49 participating institutions and 32 associate partners in 14 countries in March 2022. After three months, the feedback was limited to 21 responses, corresponding to rather low 7.2% response rate [4].

In general, there is clear evidence that accelerator community is broadly considering AM, but it is not yet fully embracing the current AM achievements and is even less enthusiastic regarding accelerator component repairs by AM. At the same time, there is a long list of already-identified components which would be benefiting from the advantages offered by AM, such as design freedom, manufacturing flexibility and processing ability of otherwise critical materials. Nonetheless, several technical challenges, along with a sort of traditionalism and reluctance to change design paradigms, are still representing barriers for the successful uptake of AM by our community.

The main lessons learned from the study are as follows:

1) AM applications in accelerators are in place since 2005 and they are growing exponentially in the recent years. They typically include: cavities, drift tubes, complex

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† toms.torims@rtu.lv

shapes with cooling circuits and heat exchangers, supports for sensors and magnets. The adoption of AM to these parts provides advantages: i.e. design freedom, manufacturing flexibility, and processing ability of critical materials.

2) It appears that particle-accelerator community is still having very limited knowledge on specific topics (which represent the next challenges to be faced in the near future to raise confidence and reduce scepticism in AM):

(i) materials for most accelerator components have strict requirements and need accurate characterization after being processed by AM;

(ii) the size of components may exceed the printing volume, while the requirements for geometrical accuracy and surface roughness of accelerator parts are often very demanding for most state-of-the-art AM systems;

(iii) specific material/part properties need to be carefully characterized before applications in particle accelerators, such as vacuum tightness, outgassing rate, electrical conductivity, high-voltage holding.

These technical gaps are being progressively filled by virtue of the dedicated research efforts. F or instance an advanced proof-of-principle, a full-size, pure-copper 750 MHz RFQ prototype was developed and additively manufactured in the frame of the I.FAST EU project (Fig. 2). It is currently at the testing and evaluation stage. To the authors' knowledge, this output represents the very first proof-of-concept confirming that AM-manufactured RFQ is feasible and achievable. Its dissemination to the widest possible audience is instrumental in raising awareness about advantages of AM in the accelerator community [5].

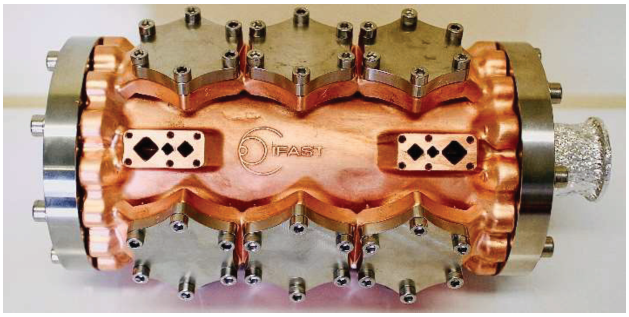

Figure 2. Proof-of-principle, a full-size, additively manufactured pure-copper RFQ.

AM APPLICATIONS AND STRATEGIES FOR REPAIRING COMPONENTS BY AM

The main goal of Task 10.3 "Repair of damaged accelerator components by AM technologies" was to understand the status of AM repair usage in the field of accelerators: to list possible repair applications for accelerators, to evaluate AM repair strategies and technologies for repairing accelerator parts, as well as to demonstrate AM repair feasibility for accelerator components [6].

To discover community's current and future intentions on repairs with AM, respondents were asked "Would you consider to use AM for accelerator component production/repairs?" with given three choices: a) they would now consider AM for accelerator component repair, b) they would not, and c) they would consider it in the future.

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). This may point out that repair is an unknown principle for the community, as there is no evidence of successful examples, or the community does not see AM as a suitable technology for repairs (Fig. 3). The survey also revealed that the majority of hardware experts and accelerator designers are already aware about the opportunities offered by AM. Most of them would currently consider AM for the manufacturing of accelerator components, while a small share 9% considers AM as an option only for the future.

Figure 3: Particle accelerator community consideration of using AM for component production and repairs.

The survey confirmed that particle accelerator technologies have high standards and requirements, i.e., high vacuum, high voltage, extremely low temperatures etc. This calls for low residual porosity, good mechanical properties, high tolerances, and excellent surface finish for parts that are commonly made from expensive materials of the highest purity. Those requirements can be challenging for AM repair technologies, mainly due to surface roughness and undesirable internal defects [7].

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 already used for component repair – directed energy deposition, powder bed fusion, cold spray AM, and additive friction stir deposition. Other fields, such as aerospace and automotive, have already implemented AM repairs, yet in particle accelerators AM is currently 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 community is not yet enthusiastic about AM repairs, as also highlighted by the survey response rate. Nonetheless, 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 is supported by all the examples of AM parts in the particle accelerator industry already showcased and by the fact that a 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 successful examples of applications.

A case study was conducted to demonstrate that particle accelerator components – ion source tantalum electrodes – can be repaired by directed energy deposition technology using both wire and powder laser melting methods [8, 9]. 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 (Fig. 4).

Figure 4. Tantalum electrodes repaired with wire (a) and powder-based Laser Metal Deposition (b).

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. Still, quick solutions through implementing AM repair are unlikely for most applications and strategies, and a step-by-step approach is necessary to demonstrate feasibility in each unique case.

CONCLUSIONS

Although, the particle accelerator community demonstrated a certain lack of knowledge on specific AM topics, there is clear evidence that this technology is rapidly taking its place in our technological programs.

Community exposed concerns regarding various challenging aspects related to: (i) material quality, including high purity, homogeneity, zero tolerance towards any defects, and well-known properties; (ii) size, geometrical accuracy, surface quality and conformity; (iii) specific accelerator component properties, including vacuum tightness, outgassing rate, el. conductivity, voltage holding, etc.

It was demonstrated that AM repair technologies can be used for accelerator components to refurbish components. However, to benefit from this, an experimental-based step-by-step approach and functional tests would be needed, especially to reach successful results for closed structures like accelerator cavities.

A multitude of accelerator components were redesigned and are now being manufactured by AM, this *inter alia* includes: accelerating cavities, supports for sensors and magnets, cooling systems and manifolds with complex shapes, synchrotron radiation absorbers, particle sources and targets, RF guns and quadrupoles [10]. For all of them, the most attractive opportunities consist in the ability to design new and optimized shapes which were considered impossible to be produced by conventional manufacturing technologies, along with the possible reduction of costs, usage of precious materials, and lead times.

In addition, AM is indispensable in strategies towards the development of compact, more accessible, less expensive, and better performing commercial accelerators – to improve and sustain the quality of our life. Medical equipment for cancer radiation therapies (proton and ion-therapy) and for the production of isotopes for imaging and nuclear medicine would greatly benefit from innovations in compact accelerators. Other industrial sectors for accelerators involve the sterilization for medical disposables and for food processing, the non-destructive testing of machine components by X-rays and γ-rays, the safety inspections of containers loaded on cargos, the treatments of fumes and exhaust gases to reduce the amount of pollutants.

With this research, initial information is being presented to the accelerator community that can open more perspectives on how to be more sustainable by using AM technologies not only in the manufacturing, but also in the repair operations within the accelerator facilities.

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