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Characterizing the influence of resource-energy-exergy factors on the environmental performance of additive manufacturing systems

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ABSTRACT

Additive manufacturing is rapidly emerging as an alternative to conventional manufacturing, including subtractive processes, often attributed to its claim for sustainable product development, e.g., reduced cost, reduced energy and material use, and the distributed production of tailored consumer products. However, many of these benefits remain unsubstantiated for large-scale production. The aim of the research herein is to identify and characterize the factors influencing the systemic environmental performance of additive manufacturing as an end use of energy, using exergy analysis and life cycle assessment. These methods have been previously applied to evaluate the environmental performance of conventional and non-conventional manufacturing processes, and offer a validated approach to explore the environmental impacts of additive manufacturing with respect to systemic material and energy losses. In this study, the environmental impacts of direct metal laser sintering (DMLS) of iron metal powder and fused deposition modeling (FDM) of acrylonitrile styrene acrylate polymer filament are characterized by performing a thermodynamic (exergy) analysis of the resources and energy utilized and lost from cradle to gate. It is found that only 10% of total DMLS process inputs contribute to material processing, while 90% of the inputs are lost as bulk waste, heat, and work. For FDM, it is found that only 7% of total process inputs contribute to material processing, while 93% are lost. Following the exergy analysis, life cycle assessment is performed to characterize the environmental impacts of the exergy losses using single-issue indicator (Global Warming Potential, GWP) and aggregate indicator (ReCiPe 2008) methods. The results show that electricity consumption is a key contributor to both focal processes and their related upstream processes. The systemic GWP for DMLS is 69 kg CO_2 equivalent, while for FDM it is 89 kg CO_2 equivalent, per kilogram of material processed. Using the ReCiPe 2008 method, damage to human health is predicted to outweigh damage to ecosystem quality and resource availability for the DMLS process. For the FDM process, damage to human health and resource availability are predicted to outweigh damage to ecosystems quality. This work concludes that electrical energy use is the key contributor to systemic environmental impacts of additive manufacturing. Thus, it is imperative that we identify solutions to generate clean electrical energy, reduce electricity transmission losses, reduce material processing energy use, and design products that enable efficient additive manufacturing.

Introduction

The US National Environmental Policy Act of 1969 [1] declared environmental protection as a national policy, stating it is necessary "to create and maintain conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations." The concept of sustainability grew rapidly from being a minor interest into a guiding influence in the working of countries due to a series of global environmental incidents and disasters, which instigated a fear of instability. Thus, the demand for broader sustainability performance augmented the demand for economic development performance thresholds, which, if crossed, would endanger the basic integrity of the human ecosystem [2]. This distinction was addressed by the term sustainable development, defined in the Brundtland report [2] as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The construct of sustainable development is varied and is characterized by an intricate relationship between environmental protection, economic development, and social welfare to represent development that maintains a holistic worldview. These three independent and co-existing categories (environment, economy, and society) were reinforced as the three pillars of sustainability at the 2005 United Nations World Summit [3]. In support of these efforts, the research herein first discusses topics

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relating to sustainability assessment of manufacturing systems with a focus on additive manufacturing. Then, an approach is presented to assess the exergy efficiency and environmental impacts of additive manufacturing processes.

Sustainable manufacturing

Manufacturing exists as a stronghold for continuous growth and development of countries, a trend that is likely to continue as demand for goods and commodities grows. It continues to play an important role in modern socio-economic systems, leading to dramatic changes in the world economy and to sustained increases in labor productivity and economic welfare [4,5]. Manufacturing drives innovation and productivity in economically stable countries, as well as promoting economic development in developing nations. Development has been supported by an annual increase in world GDP (gross domestic product) of more than 3% since 1800, largely attributed to the industrial revolution and the growth of manufacturing [6]. However, manufacturing activities also pose a significant demand on the environment, which, when quantified using indicators such as air quality, water pollution, and resource depletion, pose a threat to human welfare. For example, the growth of China as a global manufacturing base has been accompanied with significant economic benefits, but it has simultaneously fouled air quality. An estimated 99% of the urban population in China is exposed to air quality much lower than the EU air quality standard of 40 $\mu g/m^3$, which in turn has reduced average life expectancy in China [6]. This pattern of economic growth, with associated pollution growth, can be mitigated through the application of sustainable manufacturing principles to analyze and improve the economic and environmental performance of manufacturing systems.

