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ABSTRACT

Heat exchangers are a recurrent element found in an abundant number of mechanical engineering systems. The design of these heat exchangers has generally remained static due to manufacturing limitations. However, recently additive manufacturing has facilitated the production of new and previously impossible heat exchanger geometries and structures by fabricating one monolithic build layer-by-layer. For example, Direct Metal Laser Sintering (DMLS) creates approximately 20-micron thick metal layers stacked on top of one another to create a cohesive metal part. Heat exchangers can be constructed in the same way. This paper reviews the most recent developments of additively manufactured heat exchangers. Additive manufacturing is not limited to just traditional metal heat exchangers. Indeed, heat exchangers can be constructed from both ceramic and polymer materials as well. The major geometric properties that affect heat exchangers' thermal performance are discussed. With these advancements, the question posed is whether these additive manufacturing processes can be cost competitive with traditional manufacturing techniques or if there exists a hybrid approach that takes advantages of both technologies. Additive manufacturing facilitates the manufacturing of heat exchangers that have less material, reduced volume, increased thermal performance, increased reliability, and the potential to use new materials. Lastly, the needs for further research and development of additive manufacturing of heat exchangers are discussed.

Keyword: heat exchanger, additive manufacturing, thermal performance

1. INTRODUCTION

Additive Manufacturing (AM) has the potential to facilitate great innovation for the next generation of more efficient heat exchangers. Heat exchangers have previously, and still do today, rely on traditional manufacturing methods such as milling, die-casting, alignment, brazing/welding, or a combination of processes to mass produce cost efficient products (Wong et al., 2009a). Typical compact heat exchangers, such as microchannel heat exchangers, use fins to augment heat transfer and are manufactured using stamping or folding techniques (Arie et al., 2016a). These methods limit the types of geometries and size and thickness of features, such as tube walls, that can be fabricated. AM could mitigate these limitations. AM is the creation of three-dimensional objects by joining materials together, usually layer-by-layer. Typically, a 3D Computer Aided Design (CAD) model is created and then fed to splicing software, which divides the model into thin horizontal slices. These slices act as instructions for the 3D printer which creates each individual layer one at a time. AM is not limited to just using traditional plastics, but also can create parts composed of metal alloys, ceramics, composites, and even biological materials (Huang et al., 2015). Manufacturers are beginning to take advantage of the new technology. According to the 2016 Wohlers Report, AM composes about USD 5.2 Billion in 2015; about 0.04% of all manufacturing (Caffrey et al., 2016). Since parts are built by adding successive layers, complex internal geometries can be built with one monolithic build. This coupled with the fact that different types of materials can be used, facilitates the production of heat exchangers that use less material, have lower volume, and have increased thermal performance and reliability. Considering AM allows for rapid low-cost prototyping, researchers can design, fabricate, and test novel heat exchangers within a short period of time. One of the earliest examples of researchers taking advantage of metal AM to produce and test a heat exchanger was done by Tsopanos et al. (2006). Two micro-scale heat exchangers and three meso-scale heat sinks were rapidly manufactured using Selective Laser Melting (SLM) and the thermal performance experimentally determined. This literature review found the number of researchers using AM to create new cutting-edge heat exchangers and heat sinks has rapidly increased over the past three to five years. Thus, the purpose of this review is to (1) Discuss the geometric and physical properties of additively manufactured heat exchangers which affect the thermal performance, (2) Enumerate studies performed of additively manufactured heat exchangers and heat sinks organized by process material (metal alloy, polymer, and ceramic), (3) Discuss the cost competitiveness of additive manufactured heat exchangers, and (4) Highlight research trends and gaps.

