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METAL POWDER PRODUCTION TECHNOLOGIES FOR ADDITIVE MANUFACTURING

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Abstract — *Additive manufacturing, or 3D printing, has attracted significant attention and raised expectations regarding the future production and repair of components, particularly in the aerospace industry. Various techniques have been employed for the deposition of metal alloys used in the manufacture of components. These technologies offer considerable sustainability benefits, particularly by enabling new opportunities for lightweight design. However, important questions remain regarding the sustainability advantages beyond the use phase of the product. This paper investigates the material and manufacturing life-cycle stages of components produced from INCONEL 718. Energy consumption measurements obtained from the ARCAM A2X Electron Beam Melting (EBM) system are presented and compared with the embodied energy and indirect CO_2 emissions associated with raw material production, as well as with those of conventional subtractive manufacturing processes. The results indicate that both metal powder production and the additive manufacturing process itself contribute significantly to the overall energy consumption and greenhouse gas emissions. Ashby's five-step sustainability assessment methodology is also applied to provide a brief discussion of the economic and social implications of additive manufacturing.*
Keywords: Additive, manufacturing, EBM

АДДИТИВТІ ӨНДІРІС ҮШІН МЕТАЛЛ ҰНТАҚТАРЫН ЖАСАУ ТЕХНОЛОГИЯЛАРЫ

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Аңдатпа. Аддитивті өндіріс немесе 3D басып шығару, мысалы, аэроғарыш өнеркәсібінде бөлшектерді болашақта өндіру мен жөндеуге қатысты назар аударды және күтуді арттырды. Компоненттерге арналған металл қорытпаларын тұндыру үшін әртүрлі әдістер қолданылған. Бұл тұрақтылық тұрғысынан үлкен артықшылықтар бере алады, атап айтқанда, жеңіл салмақ түсірудің жаңа мүмкіндіктері. Дегенмен, пайдалану кезеңінен тыс тұрақтылық артықшылықтары туралы шешілмейтін сұрақтар бар. Бұл мақалада INCONEL 718 көмегімен өндірілген мәліметтер үшін материал мен өндірістің өмірлік циклінің кезеңдері зерттелді. ARCAM A2X электронды сәулені балқыту жүйесінен алынған энергия өлшемдері ұсынылған және шикізаттың нақтыланған энергиясы мен жанама CO2-шығарындыларымен, сондай-ақ дәстүрлі шегеруші өндіріспен салыстырылған. Металл ұнтағы өндірісі де, қоспаларды өндіру процесінің өзі де жалпы энергияны пайдалану мен шығарындыларға айтарлықтай үлес қосатыны анықталды. Эшбидің тұрақты дамуды бағалаудың 5 қадамдық әдісі қосымша өндірістің экономикалық және әлеуметтік салдарын қысқаша талқылау үшін қолданылады.

Түйінді сөздер: Аддитив, өндіріс, EBM.

ТЕХНОЛОГИИ ИЗГОТОВЛЕНИЯ МЕТАЛЛИЧЕСКИХ ПОРОШКОВ ДЛЯ АДДИТИВНОГО ПРОИЗВОДСТВА

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Аннотация. Аддитивное производство или 3D-печать привлекли внимание и повысили ожидания в отношении будущего производства и ремонта деталей, например, в аэрокосмической промышленности. Для осаждения металлических сплавов для компонентов использовались различные методы. Это может дать большие преимущества с точки зрения устойчивости, в частности, новые возможности для легкого веса. Однако есть нерешенные вопросы о преимуществах стабильности вне периода использования. В этой статье были изучены материалы и этапы жизненного цикла производства для данных, полученных с помощью INCONEL 718. Представлены измерения энергии, полученные от системы электронного луча плавления ARCAM A2X, и сравниваются с уточненной энергией сырья и косвенными выбросами CO2, а также с традиционным производством дедукции. Было обнаружено, что как производство металлического порошка, так и сам процесс производства добавок вносят значительный вклад в общее потребление энергии и выбросы. 5-ступенчатый метод оценки устойчивого развития Эшби используется для краткого обсуждения экономических и социальных последствий дополнительного производства.
Ключевые слова: аддитивный, производственный, EBM

MAIN PROVISION

This study presents a comprehensive review of metal powder production technologies for additive manufacturing, with particular emphasis on Electron Beam Melting (EBM) and the sustainability of powder-based manufacturing processes. The analysis demonstrates that metal powder production and additive manufacturing significantly influence the overall energy consumption and environmental impact of component fabrication. The study also evaluates the life-cycle implications of manufacturing INCONEL 718 components and discusses strategies for improving resource efficiency through powder recycling and lightweight design.

