Using additive and subtractive manufacturing technologies in a new remanufacturing strategy to produce new parts from End-of-Life parts

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Résumé :

La technique de fabrication additive est aujourd'hui considérée comme une technique de la troisième révolution industrielle. Cette technique permet de créer une pièce « vraie matière » par ajout de matière couche par couche à partir d'un modèle CAO. La prise en compte des performances de ces techniques dans une nouvelle stratégie de remanufacturing devrait permettre de transformer une pièce en fin de vie en une nouvelle pièce sans retourner au niveau du matériau premier. L'objectif de cet article est de découvrir la faisabilité technologique de ces techniques pour le remanufacturing, et de poser les pistes pour mettre en place une nouvelle stratégie permettant de donner une nouvelle vie aux pièces en fin de vie. Ces pièces étant destinées à un autre produit.

Mots clefs : Fabrication additive ; remanufacturing ; produits en fin de vie.

Abstract:

Nowadays, additive manufacturing technique is considered as a technique of the third industrial revolution. The technique makes it possible to build a "real-material" part by adding materials, layer by layer, based on a CAD model. Taking into account the performances of these techniques, a new remanufacturing strategy seems possible to transform an End-of-Life (EoL) part into a new part without returning to the level of raw material. The purposes of this paper is to explore the technological feasibility of such additive manufacturing techniques for remanufacturing, and then propose the ways in order to establish a new strategy for giving a new life to EoL parts. The new parts produced are intended to be different - and have different functionalities - from the original.

Keywords: Additive Manufacturing; remanufacturing; End-of-Life products.

1 Introduction

Nowadays, sustainable development has become an essential social issue and, in particular, a major challenge in the industry. The variety and quantity of End-of-Life (EoL) products lead to increase their economic and environmental impacts. Following the European Union (EU) legislations on waste, such as Waste Electrical and Electronic Equipment (WEEE) and End-of-Life Vehicle (ELV), as presented in [1], the production system must be balanced from economic and social points of view by reducing or stabilizing its environmental impacts [2]. Many voluntary standards and governmental initiatives to promote sustainable consumption and production have also been used with success in the United States, Canada, and many other countries [3].

To answer the problematic of EoL products, manufacturers are looking for strategies able to recover EoL products and upgrade them. The actual dominant strategy recovers EoL products and recycles them into raw material; then, this material is reused in a new production cycle. The standard strategy consists in separating different materials, and then recycling them [4]. However, the energy consumption of the recycling sectors remains important [4]. In addition, the added value, functionality and built-in energy of original products are lost during the recycling process [1-5]. Today, remanufacturing strategy appears to be an interesting alternative to recycling. Remanufacturing can extend the life-time of products by maintaining the performance level and then upgrading them [6], [7]. To prevent environmental impacts, it seems interesting to use an EoL part to produce a new part without going through the recycling phase. Decreasing the consumption of materials and encouraging closed loop strategies is an essential issue for a sustainable production system.

Since the end of the 1980s, additive manufacturing (AM) has been an emerging technique in manufacturing. The technique is associated with potentially strong stimulus for sustainable development because of reduced CO_2 emissions [8]. Today, AM processes are efficient enough to make products with a material compatible with the usage. Taking into account the performances of these techniques, a new remanufacturing strategy seems possible to transform an EoL part into a new part without returning to the level of raw material.

The purpose of this paper is to answer the question "Is it possible to give a new life to an EoL part with the use of AM techniques?", and then propose the ways in order to establish a new strategy for giving a new life to EoL parts. This paper is structured as follows. Section 2 presents an overview on remanufacturing. AM technologies and their performances are presented in section 3. This knowledge is one of essential inputs of the strategy. In section 4, we propose a new strategy to give a new life to an EoL part; and the associated research questions are raised. In current work, we focus on metal parts. The proposed strategy is investigated basing on the understanding of additive, subtractive and inspection processes, as well as the information of EoL parts and final parts. Finally, section 5 offers some conclusions and future work to establish such a strategy.

