The Feasibility of 316L Stainless Steel Mechanically-Generated Feedstock for Directed Energy Deposition

By

Marcus Algernon Jackson

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The dissertation is approved by the following members of the Final Oral Committee: Frank E. Pfefferkorn, Professor, Mechanical Engineering Dan J. Thoma, Professor, Materials Science and Engineering Tim Osswald, Professor, Mechanical Engineering Sangkee Min, Assistant Professor, Mechanical Engineering Lianyi Chen, Assistant Professor, Mechanical Engineering

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Nomenclature

α	rake angle of the tool, rad
CAD	Computer-Aided Design
С	Machine constant
D	Depth of cut, mm
DED	Directed Energy Deposition
ECD	Equivalent Circle Diameter, mm
η	Process efficiency, %
f	Frequency, Hz
F	Feed, mm
GA	Gas-atomized
h	Height, mm
hs	Hatch spacing, mm
l	Laser Travel Height Increment, mm
LCA	Life Cycle Analysis
т	Mass, kg or g
MFR	Mass flow rate, kg/s or g/min
MRR	Material Removal Rate, m ³ /min
n	Increment
Ν	Number of teeth on cutting tool
φ	Shear angle during cutting, rad
Р	Power, W
r	Ratio of powder mass flow rate to scan speed, g/mm
R	Cutting tool radius, mm
ρ	Density, kg/ m ³
RPM	Revolutions Per Minute, rev/min
SEC	Specific Energy Consumption, J/kg
t	Time, min or s
th	Thickness, mm
VED	Volumetric Energy Density, J/mm ³
W	Width, mm
W	Width of cut, mm

Abstract

Mechanically-generated powder could potentially provide a more sustainable and lower cost feedstock alternative for the additive manufacturing industry. The objective of this work is to study the feasibility of mechanically-generated feedstock for use in Directed Energy Deposition (DED) processing by analyzing the performance of the feedstock in a commercially available system, properties of the resultant parts, and specific energy consumption of a remanufacturing process that includes this feedstock production method. Mechanically-generated powder was created by machining 316L stainless steel bar stock followed by comminution of the resulting chips through oscillation ball milling. This methodology's production yield and processing time for the specifications of a commercially available DED system are presented along with resulting powder morphology. It was found that mechanically-generated feedstock could be created to meet deposition system requirements.

Performance of the mechanically-generated feedstock in a commercially available directed energy deposition system was compared to gas-atomized powder and evaluated based on the following figures of merit: flowability, printed part height, printed part density, printed part mass deposition behavior, and chemical compositional stability throughout processing. Resultant properties of parts printed from both feedstocks were also compared; the manufacturer's recommended power, scan speed, and powder mass flow rate settings were kept constant in these builds at 275 W, 508 mm/min, and 8.2 g/min. Compared with gas-atomized powder, mechanically-generated powder did not flow as well through the powder-delivery system. Parts printed from mechanically generated feedstock were generally taller than their counterparts from gas-atomized feedstock, but their densities were less predictable. Also, more mass was able to be deposited with gas-atomized powder. Chemical composition of prints using both feedstocks were within standard nominal compositions for 316L stainless steel. Surface texture, microstructure, and mechanical properties of were found to be similar between prints with the two

feedstocks. These findings show that mechanically-generated powder is a viable alternative in directed energy deposition processes.

A specific energy consumption model for mechanically-generated feedstock production was generated from experimental observation. The gas-atomized feedstock production energy consumption model was generated from a combination of experimental observation, reported estimates from the manufacturer, and data found in the literature. The energy consumption model of directed energy deposition was derived from experimental observation and compares favorably with reported estimates in the literature. A comparison was performed to compare the specific energy consumption in the two process paths and their application was demonstrated by estimating the energy consumption to remanufacture a bracket. The two feedstock production methods had similar specific energy consumptions. The specific energy consumption of the directed energy deposition process was the greatest component in the respective remanufacturing paths by an order of magnitude; increasing deposition rate is the most important factor for lowering the overall specific energy consumption. The analyzed remanufacturing technologies were estimated to consume less energy than replacement when repairing up to approximately 15% of the original part's mass.

Chapter 1: Introduction

1.1 Landscape of Sustainability in Manufacturing

The overarching goal of sustainability focused research and inventions in the metal manufacturing sector is to ensure the advancement of civilization can be sustained [1]. A wealth of challenges and opportunities have been identified by governments, companies, and academics to advance the state of the art of sustainable manufacturing [1–4]. The United Nations has developed sustainability metrics and indicators reflecting the shift in the globe's attention towards environmental issues [5]. The shift in manufacturing to Industry 4.0 offers several opportunities for realizing more sustainable business models that improve efficiency and therefore value creation with correlate increases in worker motivation and organizational purpose [3]. Academic research into sustainability has been categorized into model development of business systems, asset or product life-cycle management, resource/energy management, and enabling technologies [4].

While not the only metric of sustainability, much of the work in this field has centered around quantifying energy consumption in the various stages of a product's lifecycle. The manufacturing sector makes up 11 percent of the U.S. gross domestic product. Within this segment of the economy, energy consumption has decreased by 17 percent from 2002 to 2010 with only a 3 percent decrease in gross output over the same time period, suggesting an improvement in energy consumption per unit of gross domestic output [6]. Over the next 15 years, the manufacturing sector is projected to experience robust growth, but improvements in energy efficiency are required to prevent the energy demand from bloating during this boom [7,8].

Recognizing this, there has been a focus in academia on the significance of energy consumption considerations in manufacturing by developing methodologies for assessing manufacturing processes from an energy consumption perspective [9,10]. Dornfeld *et al.* defined

the "technology wedge" concept to identify the shortcomings in the current industrial practice and to illuminate the path towards more efficient usage of energy in manufacturing [11]. Also, there have been several efforts investigating improvements to current practices ranging from developing more efficient systems and sourcing energy from different renewable technologies, to developing models of manufacturing systems for more energy efficient utilization of existing technologies [12–15]. It has been shown that primary metal production processes can be modeled in order to facilitate reductions in energy consumption [12]. Machine tools to turn these castings or ingots from primary metal production into parts have also been analyzed; energy efficiency of the processing as well as the facility management level were found to be important considerations for studying energy consumption in manufacturing [13]. Accordingly, it is important to consider the energy source of the facility and seek out alternative energy sources to progress towards a more sustainable manufacturing infrastructure [14]. Additional reductions in energy consumption can be derived from optimizing shop scheduling with operation speed as the significant factor [15]. More recently, additive manufacturing technologies have become an area of energy consumption research, with investigations into polymer additive manufacturing processes providing insights into effective resource utilization and allocation [16,17].

Overall, in order to improve sustainability in manufacturing, there must be a shift in thinking among manufacturing decision makers to begin considering sustainability early and throughout the product design stage [18]. This includes of course, the material and manufacturing processes selected, but also extends to the transportation, distribution, and end-of-life logistics [18]. Also, there must be advances in technology across the multiple system scale levels described by Duflou *et al.* and fully sustainable manufacturing systems requires holistic application [19]. These levels include the unit process, the multi-machine, the factory, the multi-facility, and the supply chain; each of these have been researched independently, but a there are still areas of research needed [19]. The focus of the present work is at the unit process level.

A good comparison of energy consumption in several manufacturing processes, or the unit process level, has been conducted by Yoon *et al.* [20]. The authors sought to characterize the energy consumption of bulk forming, subtractive, and additive manufacturing processes using what is called the Specific Energy Consumption (SEC), "defined as the energy consumed in the production of a material unit." For additive and bulk forming processes the SEC is traditionally defined as Joules per unit mass of material (J/kg) processed, and for subtractive processes it is defined as Joules per unit volume of material removed (J/m³) [20]. For primary metal production this unit generally takes the form of a semi-finished part or an ingot, for machining the unit of material is that which is removed from the stock by the subtractive manufacturing operation and for additive manufacturing the unit is a deposited part [20].

1.2 Additive Manufacturing

In recent years, metal additive manufacturing has been utilized in a growing number of industries to create functional parts and has been explored in many research investigations. Metal additive manufacturing research has exploded in recent years due to its potential advantages and the complex challenges presented in realizing that potential [21]. Additive manufacturing technologies build parts through an iterative addition of material, typically in a layer-by-layer fashion [22]. There are 7 categories of additive manufacturing: material extrusion, material jetting, binder jetting, vat photopolymerization, powder bed fusion, directed energy deposition, and sheet lamination [22]. At the time of this review, material extrusion, material jetting, powder bed fusion, directed energy deposition, and sheet lamination have been utilized to print metal parts.

The metal additive technology of study in this work is Directed Energy Deposition (DED), where focused thermal energy fuses materials, either metal powders or metal wire, by melting them as they are being deposited, as illustrated in the printing step in Figure 1 [22]. DED is among the most common metal additive categories with several machines available for commercial use [23]. Laser Engineered Net Shaping (LENS®) is a process within the DED category that utilizes

a laser to melt blown powder [24]. In LENS®, a laser beam creates a melt pool on a surface, and powder is then injected into the molten pool from four nozzles aimed at the melt pool [24]. Parts are made by taking data from a CAD model and slicing the geometry into layers with prescribed scanning paths; the laser and powder are driven along these paths to create the desired part [24].

Metal parts built with a LENS® system have been studied for years now; a foundational work comparing the microstructure and mechanical properties of the printed parts to wrought material was published in 2000 [25]. It found the "real promise of the technology" is in realizing material property control through process control and in enabling the fabrication of complex internal features that cannot be created with more traditional manufacturing processes [25]. Another advantage of using the LENS® technique is the ability to repair or modify existing components which have been extensively detailed in previous reviews of the literature [26,27]. Also, this technology can enable the production of functionally grade components, for example with titanium alloys [28], ferritic and austenitic steels [29], and nickel-based super alloys [30]. Furthermore, parts can be made from a wide range of alloys, including titanium alloys, nickel-based alloys, tool steels, and stainless steels such as 304L and 316L [23].

1.3 Remanufacturing and Energy Consumption Considerations

Remanufacturing of metal parts is a branch of sustainable manufacturing that shows promise in contributing to the overall goal of reducing environmental impacts and component costs, because of the reduced demand for raw materials, reprocessing material, and the associated embedded energy as well as associated emissions. Some of the work has focused on developing frameworks, strategies, and process plans for implementing remanufacturing into the present manufacturing infrastructure [31–35]. The essential framework components in remanufacturing are: 1) assessment of the part to be remanufactured, 2) the repairing manufacturing process, and 3) the inspection and recommissioning of the part [31]. Lahrour and Brissaud suggested additional structure for the repair phase [32], and advances in software systems have allowed for automated repair process selection based on the part assessment results [33]. The inclusion of Failure Mode and Effects Analysis should also be included in any remanufacturing framework, particularly to ensure the selection of an adequate remanufacturing process [34]. A case study of remanufacturing feasibility found that a combination of additive and subtractive manufacturing process steps is a valid strategy for the direct reuse of a part that has reached its end-of-life and does not require any material recycling steps [35].

Reviews of the literature have identified how additive manufacturing technologies might be employed for remanufacturing purposes [36,37]. Ford and Despeisse outlined the advantages additive manufacturing capabilities bring in the push for more sustainable manufacturing as well as the technical and economic advancements that must be made to realize the technology's potential [36]. There have been many applications of additive manufacturing in the pursuit of advancing sustainability [37], but DED is an additive manufacturing process that has been utilized to repair damaged components with improved characteristics over previous remanufacturing techniques [38–40]. The most extensive of these studies comes from Wilson *et al.* who included a Life Cycle Assessment (LCA) analyzing the energy and material consumption as well as the CO₂ emissions from repairing a turbine blade with DED [38]. This strategy was compared to replacing the blade with a new blade made from an investment casting process and to repairing the blade using gas tungsten arc welding [38]. Their analysis found that repairing the blade with DED resulted in less energy consumption and emissions compared to the other options explored [38].

Of the methodologies heretofore explored, there is the lack of investigation into process paths that would close the loop of the product's lifecycle. In this context, closing the loop through remanufacturing is defined as restoring a damaged or end-of-life part to the quality of the original or the required quality of the new product through the reuse of material from that original part. Mechanically-generated feedstock is one enabling strategy to achieve this vision because it has the capability of turning machined material into feedstock for DED processing as shown in Figure 1.



Figure 1. Proposed remanufacturing process

1.4 Feedstock for Additive Manufacturing

Focus on downstream impacts of the feedstock has also become an emerging area within this research landscape. The effects of powder variability on the microstructure and mechanical behaviour of Alloy IN718 printed in a powder-bed fusion system were rigorously investigated by Sudbrack *et al.* [41]. They ordered feedstock powder (Argon gas-atomized, Nitrogen gasatomized, and water atomized) from a variety of producers and found that the majority of the powders exhibited acceptable chemical compositional control, but the difference in the powder production methods led to variations in particle size distributions [41]. The samples with more very small particles and more agglomerated particles were the most difficult to print with since it is likely they were more difficult to spread in the powder-bed [41]. Morrow *et al.* showed results suggesting that defects in gas-atomized powders such as porosity and nanoscale contaminations also have an impact on the resultant part [42]. These nanoparticles had not been identified in previous investigations of metal powders in AM and were found on the surface of powder particles, as well as at the bottom of dimples on the failure surface of tensile bars; they were hypothesized to be the result of the atomization process [42]. Traditionally, gas-atomized powder has been used as feedstock in metal additive manufacturing, but the "high procurement costs" of this powder has been identified as "one of the biggest barriers to adoption in industry" [43]. Reuse of unincorporated powder has been one strategy explored to make the use of these powders more economical while also maintaining printed part properties [44]. Water-atomized powders have also been studied in powder-bed and DED systems [45,46]. While they are less expensive, they are also less spherical, have particle size distributions showing low kurtosis, and parts printed using water atomized powders have generally not achieved the guality of prints produced from gas-atomized powders [45,46]. Moorehead et al. did show it was possible to utilize irregularly shaped plasma-sherardized elemental powders in DED processing for in-situ alloying [47]. All three of these powder production methods require melting to occur, which can be an energy intensive process [48]. Therefore, researchers have begun to explore feedstock production processes with potentially lower costs and reduced overall environmental footprint, such as the one envisioned in Figure 1, that utilize mechanically-generated feedstock as an alternative to gasatomized powder.

Mahmood *et al.* directly used medium carbon steel machining chips to print walls using a DED process conveying the chips "to the melt pool from a disk powder feeder through a nozzle with an annular outlet area of 33 mm², coaxial with the laser beam" [49]. Machining chips were sieved into three size ranges (<150 μ m, 151 μ m – 295 μ m, and 296 μ m – 425 μ m) and the authors studied the effects of these different chip sizes [16]. In a separate work, they reduced the size of Inconel 617 machining chips in a disk mill to obtain particles sieved to be less than 300 μ m [50].

They determined that the disk milled particles could practically be utilized for laser cladding using the same DED system in their previous study [50].

Fullenwider *et al.* utilized a two-stage planetary ball milling process to reduce the size of 304L stainless steel machined chips; single tracks of this powder were deposited in a LENSTM deposition system, but "[i]nstead of injecting the powders through the nozzles, a powder bed was created on the substrate" [51]. This work primarily focused on the morphology of the ball milled powder and the two-stage process utilized to create the powder. The first stage utilized a larger, 20 µm diameter ball to reduce the sizes of the machining chips into powder appropriate for directed energy deposition feedstock (38 µm – 150 µm) and the second stage with a smaller, 6 µm diameter ball reduced the aspect ratios of the powder to be more similar to the more commonly used powder created through gas atomization [51].

1.5 Energy Consumption in Select Manufacturing Processes

1.5.1 Energy Consumption in Machining

A substantial amount of work has been done on the energy consumption of subtractive systems, specifically for milling [52–57], turning [52,55,58,59], and drilling operations [53,59]. Kara *et al.* investigated the relationship between energy consumption and material removal rate (MRR) in milling processes, with Li *et al.* further dissecting the influence of process parameters on the energy consumption profile of a milling operation [52,55]. Also, work has been done developing a model of energy consumption of machining processes based on the numerical control code ran by the machining center and the tools chosen for the operation [53,59]. Two research groups took a step beyond characterization and have looked at how different machining strategies can reduce energy consumption in milling operations [54,56]. Environmental analysis of milling operations suggest that the energy consumed during the metal cutting portion of a milling operation is much smaller than the energy load of a modern machining center, while the

embedded energy of the stock is typically greater than the energy consumption of the milling process as a whole [57,58].

A key finding from this literature review of subtractive manufacturing comes from Kara *et al.* who developed a methodology to model energy consumption of machining operations [52]. Since the energy consumption of each machine tool is unique to each machine's specific architecture, characterization of several machines' specific Material Removal Rate (MRR) to SEC relationship was performed. They found this relationship can be described mathematically across multiple platforms using the general form in Equation 1:

$$SEC_{machining} = C_0 + \frac{C_1}{MRR}$$

where, C₀ and C₁ are machine specific coefficients and:

$$MRR = \frac{(RPM)}{60 \sec} \frac{(W)(D)(F)}{10^9 \text{ mm}^3} (N)$$
2

where, RPM is the revolutions per minute of the tool, D is the depth of cut, W is the width of cut, F is the feed, or distance the cutting tool advances per cutting edge, and N is the number of cutting edges on the tool.

1.5.2 Energy Consumption in Feedstock Production

The research previously investigating the feasibility of utilizing mechanically-generated feedstock for DED processing have not provided an understanding of the sustainability impacts including the technique in a remanufacturing process chain. As discussed previously, energy consumption in the machining aspect of mechanical feedstock generation has been modeled and validated [60]. Research has also been conducted to relate the kinematics of ball milling to the system-level energy consumption [61,62], and the energy transfer efficiency of different ball-milling strategies has also been studied [63]; though these methodologies do not offer a direct link between energy consumption and the resultant size distribution that would be required in an

analysis applied to remanufacturing, where DED processing systems have specific powder size requirements.

Feedstock production through gas-atomization has been studied, though again, not in a remanufacturing context. Theoretical mass and energy flows through the melting and atomization process chain have been compared to those reported in the literature to identify opportunities for reducing environmental impacts [64]. As with the studies of ball-milling energy consumption to date, Azevedo *et al.* did not relate their findings to the usability of the resultant powder for any additive manufacturing system [64].

1.5.3 Energy Consumption in Directed Energy Deposition

With the emergence of metal additive manufacturing into the forefront of research and development, these technologies have also become the subject of energy consumption focused case studies and model development [65,66,48]. Morrow et al. compared making a part using DED processing, to the more traditional injection molding and machining process paths [65]. In additive manufacturing, the SEC is defined as the energy consumed per unit of material deposited during the operation [20]. Their study found that the SEC for the DED process was an order of magnitude greater than any of the other single manufacturing steps examined [65]. Bourhis et al. developed a model of environmental impact for DED processing based on the electrical energy consumption and the material consumption in the form of raw materials (powder) and shielding gas [66]. The authors then applied their model to determine the environmental impact of a sample part [66]. Systems combining both DED processing and machining operations have also been studied [48]. Models have been developed from experimental measurements and the available literature to characterize the SEC of each component in the high resolution (compared to wirebased) powder-based additive manufacturing process chain and the high deposition rate (compared to powder-based) wire-based additive manufacturing process chain [48]. The results of these select studies suggest the greatest potential impact of metal additive manufacturing on

improving sustainability would be to utilize the deposition process in repair and/or remanufacturing operations.

1.6 Motivation

After a review of the literature, several knowledge gaps appear ripe for study. Firstly, feedstock for metal additive manufacturing has not yet been utilized to print parts in a commercially available system as it was intended to be used. Ball milling machining chips appear to be a viable path forward, but additional work must be undertaken to draw well-founded conclusions about such a process chain's feasibility. Secondly, can mechanically-generated powder perform in a commercially available DED system to produce parts with similar properties to those made from gas-atomized powder? Thirdly, model of specific energy consumption that accounts for mechanically-generated feedstock process parameter effects within a remanufacturing framework is warranted. An analysis comparing such a model to one for creating feedstock for remanufacture through remelting and gas-atomization would provide the proper evaluation context. Therefore, it is the objective of this work to address these gaps through experimental and analytic methods.

It appears previous efforts have not employed a production method that facilitates evaluation of mechanically-generated feedstock's performance in a commercially available DED system. Previous work has also not considered the machining process as an integral part of the feedstock production process chain; the chips were only byproducts to use as is or process through comminution. Taking all this into account, the objective of this research was to analyze a methodology to mechanically generate feedstock for DED processing and to evaluate the performance of the feedstock in the printing process. This work proposes combining machining and oscillation ball milling to mechanically generate powder, and evaluates the performance of powder produced via this method in comparison to gas-atomized powder. The effects of mechanical generation process parameters on the yield of powder in the 45 µm – 150 µm size

range and processing time are reported. This information enabled sufficient powder production volume to conduct printing experiments.

Mechanically-generated powder's performance in a LENS® system was compared to gasatomized powder based on flowability, printed part height, printed part density, printed part mass deposition behavior, and chemical composition consistency during processing. These are necessary metrics to gauge the potential of industrial adoption since the feedstock must perform similarly to conventionally utilized gas-atomized powder in a given manufacturer's system. The manufacturer's recommended power, scan speed, and mass flow rate settings were then utilized to print both feedstocks. The surface texture, microstructure, chemical composition, and mechanical properties were compared to show that parts can be successfully printed from mechanically-generated powder and have similar properties to what is produced with gasatomized powder in a LENS® system.

