

ORIGINAL RESEARCH
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ADDITIVE MANUFACTURER
GREEN TRADE ASSOCIATION

ADDITIVE SUSTAINABILITY™

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Specific Energy of Metal AM Feedstock: A Comparison

Prepared by

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INTRODUCTION TO AMGTA

The Additive Manufacturer Green Trade Association (AMGTA) is the only global organization bringing together companies throughout the manufacturing ecosystem to promote and elevate the conversation around additive manufacturing (AM) practices as an environmentally beneficial strategy for addressing lead times, supply chains, waste streams, energy consumption, technological advancements, and overall environmental and societal impacts. This informed and ongoing collaboration between AM technology developers and practitioners is enabling the overall AM industry to address the need and demand for more sustainable manufacturing and more resilient and flexible supply chains in a strategically, financially, and environmentally beneficial way. Fundamentally, the AMGTA brings together the manufacturing and sustainability communities to better understand the leverage-potential of additive manufacturing.

AMGTA members represent the entirety of the manufacturing ecosystem—from design and source materials to end products and users. These members demonstrate their industry leadership by working together to address the compelling issues around rapidly evolving manufacturing demands, stakeholder expectations, geopolitical events, climate impacts, and a changing ecology. Through member forums, rigorous research, and business use-case analysis, the AMGTA works to better understand and communicate the direct impacts and potential of additive manufacturing and the marketplace demand for more sustainable manufacturing to increase acceptance and adoption of additive practices.

The AMGTA works with member organizations to raise the profile of their sustainability efforts and the potential for more sustainable manufacturing through their products, services, and systems. The AMGTA represents its members at additive manufacturing industry forums and conferences to promote the environmental benefits of additive practices. The AMGTA also represents its members within the sustainability community to promote the power and potential of additive practices to deliver on bold environmental goals. We engage member organizations in ground-breaking research projects and business case studies to better understand the potential of AM, inform ongoing industry development, and increase acceptance and adoption of more sustainable manufacturing practices.

The AMGTA is engaging AM technology leaders, the broader manufacturing industry, and the overall sustainability community in an independent and comprehensive way in which no single company, regardless of size or position in the market, can do on its own.



Message from the Executive Director

I am pleased to release the findings of AMGTA's fifth in-depth study to better understand the environmental impacts of additive practices on the manufacturing industry. The release of these findings is significant in quantifying the impacts of metal powder production as it relates to the overall understanding of the environmental impacts of additive manufacturing. As illustrated in this study, the production of metal powders is not a single, monolithic process but rather a series of choices around process, metal, and gas selection.

Divergent Technologies, as a partner in this project, continues to demonstrate their industry leadership and quest for better and more sustainable manufacturing strategies and solutions with broad-based application.

As with most if not all studies, questions remain and the AMGTA is committed to identifying areas of question, interest, and impact. We congratulate and thank our member organizations for making this important research possible.



Sherri Monroe
Executive Director, AMGTA

Industry Collaboration

The Additive Manufacturer Green Trade Association is dedicated to transforming awareness and ambition into action through digital manufacturing. Sustainability initiatives across many industries have made considerable progress in the last decade and become a mature corporate strategy and competitive differentiator. Aspiring suppliers, particularly within the automotive sector, increasingly need to demonstrate how their technology offering contributes to a sustainable future. To achieve this within the AM industry, we are gaining fluency in life cycle analysis (LCA) and embedding it in our respective product development approaches. This drives new tool creation and greater leverage of existing advanced tools within our workflows that permit the necessary product insights for iterative improvement – a core advantage common across all AM modalities. We must measure to improve with consistency and at the necessary velocity to meet this global challenge.

Personally challenged to prepare customer-facing LCAs on high-rate processing of aluminum alloys via selective laser melting, I discovered widely varying references on AM process and powder atomization energy consumption. Much of the published literature is on single or occasionally dual-laser systems and can easily lead one astray when extrapolating these data sets and models to 4, 8, or 12+ laser systems with different processing strategies. Importantly, one can easily and inexpensively solve this data gap by implementing power monitoring on these new systems.

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Industry Collaboration cont'd.