2 Remanufacturing: strategy to extend the products' life

Following the directive (75/422/EEC) on waste of the European Economic Community, an EoL product is defined as "any substance or object which the holder discards or intends or is required to discard" [9]. Many strategies, which allow recovery and upgrading of EoL products, have been proposed, including reuse, remanufacturing and recycling (Fig. 1).

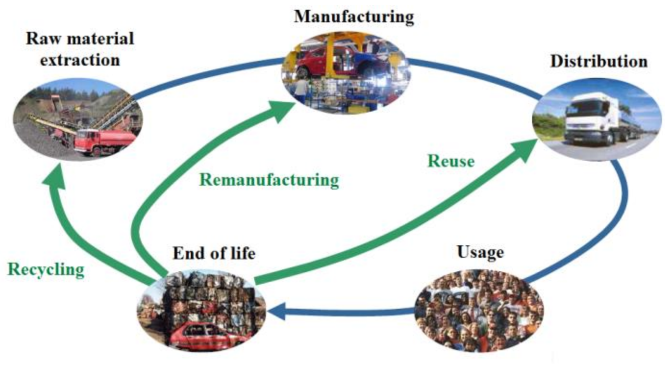

Figure 1. Cycle life of products and EoL product options.

Remanufacturing is an industrial process, which consists in restoring used products to like new conditions (including warranty). Today, remanufacturing is considered as an appropriate solution for the industry [2], [4] because it allows not only reducing waste, but also reducing environmental impacts and preserving energy and added-value of parts at the time of design and manufacture [6], [7]. Remanufacturing process consists of the following steps: disassembly, cleaning, inspection, repair, updating and replacing components, reassembly, and testing [6], [7].

Many studies on remanufacturing have been published, such as design for remanufacturing products [10], [11], and design for remanufacturing process [12]. Conventional techniques, such as machining, surface coating, are often used. The advanced technologies, such as laser direct deposition, are used to restore turbine blades with success [13]. Today, the use of AM technologies in a recovery strategy of EoL parts offers new prospects. In this research, we want to extend the remanufacturing field by proposing a new strategy which allows a preservation of the material contained EoL parts. The geometric shape of an EoL part will be modified by additive and subtractive manufacturing technologies resulting in a new part, which is intended for another products.

3 Additive manufacturing technologies and their performances

AM technique is defined as a process of "joining materials to make objects from three-dimensional (3D) model data, usually layer upon layer" [14]. AM technologies are generally based on three basic steps [15], as follows. First, a 3D solid model of a part is built and converted into a standard AM file format (the *.stl* file format). The file is then sent to an AM machine. Finally, the part is built layer by layer.

In comparison to conventional manufacturing process, AM technologies have the following main advantages [15]:

- *Material efficiency*: AM techniques use raw materials efficiently by building parts layer by layer. For some applications, especially in the metal sector, the techniques can reduce up to 40% of raw material waste when compared with subtractive processes. In addition, 95% to 98% of remaining materials (non-melted metal powders) can be recycled [16].
- *Resource efficiency*: AM processes do not require additional resources, such as jigs, fixtures, cutting tools, and coolants. Therefore, parts can be produced by small manufacturers who are close to their customers. This is an opportunity to improve part of the supply chain [15].
- *Design flexibility*: AM techniques do not require specific tools; thus, parts with complex features can be made. Moreover, it is possible to produce a part with different mechanical properties (e.g. flexible in one part and rigid in another one) [15]. This opens an opportunity for design innovation.
- *Production flexibility*: The techniques allow manufacturers to change the design of the produced part frequently without having to pay the costs of manufacturing molds and/or changing molds, especially for companies that have short product cycles.

Nowadays, AM technologies are widely used in the aerospace, biomedical and automobile sectors [17]. Particularly, AM processes are available to produce parts in many metallic alloys, such as titanium, nickel, cobalt-chrome, steel, etc. Metal processes either use a laser beam, for example Selective Laser Melting (SLM), Construction Laser Additive (CLAD) or Direct Metal Deposition (DMD), or an electron beam (e.g. the Electron Beam Melting (EBM)), to melt metal powders. The processes allow dense parts with little porosity to be achieved [18]. Generally, metal AM processes can be classified into two categories: the powder bed fusion processes (SLM and EBM) and the directed energy deposition processes (CLAD or DMD). The principles of these processes are presented in Fig. 2 and Fig. 3 respectively.

