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# The role of laser additive manufacturing methods of metals in repair, refurbishment and remanufacturing – enabling circular economy

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**Abstract**

Circular economy is an economy model where products, components, and materials are aimed to be kept at their highest utility and value at all times. Repair, refurbishment and remanufacturing processes are procedures aiming at returning the value of the product during its life cycle. Additive manufacturing (AM) is expected to be an enabling technology in circular economy based business models. One of AM process that enables repair, refurbishment and remanufacturing is Directed Energy Deposition. Respectively Powder Bed Fusion enables manufacturing of replacement components on demand. The aim of this study is to identify the current research findings and state of art of utilizing AM in repair, refurbishment and remanufacturing processes of metallic products. The focus is in identifying possibilities of AM in promotion of circular economy and expected environmental benefits based on the found literature. Results of the study indicate significant potential in utilizing AM in repair, refurbishment and remanufacturing activities.
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## 1. Introduction

It is known that current level of material and energy use of current manufacturing activities must decline to be able to sufficiently mitigate climate change. The share of industrial greenhouse gas (GHG) emissions is approximately 30% of total GHG emissions. The GHG emissions from industry originate mainly from material processing, i.e., from the conversion of natural resources or scrap into materials stocks which are then converted in manufacturing and construction and finally, into products. (Fischedick et al., 2014). It is evident that minimizing the need to converse natural resources and scrap to raw materials is an efficient measure to mitigate GHG emissions. In the case of manufacturing industry this could be achieved by adopting a circular economy model.

The European Commission defines circular economy as an economy, where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimized (European Commission, 2015). The actions planned by the European Commisions to promote Circular Economy include, for example, the development of product requirements relevant to the circular economy in the Ecodesign Directive and the Ecodesign working plan for 2015-2017 will further define on how this will be implemented. The work on Ecodesign will also include requirements on durability and the availability of repair information and spare parts as well as information on durability in the future Energy labelling measures. The EU is also supporting promising developments in the field of remanufacturing trough innovation financing programme Horizon 2020 and Cohesion Policy funds. (European Commission, 2015.)

The definition of circular economy by Ellen MacArthur Foundation (2015) considers comprehensively the role of economic benefits same time with the environmental benefits: “circular economy is one that is restorative and regenerative by design, and which aims to keep products, components and materials at their highest utility and value at all times distinguishing between technical and biological cycles.” Procedures to achieve circular economy in technical cycles when looking at the finite materials are maintaining, repairing and sharing products, reusing and redistributing products, refurbishing and remanufacturing products and recycling.

Powder bed fusion (PBF) and direct energy deposition (DED) are additive manufacturing (AM) methods of metals. It has been estimated that additive manufacturing will be a relevant technology for circular economy (Ellen MacArthur Foundation, 2015). Both PBF and DED based technologies are developing fast and studies on the energy and material consumption in the manufacturing phase have been conducted, among others, by Baumers et al. (2010) and Kellens et al. (2010). DED enables repair, refurbishment and remanufacturing procedures. Respectively PBF enables mainly manufacturing of replacement components on demand. These metal AM methods could have a significant role in enabling circular economy.

Keeping in mind the pressure from both the earth system and the future legislation from European Union and at the same recognizing the economical possibilities of circular economy the time to study the relevance of different manufacturing methods to this new economy is now. In this study a literature review was done to identify the current state of art in utilizing PBF and DED in repair, refurbishment and remanufacturing processes of metallic products. Based on the literature the aim is to identify the possibilities of additive manufacturing of metals in promoting circular economy and the expected environmental benefits of these applications.

## 2. Research area

Remanufacturing can be defined as an industrial process restoring used products to “as good as new” condition and this definition have been previously used by Steinhilper & Hudelmaier (1988) and Butzer et al. (2014). In some cases remanufactured product can also be seen “better than new” for example if the product software has been updated in the process or the functionality improved compared to the original product as discussed by Ellen MacArthur Foundation (2015). The main steps in remanufacturing process defined by Steinhilper (1999) are 1) the complete disassemble of the product, 2) thorough cleaning of all parts, 3) inspection and sorting of parts, 4) reconditioning of parts and or replenishment by new parts 5) product assembly completed with final testing.

