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SUSTAINABILITY ASPECTS OF PARTS ADDITIVE MANUFACTURING FROM METAL POWDER

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Abstract

In recent times, demand for sustainable products and systems keeps increasing. It is guided by need for reduction of energy and material consumption. Powder metallurgy (PM) has generally lower energy consumption and higher material yield than other conventional processes, such as casting, forming and machining. Also some additive manufacturing (AM) techniques use metal powder as feedstock. In this paper, the energy consumption and material yield of AM techniques using metal powders are compared with conventional manufacturing.

Keywords

Sustainability, metal powder, additive manufacturing

INTRODUCTION

Recent demand for sustainable products and systems is driven by several reasons, among others the economical and legislative ones. The main economic reasons are the reuse or recycling of components and materials, the emerging consumer preferences for green products, and the increasing disposal costs. Legislative reasons can be the more stringent regulations on industrial processes, the take-back laws and recycling standards [1].

Manufacturers have the opportunity to impact sustainability on two levels: their process or operation or via the products produced [2].

Reduction of energy and material consumption can be achieved by several approaches: the use of recycled materials, near or net shape processes, short process sequences, energy saving processes and improved efficiency processes [1].

Material consumption can be influenced by near net shape processes, using metal powders as powder metallurgy (PM) and some additive manufacturing (AM) techniques. Powder metallurgy sustainability is assessed for example in papers [3, 4, 5].

Additive manufacturing techniques using metal powder as feedstock made near net shape products and are still further developed to be more suitable for the production of small or medium series of parts. One of the key benefits are design freedom, light weight structures and new functions.

The sustainability of additive manufacturing techniques using metal powders as feedstock is still considered in various papers, [6, 7, 8, 9]. Some studies [10] even tried to assess the potential effect of AM on the global energy demand. Paper [11] tries to present a simple computational model for determining whether additive manufacturing or subtractive manufacturing is more energy efficient for production of a given metallic part.

Paper [12] reviews the capability of AM and its current development to compete or contribute to the established traditional manufacturing regions.

ENERGY CONSUMPTION AND MATERIAL YIELD OF ADDITIVE MANUFACTURING TECHNIQUES USING METAL POWDER

Additive manufacturing (AM) is the process of joining materials to make objects from 3D model data, usually layer upon layer. Main metal powder additive manufacturing technologies can be divided to two main groups: powder bed technology and blown powder technology as can be seen on Figure 1.