Models of specific energy consumption that accounts for mechanically-generated feedstock and gas-atomized process parameter effects within a remanufacturing framework were created and compared. This analysis helps elucidate the path dependence of electrical energy consumption and resultant mass outputs for mechanically-generated and gas-atomized feedstock remanufacturing process paths. SEC models and their formulation methodology will be presented for both process paths. Then, a comparison will be performed to identify the process effects on the SEC and compare the totals of the two processing paths.

Chapter 2: Production and Feedstock Characterization

The objective of this work is to characterize mechanically-generated feedstock to be used for Directed Energy Deposition (DED) processing. Mechanically-generated powder was created by machining 316L stainless steel bar stock followed by comminution of the resulting chips through oscillation ball milling. This methodology's production yield and processing time for the specifications of a commercially available DED system are presented along with resulting powder morphology.

2.1 Feedstock Production Characterization

2.1.1 Abandoned Strategies

A LENS® system (Optomec® MR7) was used as the platform to test the feasibility of mechanically-generated feedstock. The alloy selected for this study was 316L stainless steel, a common stainless steel utilized in many industrial applications. The manufacturer recommends that feedstock particles be between $45 \,\mu\text{m} - 150 \,\mu\text{m}$ as determined by a sieve analysis. For the powder hopper size and flow design, a suggested minimum of 1 kg of ferrous powder should be loaded for printing operations. With these particle size and mass output goals, initial efforts sought to produce adequate feedstock by utilizing machining parameters to directly machine chips in the required size range. Machining chip geometry consists of the chip's height, h_{chip} , width, w_{chip} , and thickness, th_{chip} . These dimensions are a function of machining conditions and cutting tool geometry as estimated by the following equations:

$$h_{chip} = D$$

$$w_{chip} = (R) \arccos\left(1 - \frac{W}{R}\right) \frac{\sin(\phi)}{\cos(\phi - \alpha)}$$

$$th_{chip} = \frac{(F)\cos(\phi - \alpha)}{(N)\sin(\phi)}$$
5

where, D is the depth of cut, R is the cutting tool radius, W is the width of cut, α is the rake angle of the tool, φ is the shear angle during cutting, F is the feed, or distance the cutting tool advances per cutting edge, and N is the number of cutting edges on the tool. The shear angle can be determined by measuring the width of the chip after machining. By manipulating these process parameters, machining chips were produced in the specified size range using both macro- and micro-machining processes. However, the process parameters to make such small chips inherently had low Material Removal Rate (MRR), which in this case can be considered the metric describing how fast machining chips are created, and has units of meters cubed per second as in Equation 2, as reproduced here:

$$MRR = \frac{(RPM)}{60 \sec} \frac{(W)(D)(F)}{10^9 \text{ mm}^3} (N)$$
2

with RPM being the revolutions per minute of the spindle. Specifically, the small depths of cut and feeds while using the two and four edge cutting tools employed in the investigation made producing 1 kg of these chips impractical, even at the upper limits of the available equipment's RPM capabilities.

Comminution methods such as a cutting mill and a planetary ball mill were considered as a path forward, but exploratory results suggested an oscillating ball mill (Retsch Mixer Mill MM 400) was the most promising method of those readily available to reduce the size of the 316L stainless steel machining chips at the fastest rate.

2.1.2 Production Characterization Methodology

Experiments were conducted to evaluate the effect of process parameters on the percent yield from the ball-milling process and the generation time of the total process chain when combined with shoulder milling. The first step in the mechanical generation process was to create machining chips from bar stock. In this study, chips were created on a vertical milling machine (HAAS TM-1) with a shoulder mill (Sandvik Coromant CoroMill® 490) that had indexable inserts

designed for roughing and finishing (490R-08T304E-ML 2030) of stainless steel. The machining process parameters utilized in this study were within the manufacturer's recommendations for this tool and insert. Nitrogen shielding gas (N₂) was blown into the cutting area in an effort to limit oxidation of the chips. While the machining chips did pick up some oxygen when compared to the bar stock (Table 5) the amount is very similar to what is found in the gas-atomized powder (Table 6). Machining was performed without the use of cutting fluid to prevent chemical contamination of the chips which would require an additional cleaning process and could interfere with the chip collection system. A vacuum-based chip collection system was utilized to collect the chips, and a barrier was erected around the workpiece to contain chips that were not captured by the collection system; these two components were shown to collect 94% of the mass machined, $\eta_{chip collection}$. The second step was to ball mill the machining chips. In the oscillation ball-milling process, the charge, in this case the machining chips, was put into two cylindrical grinding jars (35 mL) with a large ball (20 mm diameter and 28.5 g). The jars were screwed closed, loaded into the machine, and subjected to horizontal oscillation of ~25 mm at a set frequency for a set amount of time, which provided the kinetic energy for comminution.

One goal of this work was to understand the effects of processing parameters in the mechanically-generated feedstock process. Therefore, a 3^4 experimental design (4 factors at 3 levels) was used to determine the effects of ball-milling parameters on the yield of the process, $\eta_{ball milling}$, which for this DED application was the percent mass of powder between $45 \mu m - 150 \mu m$. The factors studied were the initial chip size, ECD_{chip} , the mass of the chips in the milling jar, m, oscillation frequency f, and ball-milling time $t_{ball milling}$; the values for each utilized in this study are summarized in Table 1. The values of these factors were normalized for a stepwise regression analysis to levels of -1, 0, or 1 to assess their statistical significance. Ten measurements of individual chip geometries at each of the three machining conditions used in this study, whose means are summarized in Table 2, show good agreement with Equations 1, 2,

and 3. Therefore, the Equivalent Circular Diameter (ECD) as defined in ASTM F1877 – 16 (Standard Practice for Characterization of Particles) was used to quantify the chip size, ECD_{chip} , with the assumption that the area of the chip was the estimated chip width times the estimated chip height [67]. Oscillation frequency and ball-milling time were settings that could be specified directly on the machine.

Incorporating the machining parameters impact on chip size allowed for the total process time to generate 1 kg of powder for DED from bar stock to be calculated:

$$\frac{t_{\text{processing}}}{1 \text{ kg}} = \left[(\text{MRR}) (\rho_{\text{bar stock}}) (\eta_{\text{chip collection}}) \right]^{-1} + \left[\frac{2(m)(10^{-3} \text{ kg})(\eta_{\text{ball milling}})}{(t_{\text{ball milling}})(60 \text{ sec})} \right]^{-1}$$

where, $\rho_{\text{bar stock}}$ is the density of the 316L bar stock as measured with the Archimedes method (7851 kg/m³) [68].

Machining chip morphology was analyzed using a white light focus variation metrology system (Alicona Infinite Focus) to determine the height and width of the chip, and digital calipers were used to determine the chip thickness. Powders were sieved after ball milling to be between $45 \,\mu\text{m} - 150 \,\mu\text{m}$ according to ASTM B214-16 (Standard Test Method for Sieve Analysis of Metal Powders) in order to isolate the amount of powder in the 45 $\mu\text{m} - 150 \,\mu\text{m}$ size range [69]. Following the experiments to estimate percent yield, 1 kg of mechanically-generated feedstock was generated using the conditions with the fastest processing time and the powder was loaded into the LENS® powder hopper.

 Table 1. Summary of ball-milling experimental parameters

Machine	Retsch Mixer Mill MM 400	
Material	316L Stainless Steel	
Grinding Jar Volume	35 mL	
Grinding Ball Size	20 mm Dia. and 28.5 g	
Estimated ECD _{chip} (mm)	1.41, 2.33, 3.39 mm	
<i>m</i> (g)	5, 7.5, 10 g	
f (Hz)	20, 25, 30 Hz	
t _{ball milling} (min)	10, 20, 30 min	

, 0				
Machine	HAAS TM-1 3-axis Vertical CNC Mill (Built 2004)			
Material	316L Stainless Steel			
Tool ID, Diameter, and Number of Teeth	Sandvik Coromant CoroMill 490; 0.03175 m; 4 teeth			
Insert and Rake Angle	490R-08T304E-ML 2030; 0 deg			
RPM	2000	2000	2500	
F (mm)	0.05	0.08	0.08	
D (mm)	1.25	2.50	4.00	
W (mm)	0.50	0.75	1.00	
MRR (m³/s)	2.5•10 ⁻⁷	1.2•10 ⁻⁶	3.2•10 ⁻⁶	
ECD _{chip} estimated (mm)	1.41	2.33	3.39	
ECD _{chip} measured (mm)	1.58 ± 0.20	2.23 ± 0.15	3.47 ± 0.32	

Table 2. Summary of machining conditions and resultant chip sizes

2.1.3 Production Characterization Results and Discussion

A stepwise regression of the effects the starting chip size, ECD_{chip} , the mass fill of the milling jar, *m*, the ball-milling time, $t_{ball milling}$, and the oscillation frequency, *f*, on the percent mass of the ball-milled powder sieved to be between 45 µm – 150 µm resulted in Equation 7:

$$\eta_{\text{ball milling}} = 0.241 - 0.063(\text{ECD}_{\text{chip}}) - .100(m) + 0.100(t_{\text{ball milling}}) + 0.097(f) + 0.034(m)(f) - 0.028(t_{\text{ball milling}})(f) + 0.061(m^2)$$
7

The R² in this regression was 0.74 indicating the model explains 74% of the variability of this ballmilling process' yield. An F-test of the overall regression significance had a p-value <0.001 indicating a rejection of the null hypothesis and the conclusion that the model provides a better fit than an intercept-only model that would not include the factors' effects [70]. The negative regression coefficients indicate that the larger the size of the machining chips and the more mass in the container, the lower the yield in the desired size range will be after ball milling [70]. On the other hand, the positive coefficients indicate that the longer the ball milling operation and the higher the oscillation frequency, the higher the percentage of powder mass will be in the desired range [70]. It is also evident that there are interaction effects between the mass fill of the grinding jar and the frequency of the oscillation, as well as the ball-milling time and the frequency [70]. The squared mass fill factor indicates there is some curvature in the model [70]; *i.e.* over-filling the grinding jar with too many machining chips will reduce the ability of the grinding ball to crush the chips and therefore result in lower yield. These findings are consistent with the significant factors in particle size reduction theoretically derived by researchers studying an alternative ball-milling method [71], although, this is the first work to assess the effect of all these factors on the yield within a size range specified by a DED machine's manufacturer.

The estimated maximum yield of the oscillation ball-milling process studied was 60%. These results reveal generalizable opportunities to improve the yield of mechanically-generated feedstock production by expanding the range of process parameters based on their coefficient's sign, *i.e.*, smaller machining chips, less mass in grinding jar, longer ball-milling times, and a higher frequency oscillation; although the latter would require a redesign of the ball mill currently utilized which has a maximum frequency of 30 Hz. The goals of this work were not only to understand the ball-milling process, but to also understand its role in generating feedstock for additive manufacturing exclusively by mechanical means. Therefore, with Equation 6 incorporated into Equation 5, an iterative calculation to determine the process chain parameters that would result in the fastest time to mechanically generate 1 kg of feedstock was performed. Within the range of parameters explored in this study, the fastest time was found to be 29 hours and 40 minutes. The summary of processing conditions to achieve this processing time (Table 3) illustrates the tradeoffs between the two processes to reduce the processing time. It was estimated that a small ship size (low MRR), high oscillation frequency, high grinding jar fill, and low grinding time were the parameters that gave the fastest processing time because due to the low throughput of the ballmilling process, currently limited to two 35 mL containers, most of the processing time is spent ball milling. The mechanically-generated feedstock process employed in this research would need to be scaled up to achieve industrial viability. However, it did prove feasible to create 1 kg of feedstock for DED printing studies. This work provides generalizable knowledge to aid the transition from laboratory study to industrial scale mechanically-generated feedstock production.

2500		
0.08		
1.25		
1.00		
1.67•10 ⁻⁸		
1.61		
10		
30		
10		
2 hr and 16 min		
27 hrs and 24min		
29 hrs and 40 min		

Table 3. Mechanically-generated feedstockprocessing parameters

2.2 Feedstock Characterization

2.2.1 Feedstock Characterization Methodology

The morphology of mechanically-generated and gas-atomized powder, purchased from a supplier (Carpenter), was characterized by examining samples mounted to carbon tape with a Scanning Electron Microscope (SEM) (Zeiss LEO 1550VP and Thermo Scientific[™] Quanta[™] 600). Samples of each powder type were also mounted in epoxy (Allied High Tech Products, Inc. Epoxy Powder, Black Glass Filled) and polished to a 0.05 µm alumina solution (Allied High Tech Products, Inc. 0.05 µm FinalPrep Alumina Polishing solution, De-agglomerated) final step to reveal the cross section of the feedstock. These samples were examined with a white light focus variation metrology system (Alicona InfiniteFocus). ECD and aspect ratio, also defined in ASTM F1877 – 16 (Standard Practice for Characterization of Particles), of the feedstock particles were measured using a digital microscope (Keyence VHX-5000) and its accompanying particle size measurement software [67]. From these measurements, the mean ECDs and aspect ratios of the two sieved powder samples were calculated. The white light focus variation metrology system and SEM facilitated the qualitative shape definition of the feedstock. To determine the statistical significance of the differences in the mean ECD and mean aspect ratio of the two samples, t-tests were performed [70]. Histograms, Figure 3, were drawn to understand the size distribution of the

two feedstocks. Each particle was binned based on its ECD and two evaluation metrics were used for these histograms: count percentage and area percentage. The count percentage divides the number of individual particles in a bin by the number of total particles, and hence, illustrates the number of particles in each bin. The area percentage divides the summed area of all the particles in a bin and divides by the total area of all the particles in the sample. The area percentage is more indicative of how much mass is located in a bin.

A flowability test was performed according to ASTM B213 – 17 (Standard Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel) on both the gas-atomized and mechanically-generated feedstock [72]. Four tests of distinct samples of each powder type, mechanically-generated and gas-atomized feedstock, were performed. A t-test was performed to determine the statistical significance of the difference in the mean flow rates [70].

2.2.2 Feedstock Characterization Results and Discussion

2.2.2.1 Feedstock Morphology

There was a statistically significant difference between the ECDs and aspect ratios of the feedstocks with the gas-atomized powder being smaller and more spherical. The mechanically-generated feedstock exhibits a larger deviation in both metrics. The mean ECD for the mechanically-generated feedstock sample is $109 \ \mu m \pm 57 \ \mu m$ and $82 \ \mu m \pm 24 \ \mu m$ for the gas-atomized sample; the p-value for the t-test of this difference is less than 0.001. With a p-value also less than 0.001, the difference in mean aspect ratio of mechanically-generated powder was 1.68 ± 0.51 and 1.39 ± 0.32 for gas-atomized powder. Based on standardized morphology description nomenclature, the mechanically-generated feedstock, Figure 2a, can be described as roughened flakes, and the gas-atomized feedstock, Figure 2b, can be described as smooth, round and oblong, and spherical [67]. The cross sections highlight this difference as Figure 2c shows the narrow profile of the mechanically-generated feedstock, and Figure 2d shows that the atomized powder particles are primarily spherical. However, some gas-atomized particles do have

an oblong shape due to the random agglomeration of powder particles during the atomization process. The differences in the size of the particles can also been seen in these figures. Even though both samples come from powder sieved to be between $45 \,\mu\text{m} - 150 \,\mu\text{m}$, sieving allows particles to pass through if only two dimensions are smaller than the mesh size, and in that way sieving is a 2D effort to classify 3D particles. Sieving of irregularly shaped powders has been documented to result in more particles outside the sieving range due to the stochastic nature of the sieving process when compared to more spherical particles [73,74]. This is shown in the Figure 3 distributions, where mechanically-generated feedstock has a more uniform distribution when compared to gas-atomized powder. The majority of the area of mechanically-generated powder being outside of the 45 μ m – 150 μ m range is consistent with sieve analysis of other irregular powders [74]. Due to these nuances in classification, there may be need for refined particle definitions and controls for additive manufacturing applications as the morphology of feedstocks used to print with become more diverse.



Figure 2. Representative feedstock morphologies: (a) mechanically-generated feedstock, (b) gas-atomized feedstock, (c) mechanically-generated feedstock cross-section, (b) gas-atomized feedstock cross section





2.2.2.2 Feedstock Flowability

The Hall Flow Rate Tests showed that the gas-atomized feedstock had a statistically significantly better flow rate than the mechanically-generated feedstock. The gas-atomized powder's mean hall flow rate was 18.9 ± 0.5 s/50g, and the mechanically-generated powder took

 35.0 ± 4.3 s/50g with the p-value for the t-test of the difference in means being 0.007. The Hall Flow Rate Test is a standardized test intended for the characterization of a wide range of powders in a wide range of applications [72]. In that way, it is a more fundamental measure of a given powder's flowability. Previous research has shown powder morphology directly affects flowability of powders [75], which is consistent with the results of this work finding the difference in particle size and shape correlated with a difference in Hall and in-process flow rates.

Chapter 3: Print Performance and Resultant Part Properties

The objective of this work is to study the performance of mechanically-generated feedstock in Directed Energy Deposition (DED) processing. Performance of the mechanically-generated feedstock was compared to gas-atomized powder and evaluated based on the following figures of merit: flowability, printed part height, printed part density, printed part mass deposition behavior, and chemical compositional stability throughout processing. Compared with gas-atomized powder, mechanically-generated powder did not flow as well through the powder-delivery system. Parts printed from mechanically generated feedstock were generally taller than their counterparts from gas-atomized feedstock, but their densities were less predictable. Also, more mass was able to be deposited with gas-atomized powder. Chemical composition of prints using both feedstocks were within standard nominal compositions for 316L stainless steel. The surface texture, microstructure, and mechanical properties of printed parts were also compared and found to be similar.

3.1 Feedstock Print Performance

3.1.1 Feedstock Print Performance Methodology

A study of the flowability of the powders in the LENS[™] process was also conducted. The flow rate of the powder in the Optomec MR7 is controlled by adjusting the RPM of the powder auger shown in Figure 4; increasing the RPM increases the mass flow rate of the powder. The RPM of the powder auger on the DED system used in this study is controlled with an open-loop control system. This leads to inherent differences between the RPM input by the user and the actual RPM of the auger in each hopper. Since the two powders for this test were to be loaded into different hoppers, it was necessary to correlate the programmed input to a specific auger to the actual output RPM for that auger. With no powder in the hoppers, RPM settings were varied and two measurements of the actual time it took for the auger to make a revolution were taken at each setting, in each hopper; this data is provided in supplemental material. These measurements

enabled an estimation of the actual output RPM at a given programmed RPM. Then, the mass flow rates of the powders coming out of the hopper at programmed RPMs were measured using the test set-up shown in Figure 5. With powder loaded in the hopper, an RPM command was sent to the auger via the computer control system, and a bypass was attached to the powder's exit from the hopper. Instead of flowing into the print nozzles, with this set-up, the powder was forced into the plastic collection container (Figure 5). The argon carrier gas exited this container and was filtered through water before being released into the atmosphere. The auger was run for one minute and then the change in mass of the plastic collection container was recorded to determine the mass flow rate. This was performed for both gas-atomized and mechanically-generated powders at 5 settings (2, 5, 10, 15, and 18 RPM) for four repetitions each. The two powders' flowability in the DED system was then evaluated by translating the programmed RPM settings from the powder flow rate tests into the estimated RPM based on the measurements for each hopper. A regression analysis was used to estimate each powder's mass flow rates at actual RPMs. The regression equations for the two powders were compared using Chow's test [76]. Chow's test is a statistical test that can determine if the coefficients of distinct regression equations are equal and therefore the two data sets could be represented by a single equation [76]. The null hypothesis of this test is that the coefficients of the regression equations are equal; for this work, a significance level of 0.05 was selected, and thus p-values less than this value indicate a rejection of the null hypothesis (*i.e.* the equations are structurally different) [76]. The flow rate measurements also made it possible to equate the mass flow rates of the powders at programed RPM settings for the studies of build height and density.



Figure 4. Powder-control diagram (not to scale)



Figure 5. Schematic of powder mass flow rate test (not to scale)

<u>Note:</u> As drawn, schematic shows measurement of mass flow rate for mechanically-generated powder (Hopper 2); mass flow rate was also measured for gas-atomized powder (Hopper 1) using this technique.

A design of experiments for DED processing was proposed by Sciammarella *et al.* that defined laser power, P, and the ratio of powder mass flow rate to scan speed, r, as the primary factors contributing to the evolution of the DED printed part's microstructure [24]. This study utilized their methodology to compare the height, mass deposited, and density of prints from mechanically-generated and gas-atomized powders. A 4^2 experimental design, 2 factors and 4
levels, as summarized in Table 4. along with the control parameters, was used to determine the effects of laser power and the ratio of mass flow rate to scan speed when printing with the two powders. Accordingly, 16 cuboids from each powder were printed with a programmed square footprint of 6.35 mm x 6.35 mm and a total laser travel height of 2.54 mm; representative cuboids from each build are show in Figure 6. The footprint and height of each cuboid was measured with calipers and the volume was calculated. A bandsaw was used to separate the cuboids from each other and then they were removed from the build plate with a slow speed saw. The density of each cuboid was measured using the Archimedes method utilizing a surfactant (Fluorinert™ FC-40, density = 1855 kg/m³) [68]. Relative densities of cuboids printed with mechanically-generated feedstock were based on the measured density of a bar stock sample (7851 kg/m³), and relative densities of cuboids printed with gas-atomized feedstock were based on the density provided by the supplier (7944 kg/m³). The factors were normalized to be between -1 and 1 to perform stepwise regression analyses of the densities and cuboid heights as the respective responses for cuboids from mechanically-generated and gas-atomized powder. These relative density measurements were included in the mass deposited calculation to include a metric of the quality of the print. However, when calculating the mass deposited for each cuboid, the volume and relative density were multiplied by the density of the bar stock. This was done since the proposed specific energy consumption model in Chapter 4: Specific Energy Consumption Modeling of Remanufacturing Processes begins with 316L bar stock and uses its density throughout. Chow's test was used to assess the difference in the regressions of cuboid height in prints from the two feedstocks [76].