The definition of refurbishment have been discussed by Ellen MacArthur Foundation (2015). In refurbishment rocess the product is returned to satisfactory working condition by replacing or repairing major components if they malfunction or are close to failure. Also small changes to the appearance of the product are possible. The performance of the product can be “as good as new” but also less than “as new”. The warranty given to the product is usually less than for a new or remanufactured product but it usually covers the whole product. Another term used to describe the same activity as refurbishment is reconditioning.

King et al. (2006) define repairing as a procedure where specified faults are corrected in a product. Also generally the overall condition of the repaired products is less than the remanufactured and reconditioned alternatives. The warranty of repaired products are usually less than those of newly manufactured equivalents and also it is possible that the warranty covers only the repaired components.

All of these procedures aiming to maintain the value and the life time of the product have different characteristics when compared with each other. King et al (2006) compared repair, refurbishment, remanufacturing and recycling to determine best strategy to reduce waste. They concluded that from the environmental point of view as the repairing and reconditioning procedures are the best ones, since they require the least energy and material to be added to the process. However when taking into account the consumer behavior and the current culture of fashion obsolescence King et al (2006) suggest remanufacturing as the best strategy to minimize environmental impacts. The writers of this study acknowledge that all these procedures have weakness and strengths in different production and usage scenarios. In this study these procedures are not compared with each other.

Power Bed Fusion (PBF) and Direct Energy Deposition (DED) are additive manufacturing technologies that are used for manufacturing metal parts or shapes. Term additive manufacturing refers to manufacturing technologies where parts are manufactured by joining material, typically layer upon layer, to manufacture object or shape from 3D model (ISO 2015, Wohler 2013). PBF is technology where powder material is melted layer upon layer by laser or electron beam to create shape. DED process in turn relies on dynamic material feeding and melting energy in introduced typically in form of electric arc or laser beam. Metal additive manufactured parts often need at least minor finishing procedures after manufacturing i.a. machining, grinding or different thermal processes. The purpose of the post processing is to refine geometrical accuracy, improve surface quality and relieve residual stresses.

## 3. Research methodology

This research is based on systematic literature review. The literature examined for this study where extracted trough Web of Science, when accessible. The used words for the research and search logic was: (TS=direct energy deposition OR TS=laser cladding OR TS=laser metal deposition OR TS=direct metal deposition OR TS=laser deposition welding OR TS=laser additive manufacturing OR TS=powder bed fusion OR TS=selective laser sintering OR TS=selective laser melting) AND (TS=repair OR TS=refurbishment OR TS=reconditioning OR TS=remanufacturing).

The search language was limited to English and the time of publication was set from 2000 to 2016. The chosen document types were “article”, “review” and “meeting”. Meeting category includes conference proceedings which were seen important source of information for such an emerging technology as AM and concept as circular economy.

The search resulted in total 376 records. Publications related to different fields of medicine were delimited from the scope. Also references focusing only to the process development were delimited from the scope. The elimination of processes development related studies was done in manual screening. After this further refining 89 publications were chosen for this study and 45 could be extracted. These 45 publications formed the base of this research. The publications by year are presented in Figure 1.

The publications included in this study have been published before April 2016. It is reasonable to expect, that the growing trend of publications on this topic will continue in 2016. During the research processes also relevant articles referenced by the review articles were included in the writing processes and used as a source of data.