However, trusted values for atomization of a new alloy powder that models influence of composition, particle size distribution accepted (yield), and other important variables, proved elusive.

Which brings us to the motivation behind the fifth AMGTA-sponsored research which focuses on AM feedstocks. Being process agnostic, we defined a project that would baseline the underlying physics of the conversion processes for various AM metal feedstocks and the most common methods to produce them. When evaluating the published literature on gas atomization, we found incomplete studies and often out-of-date industrial data, the vast majority of which was not at the necessary fidelity. This report serves the dual purpose of establishing a 1) transparent set of process assumptions and models from which to extrapolate and 2) educating AMGTA members about the key process levers. We trust it also will aid each of your missions to generate sustainable industrial transformation through a fully digital and system-level approach.

Michael Kenworthy
CTO of AM Technologies,
Divergent Technologies
Board Director, AMGTA



About the Researchers

Syntec Associates

Professor Julie M. Schoenung, Professor and Wofford Cain Chair III at Texas A&M University, serves as the Founding Co-Director of the World Institute for Sustainable Development of Materials (WISDOM). With a notable background, she was the Founding Department Chair, a Distinguished Professor, and held the Daniel G. Aldrich, Jr. endowed chair position at the University of California, Irvine. Formerly, she held faculty appointments at UC Davis and Cal Poly Pomona. Professor Schoenung is affiliated with institutions such as the National Academy of Engineering, the American Association for the Advancement of Science, the National Academy of Inventors, and several materials societies. Professor Schoenung earned her B.S. in ceramic engineering from the University of Illinois, Urbana-Champaign and her M.S and Ph.D. in materials engineering from MIT. With a focus on high entropy ceramics, additive manufacturing, and sustainable materials development, she pioneers research analyzing factors influencing materials-selection decisions, including economics, environmental impact, toxicity, cost-performance trade-offs, policy, and sustainability standards.



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About the Researchers cont'd.

Dr. Enrique J. Lavernia, currently serving as the Professor and College of Engineering Chair at Texas A&M University, has had a distinguished career with leadership roles, including Provost and Executive Vice Chancellor at the University of California, Irvine, and UC Davis. In 2022, he received the R&D 100 Award and ASM International Albert Sauveur Achievement Award, following his election as a Foreign Member of the Chinese Academy of Engineering in 2020. His awards include an honorary Doctor of Science from Aalto University and the 2018 Distinguished Engineering Educator Award. In 2015, he was inducted into the Hispanic Hall of Fame and in 2013 he was elected to the National Academy of Engineering. Dr. Lavernia is recognized by the Alexander von Humboldt Foundation, TMS Society, AMS International, and more. He holds fellowship status in organizations including the National Academy of Inventors and Materials Research Society. With over 670 published journal papers covering topics from nano-materials to aluminum alloys, his research focuses on synthesizing and understanding the behavior of nanostructured materials, along with additive manufacturing. He earned his B.Sc. from Brown University and MSc. and Ph.D. from MIT.



Dr. Haoyang He received his B.S in Functional Materials from Huazhong University of Science & Technology in 2015 and his Ph.D. in Materials Science and Engineering in 2020 from the University of California, Irvine. He is currently working as a postdoctoral scholar in the Department of Materials Science and Engineering at the University of California, Irvine. The major research of Dr. He is focused on green engineering and sustainability assessment, including chemical hazard assessment, life cycle assessment, alternative assessment, techno-economic analysis, and environmental decision analysis.



Salma El-Azab received her bachelor's degree in Materials Engineering from Purdue University and is currently a 5th year Ph.D. candidate in the Department of Materials Science and Engineering at the University of California, Irvine. Her research currently focuses on the mechanical behavior of high entropy oxides, a novel ceramic material with promising functional properties. Ms. El-Azab has also worked on metal additive manufacturing, where she studied how implementing ultrasonic vibration in situ during directed energy deposition influences the melt pool dynamics.