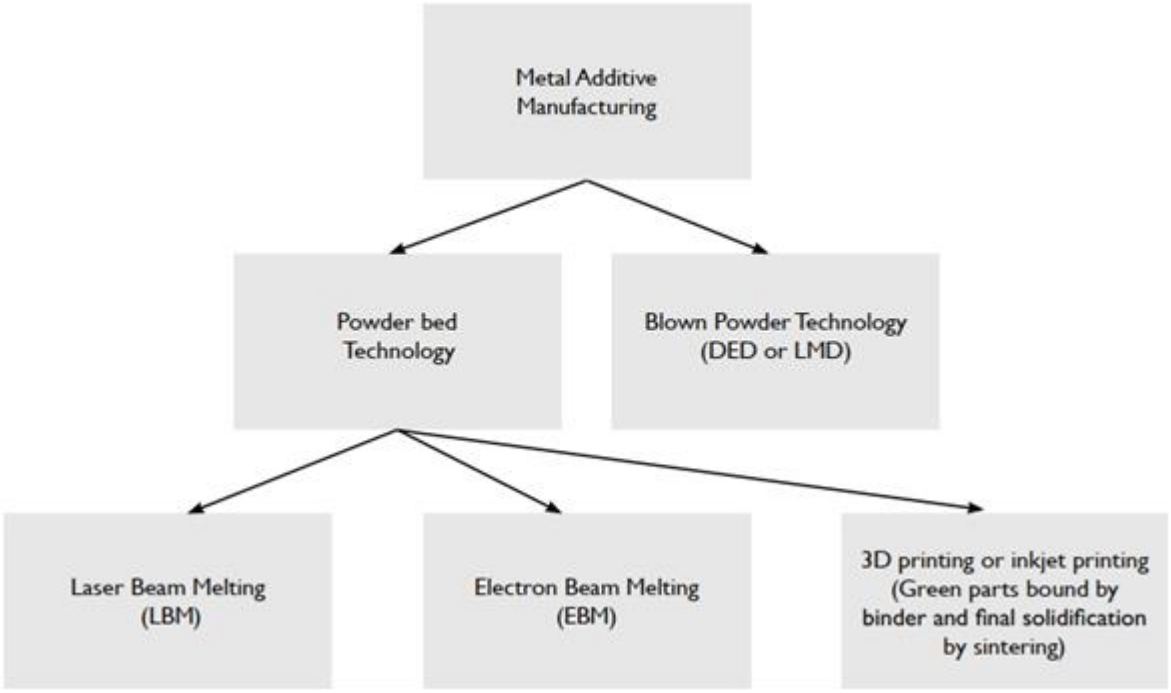


Fig. 1 *Mapping the main metal powder additive manufacturing technologies. Reprinted from [13]. LBM - Laser Beam Melting, EBM - Electron Beam Melting, DED - Direct Energy Deposition, LMD - Laser Metal Deposition*

Powder bed technologies used metal powder bed of some thickness and area depending on the machine. The metal powder bed moves down after fusing or melting of required pattern and next layer of metal powder is applied. After building the part or parts layer by layer the excessive unfused or non-molten metal powder is removed.

Blown powder technologies used metal powder, which is deposited molten onto specified surface. The build parts require support structures, which are removed after building the parts.

Metal additive manufacturing technologies offer main benefits: net shape capability, light weight structures, production of parts in small series. But the technologies also have some main limitations: production series, part size.

The AM techniques needs some post processing operations to improve dimensional tolerances and surface quality. These can include: machining, electric - discharge machining (EDM), peening, grinding, polishing, surface treatment, heat treatment, hot isostatic pressing (HIP) and control.

Table 1 provide a schematic overview of the reported specific energy consumption (SEC) values of AM systems. The mentioned energy values represent the electrical energy demand of the AM systems. The higher values of SEC compared to conventional manufacturing (CM) can be in the typical low process rates for AM.

Table 1 Specific energy consumption for AM systems [14]	
	Specific energy consumption (kWh/kg) ((MJ/kg)), 1 kWh = 3,6 MJ
Laser metal deposition	292.2 (1052)
Direct metal laser sintering	66.9 – 94.2 (241 – 339)
Direct metal deposition	2141,4 (7709)
Electron beam melting	16.9 – 49.2 (61 – 177)
Selective laser melting	23.1 – 163.3 (83 – 588)
Selective laser sintering	14.2 – 40 (51 – 144)
Note: The energy values represent the electrical energy demand of the AM systems	

Comparisons between the conventional manufacturing (CM) routes and their AM alternatives can be seen on Fig. 2. The comparisons assume equivalent product functionality and quality. By optimizing the geometry design, the energy consumption due to material usage can be significantly reduced. In three case study parts the weight reduction is from 50 % to 65 %.