A statistical test that assesses the difference in regressions, Chow's test, was performed to determine if calculating the mass of gas-atomized powder deposited with the density of the supplier versus the density of the bar stock had a statistically significant impact on the resultant regression model. It was found that there was no statistical difference between the two regressions (p-value = 0.957) meaning the equations are not structurally different. It was therefore deemed acceptable to use the bar stock density to calculate the mass deposited of the cuboids printed with gas-atomized powder.

31001						
				Laser Travel		
Laser		Mass	Scan	Height	Hatch	Hatch
Power	Ratio	Flow	Speed	Increment	Spacing	Rotation
Р	r	Rate	ν	l	hs	Angle
(W)	(g/mm)	(g/min)	(mm/min)	(mm)	(mm)	(deg)
400	0.008	2.032	254			
400	0.016	4.496	381			
400	0.024	12.192	508			
400	0.032	20.32	635			
500	0.008	3.048	381			
500	0.016	8.128	508			
500	0.024	15.24	635			
500	0.032	8.128	254	0.054	0.20	67
600	0.008	4.064	508	0.254	0.38	67
600	0.016	10.16	635			
600	0.024	6.096	254			
600	0.032	12.192	381			
700	0.008	5.08	635			
700	0.016	4.064	254			
700	0.024	9.144	381			
700	0.032	16.256	508			

 Table 4. Summary of LENS® deposition parameters for 316L stainless steel



Figure 6. Representative 316L cuboids printed with (a) mechanicallygenerated feedstock and (b) gas-atomized feedstock

3.1.2 Feedstock Print Performance Results and Discussion

3.1.2.1 Feedstock In-Process Flowability

The result of the Hall Flow Rate tests in 2.2.2.2 Feedstock Flowability is consistent with the in-process mass flow rate analysis shown in Figure 7 along with each regression's 95% confidence bands. The R² and p-values of these regressions indicate each is well aligned with the data. However, Chow's test indicates the two regressions are structurally different (p-value = <0.001) and thus it can be concluded that the powders perform differently in the LENS® system. In short, the gas-atomized powder flows through the system better; the steeper slope of the gas atomized powder means there will be a greater increase in powder mass flow rate per incremental RPM increase.



Figure 7. Powder mass flowrates vs. the RPM of the powder wheel (MG = mechanically-generated; GA = gas-atomized)

This research has shown that the comparative findings of Hall Flow Rate Tests are also indicative of how powders may perform in an industrially-available DED system. Therefore, while the powder-feeding strategy employed by the commercially available DED machine used in this study is robust enough to deliver irregular powder to the melt pool, there are real differences in the flowability of the powders. These differences must be accounted for during printing in order to achieve powder mass flow rates with mechanically-generated feedstock that are similar to what operators have come to expect from more spherical, gas-atomized powder. The in-process flowability is an especially pertinent metric of mechanically-generated feedstock's feasibility, and strategies must be pursued to improve its flowability through a deeper understanding of the process parameter's effects on morphology, or through process designs such as those explored by other researchers [51].

3.1.2.2 Printed Part Height

The stepwise regression analyses of the effects of the laser power, P, and the ratio of mass flow rate to scan speed, r, on the height of the cuboids printed with mechanically-generated, h_{MG} , and gas-atomized powder, h_{GA} , resulted in the following equations:

$$h_{\rm MG} = 5.79 + 0.53(P) + 1.29(r) - 0.97(r^2)$$
 8

$$h_{\rm GA} = 5.61 + 0.71(\rm P) + 1.14(r) - 0.38(r^2)$$
 9

Both stepwise regressions were statistically significant (p-value = <0.001) with the R² values being 0.94 for the stepwise regression of the mechanically-generated heights, and 0.97 for the stepwise regression of the gas-atomized heights. The equations show that the height of the cuboids increased with increasing laser power, and the negative coefficient of the squared ratio terms indicate there was a maximum height achievable for every power at a given ratio for both feedstock types, deposited with the parameters in this study [70]. Generally stated, as laser power increases, the ratio value that produces the tallest cuboid at that laser power also increases. This knowledge can be used by those employing DED industrially to optimize this combination of factors for their specific system design to achieve the desired printed part specifications.

The differences seen between the two visualizations of Equations 8 and 9 in Figure 8a and 8b, respectively, are confirmed by Chow's test which revealed there was a statistical difference (p-value = 0.033) in the effects of the laser power and ratio of mass flow rate to scan speed on the height of the cuboids between cuboids printed with mechanically-generated and gas-atomized feedstocks; *i.e.*, they are statistically different equations. This finding suggests that generally, at a given set of process parameters, mechanically-generated feedstock would produce a taller cuboid. These larger heights may be evidence of better powder incorporation into the melt pool, but fundamental deposition studies should be conducted on irregular powders to identify the mechanisms of the differences. Therefore, the present results offer an additional path in exploring the potential sustainability benefits of mechanically-generated feedstock. The ability to print parts with equal dimensions using less powder, a possibility shown here, would be advantageous to any industrial operator utilizing DED who is motivated to improve process.



Figure 8. Visualization of the response of cuboid height to laser power and the ratio of powder mass flow rate to scan speed for cuboids printed with a) mechanically-generated feedstock and b) gasatomized feedstock

3.1.2.3 Printed Part Density

Relative densities of the cuboids printed from mechanically-generated feedstock were consistent across the range of processing parameters explored in this study, and therefore, none of the factors were determined to have statistically significant effects (p-value >0.05). These relative densities ranged from 98.6% - 99.7%, which agrees with porosity measurements from the analysis of microstructural characteristics in 3.2.2.2 Microstructure and Porosity, and within the range of density measurements from others using gas-atomized 316L feedstock [77]. The highest relative density using mechanically-generated feedstock was found at the low power and low powder mass flow rate to scan speed ratio of the parameters in this study. This particular finding is consistent with the results of the stepwise regression analysis for the cuboids printed with gas-atomized feedstock which had relative densities ranging from 98.3% - 99.5% and resulted in the following equation:

Relative Density_{GA} =
$$0.988 + 0.002(P) - 0.003(r) + 0.003(P)(r) + 0.002(r^2)$$
 10

This equation for relative densities of cuboids printed with gas-atomized feedstock had a R^2 of 0.80 and a p-value of less than 0.001. As can be seen in the visualization of the equation (Figure 9) the model indicates that a lower ratio, r (powder mass flow rate / scan speed), will result in a more dense part. However, the curvature due to the squared ratio-term's contribution also shows that at high laser powers, it may also be appropriate to have a high ratio [70]. Un-melted powder has been identified as one contributor to porosity defects in DED processing and is an ongoing area of investigation [78–81]. This regression analysis builds upon existing studies by demonstrating in a systematic way, having too much powder blown into a melt pool, *i.e.*, at low laser powers and high ratios, will result in less dense parts [80]. Additionally, considering the section of Figure 9 with normalized ratios between approximately -0.5 to -1, there is evidence that insufficient mass delivery to the melt pool as laser power increases, *i.e.*, too low of a ratio for a given power and therefore more energy input to the substrate, results in a reduction in density. This could be caused by keyhole porosity defects like those recorded by Wolff *et al.* that occur at high laser power densities [78].



Figure 9. Visualization of Equation 10, the relative density response (for gas-atomized feedstock) to laser power and the ratio of powder mass flow rate to scan speed

It has also been shown that interactions between powder particles are one of the driving factors of particle incorporation into the melt pool in DED [78]. The mostly uniform distribution of mechanically-generated powder particles as seen in Figure 3a denotes a wider variability in sizes, which when paired with their irregular shapes, as indicated by the sample's greater mean aspect ratio, could result in more complex and diverse particle interactions. This could be the cause of the unpredictability of the densities in prints with mechanically-generated powders seen in this study, as well as the larger deviation seen in mechanical properties of parts printed with irregular powder as compared to parts from gas-atomized powder [82]. This theory would suggest that the smaller deviation in gas-atomized powder size and shape would therefore have less diverse interactions, resulting in more easily predicted print outcomes, as this study found. Further investigation into flow characteristics of mechanically-generated or irregularly-shaped feedstock is necessary to confirm this hypothesis. Additionally, more repetitions across a wider range of process conditions would add the statistical power required to assess the factors influencing density and other properties of parts printed with mechanically-generated feedstock. Thereby extending the findings of the prints from gas-atomized feedstock to this emerging alternative.

3.1.2.4 Printed Part Mass Deposited

A stepwise regression analysis was performed with the mass deposited as the response and found the following equations:

$$m_{\text{deposited MG}} = 2.67 + 0.27(P) + 0.38(r) - 0.65(r^2)$$
 11

$$m_{\text{deposited GA}} = 2.56 + 0.49(P) + 0.57(r) - 0.22(r^2)$$
 12

Both equations were statistically significant based on the F-test of overall significance in the regression analysis (p-value = <0.001 for both). The equation for mass deposited with mechanically-generated powder had an R^2 of 0.95. The equation for mass deposited with gasatomized powder had an R^2 of 0.98. At this time, no literature has been found detailing the effect of part geometry on deposition or capture efficiency; research should be conducted to illuminate this relationship. Therefore, assuming part geometry does not significantly affect deposition capture efficiency, and holding all other processing parameters constant, the effects of laser power and the ratio of powder mass flow rate to scan speed on the mass deposited in Equations 11 and 12 could be applied to any part geometry by determining the total mass printed for that part.

From the equations and visualizations in Figure 10a and 10b it can be seen that generally, the mass deposited increases with increasing laser power and increasing mass flow rate per scan speed. Also, the negative coefficient of the squared ratio terms indicates there is curvature in the models. For the mechanically-generated feedstock this results in an estimated peak in mass deposited within the bounds investigated of 3.25 g when the laser power is at the high end of those investigated and a ratio of 0.027 g/mm. The gas-atomized equation had a smaller squared ratio coefficient and as a result does not peak within the bounds investigated, but the estimated maximum within the bounds was 3.39 g at the high values of laser power and the ratio for this study. This difference will become relevant when applying these equations to the calculation of specific energy consumption. These regression equations were compared using Chow's test and

it was determined that there was a statistical difference between the two (p-value = 0.019). The coefficients for the mass deposited equations are both machine and feedstock specific in that they describe the behavior of the two feedstocks in the machine utilized in this study. The goal of this work is to provide a comparison of energy consumption utilizing mechanically-generated and gasatomized feedstock in DED processing, but the general model methodology can be transplanted to estimate energy consumption in any DED process.



Figure 10. Visualizations of mass deposited response to laser power and the ratio of powder mass flow rate

to scan speed in prints with a) mechanically-generated feedstock and b) gas-atomized feedstock

3.1.2.5 Chemical Composition Throughout Processing

Overall, the major constituents of 316L stainless steel, listed in Table 5 and Table 6, were present within prints from both processing paths within the standard limits [83]. Changes in the chemical composition during the machining process (Table 5), shows what appears to be titanium and carbon contamination most likely due to wear of the TiAIN+TiN coated tungsten-carbide tool. Silicon was found to be higher in the machining chips and nitrogen was found to be lower. Also, the increased oxygen content is due to the well documented oxidation of stainless steels at the temperatures experienced during machining [84]. Additional oxygen in the mechanicallygenerated powder is evidence of further oxidation at elevated temperatures occurring during the ball-milling process [84], although oxygen has been found in other additively manufactured 316L stainless steel samples [85]. The carbon content most likely increased during ball milling as mechanical alloying occurred with a transfer from the higher weight percent carbon in the grinding jar (X90CrMoV18) and grinding ball (X46Cr13), which have between 0.85 - 0.95 and 0.42 - 0.5weight percent carbon, respectively. Trace hydrogen was found to increase while phosphorous and silicon decreased in the ball-milled feedstock. The DED prints utilizing mechanicallygenerated feedstock had decreased oxygen, hydrogen, and manganese as compared to the powder, and increased phosphorus. The increased titanium in the print does not have clear causality except for the possibility that more tool wear occurred than previous samples detected. Nitrogen was greater in both prints than in the initial feedstocks, but oxygen was found to decrease. Printing in the reduced oxygen atmosphere of the LENS® (<10 ppm) could have contributed to this result. In the prints from gas-atomized feedstock, molybdenum and silicon were greater than in the powder, while phosphorous decreased.

	316L Standard [83]	Bar Stock	Machining Chips	Mechanically- Generated Powder	Print from Mechanically- Generated Feedstock
Element	Weight%	Weight%	Weight%	Weight%	Weight%
Carbon	0.030 max	0.014 ± 0.001	0.018 ± 0.001	0.024 ± 0.001	0.025 ± 0.001
Manganese	2.00 max	1.39 ± 0.02	1.44 ± 0.02	1.43 ± 0.02	1.28 ± 0.02
Phosphorous	0.045 max	0.013 ± 0.001	0.012 ± 0.001	0.0077 ± 0.0005	0.0096 ± 0.0005
Sulfur	0.030 max	0.026 ± 0.001	0.028 ± 0.002	0.024 ± 0.001	0.024 ± 0.001
Silicon	0.75 max	0.48 ± 0.01	0.53 ± 0.01	0.49 ± 0.01	0.51 ± 0.01
Chromium	16.0 – 18.0	16.7 ± 0.3	16.6 ± 0.3	16.8 ± 0.3	16.8 ± 0.3
Nickel	10.0 - 14.0	10.4 ± 0.2	10.6 ± 0.2	10.8 ± 0.2	10.5 ± 0.2
Molybdenum	2.00 - 3.00	2.18 ± 0.04	2.24 ± 0.04	2.19 ± 0.04	2.13 ± 0.04
Nitrogen	0.10 max	0.085 ± 0.0005	0.068 ± 0.002	0.073 ± 0.002	0.082 ± 0.0005
Oxygen	-	0.005 ± 0.0005	0.028 ± 0.002	0.166 ± 0.0005	0.110 ± 0.0005
Hydrogen	-	0.0010 ± 0.0005	0.0012 ± 0.0005	0.0023 ± 0.0005	0.0009 ± 0.0005
Aluminum	-	<0.0005 ± 0.0005	<0.0005 ± 0.0005	<0.0005 ± 0.0005	<0.0005 ± 0.0005
Titanium	-	<0.0005 ± 0.0005	0.0016 ± 0.0005	0.0010 ± 0.0005	0.0039 ± 0.0005
Iron	Balance	Balance	Balance	Balance	Balance

Table 5. Chemical composition in the mechanically-generated feedstock process path

_	316L Standard [83]	Gas-Atomized Powder	Print from Gas-Atomized Feedstock
_	Weight%	Weight%	Weight%
Carbon	0.030 max	0.004 ± 0.001	0.005 ± 0.0005
Manganese	2.00 max	1.17 ± 0.02	1.19 ± 0.02
Phosphorous	0.045 max	0.0050 ± 0.0005	0.0039 ± 0.0005
Sulfur	0.030 max	0.004 ± 0.001	0.005 ± 0.0005
Silicon	0.75 max	0.21 ± 0.01	0.40 ± 0.01
Chromium	16.0 – 18.0	16.6 ± 0.3	16.8 ± 0.3
Nickel	10.0 - 14.0	12.4 ± 0.2	12.2 ± 0.2
Molybdenum	2.00 - 3.00	2.31 ± 0.04	2.49 ± 0.04
Nitrogen	0.10 max	0.035 ± 0.005	0.053 ± 0.002
Oxygen	-	0.030 ± 0.002	0.026 ± 0.001
Hydrogen	-	0.0007 ± 0.0005	0.0008 ± 0.0005
Aluminum	-	<0.0005 ± 0.0005	<0.0005 ± 0.0005
Titanium	-	<0.0005 ± 0.0005	<0.0005 ± 0.0005
Iron	Balance	Balance	Balance

Table 6. Chemical composition of initial gas-atomized powder and resultant printed part

Based on these findings, several improvements could be made to the mechanicallygenerated feedstock process chain to improve chemical composition stability, even if the current form is within acceptable process controls. The nitrogen shielding gas did not eliminate the oxidation during machining, and therefore other methods to control atmosphere as well as temperature should be investigated. Potential strategies could include machining in an enclosure that can reliably reduce the oxygen content, or temperature reduction through the use of cryogenic cooling methods. Similar strategies could be employed in the ball-milling process to address oxidation concerns. Future alloy selection for the grinding jars and grinding balls should also consider closer alignment with the alloy to be ball milled in order to reduce mechanical alloying.

3.2 Resultant Part Properties

3.2.1 Part Printing Procedure and Characterization Methodology

After it was proven that mechanically-generated feedstock could be utilized to print in a LENS® machine, three tensile bars from each feedstock were printed on 316L stainless steel build plates; dimensions were based off of ASTM E8/E8M – 16a with reduced grip lengths and commensurate radius adjustment (Figure 11a and b). The tensile bars were 4 mm thick (Z-axis)

with the Z-axis pointing out of the build plate direction (out of the page in Figure 11a and b). The print parameters, as summarized in Table 7, were based on the LENS® machine manufacturer's recommendations to ensure sufficient melting of the blown powder in each layer and were kept constant for all prints.





Figure 11. Representative 316L tensile bars from (a) mechanically-generated feedstock and (b) gas-atomized feedstock

The top surfaces (XY-plane) of the six tensile bars were imaged using the 10x objective with a white light focus variation system (Alicona, InfiniteFocus G4) to determine their surface roughness. Vertical and lateral resolution were 500 nm and 4 µm, respectively. A 250 µm filter was applied to determine the surface roughness values found in Table 8. The tensile bars were then removed from the build plates using wire electrical discharge machining (EDM). Afterwards, both faces in the XY-plane were mechanically ground to 1600 grit. Rockwell B hardness tests were then conducted on the grips of each sample. Next, room temperature tensile tests were performed on a load frame (MTS®, Sintech) with a 50 kN load cell and 2.20 mV/V sensitivity; the

constant strain rate was 0.04 s⁻¹ and data was collected at 10 Hz. A digital image correlation (DIC) system (Correlated Solutions) was utilized to collect strain data during the tests. The force and strain data from these tests were used to calculate the properties found in Figure 14; specifically, the 0.2% offset method was used to calculate the yield strength.

stainless steel			
Print Parameter	Value		
Laser power	275 W		
Feed rate	508 mm/min		
Powder mass flow rate	8.2 g/min		
Layer thickness	0.254 mm		
Hatch distance	0.38 mm		
Hatch rotation angle	67 degrees		

 Table 7. LENS® deposition parameters for 316L

After the tensile tests, the grips of the tensile bars were cross-sectioned in the XY-plane and XZ-plane using a slow speed saw. These surfaces were mounted in epoxy and polished to a 0.05 µm alumina solution final step. The samples were then imaged with a digital microscope (Keyence, VHX-5000) using the 100x objective and the images were binarized to determine area percentage porosity. Next, the samples were electro-polished in a bath of 0.05 molar Oxalic acid at a voltage of 5.5 V for ~90s with a thin platinum wire cathode and thin platinum sheet cathode. Images were taken of the etched surface with the digital microscope and the linear intercept method for non-equiaxed grains set forth in ASTM E1382 - 97(2015) was used to characterize the microstructures.

All statistical analysis of the mean was conducted utilizing a two-tailed Student's t-test with significance level of 0.05. The null hypothesis was that the means of the printed parts are similar for a tested property, and the alternate hypothesis being that the means of the printed parts for that tested property are different. A p-value greater than 0.05 indicates that the null hypothesis is probably true: *i.e.*, the means of the tested property of the printed parts are similar [70].

3.2.2 Printed Part Properties Results and Discussion

3.2.2.1 Surface Texture

Based on the five surface texture metrics studied, Table 8 shows that there was no significant difference between the printed surfaces (*i.e.*, p-values >0.05). However, the printed surface textures generated by the two feedstocks show some qualitatively different features (Figure 12). Both surfaces in Figure 12 exhibit rippled melt tracks that indicate the laser feed direction. Protrusions are also visible on both, which could have been formed from partially-melted powder particles, from spattered particles ejected from the melt pool, or from balling. These features are typical of metal additive manufacturing surfaces [86]. Visibility of the mechanically-generated feedstock's flake-like powder particles (Figure 2a) highlights the partially-melted powder's contribution to the surface texture since the powder's morphology can be distinguished from ejection and balling features. Most metal additively manufactured surface textures suggests that parts built with mechanically-generated feedstock could be compatible with the industry's current expectations of required post-processing of a LENS® fabricated part.

	-		
Metric*	Mechanically-Generated	Gas-Atomized	p-value
Sa	9.2 μm ± 1.3 μm	7.4 μm ± 3.7 μm	0.502
Sz	198 μm ± 35 μm	142 μm ± 42 μm	0.153
Sv	81 μm ± 16 μm	60 μm ± 19 μm	0.212
Vmp	2.03 ml/m ² ± 0.15 ml/m ²	1.19 ml/m² ± 0.47 ml/m²	0.077
Vvv	1.55 ml/m² ± 0.19 ml/m²	1.26 ml/m² ± 0.54 ml/m²	0.456
*100 05470			

Table 8. Comparison of surface texture of 316L printed samples

*ISO 25178



(a)



Figure 12. Representative surfaces of samples printed with (a) mechanically-generated feedstock and (b) gas-atomized feedstock

3.2.2.2 Microstructure and Porosity

Microstructures of tensile bar samples made from the two different powders show similar characteristics. Etched samples showed the elongated grains found in DED microstructures with columnar dendrites and grain evolution in the direction of the heat flow [87], as can be seen in the micrographs of the XZ-plane in Figure 13. This is further supported by the anisotropy index values, or aspect ratio values indicating the elongation direction to be in the build direction (Table 9). Given the p-value for the difference in the means, 0.051, is close to the test significance level,

0.05, the conclusions on the difference cannot confidently be drawn using only statistical metrics. In this work, energy density and powder flowrate were identical for all prints. Previous findings from Smith *et al.* showed that given similar thermomechanical histories, DED parts will have similar microstructure and properties [88]. This builds confidence that matching the process parameters led to similar microstructures, which correlates well with the similarities found in mechanical properties of printed parts using the two feedstocks.



