

Design and Manufacture of a Functional 3D-Printed Stirling Engine: A Case Study Involving Bound Metal Deposition of 17-4 PH

Q. Campbell¹, M. Filiault¹, K. Rooney¹, J. Belding^{1,2}, and B.D. Ellis^{1,2*}

¹Mechanical Engineering Technology, University of Maine, Orono, ME 04469

²Center for Additive Manufacturing of Metals (CAMM), University of Maine, Orono, ME 04469

*brett.ellis@maine.edu

ABSTRACT

Bound metal deposition (BMD) is a recently commercialized additive manufacturing of metal (AMM) process in which metal powder-binder composites are printed, debound, and sintered. Although potentially offering significant costs savings compared to traditional AMM process, BMD is poorly understood by designers and engineers. This research seeks to addresses this problem by designing and manufacturing a beta Stirling engine (BSE) using BMD of 17-4 PH. Best practices included under- and over-sizing features for post processing, reducing aspect ratios to less than 8:1, and designing for horizontally-printed features. FARO ScanArm data indicated that as-sintered dimensions were generally within 0.07 mm [0.003 in] of the as-designed dimensions with high-aspect-ratio features deviating up to 0.50 mm [0.020 in].

Keywords: Additive manufacturing, metal, Stirling engine, design

1 INTRODUCTION

Growing at approximately 21% per year [1], additive manufacturing (AM) has primarily been utilized in applications requiring short lead times, geometric complexity, reduced part weights, reduced part counts, enhanced functionality, or a combination of the aforementioned criteria. For example, biomedical applications have benefited from AM's ability to create complex geometries; economically viable AM jet engine fuel nozzles are 25% lighter, contain 95% few parts, and have five times the service life of similar subtractive manufactured (SM) jet engine fuel nozzles [2].

Recent advances in AM of metal (AMM) machinery have resulted in fused filament fabrication (FFF) and bound metal deposition (BMD) processes, which may be operated in office environments and are expected to cost significantly less than existing Selective Laser Sintering (SLS) and Electronic Beam Melting (EBM) AMM processes. Although small differences exist, FFF and BMD are relatively similar in that both processes sequentially extrude layers of a metal-binder composite, remove a large portion of the binder via a debinding liquid, and densify the part via sintering. Despite recent advances and potential cost savings, FFF and BMD processes face a fundamental

issue: FFF and BMD processes are new and thus poorly understood by designers and engineers.

This research seeks to address this issue by designing and manufacturing a functional AMM beta Stirling engine (BSE) utilizing a BDM process. The BSE is challenging due to heat transfer, thermal expansion, sliding interfaces, pressurization, and wear resistance requirements. The remaining sections of this work describe the chosen BMD Desktop Metal Studio+ system and 17-4 PH material properties, design of the beta Stirling engine, manufacturing, geometric conformance, and conclusions.

2 DESKTOP METAL STUDIO+ SYSTEM

The Desktop Metal (DM) Studio+ System utilizes a BMD process consisting of three steps: print, debind, and sinter [3]. In the first step, user-drawn CAD files (e.g., STL, STEP, SLDPRT) are sliced via DM's Fabricate slicing software and printed via a DM Studio+ printer. Printing consists of sequentially extruding layers of either: (1) a bound-metal build media through either a 0.25- or 0.40-mm-diameter nozzle, or (2) a ceramic interface media through a 0.4-mm-diameter nozzle to manufacture a "green" part. The bound-metal build media is a two-phase composite consisting of powdered metal particles and a wax-polymer binder. The wax-polymer binder softens when heated in the extruder, thus allowing placement of bound-metal build media at 0.05-mm [0.002-in] minimum layer heights within the printer's $289 \times 189 \times 195 \text{ mm}^3$ [11.4 × 7.4 × 7.7 in³] build volume [3]. The wax-polymer binder causes two significant consequences. First, the strength of a green material is significantly less than the strength of a green material's powdered metal. Second, green parts are intentionally printed approximately 20% larger in each direction to account for shrinkage during sintering.