Powder bed fusion processes: These processes make it possible to produce complex parts that can include internal structure. Moreover, the achieved parts have good metallurgy, as well as excellent mechanical properties. However, the techniques are limited by their build envelope, the use of unique material for a single build [19]; and the build of parts that is only performed in the horizontal plane. The techniques are appropriate for production of small and medium complex parts. In addition, due to the high temperature of laser beam, the parts made by SLM process are likely to include residual stresses and thermal deformation. Hence, it is necessary to carry out heat treatment steps to remove the stresses [18]. For EBM process, due to the charge of an electron, a consolidation of powders is necessary to avoid the powders' electrostatic repulsion. This is conducted by heating each layer; and that also limits thermal gradient during the build process [18].

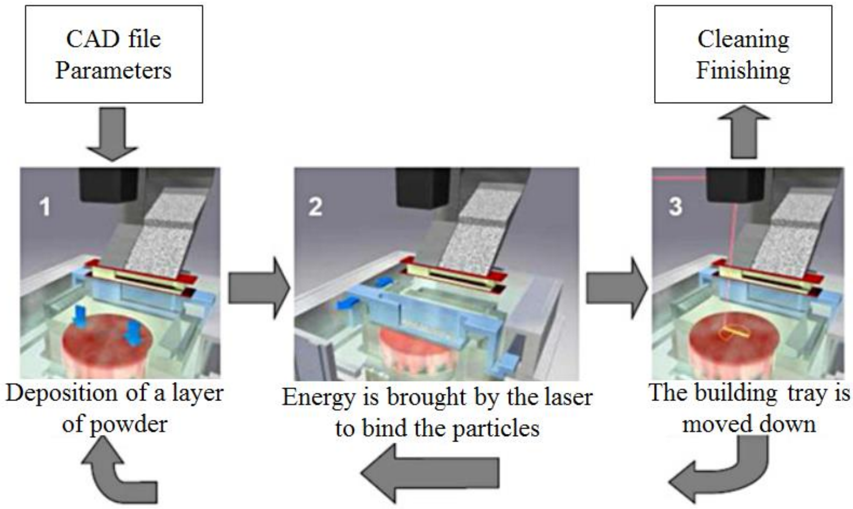

Figure 2. Principle of power bed fusion by laser [18].

Directed energy deposition processes: The processes work by injecting material into a melt pool rather than scanning a powder bed (Fig. 3). They offer a high speed deposition and a large build envelope due to a configuration of 5-axis or 5 + 1 axis machine [18], [19]. The processes can also produce multi-material parts in a single build and add materials (make new features) to existing parts [19]. However, they also have limitations, such as the capability to build internal structure (e.g. cooling channels in the molds). These techniques are better for production of larger dimension parts, remanufacturing, repairing damaged parts, or adding features to existing parts [19].

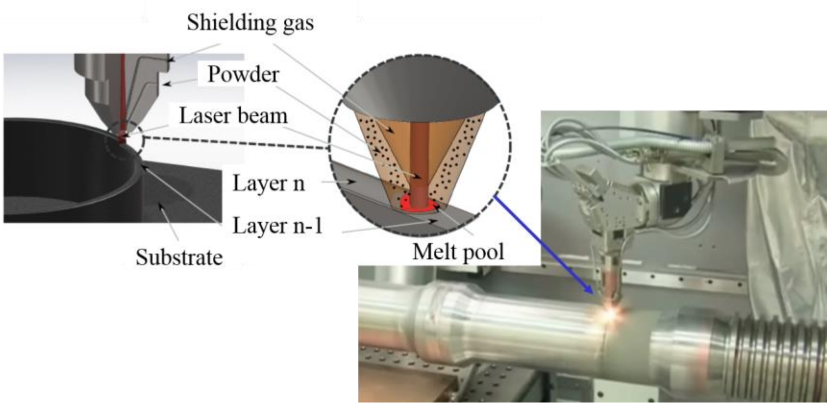

Figure 3. Principle of directed energy deposition, [20], [Trumpt].