Figure 13. Representative microstructures in the XZ-plane of a 316L print from (a) mechanicallygenerated feedstock and (b) gas-atomized feedstock

Table of Companyon (or grain eize and enape er en	e⊑ printea eampiee	
Metric*	Mechanically-Generated	Gas-Atomized	p-value
Grain size (µm)	79 ± 8	62 ± 4	0.051
Anisotropy index	0.88 ± 0.27	0.90 ± 0.23	0.925
* ASTM E1382 - 97(20	015)		

Table 9. Comparison of grain size and shape of 316L printed samples

The area percentage porosity in samples printed with gas-atomized powder at the process conditions utilized in this study was measured to be $0.14\% \pm 0.07\%$. Samples printed with mechanically-generated feedstock had an area percentage porosity of $0.51\% \pm 0.18\%$. The p-value for this test was 0.003 indicating that resulting porosity was statistically different for the two feedstocks. This optically-based analysis also does not rule out the presence of inclusions being counted as porosity, but even if they were, the porosity values of both feedstocks fall within the range found by others utilizing directed energy deposition systems [13], indicating that at these printing conditions, both feedstocks could be utilized. This finding also suggests there may be feedstock specific impacts on porosity formation which in turn could lead to the development of process parameters that reduce defects for a specific feedstock.

3.2.2.3 Mechanical Properties

The mechanical properties of the 316L stainless steel tensile samples are shown in Figure 14, and overall were found to be similar across prints with different feedstocks. The only statistically significant differences were in hardness and ultimate strength (p-values <0.05), which were greater in the tensile bars printed with mechanically-generated feedstock. Given the lack of a clear difference in the grain size between the samples and higher porosity in the samples made with mechanically-generated feedstock, the slightly higher weight percent of interstitial elements (*e.g.*, oxygen, titanium) in the samples printed with mechanically-generated feedstock is the proposed root cause of the difference in hardness and ultimate strength. Another observation is that samples printed with gas-atomized powder had less deviation in properties, potentially due to those tensile bars containing less porosity. It could also suggest that there may be a linkage between the regularity of the feedstock and the regularity of the resultant part bulk properties.

Consequently, industrial-grade powder production and deposition process controls, as are being developed for gas-atomized powder, could be explored for mechanically-generated feedstock to improve powder morphology and resultant print quality. It should be noted that the mechanical properties reported here are significantly greater than what can be found from an online search of cast 316L stainless steel; this highlights the importance of the processing history in part design and manufacturing.



Figure 14. Comparison of mechanical properties

Chapter 4: Specific Energy Consumption Modeling of Remanufacturing Processes

The objective of this work was to propose, compare, and apply energy consumption models of remanufacturing process paths that utilize either mechanically-generated or gasatomized feedstocks for directed energy deposition processing. The energy modelling was done in three stages. First, the mechanically-generated feedstock production energy consumption model was generated from experimental observation. Second, the gas-atomized feedstock production energy consumption model was generated from a combination of experimental observation, reported estimates from the manufacturer, and data found in the literature. Lastly, the energy consumption model of directed energy deposition was derived from experimental observation and compares favorably with reported estimates in the literature. With the models, the specific energy consumption in the two process paths were compared and their application was demonstrated by estimating the energy consumption to remanufacture a bracket. The two feedstock production methods had similar specific energy consumptions. The specific energy consumption of the directed energy deposition process was the greatest component in the respective remanufacturing paths by an order of magnitude; increasing deposition rate is the most important factor for lowering the overall specific energy consumption. The analyzed remanufacturing technologies were estimated to consume less energy than replacement when repairing up to approximately 15% of the original part's mass.

4.1 Specific Energy Consumption Model Methodology

The model framework presented in this study evaluates the remanufacture of an existing part into a new part. This allows for the approach detailed herein to be tailored to address the specific inputs in a given remanufacturing application (*e.g.*, machines, material, initial and final part designs). In building the models, 316L stainless steel bar stock was considered the initial "part" and a cuboid represented the final remanufactured "part." In the mechanically-generated

feedstock processing path, illustrated in Figure 15a, the bar stock is machined into chips. The chips are then crushed into powder in an oscillation ball mill and sieved to be between 45 μ m - 150 μ m; this is the size range recommended for the DED system. In the gas-atomized feedstock processing path, illustrated in Figure 15b, the bar stock is melted in an induction furnace and then gas atomized. As with the mechanically-generated feedstock, the gas-atomized powder is loaded into the hopper and used to print the designed cube. Models of energy consumption were developed based on these process paths.



Figure 15. Flow chart of energy consumption captured in models for remanufacturing with a) mechanically-generated feedstock and b) gasatomized feedstock

The models characterize the electrical energy consumption in terms of SEC, which generally is the energy consumed to produce a material unit (J/kg). In the processing path with mechanically-generated feedstock, the machining energy consumption model is based on well-validated regression analyses in the literature [48,60], and the SEC represents the energy per mass of material removed during the machining operation. A stepwise regression was performed

on experimental energy consumption measurements to derive the ball-milling model SEC, which for ball-milling was defined as the energy consumed to produce the mass of powder in the 45 µm - 150 µm size range as determined by sieve analysis. Producing gas-atomized feedstock requires induction melting which was modeled based on manufacturer's reports and experimental procedures; the gas-atomization energy consumption model is based on manufacturer's power reports and experimental results reported in the literature [89]. The energy required to melt and atomize the mass of an ingot into powder in the 45 µm - 150 µm size range as determined by sieve analysis is the SEC of induction furnace melting and of gas-atomization. A new model for directed energy deposition is proposed that was determined by regression analysis of experimental measurements of electrical energy in a LENS® system (Optomec® MR7) and a stepwise regression of the mass deposition response when printing with the two different feedstocks. The SEC for directed energy deposition is defined as the energy per mass of material fused into the part being printed. All the systems studied were research-grade units in order to provide a fair comparison between the two process paths. The modeling methodology for these systems can be extended to assess the energy consumption for any part of a given material remanufactured with industrial-scale systems by finding the process' SEC and then multiplying by the mass of the processed material.

4.1.1 Model of Specific Energy Consumption: Mechanically-Generated Feedstock Production

4.1.1.1 Machining Specific Energy Consumption Model

Kara *et al.* first presented an energy consumption model for subtractive manufacturing machines based off the Material Removal Rate (MRR). To generate the model for a particular machine, measurements of energy consumption are made at varying MRRs on that machine. Kara *et al.* showed that a regression equation, Equation 1, could then be found with the measured

energy per volume of material removed, SEC_{Machining} (J/m³), as the dependent variable and the inverse of the MRR, MRR⁻¹, as the independent variable.

To apply this general model to the remanufacturing process presented here, the regression equation developed by Kara *et al.* with machine specific constants for a vertical milling machine (HAAS TM-1) equipped with a shop vacuum-based chip collection system (Rigid, 6 Gal. Wet/Dry Vac) is divided by the material's density and the efficiency of which the chips are collected as shown in Equation 13:

$$SEC_{Machining} = \frac{4.21 \cdot 10^{11} + \frac{0.513}{MRR}}{\rho_{bar \ stock}(\eta_{chip \ collection})}$$
13

Dividing by density ($\rho_{\text{bar stock}}$) converts the SEC into energy per mass (J/kg) which eases the incorporation of this component into the rest of the remanufacturing model. Chip collection efficiency ($\eta_{\text{chip collection}}$) is an essential aspect to capture since unlike most machining operations where the remaining material constitutes the part, in this case, the removed material (*i.e.*, the machining chips) will come to make up the printed part.

For this energy consumption model, only the processing energy is considered, *i.e.*, energy consumption during idle phases is not captured in the model. The equation has an R² of 0.98, which statistically means the model captures 98% of the variability in energy consumption in the machining process. The null hypothesis for the F-test of the regression's significance states that there is no relationship between the response, $SEC_{Machining}$, and predictor variable, MRR⁻¹. The F-test of this regression had a p-value <0.001 which indicates the null hypothesis is rejected and it was concluded that there is a statistically significant relationship between the response, $SEC_{Machining}$, and predictor variable, MRR, the lower the SEC. This is due to the high baseline power load of the vertical mill; from an energy

consumption perspective of machining in isolation, machining should be performed with the highest MRR appropriate for the combination of machine, tooling, and material.

4.1.1.2 Ball Milling Specific Energy Consumption Model

Energy consumption during ball milling was measured using a power and energy monitor (Fluke, 435 Power Quality and Energy Analyzer) that had a 4 Hz sampling frequency. Energy measurements were taken during the production characterization experiments summarized in Table 1. For this work, a stepwise regression analysis was performed to determine the effect of those factors on the energy consumption of the ball mill. It found that of the processing effects considered, only the mass of the chips in the milling jar, m_{fill} , oscillation frequency, f, and ball-milling time, $t_{ball milling}$, were found to have a significant impact on the energy consumption; a comparison of the measured energy consumption to the model's estimation is shown in Figure 16 with the regression's 95% confidence interval. Dividing the regression equation for energy consumption of this oscillation ball mill by the mass fill of the chips in the milling jar and the percent mass yield function gives the specific energy consumption for the oscillation ball-milling process:

SEC_{Ball-Milling}

$$=\frac{\left[5.80+0.02(m_{\rm fill})+2.44(t_{\rm ball\,milling})+1.35(f)+0.61(t_{\rm ball\,milling})(f)-0.65(m_{\rm fill})^2-0.48(f)^2\right]\bullet10^4}{(m_{\rm fill})\left[\eta_{\rm MG\,yield}\left({\rm ECD}_{\rm chip},m_{\rm fill},f,t_{\rm ball\,milling}\right)\right]}$$
14



Figure 16. Comparison of ball milling energy consumption model to measurements

The R² for the energy consumption stepwise regression equation is 0.95 and the p-value is <0.001. The ball milling time and oscillation frequency are the two settings on the machine that can be programmed, and it follows that the energy consumption would increase as these settings increase. Also, the mass fill component captures the energy required by the machine to oscillate that mass; there is also a squared component of this variable with a negative coefficient because the machine has a maximum power draw, and therefore, the effect of the mass of the chips in the grinding jar decreases as the maximum power of the machine is approached. Likewise, the power draw to maintain the frequency reaches a maximum at the machine's maximum programable frequency setting of 30 Hz.

4.1.2 Model of Specific Energy Consumption: Gas-Atomized Feedstock Production

4.1.2.1 Induction Melting Specific Energy Consumption

Energy consumption in induction melting can most generally be modeled as shown in Equation 15:

Energy Consumption = $\left(\frac{P_{furnace}}{\eta_{furnace}} + \frac{P_{chiller}}{\eta_{chiller}}\right) t_{melt}$ 15 where the operational power of the furnace (P_{furnace}) and the furnace's chiller, P_{chiller}, are divided by their respective energy transfer efficiencies, $\eta_{furnace}$ and $\eta_{chiller}$, and the entire quantity is multiplied by the processing time.

For the specific induction meting system modeled in this research, the power of the furnace is increased at constant time intervals, t_{ramp} , by a constant increment of power, P_{ramp} , for a specified number of increases, n, until the appropriate power for a given material is reached, P_{dwell} , and then the power is held constant for a specified time, t_{dwell} . The chiller is operational for this entire time. To estimate the SEC, the energy consumption of the furnace and the chiller are divided by the mass of the bar stock melted, m_{melt} , as well as the percent of atomized powder sieved to be in the size range specified by the printing system to be employed, $\eta_{GA yield}$. Incorporating these process elements into Equation 15 produces:

$$\operatorname{SEC}_{\operatorname{Melt}} = \frac{\frac{\sum_{i=1}^{n} P_{\operatorname{ramp}}(n)(t_{\operatorname{ramp}}) + P_{\operatorname{dwell}}(t_{\operatorname{dwell}})}{\eta_{\operatorname{furnace}}} + \frac{\frac{P_{\operatorname{chiller}}[t_{\operatorname{dwell}} + n(t_{\operatorname{ramp}})]}{\eta_{\operatorname{chiller}}}}{\eta_{\operatorname{chiller}}}$$
16

4.1.2.2 Gas Atomization Specific Energy Consumption Model

Generally, energy consumption in gas atomization is a function of the power load of the gas-atomization system, $P_{atomization}$, and its energy transfer efficiency, $\eta_{atomizer}$, which is then multiplied by the time to flow the mass of the molten metal through the atomization nozzle. The power load includes the operation of the vacuum pump to maintain an inert gas atmosphere, the pressurizing gas valves, the atomization nozzle heaters, and the control system. The time can be determined by dividing the mass of molten material by its mass flowrate (MFR) through the atomization nozzle, a variable influenced by the nozzle design and the atomization gas pressure for a given metal [91,92]. This model can be generalized to apply to a given material's mass flow rate through a specific nozzle design. However, characterization of yield in the size range

specified in this work based on varying process parameters was not conducted. Such an analysis could be performed by practitioners to apply this model to their specific system's configuration. Finally, the energy consumption is divided by the mass of the molten metal flown through the atomization nozzle and the overall percent of atomized powder sieved to be in the size range specified by the printing system to be used for remanufacture ($\eta_{GA yield}$). Simplifying, yields the general SEC equation for gas-atomization:

$$SEC_{Atomization} = \frac{P_{atomization}}{MFR(\eta_{atomizer})(\eta_{GA yield})}$$
17

4.1.3 Model of Specific Energy Consumption: Directed Energy Deposition

The methodology for the SEC model in DED borrows conceptually from that set forth for machining by Kara *et al.* in that the system energy consumption is linearly correlated with the primary process parameters [60]. For additive manufacturing, these process parameters can be summarized by the Volumetric Energy Density (VED). VED is calculated using the following equation:

$$VED = \frac{P_{laser}}{v(l)(hs)}$$
18

where, P_{laser} is the laser power, v is the scan speed, l is the layer height, and hs is the hatch spacing. A linear regression can then be performed to estimate the energy consumption to produce a part at a given VED. These variables should be within the range of process parameters that produce acceptable quality parts for a given material. In order to prove the validity of this methodology, it was applied to a large set of energy consumption data of a DED system found in the literature. This analysis shows good correlation, with an R² of 0.99 as shown in Figure 17 [93], and therefore is shown to be an effective characterization method. Similar to machine tool systems, commercially available DED systems have high baseline power loads relative to axial and laser power contributions; therefore, the faster the process, the less energy consumed. Also, since the goal of DED is to deposit material to make a part, the effectiveness of the process parameters in depositing material must be included in the calculation of SEC for DED processing by dividing the linear regression by the mass deposited:

$$SEC_{DED} = \frac{C1 + C2(VED)}{m_{deposited}}$$
19

This general form can be utilized by practitioners seeking to optimize energy consumption of a DED system. To employ this model, a two-step approach should be used. First, the linear model of energy consumption for given process parameters should be determined for a part. The constants from this analysis are specific to a given machine since many DED systems are commercially available and come in a variety of configurations that will result in differing energy responses [23]. Then, the effect of process parameters on the mass deposited when printing that same part should be studied. The part studied must be the same in both studies to ensure the energy consumption is commensurate with the mass deposited. Incorporating the $m_{
m deposited}$ term provides a metric of print quality to scale process parameters based on their effectiveness in achieving the goal of DED processing, which is to deposit material. Other metal additive processes, such as powder-bed systems, can also be characterized by VED, and therefore this general formulation could potentially be applied to estimate energy consumption in metal additive manufacturing more broadly. It should be noted that this model does not account for the embedded energy in the powder flown through the nozzles but not incorporated in the print; reclaimed powder has been shown to be able to be reused with no impacts to mechanical properties for at least 10 reuse cycles [40].



Figure 17. Energy density-based modeling of DED data from Liu et al. Dashed lines indicate 95% confidence interval. Note: Non-specified process parameters were assumed to be constant in all prints.

For the remanufacturing model developed in this work, a LENS® system was analyzed by taking energy consumption measurements while printing cuboids, each with a programmed square footprint of 6.35 mm x 6.35 mm and a total laser travel height of 2.54 mm, at 5 different VED settings. The regression resulted in Equation 20 and is visualized in Figure 18:

Energy Consumption_{LENS®} = $5.92 \cdot 10^5 + 2.12 \cdot 10^3$ (VED) 20



Figure 18. Energy consumption regression of DED system (Optomec MR7). Dashed lines indicate 95% confidence interval.

4.2 Application of Specific Energy Consumption Models

4.2.1 Selected Inputs to Models

The SEC calculation for producing mechanically-generated feedstock was performed by adding Equations 2 and 3; the input values are summarized in Table 10. For the machining model utilized in this study, the coefficients are machine constants from the analysis done in previous work, [48], of a 3-axis computer numerically controlled (CNC) vertical milling machine (HAAS, TM-1) with the addition of a shop-vacuum-based chip collection system (Rigid, 6 Gal. Wet/Dry Vac) that was constructed for this research and was found to collect 94% of the mass machined, $\eta_{chip collection}$. The final input for the machining SEC is MRR, which also has an impact on the percent mass yield, $\eta_{MG yield}$, of the oscillation ball milling process as detailed in Chapter 2: Production and Feedstock Characterization. The equations from that analysis were included in an iterative calculation to determine the MRR and ball milling parameters that would result in the minimum SEC of mechanically-generated feedstock production; combinations of these factors were iteratively calculated to find this minimum value. The analysis was bounded by the range of

ball milling parameters in the previous study to maintain the validity of the multivariable regression equations. The input parameters for Equations 13 and 14 that resulted in this SEC were utilized in this case study and are summarized in Table 10. The contribution of machining and ball milling to the resulting SEC of feedstock production could then be determined. The 95% confidence intervals are reported and are calculated from the standard error of the regressions. They are reported to understand the uncertainty associated with the results of the analysis in this case study.

The SEC calculation for producing gas-atomized feedstock was performed by adding Equations 17 and 18. The primary inputs into the induction melting SEC model were the manufacturer's reported power and energy transfer efficiency values for a laboratory-scale gasatomization system (Dongyang Induction Melting Furnace Co. Ltd; Gas Atomization System with Induction Melting Furnace, 50 kW – 1650 °C) as summarized in Table 11. The energy consumption of the furnace and the chiller are divided by the mass of the bar stock melted as well as the percent of atomized powder sieved to be between 45 µm - 150 µm. At present, this percent yield of 50%, $\eta_{GA \text{ yield}}$, is derived from the work by Cui *et al.*, but it is possible to determine the percent yield for any given system and operation parameters through experimental exploration [89]. The maximum mass of 316L stainless steel that can be melted in this furnace is 5 kg, and since this would minimize the SEC of melting, it was selected as the mass to be melted, m_{melt} . The efficiencies of the furnace and chiller were reported to be between 40% - 70% and 50% -70%, respectively; these ranges were treated as uncertainty ranges when reporting the results. Calculations were made with the efficiencies at the high and low values of these ranges and the mean was taken to determine the SEC of the melting process. The mean efficiencies reported in Table 11 are the efficiencies at this mean value.

Similar to the induction melting model, the gas atomization model for remanufacturing is constructed by applying the manufacturer's estimated power load to a laboratory-scale machine (Dongyang Induction Melting Furnace Co. Ltd; Gas Atomization System with Induction Melting Furnace, 50 kW – 1650 °C); these inputs and those from the literature are summarized in Table 11. For this model, the mass flow rate, MFR, selected was utilized by Cui *et al.* to atomize 316L stainless steel at the aforementioned percent yield they found [89]. An energy transfer efficiency of the gas-atomizer, $\eta_{atomizer}$, was not provided by the manufacturer, but was assumed to have a range of, 45% at the low end (the mean of the furnace and chiller efficiencies), and at the upper end, 70% (the maximum efficiency of both machines). As with the estimation for the SEC of melting, calculations were made with the minimum and maximum efficiencies and the mean of the two values was taken to determine the SEC of atomization; the reported efficiency is the energy transfer efficiency at the mean. The SEC to melt the bar stock and the SEC to atomize the molten metal are added together to calculate the SEC to produce powder via the gas-atomization process path.

At this time, the production of gas-atomized powder does not have a process parameter dependent formulation for which a minimization effort could be performed. Future work should evaluate these aspects and use the framework developed herein to find the parameters that minimize the energy consumption. The most likely direction in this vein would be to investigate the role of mass flow rate, as dictated by nozzle design and gas pressure, on the distribution and resultant percent yield of the powder.

The SEC for DED was calculated based on Equation 19. Specifically, the constants in Equation 19 came from Equation 20, and Equations 11 or 12 were used to obtain the mass deposited value for the appropriate processing paths. This allows for the calculation of energy consumption per unit mass deposited based on the machine constants for a LENS® system (LENS®, Optomec MR7) and the process parameters. As with the mechanically-generated feedstock production calculations, combinations of process parameters were iteratively calculated to find the minimum SEC to print with the respective feedstocks; this analysis was also bounded

by the range of print parameters in the mass deposited study. For this minimization analysis the variables considered were VED, laser power, P_{laser}, and the ratio of powder mass flow rate to scan speed, *r*. The hatch spacing, *hs*, and layer height step, *l*, were kept constant; the scan speed and powder mass flow rate could be derived from the analysis' resultant VED and ratio values. The resultant print parameters of the iterative analysis are summarized in Table 12 and were utilized for the calculation of SEC of LENS® deposition in this case study. To provide a measure of uncertainty, this analysis includes a calculation of 95% confidence intervals for the SEC values in each process path that is derived from the regression analysis for the energy consumption in the LENS® system and the stepwise regression analysis of mass deposited in the same system.

