Additive Manufacturing and Circular Economy

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Additive Manufacturing (AM), also known as three-dimensional (3D) printing has emerged as a disruptive and powerful tool for industrial systems in the Industry 4.0 era by helping businesses flourish in the contemporary dynamic competitive landscape. However, their achievements and development highly rely on “take-make-waste” linear business models, which come, all too often, to the detriment of the environment. Hence, a shift to Circular Economy (CE) practices promoting the acceleration of the transition to resource-efficient systems and the minimization of environmental degradation is now more imperative than ever.

Keywords: additive manufacturing ; circular economy ; sustainable manufacturing ; Industry 4.0 ; 3D printing

1. Introduction

The proliferation of the Fourth Industrial Revolution, referred to as Industry 4.0, has undoubtedly transformed the manufacturing industry by driving dramatic increases in productivity and flexibility, enhancing strategical and operational decision-making and contributing to an improved overall industrial performance [1][2]. AM, also known as three-dimensional (3D) printing, has been presented as an essential driving force behind Industry 4.0. AM uses digital 3D models to create parts by adding material in layers [3], offering the beneficial ability to build parts with geometric and material complexities [4], as opposed to conventional subtractive manufacturing, where a product is shaped by removing material in order to achieve a desired shape [5]. The consumer driven nature of this manufacturing paradigm, in that it inherently provides opportunities for mass customization by facilitating the production of personalized products [6], justifies its growing utilization by industrial companies, which strive to meet the ever-growing customer demand and eventually blossom in this modern, continuously changing, competitive landscape.

Nevertheless, despite its economic benefits, the development of industrialization has indisputably led to serious ramifications, several of the most significant of which pertain to the deterioration of the environment. In fact, industrialization is deemed responsible for a multitude of deleterious consequences undermining the integrity of natural ecosystems, such as water [7], air [8] and soil pollution [9], resource depletion [10] and excessive land use [11]. Under these conditions, the need to ensure companies’ environmental compliance without jeopardizing their production and, therefore, financial prosperity, is now more imperative than ever. In light of the intrinsic mechanics of the conventional linear economy, in which resources are considered to be unlimited, and economic benefits are placed above all other criteria [12], the transition to a sustainable CE business model appears as a priority. The CE concept and its 3R principles, i.e., “reduce, reuse, recycle”, are fully aligned with combining economic growth and environmental protection by promoting the extension of the useful life of products which have exhausted their physical and/or functional service life and would otherwise be discarded, thus maximizing their utilization capacity and maintaining their value for as long as possible [13].

2. Recycling

As already mentioned, recycling takes place when a product can no longer serve any function and would otherwise be disposed of as waste [14]. How 3D printing can contribute to embracing the value of waste, after its collection and separation, is an issue that is of interest to researchers, since AM is capable of being used as a recycling process, exploiting materials made of recyclable components with both environmental and economic advantages [15]. Logistically speaking, the successful implementation of recycling systems is contingent upon the size and location of production facilities and new forms of manufacturing, such as AM, have the potential to decentralize them, consequently increasing overall flexibility, and reducing logistical costs and delivery times, while, at the same time, diminishing environmental impacts [16][17]. Decentralized distributed manufacturing techniques are becoming all the more common [18], providing excellent opportunities for the development of local closed-loop recycling systems [19]. In this subsection, two aspects of distributed manufacturing are investigated through the lens of AM: (1) Distributed recycling and (2) Closed-loop supply chains, followed by efforts pertinent to the (3) Recycling of different types of waste.

3. Reuse after Recycling

An important issue which must be taken into account when it comes to designing products is their subsequent disposal, explored under the lens of recycling and reuse. In other words, material selection in product design should be guided by its added value as waste for its subsequent use as feedstock for the manufacture of new products [16]. The more AM becomes acknowledged, the more powder is needed as raw material, thus highlighting the need for its recycling and reuse [20]. In fact, the production of parts made of recycled metal powder using AM methods is an emerging process that growingly attracts scientific interest [21]. Approximately 80–90%, according to the authors of [22], or even up to 95–97%, according to the authors of [23], of used powder does not melt during 3D printing and can be reused, which shows enormous potential for resource efficiency [21][23][24][25][26], rendering material waste a sustainable resource, with added value for AM [25][27].

Although the recycling of metal powder for AM is of paramount significance to the reduction of costs, processing time, energy consumption and material waste [21], the main question lies in how it affects powder quality and consequently the properties of final products [28]. Ideally, unused powder could be recycled and reused countless times [29]. However, its morphology, mechanical performance and composition change with each cycle of recycling, and material quality deteriorates [21][30] due to increases in the molecular weight of the residue [29][22][30]. This is because the repeated oxidation of recycled powder changes particle size distribution and the powder becomes thinner. Therefore, the indicated number of recycles is limited [21] so as not to jeopardize the quality of final products and, therefore, the reliability of AM [20]. There is a broad spectrum of studies in the literature presenting a variety of recycling strategies, where the same powder is used repeatedly from 5 to over 30 times [21].

There are multiple ways to recycle waste powder and, hence, bring economic benefits, as it is a less costly process than the supply of virgin raw material [20]. Since low-quality powder might affect final products, techniques to maintain its quality throughout its life are required [29][21]. Waste powder can be refreshed with virgin unused powder [31] at a rate of at least 30–50% [29][22][32][33], and thus reused for a few more times for the manufacture of high quality products [29] before it becomes waste with no way of recovery [32]. In the literature, this process of recycling and reusing waste powder from AM processes to subsequent ones has been extensively studied, aiming to reduce the energy footprint and maximize economic performance, always guided towards the adoption of a CE model where waste is not discarded but utilized in new production processes [20].