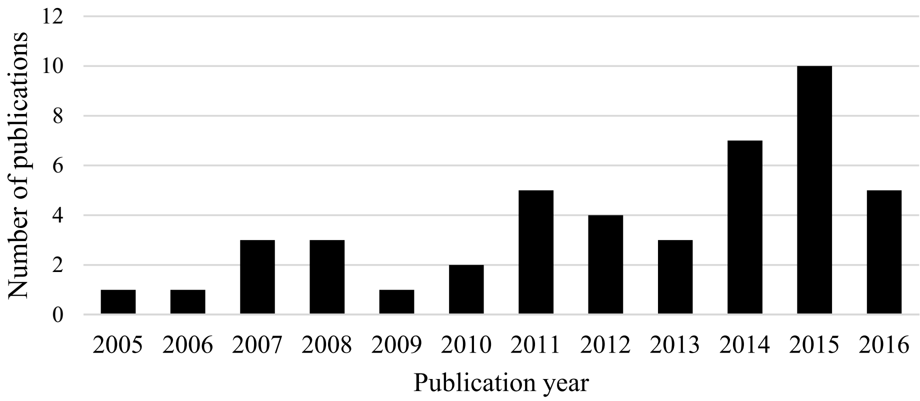


Fig. 1. Number of publications per year.

## 4. Results & Discussion

The aim of this study is to assess the current state of art in utilizing both PBF and DED in repair, refurbishment and remanufacturing processes of metallic products. The focus is especially in identifying possibilities of AM in promotion of circular economy and expected environmental benefits based on the found literature.

The assessed publications are focused mainly in evaluating the use of a DED technology in specific use application or in experimental setting simulating a possible future use application. The found literature also includes review articles either focused on the development and current state of a specific AM technology or focused on a certain industry and discussing the possibilities of AM in this field. For example Kaierle et al. (2012) discuss the current state of laser deposition welding and Flynn et al. (2016) the state of art of workstations for hybrid additive and subtractive processes. Franz et al. (2014) studied the possibilities of laser metal deposition welding in the tool and mould making industry and Angrish (2014) the possibilities of AM in aerospace applications.

Most of the publications, 42 out of 45, were focused in DED. Out of three publications discussing PBF two were literature reviews listed above. Hinojos et al. (2016) studied the applicability of electron beam melding, a class of powder bed fusion technology, in nuclear fission applications. The focus was mainly in production of new parts but also the possibility to use the technology for repair applications where materials of dissimilar composition are built on the damaged part, was discussed. It is likely, that PBF could have significant impact on spare part logistic and in that way repair business so another search was done with Boolean equation: (TS=powder bed fusion OR TS=selective laser sintering OR TS=selective laser melting) AND TS=spare part.

The search was conducted in the same database and refined with the same assumptions as the first initial search round and two relevant publications were found. In a study by Hoffman et al. (2003) PBF was used to reproduce a part via reverse engineering to test the process to be used for rare parts on demand applications. In a study by Nyamekye et al. (2015) laser additive manufacturing and CNC machining based supply chain model were compared. The results indicate that the use of AM offers possibilities to reduce downtime in supply of spare parts and reduce part inventory. This was a preliminary study and the environmental benefits of the AM based spare part supply chain were discussed but not verified by calculations. It is possible, that publications on this topic could be found from other sources not included on the database of Web of Science and with different selection of key words other publications could have been found. Nevertheless it is clear, that there are only a few published case studies evaluating the real benefits of utilizing PBF in spare part logistic supply chains.

### *4.1. Identified repair, refurbishment and remanufacturing possibilities*

A significant potential of utilizing different DED based technologies in repair applications was identified. The advantages of DED based repair processes has been discussed in number of publications and they include high precision, narrow fusion zones, and narrow heat affected zones which lead to reduced part distortion in electron beam melting when joining parts from different materials as listed by Hinojos et al. (2016). Kaierle et al. (2012) state that when the life cycle of the component is increased high cost investments for replacements tools and parts can be avoided. DED also enables the repair of work-intensive or expensive products in the case of over machined areas

Number of the publications were focused in evaluating or verifying the applicability of DED technologies in different applications and some of them and their application fields are presented in Table 1. Publications with the same focus industry have been listed together.