Machining					
Machino	HAAS, TM-1 with chip collection system powered by Rigid,				
Machine			6 Gal. Wet/Dry	y Vac	
$\eta_{chip \ collection}$	on		94%		
ρ _{bar stock}			7851 kg/m	1 ³	
W	0.5	5 mm	D		1.25 mm
RPM	4000	F	0.07 mm	Ν	4 teeth
MRR			2.67•10 ⁻⁵ m	³ /s	
	Ball milling				
Machine Retsch, Mixer Mill MM 400			00		
<i>m</i> _{fill} 10 g					
t _{ball milling} 10 min					
f 30 Hz					
ECD _{chip}			1.58 mm		
$\eta_{\text{ball milling}}$			47% ± 10%		

Table 10. Summary of case study processing parameters for mechanicallygenerated feedstock production

	Dongyang Inductio	umace Co. Lid; Gas			
Machine Atomization System v		Induction	Melting Furnace, 50 kW –		
	1650 °C				
$\eta_{GA \ yield}$		50%			
	Induction Melting				
$m_{ m melt}$	5 kg	п	29		
$t_{\rm ramp}$	1 min	t _{dwell}	30 min		
	Furnace		Chiller		
P _{ramp}	1000 W	P _{chiller}	15000 W		
P _{dwell}	30000W	$\eta_{chiller}$	50% < 58% < 70%		
$\eta_{furnace}$	40% < 51% < 70%				
	Atomi	zation			
P _{atomization}	ation 1000 W				
MFR		0.0825 kg/	Ś		
$\eta_{atomizer}$	45% < 55% < 70%				

 Table 11. Summary of case study processing parameters for gas-atomized feedstock production

 Depay and Induction Molting Europee Co. Ltd: Case

Table 12	. Summary of case study processing parameters for LENS®
printing	

printing			
Machine	LENS®, Optomec MR7		
	MG	GA	
P _{laser}	700 W	700	
ν	635 mm/min	635 mm/min	
l	0.254 mm	0.254 mm	
h	0.38 mm	0.38 mm	
VED	685 J/mm ³	685 J/mm ³	
MFR	17.40 g/min	20.32 g/min	
r	0.027 g/mm	0.032 g/mm	
$m_{ m deposited}$	3.25 g ± <0.01 g	3.39 g ± <0.01 g	

To summarize the procedure to determine the SEC of remanufacturing a 316L stainless steel part from the models that have been presented, the variables listed in Tables 10, 11, and 12 were input into their respective equations illustrated for convenience in Figure 19:



Figure 19. Summary of equations for a) mechanically-generated feedstock and b) gasatomized feedstock remanufacturing processing paths
4.2.2 Analysis of Models

SEC of the mechanically-generated and gas-atomized feedstock remanufacturing process chains were estimated to be similar as summarized in Figure 20. Statistically, the two feedstock production components were also similar. Overall, the largest component of SEC for both process paths in this case study came from LENS® deposition. Machining composes the majority of the SEC to produce mechanically-generated feedstock in that it is three times greater than ball milling. Induction melting is four orders of magnitude greater than atomization and therefore is the primary factor in the gas-atomized feedstock production process. Close examination of these SEC reveals structural limitations of the process paths and efficiency improvement opportunities as identified in Figure 21.



Figure 20. Summary of SEC in process chain comparison



Figure 21. Remanufacturing energy consumption reduction strategies

The results of the LENS® deposition analysis reveal the driving factor in reducing SEC is the rate at which material is deposited. Scan speed impacts energy consumption in that the faster a part can be made, the less electrical energy consumed during the process. Likewise, the more mass that can be deposited during that time, the lower the SEC. Therefore, the goal of energy minimization efforts in DED processing should be to deposit as much material as possible in the minimum amount of time. This is evident in the results for prints with both feedstocks. The SEC is minimized at the maximum scan speed and the maximum mass deposited within the bounds of this case study. The primary constraints on minimization in DED processing generally are the axis movement capabilities of the machine and the maximum mass flow rate in the system, which must keep pace with the scan speed to maintain a high ratio. These two aspects should be considered when designing the specifications of DED machines in the future to provide manufacturers with more energy efficient printing capabilities. Another factor in the SEC is the laser power. While laser power has an inverse effect on the electrical energy consumed by increasing the VED, the positive influence this print factor has on the mass deposited is more effectual. Accordingly, the laser power setting in this case study was the highest within the bounds analyzed so as to deposit the most mass. Because the laser power and scan speed print process parameters could be matched for both feedstocks, the difference in SEC is a result of the differences in mass deposited. Gas-atomized powder was found to be deposited in a greater amount within the bounds of this case study and therefore has the lower SEC for deposition. There is a growing body of literature on efforts in the related line of research aimed at improving deposition efficiency in DED processing, from increasing powder supply efficiency through nozzle redesigns [94] to trochoidal laser beam paths [95]. Increasing deposition efficiency could also increase deposition rate, and therefore this case study highlights the importance of those works in continuing to drive down the energy consumption in the use of additive manufacturing technologies and contributes a process parameter-based approach to further this goal.

Of the manufacturing processes within the feedstock production paths, induction melting has the highest SEC. This is due in large part to the high electrical powers required to melt an ingot of 316L stainless steel, as well as the long times these powers must be sustained. Additionally, the unit analyzed is limited to melting 5 kg per melting operation. Increasing the amount that can be melted per run could improve the SEC, however, this could require a larger furnace that would require even higher electrical powers to operate. Industrial-scale systems come in a range of configurations and capacities to meet the needs of the powder metallurgy community. Reducing operating power while increasing melt capacity must therefore be parameters of consideration for future system designs to meet the energy efficiency needs of manufacturers targeting more sustainable manufacturing techniques. Atomization is a process that occurs very quickly; the process is completed in only a little over a minute in this case study as opposed to the hour time scales for melting, machining, and ball milling. The primary influence of the atomization process on the SEC is through the efficiency of the process to produce feedstock in the range required for DED printing. As mentioned previously, developing a

correlation of atomization process factors to the resultant powder size distribution would enable powder manufacturers to control and maximize the efficiency; thereby providing additional avenues for reducing the SEC of this process path.

For the mechanically-generated feedstock production path, the SEC is primarily reduced by reducing the SEC of the ball-milling process. The MRR range explored in this case study contains high enough values that the cutting operation results in only a marginal increase in energy consumption over the intercept in Equation 13, which represents the baseline energy demands of the machine tool and chip collection system. It was seen that approximately half of the system's energy consumption came from the chip collection system. The shop vacuum increased the baseline energy consumption and therefore the overall SEC; from an energy consumption perspective, it would be important in the future to utilize a suction device that has a lower power load, which would reduce this baseline energy consumption. But given the present configuration, the machining parameters that would result in smaller machining chips (*i.e.* small ECD_{chip}) were found to produce lower overall SEC for feedstock production. These smaller chips had the effect of increasing the yield of the ball-milling process in producing chips within the desired size range. The analysis also found that the mass fill of the ball-milling canisters should be at the high end of the parameters explored. The definition of SEC explains this finding since it will be minimized by processing more mass at a given energy consumption. Also, the higher mass fill factor here indicates the inverse nature of the relationships mass fill has with the energy consumption and vield in the respective regression equations are less effectual than the benefits of processing more powder in terms of overall process path energy consumption. Generally, the time and frequency factors increase energy consumption, but also increase the yield efficiency. Since the minimum SEC for ball-milling in this case study was found to be when both these factors are at the high level, increasing the yield proves to be the more important objective when the goal is

SEC reduction. Further exploration in the mechanical-feedstock generation space should therefore consider the process efficiency space in order to sustainably advance the technique.

4.2.3 Application of Models

To demonstrate the capabilities of these models, they were utilized to estimate the energy consumption to remanufacture the bracket, with a mass of 1.97 kg, in Figure 22. The process path SECs reported in Figure 20 were multiplied by the mass of the bracket that need to be remanufactured. Also, a calculation of energy consumption to cast an entirely new part from virgin material was performed by multiplying SEC from the literature by the mass of the part; thus, including the primary metal production and then the casting process. This calculation included the SEC to produce an austenitic stainless steel derived from tracking elemental material flows in approximately 60 countries (8.01•10⁷ J/kg) [96] and the SEC to cast stainless steel using green sand casting is based on a survey of a U.S. casting facility (2.61•10⁷ J/kg) [97]. Transportation energy consumption was not considered as part of this analysis. Since most remanufacturing applications target remanufacturing only a damaged or worn section of a part, Figure 23 illustrates the energy consumed to remanufacture the part based on the percentage of the part that must be remanufactured to achieve its original mass.



Figure 22. Bracket



Figure 23. Graph of energy consumption to obtain the original part mass

This analysis shows the current formulation of remanufacturing technology is more energy consumptive than casting an entirely new part from virgin material. This is primarily due to the SEC for LENS deposition, which as has already been discussed, is the largest energy component

of the remanufacturing processing paths and more development should be conducted to drive this down; either through process improvements or baseline energy reductions. However, if remanufacturing approximately 15% or less of the part were required, from an energy consumption perspective, it would behoove the manufacturer to apply a remanufacturing process to use less energy. Additionally, *the values input into the models come from laboratory-scale machines used primarily for research.* For example, the ball-balling machine used in this study had the smallest processing capacity of the feedstock production machines at 10 g per grinding jar. Based on the models presented in this work, it would be interesting to investigate the reduction in energy consumption that could be achieved through scaling these processes up for industrial utilization. One vein of study would be examining how much the baseline energy consumption would change, the intercept in numerator of Equation 14, as the amount of mass that can effectively fill the grinding jar, the m_{fill} in the denominator in Equation 14, increases.

Overall, this work provides an order of magnitude estimate of energy consumption in two potential remanufacturing process paths and could serve as a catalyzing point for researchers to build upon and manufacturers to verify using techniques such as machine learning. The models presented herein can be expanded with data beyond the current bounds and could be applied to more complex remanufacturing applications using the same methodology. Further advances in feedstock production as well as DED processing knowledge and techniques will also impact the SEC ranges achievable. This case study proves that from an energy consumption perspective, mechanically-generated feedstock is a viable alternative to gas-atomized feedstock for use in DED processing because of the statistically similar SEC of the processing paths. More advancement of DED technology is required for these remanufacturing techniques to overtake traditional part manufacturing when energy consumption is the primary consideration.

Chapter 5: Conclusions

This work proves mechanically-generated feedstock can be used in commercially available DED systems and presents the first comparison of the surface texture, microstructure, and bulk mechanical properties of parts printed with mechanically-generated powder and those printed with gas-atomized powder using a directed energy deposition (*i.e.*, LENS®) process. Overall, the powders perform differently in the printing process but resultant parts from the two are commensurate. The experimental results lead to the following conclusions:

- A predictable feedstock generation methodology is proposed that creates machining chips that are reduced to powder via oscillation ball milling.
- The mechanically-generated powder was larger and less spherical than gas-atomized powder.
- Mechanically-generated powder had a slower Hall Flow Rate and in-process flowability compared to gas-atomized powder in the LENS® powder deliver system.
- Cuboids printed from mechanically-generated powder were taller than those printed from gas-atomized powder, but more mass was deposited in the gas-atomized powder cuboids due to their higher densities.
- Densities were higher and more predictable when printing with gas-atomized feedstock but prints from mechanically-generated feedstock did achieve relative densities between 98.6% - 99.8%.
- Prints of both feedstocks resulted in parts with chemical compositions within the specifications for 316L stainless steel.
- Identical process conditions resulted in parts with similar surface texture, microstructure, and most mechanical properties for parts with different feedstocks.
- The only significant differences were in hardness and ultimate tensile strength, which is attributed to interstitial elements in the mechanically-generated feedstock.

- There are research and development opportunities in the area of generating and applying mechanically-generated powder for metal additive manufacturing.
- Mechanically-generated feedstock is a viable alternative to gas-atomized feedstock for directed energy deposition and could enable a new generation of remanufacturing processes.

The development and use of irregular powders, such as those that have been mechanicallygenerated, is still in its infancy, with many avenues to investigate. Beyond those opportunities for continued study expounded in the following section, this feedstock production methodology offers opportunities to introduce more diverse feedstocks into use for DED since users can generate their own powder from any purchasable or castable bar stock. Now that it has been determined it is feasible to use mechanically-generated feedstock in a commercially-available DED system, more work must be done to fundamentally understand the incorporation of irregular powder into the melt pool. This would help elucidate the fundamental interactions that led to the results found in this work.

Environmental footprint has become a greater consideration for manufacturers; therefore, energy consumption models will be necessary to empower widespread adoption of this remanufacturing technology in which a closed-loop manufacturing cycle could become a reality. To this end, models were formulated to estimate the SEC of two metal additive based remanufacturing process chains: one utilizing mechanically-generated and the other gasatomized feedstock. Both process chains had statistically similar SEC values, hence using mechanically-generated feedstock instead of gas-atomized feedstock is feasible. Other conclusions that can be drawn from this research include:

• The SEC associated with depositing material, using DED, is an order of magnitude greater than the two methods of generating feedstock. Therefore, significant

improvements in total energy consumption can only be achieved by studying and improving the SEC of DED.

- All of the data for the models of the two remanufacturing process chains used laboratoryscale equipment and volumes of materials. There is potential in improving the SEC through scale-up of the processes.
- It is estimated that remanufacturing the entire part (replacing 100% of the mass), with the process chains studied in this paper, consumes approximately five times as much energy green sand casting a new part from virgin material. Remanufacturing (repairing) less than 15% of the volume would consume less energy than casting a new part. This demonstrates the need for technological advances in the machine systems to be used for remanufacturing to realize the sustainability potential of the strategy.

Remanufacturing will no doubt have a consequential role to play in the future of manufacturing as sustainability considerations permeate the industry. The march of technological advancement could bring about combination systems that employ either of the methods studied in this research, enabling closed loop component repair or redesign capabilities within a single machine footprint. Such devices would be especially beneficial in supply-chain-limited outposts such as in the middle of the ocean, at the arctic poles, or even off-world. This work provides the framework upon which such a future can be realized. From here, economic analysis can highlight gaps in the body of knowledge required to adequately assess implementation. Scrutiny of the technology's impacts to human health and system safety may offer further insights to guide development. And of course, innovator ingenuity will craft the advancements necessary to launch the field into a more sustainable manufacturing paradigm.

Chapter 6: Future Work

The present research into the feasibility of mechanically-generated feedstock for DED processing was conducted with 316L stainless steel. Similar investigations should be conducted with softer and harder metals that could be used in aerospace applications. Softer metals such as copper and aluminum alloys should be studied. They could offer different challenges for researchers such as different machining [98] and ball milling [99] behaviors that could make prediction and process control more challenging. Conversely, harder materials such as titanium alloys present their own set of challenges to process that may make prediction more difficult [98,100]. The materials are currently the subject of DED studies [101,102] and introducing an alternative feedstock would allow the generation methodology to mature alongside the printing advances. Also, overcoming the challenges presented by processing these materials may require modifications to the feedstock generation process such as the introduction of lubricants or cryogenic processing that could add complexity to achieving predictability of morphology and chemistry.

On that note, there could be additional scrutiny applied to the machining chips as the product such as a more process parameters based analysis of the oxidation evolution that has only so far been studied based on the color of the metal [84]. Such a study could also be expanded to the resultant powder post-ball milling. These analyses would expand the chemical composition results of the present work to add predictive capability based on the processing conditions and allow for better compositional control.

A few preliminary experiments have been conducted that suggest it may be beneficial to model the size and shape of the resultant ball-milled powder as probability distributions. First, the validity of the models must be determined; the research question would be to identify the probability distribution that the powder particles best follow. Second, a regression analysis should be conducted to determine if the processing parameters can predict the shape and scale parameters of the resultant powder distribution. Finally, the models should be validated with additional experimentation. Being able to control the size and shape of the powder would introduce a powerful research tool as well as provide guidance for future practitioners. With this capability, researchers could begin to study the effects of different size and shape distributions on the various important feedstock properties (*e.g.* flowability, print behavior) while also opening up a realm of mathematical optimization based on the probability distribution functions (*i.e.* optimizing distribution shape and scale parameters to illicit the most yield in a desired particle size range).

Flowability differences between gas-atomized and mechanically-generated feedstocks have been studied in the present work, but a more fundamental understanding of the interactions between powder morphology and flowability would be a valuable addition to the body of knowledge. Powder morphology effects on flowability have been studied qualitatively [75] and even relatively quantified using statistical comparisons [103]. The proposed work would use the powder distribution parameters as independent variables and flowability metrics as the dependent variables in a regression analysis. Various powder distributions would be created and the flowability of each would be testing using the Hall Flow Rate as well as the mass flow rate test in a LENS® system. Models could then be created that estimate these relationships and would allow practitioners to tailor their powder to meet the needs of their prints systems. As an aside, one avenue of research worthwhile of pursuit would be to define a quantitative relationship of Hall Flow Rates to mass flowrates across multiple deposition system designs.

All the print parameters studied in the present work should be studied with different powder particle size and shape distributions as well as in different alloys. Those studies should be used to also investigate deposition rate and deposition/capture efficiency more directly. While many are working on improving print performance metrics such as porosity [104] through processing parameters and capture efficiency [95] through scanning strategies, the proposed work would offer feedstock as an additional variable. If the recommendations in this section are pursued, mechanically-generated feedstock may allow the control of the feedstock morphology so as to enable researchers to get at the fundamental deposition interaction questions. How does the particle morphology interact with the laser beam in flight? How about in the melt pool? Mechanically-generated feedstock could be used to discover the answers without the need for a large-gas atomization system. These investigations would provide the fundamentals to understand how deposition process parameters could be programmed to control resultant part properties.

This thesis has focused on using mechanically-generated feedstock in a blown-powder DED system, but there are other additive manufacturing platforms for which the feasibility of this feedstock should be tested. Powder-bed systems are the most widely deployed in industry [21] so proving feasibility on such a platform could lead to more widespread adoption. As additive friction stir technology develops, it would be interesting to attempt mechanically-generated feedstock as opposed to the bar stock currently used [105]; that would enable an entirely solidstate manufacturing cycle. Also, with regards to industrial application, a goal for this development area should be the design and building of an integrated machine that can enable closed-lifecycle additive-subtractive processing in a single footprint. This may be beyond the realm of academic goals, but there are a few ways in which academic research can assist companies or governments in creating these devices. First, the fundamental dynamics of chip collection could be studied to identify the important variables to improve the process and enable the construction of an efficient, in terms of material and energy, system. Second, at present, an oscillation ball mill was selected as the comminution method based on preliminary studies. Other comminution methods should be compared based on the following metrics: comminution rate (defined by size range for application), resultant powder controllability, and energy efficiency (defined by SEC). Lastly,

powder feeding strategies should be studied to determine the methods that most effectively transfer powder from the hopper and allow a wider range of powders to be fed through the system.

All the suggestions in this section are based on observations made during the crafting this thesis. There are opportunities for every level of researcher, from undergraduate to industrial R&D to pick up the mantle advance the field. This is the early stages of the study of mechanically-generated feedstock and therefore, a breadth of discoveries await.

References

- [1] K.R. Haapala, F. Zhao, J. Camelio, J.W. Sutherland, S.J. Skerlos, D.A. Dornfeld, I.S. Jawahir, A.F. Clarens, J.L. Rickli, A Review of Engineering Research in Sustainable Manufacturing, J. Manuf. Sci. Eng. 135 (2013) 041013. https://doi.org/10.1115/1.4024040.
- [2] D.A. Dornfeld, Moving towards green and sustainable manufacturing, Int. J. of Precis. Eng. and Manuf.-Green Tech. 1 (2014) 63–66. https://doi.org/10.1007/s40684-014-0010-7.
- [3] T. Stock, G. Seliger, Opportunities of Sustainable Manufacturing in Industry 4.0, Procedia CIRP. 40 (2016) 536–541. https://doi.org/10.1016/j.procir.2016.01.129.
- [4] M. Garetti, M. Taisch, Sustainable manufacturing: trends and research challenges, Production Planning & Control. 23 (2012) 83–104. https://doi.org/10.1080/09537287.2011.591619.
- [5] United Nations, ed., Indicators of sustainable development: guidelines and methodologies, 3rd ed, United Nations, New York, 2007.
- [6] Manufacturing Energy Consumption Survey (MECS) Analysis & Projections U.S. Energy Information Administration (EIA), (n.d.). http://www.eia.gov/consumption/manufacturing/reports/2010/decrease_use.cfm?src=%E2 %80%B9%20Consumption%20%20%20%20%20%20Manufacturing%20Energy%20Cons umption%20Survey%20(MECS)f2&src=%E2%80%B9%20Consumption%20%20%20%20%20%20%20Manufacturing%20Ener gy%20Consumption%20Survey%20(MECS)f2&src=%E2%80%B9%20Consumption%20%20%20%20%20%20%20%20Manufacturing%20Ener
 - gy%20Consumption%20Survey%20(MECS)-f2 (accessed November 11, 2015).
- [7] Annual Energy Outlook 2014, (2014).
- [8] World Energy Outlook 2015, (2015).
- [9] B.S. Linke, G.J. Corman, D.A. Dornfeld, S. Tönissen, Sustainability indicators for discrete manufacturing processes applied to grinding technology, Journal of Manufacturing Systems. 32 (2013) 556–563. https://doi.org/10.1016/j.jmsy.2013.05.005.
- [10] J.R. Duflou, K. Kellens, Renaldi, Y. Guo, W. Dewulf, Critical comparison of methods to determine the energy input for discrete manufacturing processes, CIRP Annals -Manufacturing Technology. 61 (2012) 63–66. https://doi.org/10.1016/j.cirp.2012.03.025.
- [11] D. Dornfeld, P. Wright, "Technology Wedges" for Implementing Green Manufacturing, Transactions of NAMRI/SME. 35 (2007). http://escholarship.org/uc/item/3hh38250 (accessed November 10, 2015).
- [12] K.R. Haapala, J.L. Rivera, J.W. Sutherland, Reducing environmental impacts of steel product manufacturing, in: 37th Annual North American Manufacturing Research Conference, NAMRC 37, May 19, 2009 - May 22, 2009, Society of Manufacturing Engineers, 2009: pp. 419–426.
- [13] K. Salonitis, P. Ball, Energy Efficient Manufacturing from Machine Tools to Manufacturing Systems, Procedia CIRP. 7 (2013) 634–639. https://doi.org/10.1016/j.procir.2013.06.045.
- [14] C. Yuan, D. Dornfeld, Reducing the Environmental Footprint and Economic Costs of Automotive Manufacturing through an Alternative Energy Supply, Laboratory for Manufacturing and Sustainability. (2009). http://escholarship.org/uc/item/1tv7d8j3 (accessed November 10, 2015).
- [15] K. Fang, N. Uhan, F. Zhao, J.W. Sutherland, A new approach to scheduling in manufacturing for power consumption and carbon footprint reduction, Journal of Manufacturing Systems. 30 (2011) 234–240. https://doi.org/10.1016/j.jmsy.2011.08.004.
- [16] L. Clemon, A. Sudradjat, M. Jaquez, A. Krishna, M. Rammah, D. Dornfeld, Precision and Energy Usage for Additive Manufacturing, Proceedings of the ASME 2013 International

Mechanical Engineering Congress & Exposition. (2013). http://escholarship.org/uc/item/4c11k74w (accessed February 10, 2016).