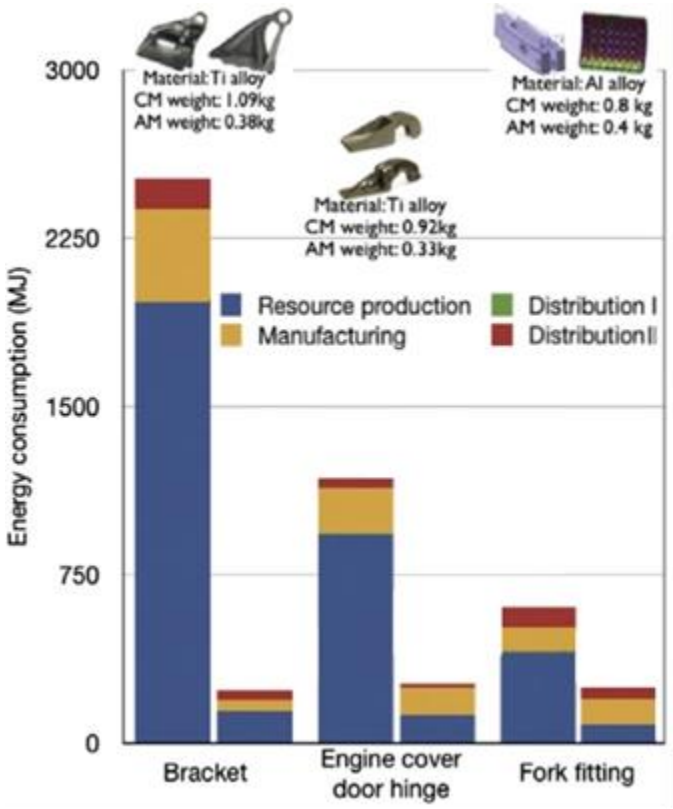


Fig. 2 *Cradle to gate primary energy savings for 3 case study parts, left columns - conventional manufacturing (CM), right columns - additive manufacturing (AM). (3,6 MJ is equal to 1 kWh) Adapted from [15].*

The powder bed processes can have some issues with unfused powder which in many cases could not be used directly again. Paper [16] states that previous studies underestimated resource metal powder consumption for powder bed processes due to overestimation of material utilization factor (estimated: 65 % to 99 %, measured: 12 % to 32 % [17], [18], [19])) in AM and neglecting the energy consumption to produce the desirable feedstock powder (for example energy for melting of iron before atomization: 0.414 kWh/kg (1.49 MJ/kg)). Recycling and reuse of the unfused powder as the feedstock for subsequent deposition can improve the sustainability of powder bed processes.

The material utilization factor and specific energy consumption can be improved by building more parts at once as can be seen on Fig. 3.

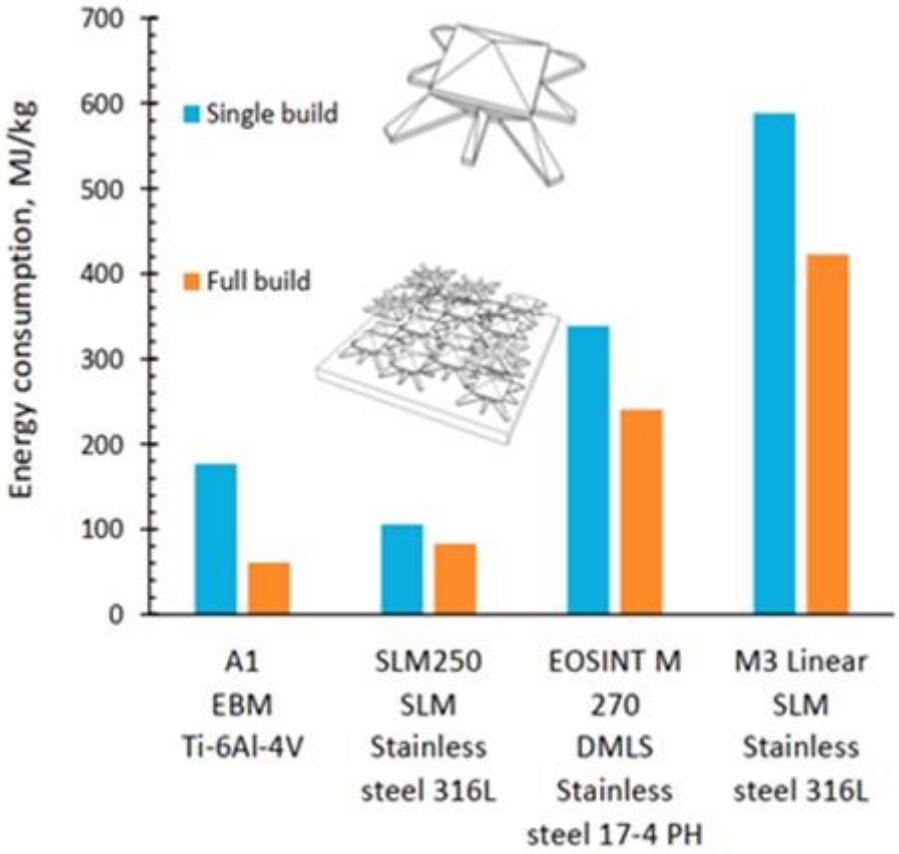


Fig. 3 *Energy consumption of single build vs. full build (3.6 MJ/kg is equal to 1kWh/kg). Reprinted from [20].*

The specific energy consumption to produce the feedstock powder should also contain energy for mining and primary production as can be seen in Table 2. The values can vary for different types of metals and alloys.