Table 1. Repair focused publications with their application industries.

| Possible application fields identified and evaluated in the studies | Publications |
|---|---|
| Gas-turbine hot section, Turbine blade knife-edges, Deteriorated steam circuit parts, Gas turbine blade repair | Acharya & Das (2015); Bi & Gasser (2011); Díaz et al. (2012); Kim et al. (2012) |
| Mould repairing process, Die repair applications, Die Repair, Repair applications in tooling industry | Borrego et al. (2009); Kattire et al. (2015); Leunda et al. (2011); Lestan et al. (2013) |
| Rail steel; Repairing and enhancing rails | Clare et al. (2013); Lewis et a. (2015) |
| Reconditioning of crankshafts | Koehler et al. (2010) |
| Repair of critical steel components in aerospace industry, Refurbishment and repair of structural components in aerospace industry | Lourenço et al. (2016); Raju et al. (2015) |

Many of the listed application fields are such that the components have special material properties and requirements and complex structures or they need to endure severe working conditions, or both. Due to these facts the components are often expensive and vital to the whole process which they are part of and it is justifiable to examine the possibility of repairing them instead of replacing them in case of failure. At the same time it has to be kept in mind that the repair quality should be the first priority. For example according to Wen et al. (2015) in the case of load bearing parts, such as turbine parts and shafts in power plants, the overall properties of repaired components should be equal to the base material to assure service performance and life.

Repair or conditioning of parts of different types of turbines or other deteriorated steam circuit parts were discussed, among others, by Kim et al. (2012) and Acharya & Das (2015). The condition of the turbine parts has a significant effect on the process efficiency and especially important are turbine blades. In many cases the repair of turbine blade is more feasible than a new part. According to Díaz et al. (2010) DED has advantages compared to conventional welding processes, for example lower thermal strains, smaller heat affected zones and dilution between coating and base material.

Number of articles discussed the use of AM methods in mold and die repair (Jhavar et al., 2013; Borrego et al., 2009; Kattire et al. 2015). Jhavar et al. (2013) state that this can be very expected due to the key position of this industry in mass production and the nature of the industry: downtime means lost profit and due to the high costs of mold and dies the quick-repairing mechanism is naturally more economical solution then a stand-by system. Laser, electron beam and micro welding processes have been recorded to be technically and economically feasible in mold and die repair, but there is still a need of further research in the appropriate repair material selection and repair methodology.

Also a recognized and tested application field for DED is rail track repair and this application have been studied among other by Clare et al. (2013) and Lewis et a. (2015). According to Lewis et al. (2015) especially components such as switches and crossings are particularly prone to wear and their maintenance costs can be even 330 times greater than those of straight track parts on a per meter basis.

Marine diesel engine crankshafts were repaired with DED in a study by Koehler et al. (2010) and the influence of this procedure further evaluated in Koehler et al. (2011). It was concluded that the cladding resulted a decrease in fatigue strength. There is a need for further research to understand the fracture mechanisms of these components.

Lourenço et al. (2016) studied the fatigue and fracture behavior in DED of ultra-high strength steel, applicable for aerospace components. Fiber laser technique with filler wire addition, a form of DED, was found potential for repair and remanufacturing in aerospace applications by Zhang et al. (2013). For a successful AM aided repair and service business models the method to acquire the design models is crucial. In repair processes often the original CAD model of the design stage can't be used for the repair process. It might not be suitable for repairing process and also it is possible it is not available and this complicates the precise repairing of complex components. Gao et al. (2008) tested integrated repair solution adaptive to worn component geometry to aerospace components with positive results.

Wilson et al. (2014) list a number of reasons why DED technologies provide a possibility for remanufacturing practices not available before especially for aerospace and automotive industries. The current state in this industries is such that many components reach the end of their operational life time prematurely because of limitations in overhauling techniques. This is due to the fact that great part of components in these industries are made of high strength alloys which make possible the needed good thermo-mechanical properties. These materials need special tooling and their manufacturing processes are energy intensive. Also the raw material costs are high. Same issues were raised also by Wen et al. (2015) in the case of turbine parts and shafts in power plants.

Morrow et al. (2007) conducted a study focused on the environmental aspects of laser-based and conventional tool and die manufacturing. The study concluded that regardless of how the tooling is originally produced DED present possibilities for environmental benefits in repair and remanufacturing procedures.