- [17] Jeremy Faludi, Cindy Bayley, Suraj Bhogal, Myles Iribarne, Comparing environmental impacts of additive manufacturing vs traditional machining via life-cycle assessment, Rapid Prototyping Journal. 21 (2015) 14–33. https://doi.org/10.1108/RPJ-07-2013-0067.
- [18] K. Ramani, D. Ramanujan, W.Z. Bernstein, F. Zhao, J. Sutherland, C. Handwerker, J.-K. Choi, H. Kim, D. Thurston, Integrated Sustainable Life Cycle Design: A Review, J. Mech. Des. 132 (2010). https://doi.org/10.1115/1.4002308.
- [19] J.R. Duflou, J.W. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild, K. Kellens, Towards energy and resource efficient manufacturing: A processes and systems approach, CIRP Annals. 61 (2012) 587–609. https://doi.org/10.1016/j.cirp.2012.05.002.
- [20] H.-S. Yoon, J.-Y. Lee, H.-S. Kim, M.-S. Kim, E.-S. Kim, Y.-J. Shin, W.-S. Chu, S.-H. Ahn, A comparison of energy consumption in bulk forming, subtractive, and additive processes: Review and case study, Int. J. of Precis. Eng. and Manuf.-Green Tech. 1 (2014) 261–279. https://doi.org/10.1007/s40684-014-0033-0.
- [21] Wohlers Associates, Wohlers Report 2019: 3D Printing and Additive Manufacturing State of the Industry, 2019.
- [22] ISO/TC 261, ASTM F42, ISO/ASTM 52900:2015(E) Standard Terminology for Additive Manufacturing General Principles Terminology, (2015).
- [23] W.E. Frazier, Metal Additive Manufacturing: A Review, J. Mater. Eng. Perform. 23 (2014) 1917–1928. https://doi.org/10.1007/s11665-014-0958-z.
- [24] C. Atwood, M. Griffith, L. Harwell, E. Schlienger, M. Ensz, J. Smugeresky, T. Romero, D. Greene, D. Reckaway, Laser engineered net shaping (LENS[™]): A tool for direct fabrication of metal parts, ICALEO. 1998 (1998) E1–E7. https://doi.org/10.2351/1.5059147.
- [25] M.L. Griffith, M.T. Ensz, J.D. Puskar, C.V. Robino, J.A. Brooks, J.A. Philliber, J.E. Smugeresky, W.H. Hofmeister, Understanding the microstructure and properties of components fabricated by Laser Engineered Net Shaping (LENS), in: Solid Freeform and Additive Fabrication -2000, April 24, 2000 - April 26, 2000, Materials Research Society, 2000: pp. 9–20.
- [26] A. Saboori, A. Aversa, G. Marchese, S. Biamino, M. Lombardi, P. Fino, Application of Directed Energy Deposition-Based Additive Manufacturing in Repair, Applied Sciences. 9 (2019) 3316. https://doi.org/10.3390/app9163316.
- [27] M. Matsumoto, S. Yang, K. Martinsen, Y. Kainuma, Trends and research challenges in remanufacturing, Int. J. of Precis. Eng. and Manuf.-Green Tech. 3 (2016) 129–142. https://doi.org/10.1007/s40684-016-0016-4.
- [28] W. Liu, J.N. DuPont, Fabrication of functionally graded TiC/Ti composites by Laser Engineered Net Shaping, Scripta Materialia. 48 (2003) 1337–1342. https://doi.org/10.1016/S1359-6462(03)00020-4.
- [29] J.S. Zuback, T.A. Palmer, T. DebRoy, Additive manufacturing of functionally graded transition joints between ferritic and austenitic alloys, Journal of Alloys and Compounds. 770 (2019) 995–1003. https://doi.org/10.1016/j.jallcom.2018.08.197.
- [30] B.E. Carroll, R.A. Otis, J.P. Borgonia, J. Suh, R.P. Dillon, A.A. Shapiro, D.C. Hofmann, Z.-K. Liu, A.M. Beese, Functionally graded material of 304L stainless steel and inconel 625 fabricated by directed energy deposition: Characterization and thermodynamic modeling, Acta Materialia. 108 (2016) 46–54. https://doi.org/10.1016/j.actamat.2016.02.019.
- [31] J.L. Rickli, A.K. Dasgupta, G.P. Dinda, A descriptive framework for additive remanufacturing systems, International Journal of Rapid Manufacturing. 4 (2014) 199–218. https://doi.org/10.1504/IJRAPIDM.2014.066043.

- [32] Y. Lahrour, D. Brissaud, A Technical Assessment of Product/Component Remanufacturability for Additive Remanufacturing, Procedia CIRP. 69 (2018) 142–147. https://doi.org/10.1016/j.procir.2017.11.105.
- [33] J. Um, M. Rauch, J.-Y. Hascoët, I. Stroud, STEP-NC compliant process planning of additive manufacturing: remanufacturing, Int J Adv Manuf Technol. 88 (2017) 1215–1230. https://doi.org/10.1007/s00170-016-8791-1.
- [34] S.T.M. Kin, S.K. Ong, A.Y.C. Nee, Remanufacturing Process Planning, Procedia CIRP. 15 (2014) 189–194. https://doi.org/10.1016/j.procir.2014.06.087.
- [35] V.T. Le, H. Paris, G. Mandil, The development of a strategy for direct part reuse using additive and subtractive manufacturing technologies, Additive Manufacturing. 22 (2018) 687–699. https://doi.org/10.1016/j.addma.2018.06.026.
- [36] S. Ford, M. Despeisse, Additive manufacturing and sustainability: an exploratory study of the advantages and challenges, Journal of Cleaner Production. 137 (2016) 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150.
- [37] D.-G. Ahn, Direct metal additive manufacturing processes and their sustainable applications for green technology: A review, Int. J. of Precis. Eng. and Manuf.-Green Tech. 3 (2016) 381–395. https://doi.org/10.1007/s40684-016-0048-9.
- [38] J.M. Wilson, C. Piya, Y.C. Shin, F. Zhao, K. Ramani, Remanufacturing of turbine blades by laser direct deposition with its energy and environmental impact analysis, Journal of Cleaner Production. 80 (2014) 170–178. https://doi.org/10.1016/j.jclepro.2014.05.084.
- [39] G. Payne, A. Ahmad, S. Fitzpatrick, P. Xirouchakis, W. Ion, M. Wilson, Remanufacturing H13 steel moulds and dies using laser metal deposition, in: 14th International Conference on Manufacturing Research, GBR, 2016: pp. 93–98. https://doi.org/10.3233/978-1-61499-668-2-93 (accessed April 16, 2020).
- [40] Z.F. Li, C.K. Du, S.Q. Huang, Research on Remanufacturing of Gear Reducer, Advanced Materials Research. 945–949 (2014) 3045–3049. https://doi.org/10.4028/www.scientific.net/AMR.945-949.3045.
- [41] C.K. Sudbrack, B.A. Lerch, T.M. Smith, I.E. Locci, D.L. Ellis, A.C. Thompson, B. Richards, Impact of Powder Variability on the Microstructure and Mechanical Behavior of Selective Laser Melted Alloy 718, in: Proceedings of the 9th International Symposium on Superalloy 718 & Derivatives: Energy, Aerospace, and Industrial Applications, Springer, Cham, 2018: pp. 89–113. https://doi.org/10.1007/978-3-319-89480-5_5.
- [42] B.M. Morrow, T.J. Lienert, C.M. Knapp, J.O. Sutton, M.J. Brand, R.M. Pacheco, V. Livescu, J.S. Carpenter, G.T. Gray, Impact of Defects in Powder Feedstock Materials on Microstructure of 304L and 316L Stainless Steel Produced by Additive Manufacturing, Metall and Mat Trans A. 49 (2018) 3637–3650. https://doi.org/10.1007/s11661-018-4661-9.
- [43] M.K. Thompson, G. Moroni, T. Vaneker, G. Fadel, R.I. Campbell, I. Gibson, A. Bernard, J. Schulz, P. Graf, B. Ahuja, F. Martina, Design for Additive Manufacturing: Trends, opportunities, considerations, and constraints, CIRP Annals. 65 (2016) 737–760. https://doi.org/10.1016/j.cirp.2016.05.004.
- [44] K.L. Terrassa, J.C. Haley, B.E. MacDonald, J.M. Schoenung, Reuse of powder feedstock for directed energy deposition, Powder Technology. 338 (2018) 819–829. https://doi.org/10.1016/j.powtec.2018.07.065.
- [45] H. Irrinki, M. Dexter, B. Barmore, R. Enneti, S. Pasebani, S. Badwe, J. Stitzel, R. Malhotra, S.V. Atre, Effects of Powder Attributes and Laser Powder Bed Fusion (L-PBF) Process Conditions on the Densification and Mechanical Properties of 17-4 PH Stainless Steel, JOM. 68 (2016) 860–868. https://doi.org/10.1007/s11837-015-1770-4.
- [46] M. Ansari, A. Mohamadizadeh, Y. Huang, V. Paserin, E. Toyserkani, Laser directed energy deposition of water-atomized iron powder: Process optimization and microstructure of single-tracks, Optics & Laser Technology. 112 (2019) 485–493. https://doi.org/10.1016/j.optlastec.2018.11.054.

- [47] M. Moorehead, K. Bertsch, M. Niezgoda, C. Parkin, M. Elbakhshwan, K. Sridharan, C. Zhang, D. Thoma, A. Couet, High-throughput synthesis of Mo-Nb-Ta-W high-entropy alloys via additive manufacturing, Materials & Design. 187 (2020) 108358. https://doi.org/10.1016/j.matdes.2019.108358.
- [48] M.A. Jackson, A. Van Asten, J.D. Morrow, S. Min, F.E. Pfefferkorn, Energy Consumption Model for Additive-Subtractive Manufacturing Processes with Case Study, Int. J. of Precis. Eng. and Manuf.-Green Tech. 5 (2018) 459–466. https://doi.org/10.1007/s40684-018-0049-y.
- [49] K. Mahmood, W.U.H. Syed, A.J. Pinkerton, Innovative reconsolidation of carbon steel machining swarf by laser metal deposition, Optics and Lasers in Engineering. 49 (2011) 240–247. https://doi.org/10.1016/j.optlaseng.2010.09.014.
- [50] K. Mahmood, N. Stevens, A.J. Pinkerton, Laser surface modification using Inconel 617 machining swarf as coating material, Journal of Materials Processing Technology. 212 (2012) 1271–1280. https://doi.org/10.1016/j.jmatprotec.2012.01.014.
- [51] B. Fullenwider, P. Kiani, J.M. Schoenung, K. Ma, Two-stage ball milling of recycled machining chips to create an alternative feedstock powder for metal additive manufacturing, Powder Technology. 342 (2019) 562–571. https://doi.org/10.1016/j.powtec.2018.10.023.
- [52] S. Kara, W. Li, Unit process energy consumption models for material removal processes, CIRP Annals - Manufacturing Technology. 60 (2011) 37–40. https://doi.org/10.1016/j.cirp.2011.03.018.
- [53] Y. He, F. Liu, T. Wu, F.-P. Zhong, B. Peng, Analysis and estimation of energy consumption for numerical control machining, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. 226 (2012) 255–266. https://doi.org/10.1177/0954405411417673.
- [54] N. Diaz, E. Redelsheimer, D. Dornfeld, Energy consumption characterization and reduction strategies for milling machine tool use, in: 18th CIRP International Conference on Life Cycle Engineering: Glocalized Solutions for Sustainability in Manufacturing, May 2, 2011 -May 4, 2011, Springer Science and Business Media, LLC, 2011: pp. 263–267. https://doi.org/10.1007/978-3-642-19692-8-46.
- [55] L. Li, J. Yan, Z. Xing, Energy requirements evaluation of milling machines based on thermal equilibrium and empirical modelling, Journal of Cleaner Production. 52 (2013) 113–121. https://doi.org/10.1016/j.jclepro.2013.02.039.
- [56] S. Pervaiz, I. Deiab, A. Rashid, M. Nicolescu, An experimental analysis of energy consumption in milling strategies, in: 2012 International Conference on Computer Systems and Industrial Informatics, ICCSII 2012, December 18, 2012 - December 20, 2012, IEEE Computer Society, 2012: p. Samsung; EMARATECH. https://doi.org/10.1109/ICCSII.2012.6454527.
- [57] J.B. Dahmus, T.G. Gutowski, An environmental analysis of machining, in: 2004 ASME International Mechanical Engineering Congress and Exposition, IMECE 2004, November 13, 2004 - November 19, 2004, American Society of Mechanical Engineers, 2004: pp. 643–652. https://doi.org/10.1115/IMECE2004-62600.
- [58] P.T. Mativenga, M.F. Rajemi, Calculation of optimum cutting parameters based on minimum energy footprint, CIRP Annals - Manufacturing Technology. 60 (2011) 149–152. https://doi.org/10.1016/j.cirp.2011.03.088.
- [59] R. Neugebauer, A. Schubert, B. Reichmann, M. Dix, Influence exerted by tool properties on the energy efficiency during drilling and turning operations, CIRP Journal of Manufacturing Science and Technology. 4 (2011) 161–169. https://doi.org/10.1016/j.cirpj.2011.06.011.

- [60] S. Kara, W. Li, Unit process energy consumption models for material removal processes, CIRP Annals - Manufacturing Technology. 60 (2011) 37–40. https://doi.org/10.1016/j.cirp.2011.03.018.
- [61] H. Hashimoto, R. Watanabe, Model Simulation of Energy Consumption during Vibratory Ball Milling of Metal Powder, Mater. Trans., JIM. 31 (1990) 219–224. https://doi.org/10.2320/matertrans1989.31.219.
- [62] M. Magini, A. Iasonna, F. Padella, Ball milling: An experimental support to the energy transfer evaluated by the collision model, Scripta Materialia. 34 (1996) 13–19. https://doi.org/10.1016/1359-6462(95)00465-3.
- [63] D.W. Fuerstenau, A.-Z.M. Abouzeid, The energy efficiency of ball milling in comminution, International Journal of Mineral Processing. 67 (2002) 161–185. https://doi.org/10.1016/S0301-7516(02)00039-X.
- [64] J.M.C. Azevedo, A. CabreraSerrenho, J.M. Allwood, Energy and material efficiency of steel powder metallurgy, Powder Technology. 328 (2018) 329–336. https://doi.org/10.1016/j.powtec.2018.01.009.
- [65] W.R. Morrow, H. Qi, I. Kim, J. Mazumder, S.J. Skerlos, Environmental aspects of laserbased and conventional tool and die manufacturing, Journal of Cleaner Production. 15 (2007) 932–943. https://doi.org/10.1016/j.jclepro.2005.11.030.
- [66] F.L. Bourhis, O. Kerbrat, J.-Y. Hascoet, P. Mognol, Sustainable manufacturing: evaluation and modeling of environmental impacts in additive manufacturing, International Journal of Advanced Manufacturing Technology. 69 (2013) 1927–1939. https://doi.org/10.1007/s00170-013-5151-2.
- [67] F04 Committee, ASTM F1877-16 Standard Practice for Characterization of Particles, ASTM International, n.d. https://doi.org/10.1520/F1877-16.
- [68] B09 Committee, ASTM B962-17 Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes Principle, ASTM International, n.d. https://doi.org/10.1520/B0962-17.
- [69] ASTM International, B214-16 Standard Test Method for Sieve Analysis of Metal Powders, ASTM International, West Conshohocken, PA, 2016. http://www.astm.org/cgibin/resolver.cgi?B214-16 (accessed March 1, 2019).
- [70] C.F.J. Wu, M.S. Hamada, Experiments: Planning, Analysis, and Optimization, 2nd ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 2009.
- [71] A.I. Gusev, A.S. Kurlov, Production of nanocrystalline powders by high-energy ball milling: model and experiment, Nanotechnology. 19 (2008) 265302. https://doi.org/10.1088/0957-4484/19/26/265302.
- [72] B09 Committee, ASTM B213-17 Test Methods for Flow Rate of Metal Powders Using the Hall Flowmeter Funnel, ASTM International, n.d. https://doi.org/10.1520/B0213-17.
- [73] R. Hogg, M. I. Turek, E. Kaya, The Role of Particle Shape in Size Analysis and the Evaluation of Comminution Processes, Particulate Science & Technology. 22 (2004) 355– 366. https://doi.org/10.1080/02726350490516019.
- [74] H.N. Rosen, H.M. Hulburt, Size Analysis of Irregular Shaped Particles in Sieving, Industrial & Engineering Chemistry Fundamentals. 9 (1970) 658–661.
- [75] X. Fu, D. Huck, L. Makein, B. Armstrong, U. Willen, T. Freeman, Effect of particle shape and size on flow properties of lactose powders, Particuology. 10 (2012) 203–208. https://doi.org/10.1016/j.partic.2011.11.003.
- [76] G.C. Chow, Tests of Equality Between Sets of Coefficients in Two Linear Regressions, Econometrica. 28 (1960) 591–605. https://doi.org/10.2307/1910133.
- [77] M. Ma, Z. Wang, D. Wang, X. Zeng, Control of shape and performance for direct laser fabrication of precision large-scale metal parts with 316L Stainless Steel, Optics & Laser Technology. 45 (2013) 209–216. https://doi.org/10.1016/j.optlastec.2012.07.002.

- [78] S.J. Wolff, H. Wu, N. Parab, C. Zhao, K.F. Ehmann, T. Sun, J. Cao, In-situ high-speed Xray imaging of piezo-driven directed energy deposition additive manufacturing, Scientific Reports. 9 (2019) 1–14. https://doi.org/10.1038/s41598-018-36678-5.
- [79] S. Wolff, T. Lee, E. Faierson, K. Ehmann, J. Cao, Anisotropic properties of directed energy deposition (DED)-processed Ti–6Al–4V, Journal of Manufacturing Processes. 24 (2016) 397–405. https://doi.org/10.1016/j.jmapro.2016.06.020.
- [80] M. Fujishima, Y. Oda, R. Ashida, K. Takezawa, M. Kondo, Study on factors for pores and cladding shape in the deposition processes of Inconel 625 by the directed energy deposition (DED) method, CIRP Journal of Manufacturing Science and Technology. 19 (2017) 200–204. https://doi.org/10.1016/j.cirpj.2017.04.003.
- [81] B. Zheng, J.C. Haley, N. Yang, J. Yee, K.W. Terrassa, Y. Zhou, E.J. Lavernia, J.M. Schoenung, On the evolution of microstructure and defect control in 316L SS components fabricated via directed energy deposition, Materials Science and Engineering: A. 764 (2019) 138243. https://doi.org/10.1016/j.msea.2019.138243.
- [82] M.A. Jackson, J.D. Morrow, D.J. Thoma, F.E. Pfefferkorn, A comparison of 316 L stainless steel parts manufactured by directed energy deposition using gas-atomized and mechanically-generated feedstock, CIRP Annals. (2020). https://doi.org/10.1016/j.cirp.2020.04.042.
- [83] A01 Committee, ASTM A240/A240M-18 Specification for Chromium and Chromium-Nickel Stainless Steel Plate, Sheet, and Strip for Pressure Vessels and for General Applications, ASTM International, n.d. https://doi.org/10.1520/A0240_A0240M-18.
- [84] D.J. McAdam, G.W. Geil, Rate of oxidation of steels as determined from interference colors of oxide films, Journal of Research of the National Bureau of Standards. 23 (1939) 63. https://doi.org/10.6028/jres.023.041.
- [85] G. Meric de Bellefon, K.M. Bertsch, M.R. Chancey, Y.Q. Wang, D.J. Thoma, Influence of solidification structures on radiation-induced swelling in an additively-manufactured austenitic stainless steel, Journal of Nuclear Materials. 523 (2019) 291–298. https://doi.org/10.1016/j.jnucmat.2019.06.012.
- [86] R.K. Leach, D. Bourell, S. Carmignato, A. Donmez, N. Senin, W. Dewulf, Geometrical metrology for metal additive manufacturing, CIRP Annals. 68 (2019) 677–700. https://doi.org/10.1016/j.cirp.2019.05.004.
- [87] M. Ziętala, T. Durejko, M. Polański, I. Kunce, T. Płociński, W. Zieliński, M. Łazińska, W. Stępniowski, T. Czujko, K.J. Kurzydłowski, Z. Bojar, The microstructure, mechanical properties and corrosion resistance of 316L stainless steel fabricated using laser engineered net shaping, Materials Science and Engineering: A. 677 (2016) 1–10. https://doi.org/10.1016/j.msea.2016.09.028.
- [88] T.R. Smith, J.D. Sugar, C. San Marchi, J.M. Schoenung, Strengthening mechanisms in directed energy deposited austenitic stainless steel, Acta Materialia. 164 (2019) 728–740. https://doi.org/10.1016/j.actamat.2018.11.021.
- [89] C. Cui, V. Uhlenwinkel, A. Schulz, H.-W. Zoch, Austenitic Stainless Steel Powders with Increased Nitrogen Content for Laser Additive Manufacturing, Metals. 10 (2020) 61. https://doi.org/10.3390/met10010061.
- [90] M.A. Jackson, A. Kim, J.A. Manders, D.J. Thoma, F.E. Pfefferkorn, Production of mechanically-generated 316L stainless steel feedstock and its performance in directed energy deposition processing as compared to gas-atomized powder, CIRP Journal of Manufacturing Science and Technology. (2020). https://doi.org/10.1016/j.cirpj.2020.05.014.
- [91] S.P. Mates, G. Settles, High-speed imaging of liquid metal atomization by two different close-coupled nozzles, Adv. Powder Metall. Part. Mater. 1 (1996) 67–80.
- [92] P. Zhu, S. Zhang, J. Xu, X. Zhu, X. Zhao, Effects of processing parameters of gas atomization on particle size of 316L stainless steel powders, Materials Science and

Engineering of Powder Metallurgy. 15 (2010). http://en.cnki.com.cn/Article_en/CJFDTotal-FMGC201004016.htm (accessed April 2, 2020).