Table 2 Embodied specific energy of feedstock for AM processes [21]

Metal or alloy	**Energy consumption (kWh/kg) ((MJ/kg))**
Carbon steel powder	15.58 (56.1)
Stainless steel powder	21.67 – 26.94 (78 – 97)
Aluminium powder	44.44 – 63.89 (160 – 230)
Ti alloy powder	155.72 (560.6)
Nickel powder	37.22 – 71.94 (134 – 259)
Steel wire	19.75 (71.1)

The comparison of breakdown of specific energy consumption for manufacturing titanium aerospace part by different AM processes (using metal wire and metal powder) and machining can be seen on Fig. 4. The largest amount of energy is consumed for mining and primary production of metals and alloys. Joule printing and wire DED use metal wire.

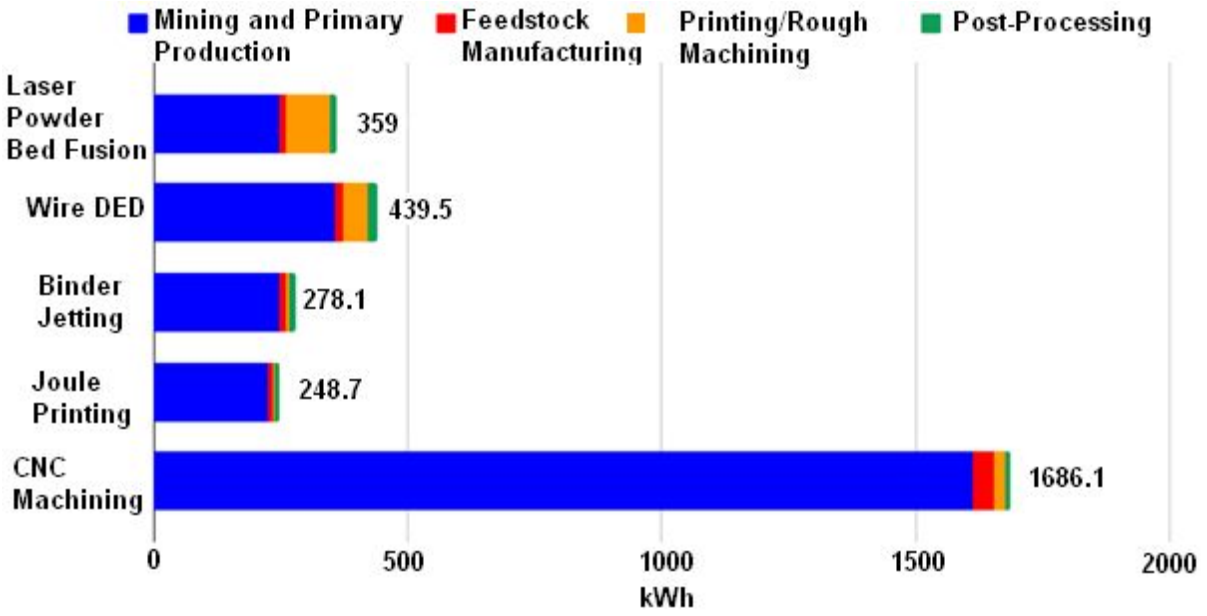


Fig. 4 *Total energy consumed (kWh) by the different process to manufacture an example 1 kg titanium aerospace part. Adapted from [22]. 1 kWh=3.6 MJ*

Next comparisons on Fig. 5 and 6 shows specific energy consumption for manufacturing titanium and tool steel parts by different AM processes (using metal wire and metal powder). Here only the feedstock manufacturing energy is considered.