Most AM-built parts need a post processing procedure such as finishing machining. In fact, the surfaces of part have a significant roughness and a granular aspect due to the binding of un-molten particles on the exterior of the parts [18]. The quality of SLM-built surfaces is better than the ones made by EBM, DMD or CLAD. The SLM-built surfaces' arithmetic roughness can reach between 9 and 12 µm, while that of EBM-built surfaces is usually between 25 and 35 µm [18], [19]. The roughness of surfaces achieved by these processes depends on the scanning speed, the size of powders and the thickness of layers [21]. The arithmetic roughness of DMD-built surfaces is more important, between 20 and 50 µm, that depends on beam size [19]. As the surface quality can have significant influence on mechanical properties, in particular the fatigue, the functional surfaces of AM-built parts must be machined to achieve the required quality.

4 New remanufacturing strategy to produce new parts from EoL parts

In Section 3, the characteristics, the constraints and the limits of metal AM processes were presented. Their understanding allows us to propose a new remanufacturing strategy based on these techniques. The aim of the proposed strategy is to transform an EoL part 'X' into a new part 'Y' with new features that are different from the original ones on the part 'X' (Fig. 4). The strategy will be defined by combining the additive, subtractive, inspection and heat treatment processes

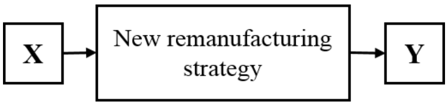

Figure 4. Principle of the proposed strategy.

In comparison to traditional remanufacturing processes where the parts/components are restored in the like new condition and reuse for the same products, in this strategy, the EoL parts are used as the given raw material to produce the new parts, which will be used for other products (i.e. giving new life to EoL parts). Hence, the material of EoL parts is directly reused without passing through the recycling process. Moreover, producing new parts directly from existing parts by this strategy allow the use of material more efficiently than the production of parts from workpieces, which results in reducing waste. The combination of additive and subtractive processes allow not only taking the advantages of each process (such as, building complex geometries by AM technologies, and achieving high precision components by machining (e.g. CNC machining)), but also minimizing their disadvantages (e.g. the poor surface quality and tolerance of AM-built parts, and the limited tool accessibility in machining processes).

To validate the feasibility of AM technologies to achieve new parts by adding new features on existing parts, an investigation on mechanical characterizations of new part, which was obtained from existing parts and added material by EBM process, was conducted. In this work (to be published), an EBM machine (Arcam A1) was used to produce new Ti-6Al-4V features on Ti-6Al-4V plates. Then, the samples were investigated in term of their microstructure and mechanical properties. The results obtained in this work demonstrate that the new features have a strong mechanical bonding with the plate, and behave as a unique part. Moreover, EBM process allow building new features with a good metallurgy and excellent mechanical properties; and the initial part dose not alternate mechanical properties. This research provides an important evidence that EBM technology, as well as other metal AM technologies allow achieving new parts from existing parts/EoL parts.

For defining the strategy, we firstly consider that the part ‘Y’ is known. Thus, the problem consists in analyzing the characteristics of the different potential parts in order to choose the best part ‘X’ as a root to produce the part ‘Y’. The following questions are then proposed before designing a production process suitable with such strategy:

- How can we characterize the different potential parts ‘X’ and choose the best one to produce the part ‘Y’?
- How can we define a sequence of operations: adding material, subtracting material, inspection, and heat treatment to build the part ‘Y’ from the part ‘X’?

The geometry of the part ‘X’ will be modified with additive and/or subtractive manufacturing techniques in order to obtain the part ‘Y’. Moreover, the energy and environmental balance must be positive *vis-à-vis* the production of new part from raw material. The material also has to be “strong” *vis-à-vis* the usage of the part ‘Y’; and, it must be in line with additive and subtractive manufacturing techniques to implement. This leads us to propose the following questions:

- What methods can be used to assess the economic efficiency and environmental impacts of the strategy?
- Is such strategy compatible with the production of single part, small batches, or big batches?