4. Reuse without Recycling

The authors of [34] worked on the issue of direct material reuse without the need for recycling. In particular, their study investigated a combination of additive (EBM, SLM, Direct Metal Deposition—DMD) and subtractive (Computer Numerically Controlled—CNC machining) manufacturing, a strategy that leads to the creation of metal components directly from end-of-life parts. This strategy makes full use of resources, reduces waste production and energy consumption and, hence, helps alleviate environmental impacts. The authors of [35] developed a project called EDUCABOT3D in order to raise awareness in high school students about e-waste with the support of AM. A mobile robot chassis was modeled using two ways of control between sensors and actuators, one with a rapid prototyping board and another one assembled with components of obsolete electronic devices in a printed circuit board. The authors of [36] also conducted in-depth research on waste reuse without recycling. “Project RE_” explores AM as a “do-it-yourself” tool for the reuse of end-of-life products. For instance, used cans and jars were transformed into pencil holders or piggy banks through the addition of customized lids.

In summary, powder reuse—after or without recycling—appears as an extremely useful practice, promoting the sustainability, quality and cost-effectiveness of parts. However, powders of different materials can be affected in different ways depending on a plethora of factors. These factors include the number of recycles prior to reuse, the rate of refreshment with virgin powder, the AM process employed, material properties, experimental conditions, etc., giving the space to explore a multitude of scenarios, which is a necessary step towards the optimization of the process. Moreover, the limited number of publications on reuse without recycling reflects the need for additional research on the matter, given its potential to dispense businesses—whenever possible—from the cost of recycling as well as to provide resource efficiency.

5. Repair

The implementation of effective production techniques designed to extend a product’s lifespan through repair is a topic that has been of great concern to researchers [37][36], and although AM has been generally used for prototyping, its use for repair, especially through the 3D printing of spare parts, is increasing rapidly [38]. The key difference between repair and remanufacturing lies in the fact that in order to repair a part, the issue causing its failure would have to be recognized and then repaired, whereas in remanufacturing, that part would have to undergo diverse processes and end up indiscernible from a new one, meaning that it would essentially restart its lifecycle [39]. While conventional processes necessitate the manual reparation of a component and then it's attachment to the broken part, AM can directly build-up in the position of the broken part layer by layer [40][41]. The ability to immediately repair an item instead of dumping it in a landfill actively combats waste generation and resource depletion [38], thus promoting CE principles.

Of the different AM techniques, only three are applied for repair, namely DED, FDM and PBF [42]. In [42], each of the three AM methods used for repair was meticulously analyzed. Laser Cladding (LC), which is commonly used in the application of DED, is able to repair damaged parts—even in the case of wide solid constructions—or cracks by applying material on the damaged surface. It is worth noting that geometrical complexity remains a major challenge in this process. FDM is used to create new parts and fit to replace damaged ones, considering that it might be more advantageous for a part to be self-produced by the user instead of ordered from the manufacturer, especially for parts no longer available for purchase. Last but not least, PBF—in contrast to the aforementioned two methods—requires the object surface to be flat and parallel to the platform previous to the repair process. The authors of [43] analyzed a polymerization strategy to develop 3D printing reprocessable thermosets allowing users to convert a printed 3D structure into a new shape, repair a broken part by simply 3D printing new material onto the damaged site and recycle unwanted printed parts so that the material can be reused. With conventional thermosetting 3D printing materials, when a part is broken, it is not able to be repaired since its chemically crosslinked networks are permanently damaged. However, with this approach, printed parts are repairable through thermally activated self-healing.

The authors of [44] compared the environmental ramifications of conventional and LBM-based manufacturing through a case study for the repair of a gas turbine burner. Contrary to the conventional repair process, only a low percentage of material needs to be removed and turned into scrap through the AM repair process, thus preventing additional material waste. The work presented in [19] deals with 3D printing surface finishing post-processing with the use of recycled plastic waste. In this study, the proposed process was performed on four types of surface defects, i.e., (1) warping holes, (2) skip layers or intermittent deposition, (3) stair effect gaps and (4) excessive air gap, using plastic paste made of recycled FDM waste. This method makes it possible to substantially reduce the use of support materials, hence directly promoting waste recycling and indirectly reducing waste generation. The authors of [45] described a project in which secondary raw materials are reused for the repair of vending machines for beverage containers (internal aluminum structures and 3D printed plastic parts).

As a final note, a key parameter in complying with CE criteria is optimizing part design and guiding it towards easy maintenance, repair and restoration, i.e., ease of assembly and disassembly, consideration of the degree to which the component can be repaired by the user himself/herself, etc. [16]. A way to facilitate this orientation process is by making a technological leap through the creation of digital databases where spare part designs are stored and utilized at all times for various functions of the supply chain [37]. Digital storages of spare part designs allow direct exchange of information for their production and custom repair, thereby enabling the production of spare parts on-demand, fast repair and the reduction of required storage capacity for inventory to a minimum [36].

In summation, the superiority of remanufacturing—in terms of energy expenditure and material utilization—against conventional landfilling and recycling processes renders it a prominent practice for the treatment of end-of-life products. At the same time, it triggers the need for more research on the issue, with an emphasis on the application of information and technology as well as innovations, not only allowing the optimization of the products' upgrade, restoration and repair, but also assisting the operation of the entire supply chain.

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