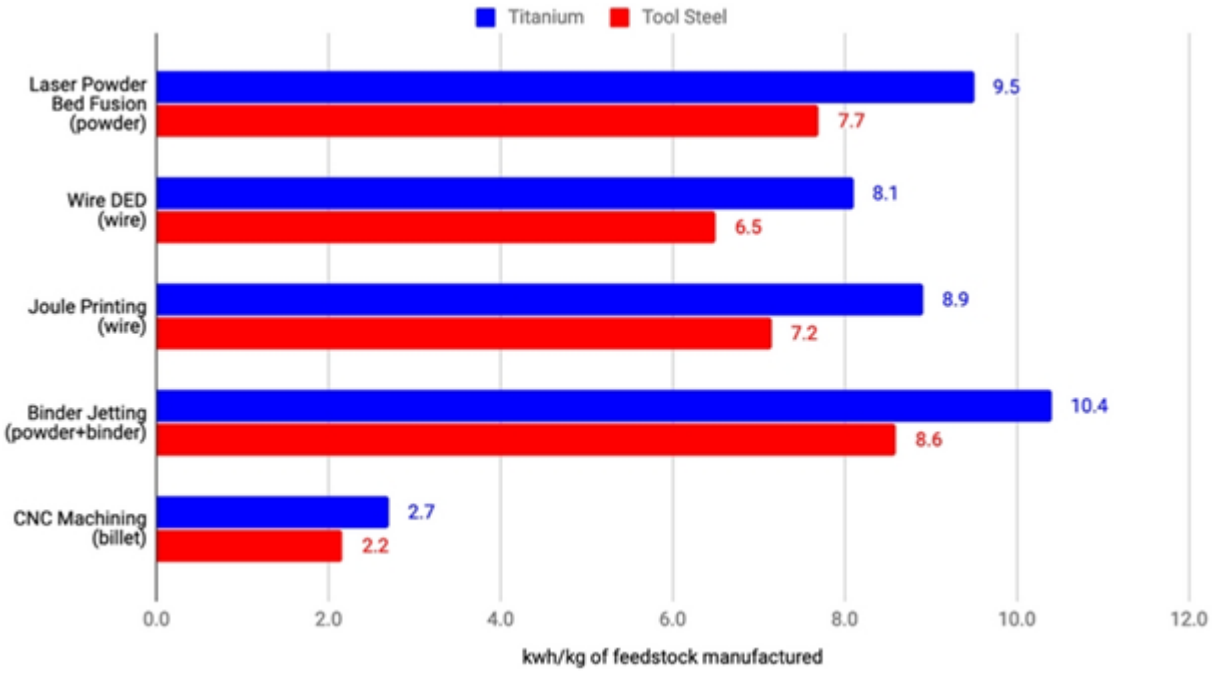


Fig. 5 *Feedstock processing energy consumption. Reprinted from [23].*

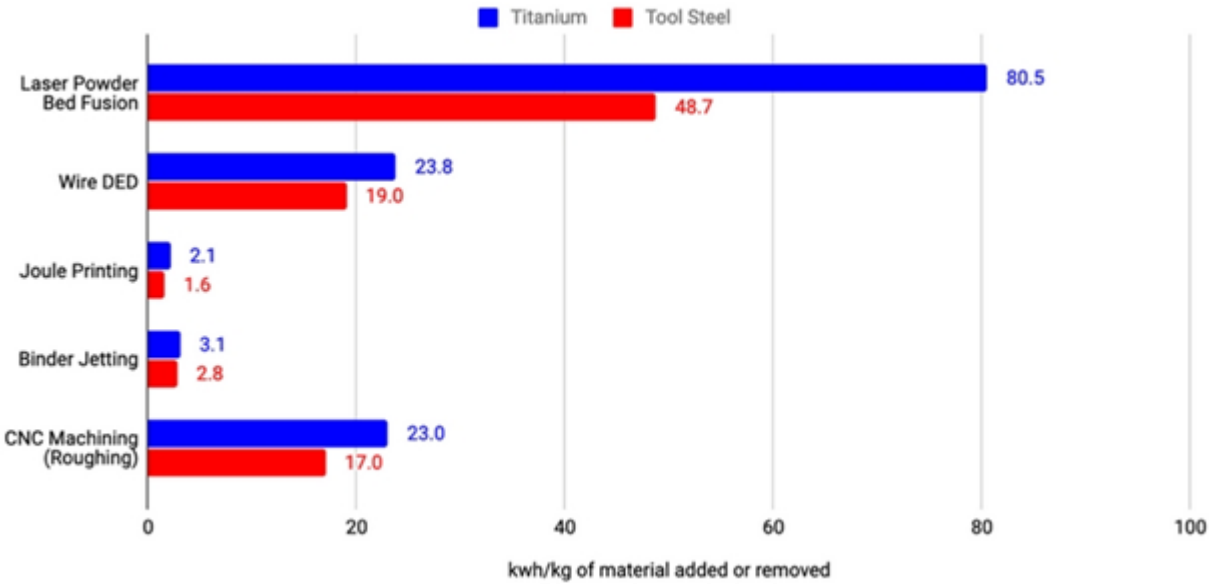


Fig. 6 *Manufacturing process energy consumption. Reprinted from [23].*

When the various AM processes energy consumption breakdown is compared the different machine parts or different phases of manufacturing can be considered as can be seen in Fig. 7 and Fig. 8.