- [93] Z. Liu, F. Ning, W. Cong, Q. Jiang, T. Li, H. Zhang, Y. Zhou, Energy Consumption and Saving Analysis for Laser Engineered Net Shaping of Metal Powders, Energies. 9 (2016) 763. https://doi.org/10.3390/en9100763.
- [94] R. Koike, S. Takemura, Y. Kakinuma, M. Kondo, Enhancement of powder supply efficiency in directed energy deposition based on gas-solid multiphase-flow simulation, Procedia CIRP. 78 (2018) 133–137. https://doi.org/10.1016/j.procir.2018.09.061.
- [95] M. Soshi, K. Odum, G. Li, Investigation of novel trochoidal toolpath strategies for productive and efficient directed energy deposition processes, CIRP Annals. 68 (2019) 241–244. https://doi.org/10.1016/j.cirp.2019.04.112.
- [96] J. Johnson, B.K. Reck, T. Wang, T.E. Graedel, The energy benefit of stainless steel recycling, Energy Policy. 36 (2008) 181–192. https://doi.org/10.1016/j.enpol.2007.08.028.
- [97] R. Eppich, Energy Use in Selected Metalcasting FAcilities 2003, U.S. Department of Energy; Eppich Technologies, 2004. https://www.energy.gov/sites/prod/files/2013/11/f4/energyuseinselectedmetalcasting_5_28 _04.pdf.
- [98] G.S. Goindi, P. Sarkar, Dry machining: A step towards sustainable machining Challenges and future directions, Journal of Cleaner Production. 165 (2017) 1557–1571. https://doi.org/10.1016/j.jclepro.2017.07.235.
- [99] O.V. Rofman, A.S. Prosviryakov, A.V. Mikhaylovskaya, A.D. Kotov, A.I. Bazlov, V.V. Cheverikin, Processing and Microstructural Characterization of Metallic Powders Produced from Chips of AA2024 Alloy, JOM. 71 (2019) 2986–2995. https://doi.org/10.1007/s11837-019-03581-x.
- [100]C.J. Lu, J. Zhang, Z.Q. Li, Structural evolution of titanium powder during ball milling in different atmospheres, Journal of Alloys and Compounds. 381 (2004) 278–283. https://doi.org/10.1016/j.jallcom.2004.03.130.
- [101]A. Dass, A. Moridi, State of the Art in Directed Energy Deposition: From Additive Manufacturing to Materials Design, Coatings. 9 (2019) 418. https://doi.org/10.3390/coatings9070418.
- [102]F.M. Sciammarella, M. Gonser, M. Styrcula, Laser Additive Manufacturing of Pure Copper, Rapid. (2013) 1240–1248.
- [103]P. Kiani, U. Scipioni Bertoli, A.D. Dupuy, K. Ma, J.M. Schoenung, A Statistical Analysis of Powder Flowability in Metal Additive Manufacturing, Advanced Engineering Materials. n/a (2020) 2000022. https://doi.org/10.1002/adem.202000022.
- [104]F.M. Sciammarella, B. Salehi Najafabadi, Processing Parameter DOE for 316L Using Directed Energy Deposition, Journal of Manufacturing and Materials Processing. 2 (2018) 61. https://doi.org/10.3390/jmmp2030061.
- [105]H.Z. Yu, M.E. Jones, G.W. Brady, R.J. Griffiths, D. Garcia, H.A. Rauch, C.D. Cox, N. Hardwick, Non-beam-based metal additive manufacturing enabled by additive friction stir deposition, Scripta Materialia. 153 (2018) 122–130. https://doi.org/10.1016/j.scriptamat.2018.03.025.

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Appendices

Appendix A – LENS Optomec MR7 Datasheet



How the LENS system works:

LENS systems utilize a high-power laser together with powdered metals to build fully dense structures directly from a 3-dimensional CAD solid model. The CAD model is automatically sliced into a tool-path, which instructs the LENS machine how to build the part. The part is constructed layer by layer under the control of software that monitors a variety of parameters to ensure geometric and mechanical integrity. The LENS process is housed in a chamber which is purged with argon such that the oxygen level stays below 10 parts per million to ensure there is no impurity pick-up during deposition. The metal powder is fed to the process by Optomec's proprietary powder-feed system, which is able to flow small quantities of powder very precisely. When complete, the part is removed and can be heat-treated, Hot-Isostatic-Pressed, machined, or finished in any other manner.







produced by the LENS process

LENS MR-7 Typical Performance Parameters

Process Work Envelope	300 x 300 x 300 mm
Enclosure	Class I Laser Enclosure, Hermetically sealed to maintain process environment and safety
Motion Control	3-axes standard: XY linear table motion Z gantry motion Additional Axis Optional rotary axis All axes under full CNC control
Positional Accuracy	+/- 0.015mm
Linear Resolution	+/- 0.009mm
Motion Velocity	60 mm/s
Deposition Rate per Hour	200 to 300 g/kW, material dependent
Gas Purification System	Unit maintains 02 level ≤10 ppm
Dual Powder Feeders	Each feeder holds up to 2 liters of powder Gradient capability Optionally up to four feeders
Lasers	500W or 1kW IPG Fiber Laser
Software	Software Workstation Control; PartPrep slicing
Thermal Imager	Optional Thermal Imager Dual Wavelength Pyrometer Image Acquisition and Analysis Software
Enclosure Dimensions	$3 \times 1.5 \times 2.5$ m without gas purification system or laser
Monitoring and Controls	Optional SMART-AM [®] melt pool sensor Optional Thermal Imager

ABOUT OPTOMEC

Optomec® is a privately-held, rapidly growing supplier of Additive Manufacturing systems. Optomec's patented Aerosol Jet Systems for printed electronics and LENS 3D Printers for metal components are used by industry to reduce product cost and improve performance. Together, these unique printing solutions work with the broadest spectrum of functional materials, ranging from electronic inks to structural metals and even biological matter. Optomec has more than 300 marquee customers around the world, targeting production applications in the Electronics, Energy, Life Sciences and Aerospace industries. For more information about Optomec, visit http://www.optomec.com.



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Appendix B – HAAS TM-1 Vertical Milling Machine

X Y Z Table Length Width T-Slots T-Slot Width Number of T-Slots	30° ,762 mm 12* 305 mm 16" 406 mm 47.75" 1213 mm 10.5" 268 mm
Y Z Table Length Width T-Slots T-Slot Width Number of T-Slots	,762 mm 12* 305 mm 16* 406 mm 47.75* 1 213 mm 10.5* 268 mm
Y Z Table Length Width T-Slots T-Slot Width Number of T-Slots	12" 305 mm 16" 406 mm 47.75" 1213 mm 10.5" 268 mm
Z Table Length Width T-Slots T-Slot Width Number of T-Slots	16" 406 mm 47.75" 1 213 mm 10.5" 268 mm
Table Length Width T-Slots T-Slot Width Number of T-Slots	406 mm 47.75* 1213 mm 10.5* 268 mm
Table Length Width T-Slots T-Slot Width Number of T-Slots	47.75* 1213 mm 10.5* 268 mm
Length Width T-Slots T-Slot Width Number of T-Slots	47.75" 1 213 mm 10.5" 268 mm
Width T-Slots T-Slot Width Number of T-Slots	1213 mm 10.5" 268 mm
T-Slots T-Slot Width Number of T-Slots	268 mm
T-Slots T-Slot Width Number of T-Slots	
T-Slot Width Number of T-Slots	
Number of T-Slots	0.625"
Number of T-Slots	15.875 mm
	3
Center Distance	4.00"
Spindle	102 11111
Taper Size	#40 Taper
Speed	0-4,000 rpm
Transmission Direct Spe	ed, Belt Drive
Spindle Motor Max Rating	7.5 hp
	5.6 kW
Spindle Nose to Table Top	4-20*
	102 - 508 mm
	A

C-

Brushless Axis Motors	SR SA AND SA
Max Rating	3.0 hp 2.24 kW
Max Thrust Rating	2,000 lb 8 896 N
eedrates	
X-Axis Rapids	200 ipm 5.1 m/min
Y-Axis Rapids	200 ipm 5.1 m/min
Z-Axis Rapids	200 ipm 5.1 m/min
Max Cutting	200 ipm 5.1 m/min
ool Changer (Optional)	
Capacity	10
Туре	CT 40
Max Tool Diameter	3.5" 89 mm
Max Tool Weight	12 lb 5.4 kg
ieneral	
Machine Weight	3,300 lb 1 497 kg
Air Required	4 scfm, 100 psi 113 lpm, 6.9 bar
Power Required (min)	208 VAC 3-Phase 240 VAC 1-Phase
Footprint	85" x 64" 2 159 x 1 626 mm

Dimensions

А.	Max Operating Height	109.0"	2767 mm
Β.	Monitor Height	68.0"	1727 mm
C.	Chip Tray Width	52.0"	1 321 mm
D.	Max Operating Width	84.5*	2146 mm
E.	Table Height	36.0*	914 mm

Machine depth is 64* (1 626 mm) and requires additional 35* (889 mm) to open rear service panel.

Warranty: 6 Months Parts and Labor

ppendi 4490	x C – A490-032E -032EH25-	H25-08M Sho -08M Ca	ulder Mill	Customize	Build tool asse
Tool item	Matching inserts (109)	Matching products	- machine direction ((52) Spare/	included parts (2
Drice info	rmation	Spe	cific representation	10	
List price	SD		ISO	125-08M	Material Id
-	1 +))) Add	ANSI A490-032EF	125-08M	EAN 26416898



Generic representation

Product data

Cutting diameter (DC) 31.75 mm

Cutting item count (CICT) 4

Part 2 of cutting item interface identifiers (CUTINTMASTER) CoroMill 490 -size 08 (490R-08T308..)

Centre cutting capability (CCC) false

Maximum ramping angle (RMPXFFW) 0 deg

Cutting pitch differential (CPDF) false

Adaptive interface machine direction (ADINTMS) Coromant EH -inch - E25

Damping property (DPC) false

Coolant pressure (CP) 10 bar

Functional diameter (DFC) 17.66 mm

Torque (TQ) 1.2 Nm

Rotational speed maximum (RPMX) 34100 1/min

Sensor embedded property (SEP) 0

Release pack id (RELEASEPACK) 13.2

Cutting item count (CICTTOT) 4

Clamping type code (MTP) S

Depth of cut maximum (APMXPFW) 5.486 mm

Depth of cut maximum (APMXFFW) 5.486 mm

 $\begin{array}{l} \text{Maximum plunge depth} (\text{AZ}) \\ 0 \ mm \end{array}$

Peripheral effective cutting edge count (ZEFP) 4

Hand (HAND) R

Coolant entry style code (CNSC) 1: axial concentric entry

Connection diameter (DCON) 24.5 mm

Functional length (LF) 35 mm

Body material code (BMC) Steel

Weight of item (WT) 0.144 kg

Life cycle state (LCS) Released

Appendix D - 490-08T204E-ML 2030 Cutting Insert 490R-08T304E-ML 2030 Calculate cutt Calculate cutting data

CoroMill® 490 insert for milling

Insert	Matching tools (164)	Similar products (17)		
Price i	nformation	Generi	c representation Ordering code	
List pr 27.25	ice USD		ISO 490R-08T304E-ML 2030	Material Id 5762199
-	1 +))) Add	490R-08T304E-ML 2030	EAN 12437493

Build tool assembly



Generic representation

Product data

Material classification level 1 (TMC1ISO)
PMS

Insert size and shape (CUTINTSIZESHAPE) CoroMill 490 -08T3

Inscribed circle diameter (IC) 8.5 mm

Cutting edge effective length (LE) 5.6 mm

Corner radius (RE) 0.4 mm

Hand (HAND) R

Substrate (SUBSTRATE) HC

Insert thickness (S) 3.3 mm

Depth of cut maximum (APMX) 5.5 mm

Life cycle state (LCS) Released Insert mounting style code (IFS) 3

Cutting edge count (CEDC) 4

Insert shape code (SC) S

Wiper edge length (BS) 1.5 mm

Major cutting edge angle (KRINS) 90 deg

Grade (GRADE) 2030

Coating (COATING) PVD TIALN+TIN

Weight of item (WT) 0.002 kg

Sensor embedded property (SEP) 0

Release pack id (RELEASEPACK) 09.2

Start values



fz 0.13 mm(0.08-0.18) vc 245 m/min(255-240)

Appendix E – Rigid 6 Gallon Shop Vacuum



WD0670 6 Gallon High Performance Wet/Dry Vac

The RIDGID® 6 Gallon High Performance Wet/Dry Vac is designed for DIY'ers who want a traditionally styled, compact vac that delivers the powerful performance and rugged durability required for job site clean-up. This vacuum has a 6 gallon drum size that results in a more compact design that requires less storage space on a service truck or in a work shop or garage. And its top carry handle makes transporting easier than ever. It features the Patented Qwik Lock® Filter Fastening System that makes installing or removing your filter quick, easy & secure.

FEATURES	BENEFITS
 Powerful 3.5 Peak HP Performance 	Great for general purpose use around the garage and shop. Integrated blowing port for added versatility.
6 Gallon Drum	Provides capacity for clean-up of spills & messes at job-sites and busy shops.
 Rugged Casters with On-Board Accessory Storage 	Moves easily over various terrain. Storage space for 4 accessories.
Lower Center of Gravity	Design lowers the center of gravity to help prevent tipping. Compact design stores more easily.
 Patented Qwik Lock[®] Filter Fastening System 	Makes installing or removing your filter quick, easy and secure. Replacement filter VF4000.
 1-7/8" x 7' Tug-A-Long[®] Positive Locking Hose— 	Locks onto vac for uninterrupted cleaning, won't pull loose during use. Hose can be stored on vac.
Top Carry Handle	Large carrying handle makes transportation easy.
Included Accessories	1-7/8" x 7" Tug-A-Long® Locking Hose, 2 Extension Wands, Utility Nozzle & 1-Layer Paper Pleated Filter
Accepts Vacuum Bag	Simply remove the dust bag from the drum, allowing for quick, easy and clean debris disposal Accepts Dust Bag VF3503, Sold Separately.



SPECIFICAT	TONS
Drum Size	6 gal.
Motor	
- Peak Horsepower	3.5
- Air Watts	124
- Voltage	120
- Amps	7.8
Cord Length	10'
Construction High Imp	act Polypropylene
U.L.Listed	Yes
Filter	Pleated Paper
Replacement Filters	VF4000
	VF5000
	VF6000
Optional Wet Filter	VF7000
Optional Vacuum Bag	VF3503
Accessory Size	1-7/8*
Shipping Weight	15.1 lbs.
Net Weight	12,6 lbs.





Tug-A-Long® Locking Hose



Great In The Workshop & Garage



RIDGID

FULL LIFETIME

Appendix F – Retsch Mixer Mill MM 400 Mixer Mill MM 400

General Information

The mixer mill MM 400 is a compact versatile bench-top unit, which has been developed specially for dry, wet and cryogenic grinding of small amounts of sample.

It can mix and homogenize powders and suspensions in only a few seconds. It is also perfectly suitable for the disruption of biological cells as well as for DNA/RNA and protein extraction. With its high performance and great flexibility the mixer mill MM 400 is a unique product in the market.

You may also be interested in the High Energy Ball Mill Emax, an entirely new type of mill for high energy input. The unique combination of high friction and impact results in extremely fine particles within the shortest amount of time.



alloys, animal feed, bones, ceramics, cereals, chemical products, coal, coke, drugs, electronic scrap, glass, grains, hair, minerals, oil seeds, ores, paper, plant materials, plastics, sewage sludge, soils, straw, tablets, textiles, tissue, tobacco, waste samples, wood, wool, ...

Product Advantages

- · reproducible, efficient grinding, mixing and homogenization in seconds
- powerful grinding by impact and friction, up to 30 Hz for up to 20 samples per run
- · 3 different grinding modes (dry, wet or cryogenic)
- · screw-top grinding jars for leak-proof grinding
- · 9 SOPs can be stored
- wide range of accessories including various jar and ball sizes, adapter racks for single use vials and tubes, grinding tool materials, CryoKit
- efficient cell disruption of max. 240 ml cell suspension for DNA/RNA- and protein extraction
- isolation of bacteria from tissue in 8 x 30 ml bottles or 10 x 5 ml vials for accurate diagnosis of infections

Features

Applications	size reduction, mixing, homogenization, cell disruption, cryogenic grinding
Field of application	agriculture, biology, chemistry / plastics, construction materials, engineering / electronics, environment / recycling, food, geology / metallurgy, glass / ceramics, medicine / pharmaceuticals
Feed material	hard, medium-hard, soft, brittle,



Mixer Mill MM 400

	elastic, fibrous
Size reduction principle	impact, friction
Material feed size*	≤ 8 mm
Final fineness*	~ 5 µm
Batch size / feed quantity*	max. 2 x 20 ml
No. of grinding stations	2
Setting of vibrational frequency	digital, 3 - 30 Hz (180 - 1800 min-1)
Typical mean grinding time	30 s - 2 min
Dry grinding	yes
Wet grinding	yes
Cryogenic grinding	yes
Cell disruption with reaction vials	yes, up to 20 x 2.0 ml
Self-centering clamping device	yes
Type of grinding jars	screw top design
Material of grinding tools	hardened steel, stainless steel, tungsten carbide, agate, zirconium oxide, PTFE
Grinding jar sizes	1.5 ml / 5 ml / 10 ml / 25 ml / 35 ml / 50ml
Setting of grinding time	digital, 10 s - 99 min
Storable SOPs	9
Electrical supply data	100-240 V, 50/60 Hz
Power connection	1-phase
Protection code	IP 30
Power consumption	150 W
W x H x D closed	371 x 266 x 461 mm
Net weight	~ 26 kg
Standards	CE
Please note:	

*depending on feed material and instrument configuration/settings

Videolink

http://www.retsch.com/mm400

Function Principle

The grinding jars of the MM 400 perform radial oscillations in a horizontal position. The inertia of the grinding balls causes them to impact with high energy on the sample material at the rounded ends of the grinding jars and pulverize it. Also, the movement of the grinding jars combined with the movement of the balls result in the intensive mixing of the sample. The degree of mixing can be increased even further by using several smaller balls. If several small balls are used (e.g. glass beads) then, for example, biological cells can be disrupted. The large frictional impact effects between the beads ensure effective cell disruption.