INTRODUCTION

The implementation of additive manufacturing (AM) is expected to drive disruptive changes across many sectors of industrial production, affecting all three dimensions of sustainable development: economic, social, and environmental. AM is already being used to reduce maintenance costs and decrease the number of components in certain products [1]. Novel geometries and lightweight components are projected to reduce manufacturing costs by hundreds of billions of U.S. dollars by 2025 [2]. Furthermore, AM enables digitalized, flexible, and localized production of parts, thereby transforming supply chains for numerous products.

Although lightweight components in the transportation and aerospace sectors contribute to lower fuel consumption and, consequently, reduced CO_2 emissions, this alone will not be sufficient to achieve international greenhouse gas reduction targets, such as those established under the Paris Agreement. In fact, these emission reduction targets may still not be met [3]. Therefore, substantial reductions in greenhouse gas emissions will require a transition from fossil fuels to renewable energy sources. Under such circumstances, the significance of energy consumption and emissions associated with the material and manufacturing phases of a product's life cycle will increase. It is also conceivable that manufacturers will use environmental sustainability credentials as a competitive advantage. Consequently, it is essential to investigate the impact of additive manufacturing on sustainability.

According to the Brundtland Report, sustainable development is based on three fundamental dimensions: economic, social, and environmental. This concept inspired the three Ps of sustainability: People, Planet, and Profit (or Prosperity), commonly referred to as the Triple Bottom Line (TBL) approach [4]. A pragmatic methodology for assessing the sustainability of technologies and processes, primarily intended for educational purposes, was proposed by Ashby and colleagues [5]. In this methodology, the three dimensions of sustainability are considered separately and are represented as different forms of capital: financial capital, corresponding to Profit; natural capital, representing the Planet; and human capital, representing People. This framework provides an appropriate basis for evaluating the impact of additive manufacturing on these three forms of capital.

This paper presents a brief comparative review of additive manufacturing processes relevant to aerospace and transportation applications. The discussion is limited to manufacturing processes based on metal powders. As a case study, energy consumption measurements obtained from an Electron Beam Melting (EBM) system are presented, and their implications for sustainability are discussed.

Research gap. Although additive manufacturing has been widely recognized as a promising technology for producing complex metal components with reduced material waste, limited attention has been devoted to the contribution of metal powder production to the overall environmental and energy performance of additive manufacturing systems. In particular, comprehensive assessments integrating powder production, manufacturing energy consumption, and sustainability considerations for nickel-based superalloys such as INCONEL 718 remain scarce. Therefore, there is a need for an integrated evaluation of metal powder production technologies and their influence on the sustainability of additive manufacturing processes.

Novelty statement. The novelty of this study lies in the integrated assessment of metal powder production technologies together with the energy consumption of Electron Beam Melting (EBM)-based additive manufacturing. Unlike previous studies focusing primarily on manufacturing performance, this work evaluates the contribution of raw material production, powder atomization, and additive manufacturing to the overall environmental impact and sustainability of the production process.

METODOLOGY

ASTM has identified seven categories of additive manufacturing (AM) processes: Powder Bed Fusion (PBF), Directed Energy Deposition (DED), Material Extrusion, Vat Photopolymerization, Binder Jetting, Material Jetting, and Sheet Lamination [6]. Among these, Material Extrusion, Vat Photopolymerization, and Material Jetting are generally not applicable to the production of metal components. The three most widely used technologies for manufacturing metal parts are Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Directed Energy Deposition (DED). These three processes, together with Binder Jetting, can all utilize metal powders as the feedstock material. The classification of powder bed technologies and deposition technologies is illustrated in Figure 1 below.

Figure 1. Schematic overview of the main additive manufacturing technologies.