The second step of the DM Studio+ System is debinding in which a proprietary organic solvent removes the vast majority of the wax-polymer binder from the metal powder. The resulting open-pore microstructure of the "brown" part consists primarily of metal powder with a small fraction of binder. Lacking the vast majority of the binder, brown materials are weaker than green materials.

In the third step, the brown part is heated in a 97.2% argon-2.8% hydrogen gas mixture at approximately 100-Torr [1.9-psi] pressure to approximately 400 °C to boil off

the remaining binder, then heated to just below the melting temperature of the metal powder (*e.g.*, approximately 1400 °C sintering temperature for 17-4 PH having a melting point between 1404 °C and 1440 °C [4]) to sinter the powdered metal part [5]. Lastly, the part is cooled to room temperature resulting in the as-sintered part. The process typically requires up to 48 hours and results in 96% to 99% densification (*i.e.*, 1% to 4% porosity). Sintering results in an approximate 20% linear shrinkage in all directions.

2.1 17-4 PH Stainless Steel

17-4 PH (UNS S17400) is a precipitate hardening martensitic stainless steel available in solution treated and various aged conditions, including H900 and H1075 [4]. Recommended heat treating for 17-4 PH includes solution treating at 1025 to 1050 °C, quenching in oil, aging for several hours at the temperature in °F specified in the “H” condition number, and air cooling to room temperature [6]. Table 1 shows a comparison of 17-4 PH mechanical properties in the as-sintered AMM and non-AMM H1025 conditions. The most significant difference is the as-sintered AMM’s 34% reduced yield strength, which is partially attributable to the inverse relationship between porosity and relative strength [7].

Property	As-sintered AMM [8]	Non-AMM at H1025 [9]
Stiffness (GPa)	195	200 [8]
Yield strength (MPa)	660	1,000
Tensile strength (MPa)	1,042	1,070
Elongation at break	8.5%	12%
Hardness (HRC)	37	35
Relative density	98%	100% [8]

Table 1. Comparison of 17-4 PH mechanical properties in as-sintered AMM and non-AMM H1025 conditions.

3 STIRLING ENGINE DESIGN

A Stirling engine was chosen as the demonstration piece in order to explore the limitations of AMM in a functional thermo-mechanical application and to manufacture a portable artifact that demonstrates AMM capabilities. A beta Stirling engine (BSE) was chosen instead of alpha or gamma Stirling engines to highlight AMM’s geometric freedom and differences between AMM and SM designs.

The desire for an operational and relatively transportable BSE guided other preliminary decisions, including working fluid, overall size, heat source, and orientation. Air was chosen as the working fluid due to air’s availability and non-combustibility. The overall size should be sufficiently small as to allow for easy portability. A 14-gram hexamine (aka “Esbit”) fuel tablet was chosen based upon its 12-min burn time, 760 °C [1,400 °F] maximum temperature, and relative ease of procurement, transportation, and use [10]. A horizontal orientation was

chosen to prevent hot hexamine exhaust gasses from inadvertently heating the cold-side heat exchanger.

The extent to which AMM parts were utilized within the BSE influenced the final design. For example, the BSE could include all AMM parts or as few as one AMM part. Considered extents of AMM included: (1) 100% AMM, (2) the amount of AMM that minimizes total manufacturing costs; (3) the amount of AMM that maximizes the BSE’s power to piston displacement ratio; (4) the amount of AMM that maximizes the BSE’s power to mass ratio; (5) the amount of AMM that minimizes lead time; (6) the amount of AMM and additive manufacturing of polymers (AMP) that minimizes manufacturing costs; and (7) others not listed here. The chosen extent of AMM seeks to minimize the total manufacturing costs for a desktop size BSE while allowing for AMM and AMP parts. The designed AMM BSE is 265.7 (L) × 95.3 (T) × 121.7 (W) mm³ and consists of 14 AMM parts, 10 polylactic acid (PLA) AMP parts, and 21 purchased parts.

Figure 1 shows a SolidWorks rendering of the BSE; Figure 2 shows a section view of the BSE with key components labeled. Three of the parts – Base Plate Left, Base Plate Right, and cylinder – were designed to be brazed together after sintering.