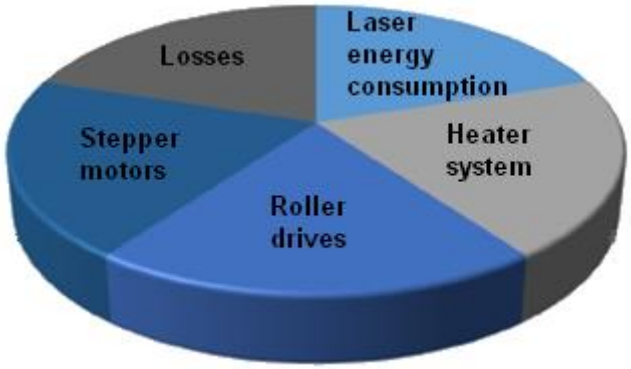


Fig. 7 *Consumption of energy by SLS machine components. Adapted from [24].*

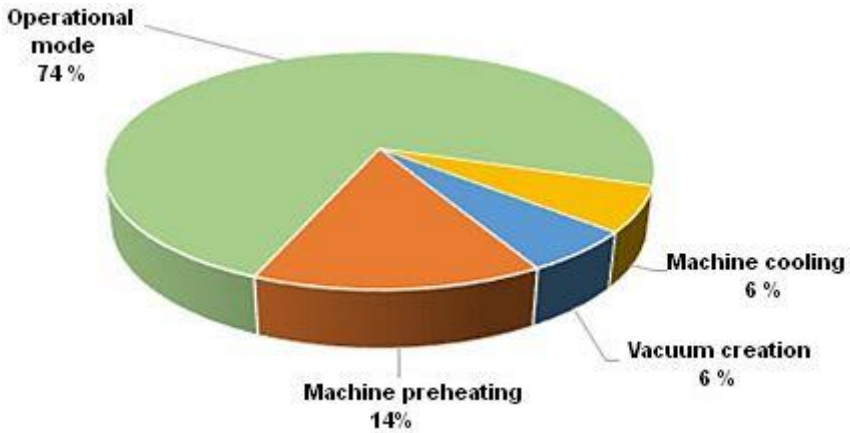


Fig. 8 *Distribution of energy consumption for the EBM production. Adapted from [25].*

At selective laser melting the laser is used to generate the required heat and according to [26] only 9 % of the energy supplied to the machine actually reaches the workpiece.

The energy consumption of AM techniques using metal powder manufacturing various parts is in quite wide range as it is in powder metallurgy production. Some factors as feedstock powder production and finishing are similar other vary. The energy consumption for various complexity PM parts can be in range from 2 kWh/kg to 20 kWh/kg (7.2 MJ/kg to 72 MJ/kg) [5]. There is an obvious correlation between the process or type of manufactured PM parts and energy consumption. The production of heavy and compact parts without complicated special treatment and finishing has the lowest energy consumption. Complex, high performance parts which need special compaction and sintering processes, implying higher energy consumption.

SUMMARY

Additive manufacturing techniques using metal powder are promising from the point of view of material yield and shaping capabilities, and lightweight products.

Energy consumption of additive manufacturing techniques is primarily influenced by used amount of metal powder. Not all of the metal powder remaining after powder bed production processes can be directly used for further manufacturing. And blown powder production processes require some metal support structures. Secondly, the energy consumption is in largest degree influenced by effectivity of heat transfer for metal powder fusing or melting. The laser techniques have usually largest energy consumption because of smallest efficiency of heat transfer.

To decrease the energy consumption and increase the material yield of AM techniques, the whole production chain must be reconsidered and even the part lifetime should be considered.

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