Fig. 5 presents a generic process of a strategy able to transform the part ‘X’ into new part ‘Y’. This process consists of three following major steps:

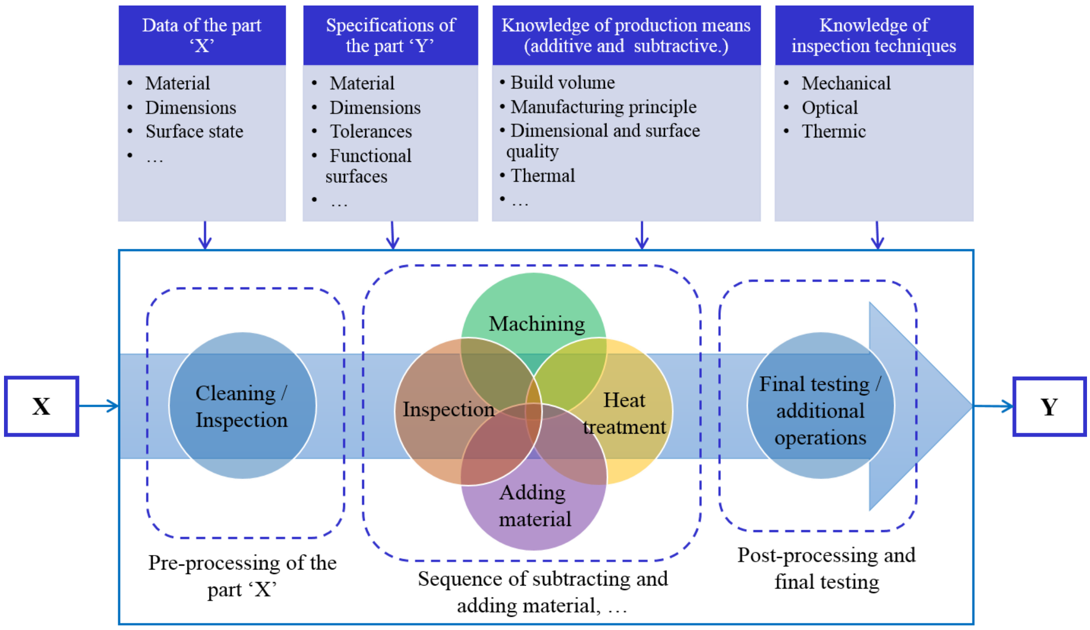

Figure 5. Generic process of the proposed strategy.

- *Pre-Processing of the part ‘X’*: this step includes cleaning and inspection operations of selected part ‘X’. EoL part geometry will be identified in this steps by initial inspections. Then, a CAD model of the part ‘X’ can be generated. This information is one of needed inputs to design the process.
- *Removing and adding material processes*: Comparing the geometry of the part ‘Y’ with that of the part ‘X’, an operation sequence, including removing material, adding material and inspection, as well as heat treatment process, is defined. The sequence will be intelligently defined by additive and subtractive operations, even heat treatment to achieve the geometry

and the quality of the part 'Y'. The inspection operations are placed in the way to rehabilitate the sequence if the part is not good, and thus avoid the waste.

- *Post-processing and final testing*: The final testing of the part and additional operations, such as labelling…, are performed during this step.

5 Conclusions and future work

Today AM technologies are increasingly used in mechanical and biomedical fields. Taking into account the performance of AM in a new remanufacturing strategy become a potential prospect for sustainable production system. This makes it possible to transform EoL parts into new parts. Thus, the development of tools and models, as well as methodologies to support such a strategy is necessary. In this paper, the problematic associated with the strategy has been presented. A generic process compatible with the strategy has also been proposed. Future work will consist in the definition of the operations and the operation sequence of the extended remanufacturing process. Future works will continue by focusing on the selection of the starting 'X' part among available EoL parts. Finally some models for the assessment of this strategy in terms of economic and environmental performance will be proposed.

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