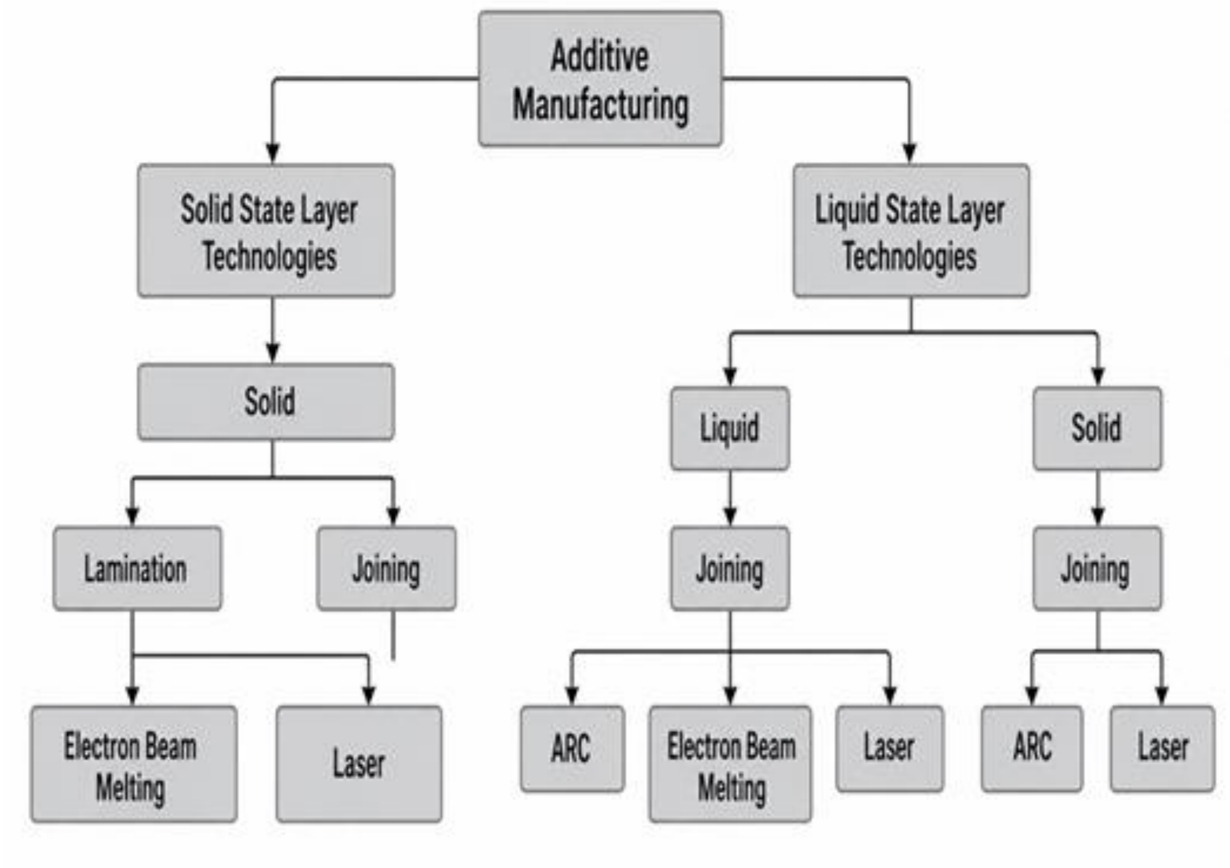


Figure 1 Schematic overview of the main additive manufacturing technologies.

RESEARCH RESULTS

The significance of recycled feedstock and powder reuse is briefly discussed in the following section. The energy consumption associated with producing a component from virgin raw materials through the additive manufacturing (AM) process includes the following stages:

1. Material production, from mining and extraction of raw materials to feedstock preparation, including transportation and related processes.