1.0 EXECUTIVE SUMMARY

Additive manufacturing (AM) has revolutionized the production of net-shaped metal components with massive impacts on the industry. There are a variety of AM techniques that use different types of feedstock materials, such as powder and wires. Each feedstock has a variety of processing routes that can be used for its manufacture. Here, we report on a study involving the manufacture of powders and wire as feedstocks for AM. We selected three processing approaches. The first is gas atomization, which is the energetic disintegration of liquid into droplets that solidify into micrometer-sized powder particles, which are collected to create batches of powder. The second is mechanical milling, specifically ball milling, which is a process where solids are broken down into smaller pieces through comminution, the act of reducing materials into minute fragments through impact, shear, attrition, and compression. The last is wire drawing, in which a cylindrical rod of metal is deformed to reduce its diameter by being pulled through a die. The objective of this study is to evaluate the energy requirements associated with producing these feedstock materials through fundamental process analysis and literature review.

To compare the energy requirements for different techniques for manufacturing feedstock materials for AM, we began with a thorough literature review to understand the variables and phenomena that contribute to energy consumption. The literature review was guided by the following topics: material, thermodynamics, equipment design, and processing parameters. Based on our literature review, we used literature-based assumptions to formulate different approaches to calculate the specific energy consumption of each process. We estimated and compared energy requirements for alloys commonly used in AM processes that are typically available in both powder and wire forms, such as nickel superalloys (Inconel 718, Inconel 625), stainless steel (SS 316L, SS 304L), and aluminum alloys (Al 6061, Al 5083).

Gas atomization is deemed a promising technology for producing stock powders for AM and sustainability assessment focused on the energy consumption of gas atomization is gaining wide attention. However, our literature review showed that the various energy consumption values ranging from 0.27-15.44 kWh/kg were observed for different studies, which are impacted not only by the different materials and atomization gases selected for evaluation but also by the different calculation methods and modeling approaches embedded. Some other key parameters that affect the energy consumption of gas atomization, such as the yield of the powder and the gas usage and pressurization energy, also vary in different studies. The studies reviewed can be categorized into three types. Type-1 and Type-2 studies rely on literature values from previous publications or approximate estimates of the energy consumption for gas atomization. Type-3 studies are the most valuable as they use rigorous theoretical calculations or validated empirical models to analyze energy consumption. However, out of all the studies reviewed, only two fell under the Type-3 category. Even with these two studies, there are variations in the reported energy consumption values due to different assumptions and processing parameters used.

To better understand the complex mass and energy transfer processes in gas atomization due to the dynamic interaction of the molten metal stream and high-velocity gases, our approach for calculating the energy consumption of gas atomization is based on solving governing equations

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1.0 Executive Summary cont'd.

deduced theoretically for important energy components: the energy required for gas atomization pressure (E_{gas}) and energy required for melting and superheating ($E_{melting}$); and processing parameters: gas flow rate (\dot{m}_g) and melt flow rate (\dot{m}_l), and the associated gas-to-metal ratio during the atomization process. More specifically, sensitivity analysis is performed accounting for different types of alloys: stainless steel 316L, aluminum alloy 5083, and Inconel 718; and inert gases: nitrogen, argon, and helium, as well as key system operational parameters to explore the variations on energy consumption values brought by them. The results show that Inconel 718 has the highest energy consumption followed by stainless steel 316L and aluminum alloy 5083, while nitrogen has the highest energy consumption among the inert gases, followed by argon and helium. The results of our study emphasize three important findings. Firstly, induction melting is the primary factor contributing to the energy consumption of gas atomization. Secondly, the inherent properties of alloys and gases have a significant impact on energy consumption. Lastly, equipment parameters, such as delivery tube and jet tube diameters, greatly influence the flow rate and should be meticulously designed.