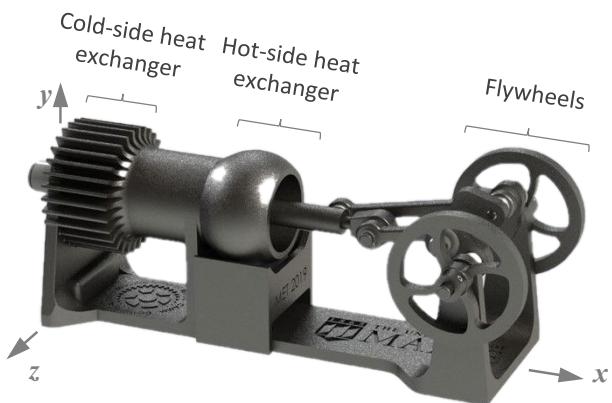


Figure 1: SolidWorks rendering of AMM beta Stirling engine design.

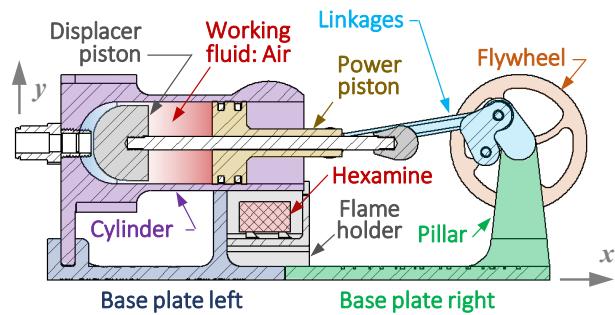


Figure 2: Section view of AMM beta Stirling engine.

The BSE is operated by sliding the flame holder in the positive x direction, placing a hexamine tablet into the flame holder, lighting the hexamine tablet, and sliding the flame holder in the negative x direction until the flame holder is underneath the hot-side heat exchanger. The heated hot-side heat exchanger heats the compressed air working fluid within the cylinder, which ultimately causes the displacer and power pistons to translate, causing the flywheels to rotate. Heat is rejected to atmosphere through the cold-side heat exchanger.

The BMD process imposed additional constraints on the design, including the incorporation of blending radii to reduce interlayer stress concentrations, under- and oversizing features to permit SM post processing, an 8:1 aspect ratio for features, and horizontally-printed bearing and threaded features.

3.1 Under- and Over-sizing Features for Post Processing

Although possible to print, debind, and sinter internal and external threads and bearing surfaces, threads and bearing surfaces were printed with extra skin layers, each 0.40-mm thick, which were then subtractive machined. Features that were to be internally threaded were designed and printed under-sized with 8 skin layers. In contrast, non-tapped external surfaces were printed with 6 skin layers.

3.2 Aspect Ratio Limitations

To prevent unsupported vertically-printed features from falling during sintering, DM recommends a maximum 8:1 aspect ratio (AR), defined here as a feature's height to the feature's diameter (*or minimum width*) [11]. The 8:1 AR guideline influenced the BSE design, including decreasing the maximum radii of cold-side heat exchanger cooling fins (*cf.* Figure 1), and truncating thin-features on the Base Plate Left's cylinder support bracket which after sintering is brazed to the Cylinder (*cf.* Figure 2).

Although ARs may be calculated for horizontally-printed features, the interpretation of AR for horizontally-printed features is unhelpful. Nonetheless, a generalized aspect ratio (GAR) was defined as the ratio of a feature's maximum dimension to the feature's minimum dimension, with both dimensions including raft thickness if applicable. The GAR influenced the design of the two flywheels and the baseplate. First, the outside diameter of each flywheel was reduced to 63.5 mm [2.50 in] such that the 3.8-mm [0.15-in] wide by 6.35-mm [0.25-mm] thick radial arms were 19.1-mm [0.75-in] long. The resulting GAR was approximately 5.0.