Wilson et al. (2014) conducted a successful repair of defective voids in turbine airfoils based on DED and state that the study demonstrates the applicability of DED in remanufacturing. Lu et al. (2015) studied the mechanical properties of damaged steel pipelines with the aim to provide reference data for the planning DED based remanufacturing activities. Xu et al. (2015) investigated the selection of process parameters for DED to be used in further study aiming to remanufacture rotary cutting die equipment, piston head and exhaust valves.

Studies by Grant & Tabakoff (1975) and Antony & Goward (1988) have concluded that in metallic components with high added value the damages often occur in the form of cavities and voids in the material. The component can no longer be used when the material have degraded under permitted level or the when components do not no longer comply with the specified dimension. Wilson et al. (2014) describe that after successful remanufacturing process such components can be as efficient as before or regain even better use properties due to improved design or advanced design. Previous study by Zhang et al. (2002) demonstrate that there have not been cost-efficient methods for remanufacturing before. Wilson et al. (2014) discuss that GTAW is not compatible with a number of advanced material and their high operating temperatures and do not result in adequate component design.

Flynn et al (2015) discuss the current state of the art and future of workstations for hybrid additive and subtractive processing (WHASP), and the relevance of the technology for enabling remanufacturing processes. Flynn et al (2015) state that WHASP's ability to work, inspect and then rework material until the part conforms to tolerances and specifications may result in considerable changes in quality management. Flynn et al (2015) expect that implementation of WHASPs will lead to reductions of costs related to floor space requirements, generation of scrap and resulting in potentially improved processing times.

### *4.2. Identified expected environmental benefits*

Publication by Morrow et al. (2007) focus on the environmental impacts of AM in tool and die manufacturing industry and Wilson et al. (2014) conducted a life cycle assessment of remanufacturing procedure. Some of the other publications among the assessed literature discussed the environmental benefits but no calculations were performed to verify these claims.

The aim of the study by Morrow et al. (2007) was to determine if DED based manufacturing of moulds and dies could result in reduced environmental impacts when compared to conventional manufacturing pathways. In the study three case studies were performed. Case study A compared manufacture of injection mold insert with CNC milling to DED, case study B compared mirror fixture manufacturing with CNC milling to DED and case study C studied remanufacturing of tooling. One conclusion of the study was, that simple moulds with high-solid-to cavity volume and minimal finishing machining are more environmentally sustainable to be manufactured via CNC milling than via DED. In the case of moulds with low solid-to-cavity volume it was found that they are more environmentally sustainable to be manufactured via DED. Morrow et al. (2007) define the solid-to-cavity volume ratio "as the ratio of the solid mass of the tool to the total mass of the minimally bounding volume of the tool assuming it were completely solid and made of the same material as the tool".

Wilson et al. (2014) executed a comparative life cycle assessment between remanufacturing a turbine blade with DED and compared it to manufacturing a new turbine blade. According to the results it depends on the repair volume which route results in less environmental impacts. When the repair volume in the turbine blade was 10 % there was approximately 45% reduction in the associated greenhouse gas emissions and 36 % reduction in energy consumption compared to the manufacture of a new replacing turbine blade.

## 5. Conclusions

A considerable number of the publications is focusing in either one or two possible procedures for realizing circular economy. The aim of most of the publications is to study the technical feasibility of the technology in some specific applications. There are not many publications discussing the possibilities of the PBF and DED technologies as enablers of circular economy. However, based on the literature review it can be concluded that these technologies could have a significant role in the building of circular economy.

Tool and die, power plant and aerospace metal component manufacturers and process owners, among others, could benefit in their service business and modes of operation from further determining the possibilities of AM technologies in repair, refurbishment and remanufacturing actions. Futher research should be done to identify and verify possible new applications and their technical performance. At the same time, it is essential to assure that the new manufacturing pathways reduce environmental impacts compared to conventional manufacturing pathways. When doing these comparisons it is essential that the evaluation is done from the full life cycle perspective instead of focusing only in the manufacturing phase.

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