2. Powder production, for example, through atomization of the raw material, including the melting process.

3. Energy supplied for melting or fusing the metal powder within the additive manufacturing (AM) system.

The first stage represents the energy required to produce billets or ingots from ores or other raw materials. This was evaluated using data from the CES Selector database [7], which provides estimates of the embodied energy and carbon footprint (CO_2 emissions) of bulk INCONEL 718 superalloy. The database contains well-established data that are widely used in the aerospace industry [8]. It was developed based on up-to-date and reliable sources, including Life Cycle Assessment (LCA) databases (e.g., ILCD and Ecoinvent), publicly available environmental reports from industrial associations (such as the World Steel Association and the European Aluminium Association), as well as peer-reviewed scientific publications.

For the second stage, quantitative data for INCONEL 718 were not available in the literature. Therefore, published values for a similar superalloy (NISTELLE 625) were used as a substitute [9].

Finally, the third stage was evaluated through an experimental measurement performed during the fabrication of the test structure described in the following section.

The experimental data were collected during a five-day continuous build using an ARCAM A2X Electron Beam Melting (EBM) system, as shown in Figure 2(a). The connection of the energy measurement probes is illustrated in Figure 2(b).

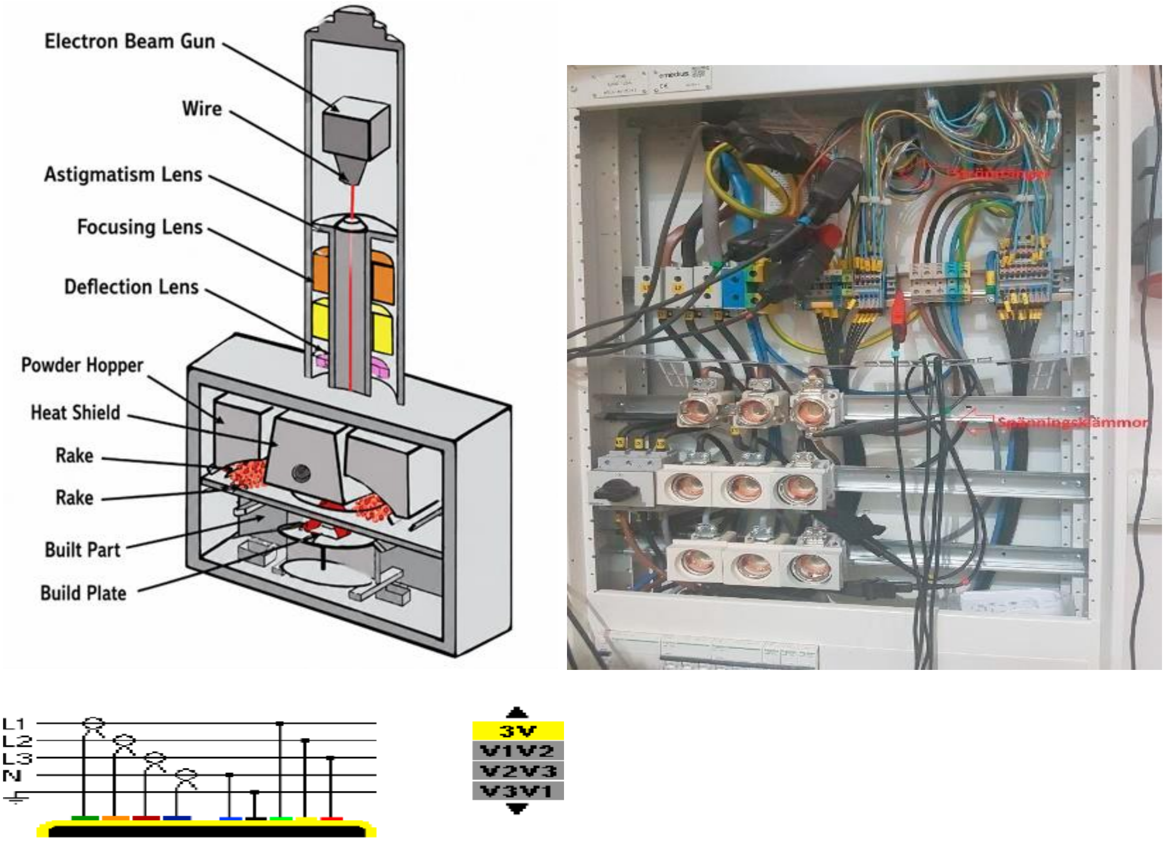


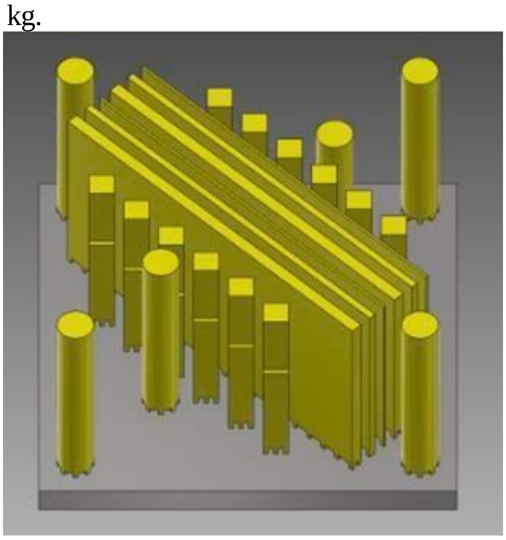
Figure 2 - (a) Schematic illustration of the EBM-based additive manufacturing technology; (b) Energy measurement probes for monitoring input power consumption.

The energy consumption during the additive manufacturing (AM) process was measured using a CA 8335 Power and Energy Analyzer. This instrument monitors the voltage and current of the three-phase power supply, as well as active and reactive power. The recorded data are stored on a computer and analyzed using Power Analyzer Transfer 1 and 2 (PAT1 and PAT2) software. The measurement uncertainty is within 1%. However, the non-contact current probes (MN88) are specified to have a maximum uncertainty of 5%.