Appendix G – Alicona InfiniteFocus



GENERAL SPECIFICATIONS								
Measurement principle	non-contai	ct, optical, three-dime	insional, based on Fo	cus-Variation				_
Max. number of measurement points in a single measurement	X: 1840, Y:	: 1840, X x Y: 3.3 milli	an					_
Max. number of measurement points	X: 540000	, Y: 540000; X x Y: 50	0 million					
Positioning volume (X x Y x Z)	100 mm x	100 mm x 100 mm •	1000000 mm ³ (optic	nal: 200 mm x 200 m	m x 100 mm = 400000	0 mm²)		_
Maintenance	maintenan	ice free						_
Coaxial illumination	white LED	coaxial illumination,	high-power, electroni	cally controllable				_
Ring light illumination (optional)	white LED	high-power ring light	24 segments, wirele	ss, snap-on system				_
System monitoring	automatic	self-diagnosis due to	10 temperature and	3 vibration sensors, in	iternal current and volt	age monitoring		_
ControlServerHP	12 Core, 3:	2 GB, 27" Full HD LED	Monitor					_
DIMENSIONS AND ENVIRONMI	ENTAL	CONDITIONS						
Dimensions (W x D x H)	measurem	ent instrument: 810 i	mm x 640 mm x 700	mm (up to 948 mm); (ControlServerHP: 190 r	nm x 500 mm x 450 r	nm	_
Mass	measurem	ent instrument: 105 I	kg - 120 kg; CantrolSk	arverHP: 20 kg				_
Ambient temperature range	measurem ControlSer	verHP: possible: 5° C	ible: 18° C+28° C; c: : + 30° C	librated for: 18° C • 22	^o C, (can be calibrated)	i for other temperatur	e ranges);	
Permissible temperature gradient	less than 1	I° C/h						
Permissible relative humidity	recommen	nded: 45 % (+/-5 %); p	ossible: 45 % (+/-15 %	6)				
Supply voltage and current electric power	1000 W; 10	00 - 240 VAC; 50 - 60	Hz					_
MEASUREMENT OBJECT								
Surface texture	surface to	pography Ra above 0	.009 μ m with λ_{e} 2 μ m	; depending on surfac	e structure			_
Max. height	100 mm - :	345 mm						_
Max. weight	30 kg; mor	e on request						_
Preparation	none							_
OBJECTIVE SPECIFIC FEATURE	S							
Objective magnification (*)		2.5x	5x	10x	20x	50x	100x	_
Numerical aperture		0.075	0.15	0.3	0.4	0.6	0.8	_
Working distance	m	8.8	23.5	17.5	19.0	11	4.5	_
Lateral measurement range (X,Y)	mm	5.63	2.82	1.62	0.81	0.32	0.16	_
(X x Y)	mm²	31.7	7.95	2.62	0.66	0.10	0.03	_
Measurement point distance	ħ	3.52	1.76	0.88	0.44	0.18	0.09	_
Calculated lateral optical limiting resolution	Ш	4.35	2.18	1.09	0.82	0.54	0.41	_
Finest lateral topographic resolution	'n	7.04	3.52	1.76	0.88	0.64	0.44	_
Measurement noise	m	800	120	30	10	ω	_	_
Vertical resolution	m	2300	410	100	50	20	10	_
Vertical measurement range	m		22.5	16.5	18	10	4	_
Vertical scanning speed	s/unt	3000	3000	1000 - 3000	500-3000	200-2000	100 - 1000	_
Measurement speed			51	.7 million measureme	nt points/sec.			_
(*) Objectives with longer working distance available	ble upon re	quest						
EXTENDED MEASUREMENT RA	ANGE							
Objective magnification		2.5x	5x	10x	20x	50x	100x	_
Extended lateral measurement range (X,Y)(*)	mm	100	100	100	110 56	47.83	23.91	_
(X X Y) (**)	mm²	6195.26	1548.42	387.30	96.83	15.49	3.87	_

 (X × Y)(**)
 mm²
 10000
 10000

 Optional
 40000
 40000
 40000

 (Y) Maximum undirectional measurement area along the X- and Y-axis (**) Maximum X/Y-measurement
 10000
 10000
 Extended lateral measurement range with data reduction (X,Y)(*) Optional mm area 40000 200 10000 24780 3965 100x 23.91 23.91 3.87 <u>9</u>99

RESOLUTION AND APPLICATION LIMITS

	Max. measurable slope angle	Min. measurable wedge angle	Min. measurable radius	Min. measurable roughness (Sa)	Min. measurable roughness (Ra)	Max. measurable profile length Optional	Max. measurable area Optional	Height step accuracy (1 mm)	Max. measurable height	Min. measurable height	Objective magnification		
	۰	۰	μη	hu	mı	mm	mm²	æ	mm	hun			
			20	3.5	7		10000 40000	n.a.	8	2.3	2.5x		
5/			10	0.6	1.2		10000 40000	0.05	22.5	0.41	5x		
		2	5	0.15	0.3	11	10000 40000	0.05	16.5	0.1	10x		
	57	0	ω	0.075	0.15	88	10000 24780	0.05	18	0.05	20x		
			2	0.03	0.06				3965 3965	0.05	10	0.02	50x
			1	0.015	0.03		066 066	0.05	4	0.01	100x		

5

ACCURACY		
Flatness deviation	1 mm x 1 mm with 10x abjective	U = 0.1 µm
Maz. deviation of a height step measurement	height step 10000 µm height step 1000 µm height step 100 µm height step 10 µm height step 1 µm	E _{sera} eee, we 0.3 µm, c=0.4 µm E _{we} aeee, we 9.5 µm, c=0.05 µm E _{we} aeee, we 0.4 µm, c=0.05 µm E _{we} aeee, we +0.3 µm, c=0.005 µm E _{wea} eee, we +0.3 µm, c=0.01 µm
Profile roughness	Ra = 0.1 µm Ra = 0.5 µm	U = 0.025 μm, a = 0.002 μm U = 0.04 μm, a = 0.002 μm
Area roughness	Sa = 0.1 µm Sa = 0.5 µm	U = 0.02 µm, o = 0.002 µm U = 0.03 µm, o = 0.002 µm
Distance measurement	XY up to 1 mm XY up to 10 mm XY up to 20 mm	Exchangione = 0.0 Jum Exchangione = 1.0 Jum Exchangione = 2.0 Jum
Wedge angle	β = 70 ° • 110 °	U = 0.15°, a = 0.02°
Edge radius	R = 5 µm + 20 µm R > 20 µm	U = 1.5 µm, o = 0.15 µm U = 2 µm, o = 0.3 µm

Eurescos, we & Errans, we conform to ISO 10360-6	3
SOFTWARE	
Measurement modules	Standark 30 data septining profile form, profile roughness (Pa, Rq, Rz.,), surface tenture (Sa, Sg, Sg.,), volume, 20; Marona Inspect (30 Inspection Incl. 00:17) Optional: automatic multi inessurement; fusion; form/contour/difference; various application specific measurement object Measurement: Parkage (Fedge adhund/mm/contour/difference; various application specific measurement; mult degr measurement). Morous inspect for Decisional; tabum measurement mult degr measurement; Morous inspect for Decisional; tabum measurement; mult degre measurement; Morous inspect for Decisional; tabum measurement; mult degre measurement; Morous inspect for Decisional; tabum measurement;
Automation	Integrated scripting language, LabVIEW framework; .VET remoting interface; Alicona Inspect Professional (enables GD&T measurement)
Database	intuitive, graphical database
Languages	German, English, French, Korean, Japanese, Chinese
Export formats	3D data sets (e.g.: AL3D, STL, G3D, Open GPS, CVS, QDAS); image formats (e.g.: BMP, JPG, PNG)

mark Alicona specific values. Initiative Fair Sheet

Import formats

Standard: 3D data sets (e.g.: AL3D, STL, G3D, IGES, STEP); image formats (e.g.: BMP, JPG, PNG) Optional: Alicona Inspect Professional (Solid/Works; CATIA V4, V5, V6; Pro/E)

Appendix H – 316L Gas-Atomized Powder from Carpenter



CarTech[®] 316/316L Stainless

Email Datasheet Add to My Materials

Print Now

Unit Display: English V

Identification

UNS Number

S31600/S31603

Type Analysis

Single figures are nominal except where noted.

Carbon (Maximum)	0.03 %	Manganese (Maximum)	2.00 %
Phosphorus (Maximum)	0.045 %	Sulfur (Maximum)	0.030 %
Silicon (Maximum)	1.00 %	Chromium	16.00 to 18.00 %
Nickel	10.00 to 14.00 %	Molybdenum	2.00 to 3.00 %
Iron	Balance		

General Information

Description

CarTech 316/316L stainless is a low carbon version of conventional CarTech 316 stainless.

In this low-carbon austenitic alloy, control of carbon to a maximum of 0.03% has been shown to minimize carbide precipitation during welding. Customers have reported the use of this steel in the as-welded condition in a variety of corrosive applications.

CarTech 316/316L stainless is suggested for applications requiring a moderate level of improvement in machinability for shorter runs of less complex parts, particularly at larger bar diameters.

Manufacturers interested in realizing the potential economic benefits and lower costs associated with higher machining speeds and lower cycle times should consider CarTech 316/316L Project 70+® stainless.

Customers have reported that CarTech 316/316L Project 70+ stainless offers significantly improved machinability characteristics over generic CarTech 316/316L stainless. This includes up to 50% and higher machining speeds, with improved finishes and longer tool life.

Applications

CarTech 316/316L stainless should be considered for use in paper pulp handling equipment, process equipment for producing photographic chemicals, inks, rayon, rubber, textile bleaches and dyestuffs, as well as various high temperature equipment applications.

Scaling

The safe scaling temperature for continuous service is 1600°F (871°C).

Corrosion Resistance

Carpenter Stainless Type 316/316L has been used in sulfite pulp mills to resist corrosion by sulfurous acid compounds. Due to its superior corrosion resistance, its use has been extended to handling many of the chemicals used by chemical process industries.

The alloy is more resistant to pitting than conventional 18-8 alloys.

For optimum corrosion resistance, surfaces must be free of scale, lubricants, foreign particles, and coatings applied for drawing and heading. After fabrication of parts, cleaning and/or passivation should be considered.

Important Note: The following 4-level rating scale is intended for comparative purposes only. Corrosion testing is recommended; factors which affect corrosion resistance include temperature, concentration, pH, impurities, aeration, velocity, crevices, deposits, metallurgical condition, stress, surface finish and dissimilar metal contact.

Nitric Acid	Good	Sulfuric Acid	Moderate
Phosphoric Acid	Moderate	Acetic Acid	Good
Sodium Hydroxide	Moderate	Salt Spray (NaCl)	Good
Sea Water	Moderate	Sour Oil/Gas	Moderate
Humidity	Excellent		

Properties						
Physical Properties						
Specific Gravity						
	7.95					
Density						
	0.2870 lb/in³					
Mean Specific Heat						
32 to 212°F	0.1200 Btu/lb/°F					
Mean CTE						
32 to 1200°F	10.3 x 10 ⁻⁶ in/in/°F					
Electrical Resistivity						
73°F	445.0 ohm-cir-mil/ft					

Heat Treatment

Annealing

Heat to 1850/2050°F (1010/1121°C) and water quench. Brinell hardness approximately 150.

Hardening

Cannot be hardened by heat treatment. Hardens only by cold working.

Workability

Forging

Carpenter Stainless Type 316/316L can be readily forged, upset and hot headed.

To forge, heat uniformly to 2100/2300°F (1149/1260°C). Do not forge below 1700°F (927°C). Forgings can be air cooled.

Best corrosion resistance is obtained if the forgings are given a final anneal.

Cold Working

Carpenter Stainless Type 316/316L can be deep drawn, stamped, headed and upset without difficulty. Since this alloy work hardens, severe cold forming operations should be followed by an anneal.

Machinability

Carpenter Stainless Type 316/316L machines with chip characteristics that are tough and stringy. The use of chip curlers and breakers is advised. Since the austenitic stainless steels work harden rapidly, heavy positive feeds should be considered.

Following are typical feeds and speeds for Carpenter Stainless Type 316/316L.

Typical Machining Speeds and Feeds—Carpenter Stainless Type 316/316L

The speeds and feeds in the following charts are conservative recommendations for initial setup. Higher speeds and feeds may be attainable depending on machining environment.

Turning—Single-Point and Box Tools

Depth	Micro-Melt	® Powder I	IS Tools	Carbide Tools (Inserts)				
of Cut	Tool Speed Feed		Tool	Speed	Feed			
(inches)	Material	(fpm)	(ipr)	Material	Uncoated	Coated	(ipr)	
.150	M48,T15	102	.015	C2	350	450	.015	
.025	M48,T15	120	.007	C3	400	525	.007	

Turning—Cut-Off and Form Tools

Tool Material				Feed (ipr)							
Micro-Melt®	Carbide	Speed (fpm)	Cut-C	Xff Tool V	Vidth (ind	ches)	Fori	n Tool W (inches)	idth		
Powder HS	Tools	(1,1,1,1)	1/16	1/8	1/4	1/2	1	1½	2		
M48,T15		90	.001	.0015	.002	.0015	.001	.001	.001		
	C2	330	.004	.0055	.007	.005	.004	.0035	.0035		

Rough Reaming

Micro-Melt@ HS	® Powder S	Carbide	e Tools	Feed (ipr) Reamer Diameter (inches))	
Tool Material	Speed (fpm)	Tool Material	Speed (fpm)	1/8	1/4	1/2	1	11/2	2
M48,T15	84	C2	90	.003	.005	.008	.012	.015	.018
Drilling

Tools										
Tool	Speed (ipm)	Feed (inches per revolution) Nominal Hole Diameter (inches)								
Material		1/16	1/8	1/4	1/2	3/4	1	1 1⁄2	2	
M42	50-60	.001	.002	.004	.007	.010	.012	.015	.018	
C2-Uncoated	110		.002	.004	.006	.0085	.0096	.0113	.0113	
C2-Coated	140	.0005	.002	.004	.006	.0085	.0096	.0113	.0113	

Die Threading

FPM for High Speed Tools							
Tool Material	7 or less, tpi	8 to 15, tpi	16 to 24, tpi	25 and up, tpi			
M7, M10	8-15	10-20	15-25	25-30			

Milling, End—Peripheral

t	Micro-Melt® Powder HS Tools							Carbide Tools					
f Cu es)	Feed (ipt) Cutter Diameter (inches)					-		Feed (ipt) Cutter Diameter (inches)					
Depth of (inche	Tool Materia	Speed (fpm)	1/4	1/2	3/4	1-2	Tool Materia	Speed (fpm)	1/4	1/2	3/4	1-2	
.050	M48, T15	90	.001	.002	.003	.004	C2	270	.001	.002	.003	.005	

Tapping		Broaching			
High Spee	d Tools	High Speed Tools			
Tool Material	Speed (fpm)	Tool Material	Speed (fpm)	Chip Load (ipt)	
M7, M10	12-25	M48, T15	18	.0040	

Additional Machinability Notes

When using carbide tools, surface speed feet/minute (SFPM) can be increased between 2 and 3 times over the high-speed suggestions. Feeds can be increased between 50 and 100%.

Figures used for all metal removal operations covered are average. On certain work, the nature of the part may require adjustment of speeds and feeds. Each job has to be developed for best production results with optimum tool life. Speeds or feeds should be increased or decreased in small steps.

Weldability

Carpenter Stainless Type 316/316L can be satisfactorily welded by the shielded fusion and resistance welding processes. Since austenitic welds do not harden on air cooling, the welds should have good toughness.

Oxyacetylene welding is not recommended since carbon pickup in the weld may occur.

The alloy can be welded without loss of corrosion resistance due to intergranular carbide precipitation. Usually the alloy can be used in the as-welded condition; however, for service in the most severe environments, the welded structure should be reannealed after welding.

Where a filler metal is required, AWS E/ER316L welding consumables should be considered.

Other Information							
Applicable Specifications							
 AMS 5648 	 AMS 5653 						
ASME SA479	ASME SA479 • ASTM A182						
 ASTM A276 	 ASTM A314 						
 ASTM A479 	 MIL-S-862 						
• QQ-S-763							
Forms Manufactured							
Bar-Hexagons	Bar-Rounds						
Technical Articles							
A Designer's Manual On Specialty Alloys For Critical Automotive Components							
Alloy Selection for Cold Forming (Part I)							
Alloy Selection for Cold Forming (Part II)							
How to Select the Right Stainless Steel or High Temperature Alloy for Heading							
New Ideas for Machining Austenitic Stainless Steels							
Selecting Optimal Stainless Steels for Bio-Pharmaceutical Service							
Selecting Stainless Steels for Valves							

- Selection of High Strength Stainless Steels for Aerospace, Military and Other Critical Applications
- · Stainless Steel Rebar For Concrete Reinforcement: An Update And Selection Guide

Disclaimer:

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Appendix I – Zeiss LEO 1550VP ZEISS LEO 1550VP FESEM/EDS

FOM Name: SEM LEO 1550VP Model: Zeiss Leo 1550VP Contact: Anna Kiyanova (anna.kiyanova@wisc.edu, 608-263-1735) Center: <u>SMCL</u> Location: B29 Engineering Hall

The Zeiss LEO 1550VP is a high-performance Scanning Electron Microscope (SEM) equipped with a Schottky type field emission gun, various detectors (in-lens and chamber-mount secondary electron detectors, detector for energy-dispersive x-ray analysis), and e-beam patterning system. A close relative to the LEO 1530 SEMs in the NIAC, this system is positioned as having a cleaner chamber and better vacuum to optimize the performance for contamination sensitive samples (for example, low contrast self-assembled blockcopolymer coatings) and high-resolution patterning. To ensure the clean environment, the SEM is equipped with air lock system for sample exchange without opening the main chamber on atmosphere.

Expand all | Collapse all

- Configuration

- Accelerating voltage: 100 V to 30 kV.
- Image resolution: 1.0 nm at 20 kV, 2.5 nm at 1 kV.
- In-lens secondary electron detector: standard, used up to 20 kV.
- Chamber-mount secondary electron detector: works at > 20 kV.
- Topography sensitive.
- EDS: Thermo Noran Energy dispersive X-ray microanalysis system, a light element detection limit of boron.
- Patterning: J.C.Nabity Lithography Systems Nanometer Pattern Generation System (NPGS) ver. 9.1.
- Sample stage: motorized 125 mm X travel, 100 mm Y travel, 35 mm Z travel, 0° to 90° tilt, 0° to 360 ° rotation.



Appendix J – Quanta 600 (Initially made by FEI, rebranded under Thermo Scientific)

FEI ESEM Quanta 600 FEG – Environmental Scanning Electron Microscope



The FEI ESEM Quanta 600 FEG is a versatile scanning electron microscope with three imaging modes. The "high vaccum mode" (HV) is a conventional SEM mode with the need of conventional specimen preparation. In the "low vacuum mode" (LV) electrically non conductive samples can be imaged without the need of a conductive layer (*e.g.* carbon, gold etc.). Additionally in the "ESEM mode" (ESEM) wet samples can be investigated in their "natural" state. The thermally assisted field emission gun (FEG) delivers high brightness of the electron beam and high imaging resolution. Additionally the microcroscope can be equipped with a tensile stage, a Peltier cooled specimen stage, a heating stage and an in situ ultramicrotome.

Key Features

- Seamless "point and click" transition between imaging modes
- Superior low vacuum, low kV imaging simultaneous secondary electron (SE) and backscattered electron (BSE) imaging in LV mode
- Allows for in situ dynamic experiments
- True surface (SE) imaging in all vacuum modes and voltages
- Easy-to-use, four quadrant/single quadrant user interface

Essential Specifications

Resolution

- < 2.0 nm @ 30 kV SE @ HV
- < 2.0 nm @ 30 kV SE @ ESEM
- < 3.5 nm @ 3 kV SE @ LV
- < 1.5 nm @ 30 kV STEM @ HV

Emitter

Thermal Field Emission Gun (FEG)

Accelerating Voltage

0.2 – 30 kV

Probe Current

Can be measured externly with a Faraday cup

Detectors

- Everhart Thornley Detector (ETD): SE, BSE @ HV
- Large Field Detector (LFD): SE @ LV
- Solid State Backscattered Electron Detector SSD-BSD:BSE @ HV, LV
- Gaseous Secondary Electron Detector(GSED):SE @ESEM
- EDS Detector Thermo Noran Vantage

5-Axes Motorised Eucentric Specimen Stage

- X = 150 mm / Y = 150 mm / Z = 60 mm
- Rotation = 360° (continuous)
- Tilt = $-5^{\circ} +70^{\circ}$

Image Processing

- Resolution: up to 3584 x 3094 pixel
- Dwell: 100 ns 1 ms per pixel

System Control

• Windows 2000™ based 32-bit graphical user interface

Appendix K – Keyence VHX–5000

KEYENCE VHX-5000

The VHX is an all-in-one microscope that incorporates observation, image capture, and measurement capabilities. Any user, regardless of their experience, can now obtain high-quality, fully-focused images in an instant.

System Features

- Three dimensional measurement/profilometry and imaging down into deep DRIE etched structures
- Large depth of field and instant full-focus depth-composition give SEM-like color images
- Automated XY & Z stage, focus and image capture
- Tilted views with 3D model extraction, XYZ measurements and rotating viewing
- 54 megapixel CMOS camera with real-time, live imaging
- Video recording and timer interval image capture function
- 16 bit color with High-resolution HDR mode
- Large capture area and image stitching at high resolution
- Particle counting and analysis
- One click snap-to-image template measurement tools (length, varea, radius, angle, etc)
- Template output and easy report generation of measurements and images
- External monitor driver for display on large classroom screens



Appendix L – LPW PowderFlow[™] Kit



Introducing LPW PowderFlow[™]

LPW PowderFlow is a comprehensive powder flow measurement kit which allows you to quickly and accurately characterise the powder flow to known ASTM standards and determine whether powder is changing during the AM process. A variation in powder is disruptive to the end product, so early identification of powder quality is key to differentiating whether a problem may be attributed to machine, process or powder. Using PowderFlow can significantly reduce time and cost wasted in identifying any source of concern, adding efficiency to the metal additive manufacturing process.

PowderFlow is delivered in a robust case and allows you to determine the following:

- Apparent Density ASTM B212
- Angle of Repose no applicable standard
- Hall Flow ASTM B213
- Carney Flow ASTM B964

PowderFlow contains the following items:

- Base Plate, Support Rod, Collar
- Hall Flow Funnel
- Carney Flow Funnel
- Apparent Density Cup
- Stopwatch
- Calibration Powder
- Standard Operating Procedure
- Height Gauge



Note: LPW was acquired by Carpenter Additive® in 2018