Second, the base plate was divided into two parts – the Base Plate Left and the Base Plate Right. When brazed together after sintering, the base plate is approximately 6.35-mm [0.25-in] thick by 44.45-mm [1.75-in] wide and 233.4 mm [9.19 inches] long. For GAR calculations, the

6.35-mm [0.25-in] thick raft was assumed to augment the thickness of the part. If the base plate were not divided into two parts, the GAR would have been 18.4, which is well above the 8:1 AR guideline for vertically-oriented features. By splitting the base plate into two parts, the GAR was 9.7, which was approximately 20% greater than the 8:1 AR recommended for vertically-oriented printed features.

3.3 Horizontally-printed threaded and bearing features

Threaded and bearing features that were horizontally-oriented during printing were drawn in SolidWorks as square cross-section voids rotated 45° about their longitudinal axis (*cf.* square cross-section voids in the pillars in Figure 3) instead of cylindrical voids. After sintering, the as-printed feature was subtractive machined to the correct diameter and, if applicable, tapped to the correct thread size. This change permitted the square cross-sections to be self-supporting during printing, thus eliminating potential distortion caused by requisite interface and support materials for horizontally-printed cylindrical holes.

4 MANUFACTURING

The 14 AMM parts were printed and debound by DM Studio+ machines at DM's print farm in Burlington, MA using 0.4-mm-diameter extruder nozzles for 17-4 PH build and ceramic interface materials. Nine (9) of the 14 parts were sintered by DM; the remaining five (5) parts have yet to be sintered. The as-sintered parts were measured and post-processed at the University of Maine's Center for Additive Manufacturing of Metal (CAMM). The 10 PLA parts were printed on Ultimaker 2+ printers. The 21 purchased parts (*e.g.*, pressure relief valve, piston rings, and bearings) were procured from commercial vendors.

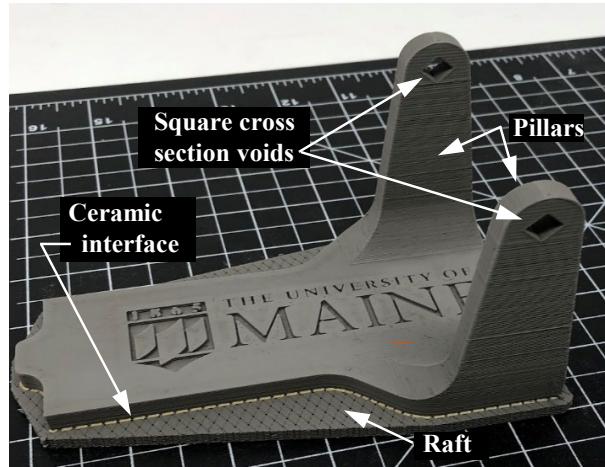


Figure 3: As-printed green Base Plate Right showing the raft, ceramic interface media (white), and square cross-section voids for subsequent subtractive machining.

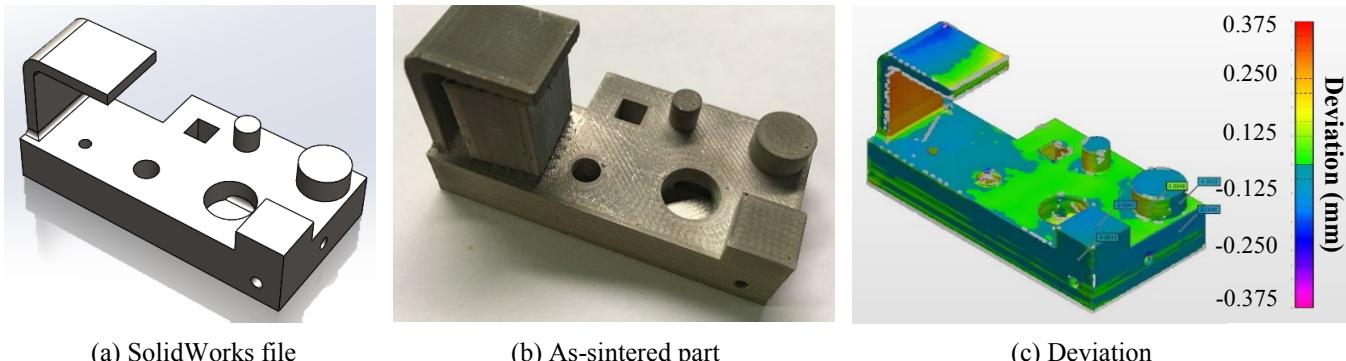


Figure 4: Geometric conformance of a test part having internal and external features orientated in three orthogonal directions, showing the (a) SolidWorks file; (b) as-sintered part; and (c) deviation between as-sintered part and SolidWorks file.