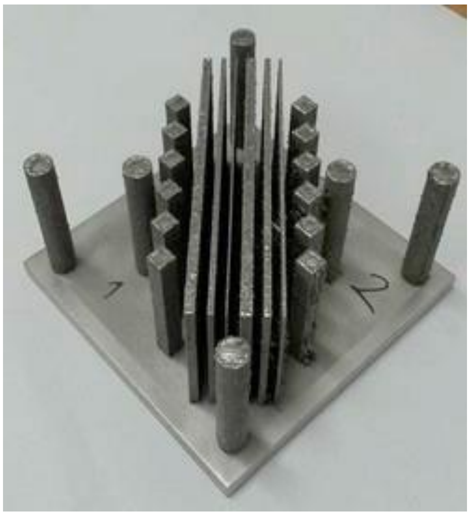
The main energy-consuming components of the system include the high-voltage power supply, vacuum pumps, heat exchanger and cooling equipment, motors for the rake and build platform, the programmable logic controller (PLC), the display unit, and the electron beam (EB) gun. Only the total energy consumption of the system, dominated by the electron beam gun/high-voltage unit, was measured.

According to the CES Selector database, the embodied energy of bulk INCONEL 718 ranges from 291 to 321 MJ/kg [7]. As mentioned previously, no published data were found regarding the energy required for atomizing INCONEL 718 powder for additive manufacturing. Therefore, the value reported for NISTELLE 625, a nickel-based superalloy containing less iron but a similar chromium content, was used as an approximation. The reported energy consumption for the atomization stage is 55.6 MJ/kg [9].

The geometry of the manufactured components and the results of the energy measurements obtained during the entire five-day build process are presented in Figures 3 and 4, respectively. The manufactured component has a volume of 392.5 cm³ and a mass of 3.23 kg.



a)



b)

Figure 3. (a) CAD model of the component; (b) Final INCONEL 718 component manufactured using Electron Beam Melting (EBM).

The results indicate that a total of 378 MJ of energy was consumed during the build process, corresponding to a specific energy consumption of 117 MJ/kg for the manufactured component.

The initial stage, which lasted approximately 5 hours, exhibited an average power consumption of about 4 kW. This was followed by a 112-hour melting stage, during which the electron beam required significantly less power. Based on the recorded measurements, the average power consumption during this stage was estimated to be 0.71 kW, as illustrated in the graph.