Ball milling is generally defined as a comminuting process that uses rotating cylindrical vessels containing loose balls that crush raw material through free movement. Ball milling is of particular interest because it allows for the production of relatively equiaxed particles from a wide variety of feedstock materials, including various types of waste and scraps such as machining chips. Important processing parameters to consider include milling speed and mill capacity, which must be carefully balanced to achieve the proper trajectory of mill contents during the process. The type of mill and milling media influence the size distribution and morphology of the final milled product, though the morphology is largely material dependent. There are several approaches to estimating the energy consumption during comminution in ball milling, which include taking the ratio of energy required to create a new surface to the mechanical energy supplied to the machine performing the size reduction, and the consideration of the energy required for mechanical breakage of single particles. For our purposes, we adopt the second approach, and defined our system boundary as the work required for particle size reduction in comminution. The specific energy consumption values for a small batch ball mill were estimated based on ball mill dimensions, motor specifications, and milling time, which was extrapolated from data available in literature. Based on our findings, nickel superalloys and stainless steels require a similar amount of work to reduce to specific particle sizes, and aluminum alloys require the least, as per the Morrell equation. The main takeaways for this portion of our study are: 1) the energy consumption of ball milling is largely dependent on a material's mechanical properties; and 2) the finer the desired particle size, the more energy is consumed in ball milling.

Wire drawing is the reduction of a metal rod's diameter, which is achieved by pulling it through a die. This process oftentimes requires multiple passes to achieve the desired wire specifications. Important wire drawing parameters include the rod diameter, amount of reduction per pass, the die semi-angle, the drawing stress, the back stress, and the frictional stress. In wire drawing, the power of electric energy is converted by a motor into mechanical energy, which is spent to overcome the shape change of the wire (i.e., plastic deformation), friction between the wire and working surface

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of the die, and counter-tension in the wire as it is drawn. The plastic deformation depends on the mechanical properties of the material being drawn, specifically the flow stress. The drawing stress, or force required for wire drawing, is the sum of the uniform work, nonuniform work, and friction work. Our approach for estimating the specific energy consumption during wire drawing is based on our system boundary, which is defined as the work required to deform the feedstock. The specific energy consumption is estimated by calculating the three components of drawing stress based on wire drawing processing routes from real wire drawing machines available on the market. The estimation of specific energy consumption of a wire drawing machine was based on motor specifications for each machine, and an assumed feedstock mass. Based on our findings, nickel superalloys require the most work for deformation, and stainless steels require the least. The main takeaways for this study are that the energy consumption of wire drawing is largely material-dependent, as each material's mechanical and thermal properties influence the work required for deformation, and each processing route is tailored based on the material.

The following tables summarize the key findings from this study, noting the significantly higher specific energy consumption associated with gas atomization of metal powder, compared to that for ball milling and wire drawing.

Table 1.1: Estimated total specific energy consumption (SEC) for gas atomization.

SEC _{gas atomization} (kWh/kg alloy)	when $d_{\text{mmm}} = 20 \mu\text{m}$, using 70% efficiency for induction melting		
Alloy\Gas	Argon	Helium	Nitrogen
Stainless steel 316L	0.50	0.44	0.55
Aluminum alloy 5083	0.45	0.44	0.47
Inconel 718	0.51	0.39	0.61

Table 1.2: Estimated work (W , for three final particle sizes: 20, 45 and 150 μm) and specific energy consumption (SEC) for size reduction using ball milling.

Alloy	W_{20} (kWh/kg)	W_{45} (kWh/kg)	W_{150} (kWh/kg)	SEC _{ball mill} (kWh/kg)
Stainless steel	0.007	0.005	0.003	0.02
Aluminum alloy	0.005	0.004	0.002	0.02
Nickel superalloy	0.008	0.005	0.003	0.03

Table 1.3: Estimated work (W) and specific energy consumption (SEC) for wire drawing.

Alloy	$W_{\text{deformation}}$ (kWh/kg)	SEC _{wire drawing} (kWh/kg)
Stainless steel	0.04	0.05
Aluminum alloy	0.09	0.22
Nickel superalloy	0.10	0.14

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1.0 Executive Summary cont'd.

As detailed above, gas atomization of commonly used alloys via helium resulted in the least total specific energy consumption when compared to gas atomization using either argon (13% better on average) or nitrogen (28% better on average). When compared with gas atomization via nitrogen, argon-atomized powder resulted in a 12% better option. For all alloys studied (SS316L, Al5083, and IN718), nitrogen-atomized powder routinely resulted in the highest SEC of any gas.

Separately, mechanical milling (ball milling) resulted in approximately a 90% SEC improvement when compared to gas atomization, comparable to that of wire drawing. More research should be done to determine the applied impact within specific product categories of using helium-atomized powder and/or ball milled powder.

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