5 GEOMETRIC CONFORMANCE

Geometric conformance between each as-designed SolidWorks file and each as-sintered part was determined by measuring the as-sintered part with a FARO Edge Arm and FARO Blue Light HD Scanner having an accuracy of $\pm 25 \mu\text{m}$ [$\pm 0.001 \text{ in}$] [12] and comparing the as-designed SolidWorks file to the point cloud generated from the as-sintered part via PolyWorks Inspector. A $60 \times 30 \times 30 \text{ mm}^3$ overall dimension test part having internal and external circular and rectangular features oriented in three orthogonal directions was designed, printed, and measured. Figure 4 shows the (a) SolidWorks file, (b) as-printed part, and (c) the geometric deviation between the SolidWorks files and the as-sintered part.

As shown in Figure 4c, the as-sintered test part was typically within 0.05 mm [0.002 in] of the as-designed dimensions. Deviations of up to 0.35 mm [0.014 in] were observed for the relatively thin vertical feature supporting the overhang feature. Measurements of the nine (9) BSE AMM parts sintered to date indicate similar results, *i.e.*, geometric conformance was generally within 0.07 mm [0.003 in] across most of the part with high aspect ratio features deviating up to 0.50 mm [0.020 in]. Future research should quantify and work towards predicting deviations as a function of aspect ratios and process parameters.

6 CONCLUSIONS

This research documents the design and manufacture of a functional beta Stirling engine utilizing a bound metal deposition (BMD) additive manufacturing of metals (AMM) process. Results indicate that BMD AMM process dependency must be accounted for when designing features, *e.g.*, under- and over-sizing features for subtractive post processing, reducing aspect ratios to less than 8:1, reducing generalized aspect ratios, and accounting for feature orientation during printing. Empirical results indicated that as-sintered dimensions were generally within

0.07 mm [0.003 in] of the designed dimensions with high-aspect-ratio features deviating up to 0.50 mm [0.020 in].

ACKNOWLEDGEMENTS

The authors thank David Shrayber and Desktop Metal for technical support, manufacturing assistance, and the photograph shown in Figure 3. Financial support was provided by Maine Technology Institute grant #CIP209 and the University of Maine's Advanced Manufacturing Center (AMC) and Center for Additive Manufacturing of Metals (CAMM).

REFERENCES

- [1] Wohlers et al. Eds., “Wohlers report 2018: 3D printing and additive manufacturing state of the industry annual worldwide progress report,” 2018.
- [2] “A printed smile: 3D printing is coming of age as a manufacturing technique,” *The Economist*, 2016.
- [3] Desktop Metal, “Studio system+ printer specifications,” 2018.
- [4] KVA Stainless, “17-4 stainless steel,” available at: <http://www.kvastainless.com/17-4.html>, 2019.
- [5] Desktop Metal, “Studio System sintering guidelines for 3rd party furnaces.” 2018.
- [6] Unterweiser, Boyer, and Kubbs, Eds., Heat Treater’s Guide. American Society of Metals, 1993.
- [7] Sung et al., “An investigation on the strength-porosity relation in sintered 17-4 PH STS produced by powder injection molding, *Matl Sci Forum*, 2004.
- [8] Desktop Metal, “17-4 PH stainless steel.” 2018.
- [9] Avallone, Baumeister, and Sadegh, Eds., Marks’ Standard Handbook for Mechanical Engineers, 11th ed. McGraw-Hill, 2007.
- [10] Industrial Revolution, “Esbil solid fuel 12pc x 14g,” available at <https://www.industrialrev.com/esbil-solid-fuel-12pc-x-14g-e--fuel--12x14>, 2019.
- [11] Desktop Metal, “Aspect ratio and stability during sintering,” 2019.
- [12] FARO, “FARO 8-axis quantum FAROARM,” 2018.