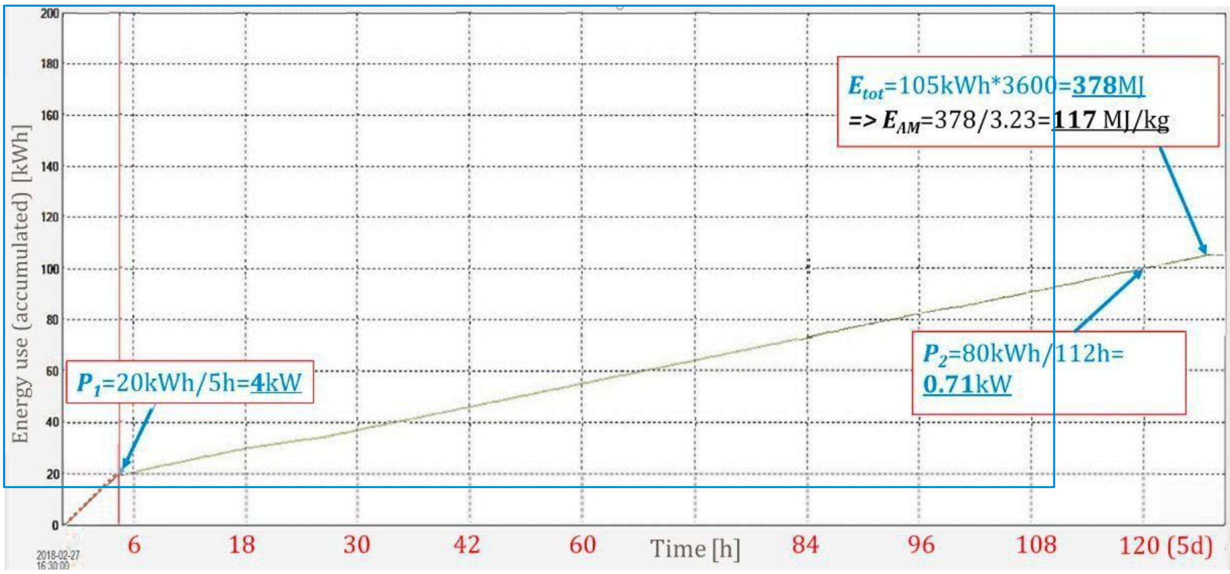


Figure 4. Cumulative energy consumption of the Electron Beam Melting (EBM)-based additive manufacturing system derived from active power measurements.

DISCUSSION

This case study has illustrated several important characteristics of metal powder-based additive manufacturing and assessed its sustainability. Although additive manufacturing of superalloys is associated with high overall energy consumption, the results indicate that several strategies can improve its environmental and economic performance.

Weight reduction offers significant opportunities to lower both production costs and greenhouse gas emissions. A study by Huang et al. [6] on lightweight aircraft components demonstrated that the weight-saving benefits of additive manufacturing, compared with conventional manufacturing, vary considerably depending on the geometry of the component.

Powder production requires a substantial amount of energy; therefore, powder recovery and recycling are of critical importance. Compared with subtractive manufacturing, material waste can be significantly reduced, although the extent of this reduction depends on the specific application. In addition, additive manufacturing can contribute to more efficient resource utilization by enabling remanufacturing and providing new opportunities for maintenance and repair.

The findings also suggest that the economic and environmental advantages of additive manufacturing are highly application-dependent. While the technology provides clear benefits for material efficiency and component optimization, its high energy demand remains a significant limitation, particularly for large-scale industrial implementation.

CONCLUSION

The present study demonstrates that, despite its relatively high energy consumption, metal powder-based additive manufacturing offers considerable sustainability benefits through weight reduction, lower material waste, powder recycling, and extended component life via repair and remanufacturing. However, due to the substantial time and energy requirements of the manufacturing process, large-scale mass production is not yet economically viable. Therefore, in the near future, additive manufacturing is expected to be most effective for producing high-value, low-volume components with complex geometries, where its technical and environmental advantages can outweigh its higher energy costs.

Author Contribution Statement (CRediT Taxonomy): **A.M. Abdirashit:** Conceptualization, Methodology, Investigation, Formal Analysis, Data Curation, Validation, Visualization, Writing – Original Draft. **Yu. Onuralp:** Conceptualization (lead), Methodology, Validation, Writing – Review & Editing, Supervision.

All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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