Sustainable additive manufacturing

Additive manufacturing (AM) has rapidly increased in popularity due to its many advantages, such as reduced waste, streamlined supply chains, and less restrictive design space [7,8]. These advantages have allowed industry to consider AM as a more sustainable option in terms of reduced environmental burden and improved economic and social benefits. However, AM as a sustainable manufacturing technique has not been fully investigated, resulting in little information about the farther-reaching benefits and effects on the environment and economy [9]. Some AM processes, for example, utilize high-powered peripheral heating devices, such as lasers, to melt and reform the metal powders into net shape products in a layer-by-layer fashion [10]. Electrical energy is required to provide the thermal energy required to overcome material melting temperatures to generate part layers. This high intensity energy use seems largely inconsequential, as the cost of electricity has been stagnant at an average of about 10 cents per kWh for the last 50 years in the United States [11]. Hence, electricity use does not greatly contribute towards the cost of products manufactured using AM. However, looking at AM processes as end uses of resources and energy, and analyzing the conversion of energy in upstream processes (e.g., resource extraction and electricity production) leading to end products (and process wastes), can better portray the environmental performance of AM product manufacturing. Thus, our research aims are to identify the resource-energy-exergy factors impacting additive manufacturing and to characterize their effects on systemic environmental performance. These aims will be accomplished through the application of exergy analysis and life cycle assessment (LCA) as described in the next section.

Additive manufacturing as an end use of energy and exergy

Resources are extracted, transformed, and consumed as energy in our everyday lives. Availability of energy in different forms is imperative to human development and economic growth. An energy system can be represented as primary energy resources, energy carriers, and end use energy services [12]. Primary energy resources represent the sources of energy that can be directly used, as they exist in nature (e.g., coal, natural gas, nuclear fuels, solar energy, wind energy, and hydroelectric energy). They represent a reservoir of energy that can be extracted and directly used, or converted into secondary energy forms or energy carriers, such as electricity or liquid fuels. The energy carriers or secondary energy resources can then be converted or used in various end-use applications in different forms (e.g., kinetic, thermal, and light) to provide energy for services such as transportation, HVAC, lighting, and industrial processes [12].

Two AM systems, one for producing parts using fused deposition modeling (FDM) and the other direct metal laser sintering (DMLS), are considered in this study as energy end use applications that consume primary energy resources in the form of an energy carrier (electricity). Energy consumption is a measure of the total quantity of energy utilized by the system. However, this metric does not represent the efficiency with which energy is used to complete a useful task or produce useful work. Hence, we consider useful work, or exergy, here as a measure of the quality of energy consumed within a system. Doing so provides a singular representation of all the energy forms from cradle (resource extraction) to gate (process wastes) and offers a clearer distinction of process energy efficiency [13]. Exergy analysis can be used to account for resource and energy use, as well as to evaluate the efficiency of conversion to produce an end product [13].

Background

The efficient use of energy is an area of interest to reduce environmental burdens due to resource extraction and emission of pollutants, among other impacts. Many studies have been conducted to analyze the energy efficiency of manufacturing processes [14]. To assess the environmental performance of AM, studies reported in the literature focus on energy use as a key indicator of performance. Prior studies reflect on LCA methodology to evaluate process energy consumption and help to identify research gaps that require attention in application to AM [15,16]. Luo et al. [17] presented a method for environmental assessment of solid freeform fabrication-based rapid prototyping and rapid tooling processes. They evaluated the environmental impact of each life cycle stage using the Eco-indicator 95 life cycle impact assessment (LCIA) methodology. They found that process parameters, such as scanning speed, could affect the environmental consequences of the process when material use, energy use, and human health impacts are considered. A study performed by Mognol et al. [18] aimed at integrating the environmental aspects of AM with design and manufacturing parameters for three AM processes, namely, thermojet, fused deposition modeling (FDM), and laser sintering, to produce standard test-build parts. They aimed at developing guidelines to reduce electrical energy consumption, and found that build time was the most influential factor. They concluded part height should be minimized for thermojet and laser sintering processes, while support volume should be minimized for the FDM process. However, the authors were not able to report a general rule for reducing energy consumption for the processes analyzed. Meteyer et al. [19] analyzed the energy and material flow in a binder-jetting process to create a unit process model and build a life cycle inventory (LCI) for performing an LCA of the process. However, they did not apply the model to investigate the influence of varying part designs on energy and material use. The authors performed another study to model the energy consumption in the binder-jetting process by including part geometry information [20]. They observed that the model could represent the energy use in the manufacturing process with up to 99.3% accuracy. The authors emphasize that the energy data could aid in creating life cycle inventory for binder-jetting process for further LCA studies.

Compared to process-level studies, mapping the complex flows of energy over the product life cycle has received less attention. Cullen

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