2. GEOMETRIC AND PHYSICAL PROPERTIES

2.1 Surface Roughness

The effect of surface roughness on heat transfer ability is still an active area of research, especially for minichannel and microchannel heat exchangers. AM processes typically produce parts that have a higher surface roughness compared to the raw material. The common AM technique Selective Layer Sintering (SLS) has been reported to produce parts with a surface roughness of 5-35 μm (Kumbhar and Mulay, 2016). Surface roughness is highly dependent on the AM process, machine parameters, and build direction. Surface roughness has been shown to increase heat transfer. For the simple case of convective heat transfer over a cylinder, in the trans critical flow regime, surface roughening increased the heat transfer by a factor of approximately 2.5 (Achenbach, 1977). If the roughness element height is of the same order of magnitude as the laminar sublayer thickness in turbulent flow, the roughness element tends to break up the laminar sublayer, thereby, increasing the wall shear stress and heat transfer (Shah and Sekuliac, 2003). Multiple studies have been performed to study the effects of additively manufactured surface roughness on heat transfer. Stimpson et al. (2016a) experimentally studied pressure drop and heat transfer performance through small channels manufactured using DMLS. With decreasing hydraulic diameter, the friction factor increased due to higher roughness-to-hydraulic diameter ratios. The friction and heat transfer augmentation of the additively manufactured channels were compared to channels with grooves, which have been reported to have enhanced thermal performance. The thermal performance of the additively manufactured channels had comparable heat transfer performance to the grooved channels. Another study investigated the potential of the artificial roughness in manufacturing flat and finned heat sinks for electronics cooling (Ventola et al., 2014). The convective heat transfer was enhanced, on average, by 63% for flat surfaces and 35% for finned surfaces. As researchers and manufacturers use AM to create channels, more quantitative information is needed to help predict the heat transfer and fluid flow through these channels. With regard to correlations and quantification of flow and heat transfer of additively manufactured channels, Stimpson et al. (2016b) conducted a thorough study on the effect of DMLS caused channel roughness on channels of various hydraulic length scales. They developed necessary tools for designers that use AM for building parts. A correlation was presented that correlates the relative arithmetic mean roughness with the relative equivalent sand grain roughness for use of estimating the friction factor of flow through a DMLS rough channel. This can be used to predict the Nusselt number of the flow. A downfall of the increased surface roughness is the increased pressure drop which can decrease the performance of the heat exchanger. This can be explained by the increased friction factor (Stimpson et al., 2016a). However, new geometries can facilitate lower pressure drop if designed correctly. There is a clear tradeoff between the ability to create new geometries and the increase in pressure drop on the performance of the heat exchanger.

2.2 Material Porosity

There are numerous AM processes that produce parts with internal porosity which is considered a very common defect. Porosity in SLM created parts are a result of shrinkage, gas entrapment during solidification, and adhesion of partially molten particles to surfaces between layers (Bauereiß et al., 2014; Aqida et al., 2004; Tapia et al., 2016). The porosity affects the performance of heat exchangers in two major ways; they include the thermal conductivity of the material and the tensile and fatigue strength. Processed material that is less dense (more porous) than the pure material curtails the thermal conductivity and can negatively affect the performance of the heat exchanger. Wong et al. (2009b) used 6061 Aluminum with a bulk conductivity of 170 $\frac{W}{m-K}$ to create multiple heat sinks with different geometries using the AM process SLM. However, the effective thermal conductivity of the produced part was only reported to be 70 $\frac{W}{m-K}$ partly because the solids produced were 90% dense. It is also well established that excessive porosity can contribute to a reduction in tensile strength, ductility, and fatigue properties (Tapia et al., 2016). This poses an issue for the design and reliability of heat exchanger design. Undesirable porosity could contribute to the mechanical failure of these heat exchangers. Furthermore, the layer thickness, which can limit the feature size, affects the porosity (Zhang et al., 2017).

2.3 Feature Thickness

As the accuracy of AM increases, the possibility to design and manufacture extremely thin features arises. These extremely thin features facilitate the creation of new geometries, increased complexity at smaller scales, and most importantly the reduction of tube wall thickness. As the wall thickness becomes smaller, the overall thermal resistance decreases and hence the effectiveness of the heat exchanger increases as well. Thus, smaller and more compact heat exchangers can be designed and manufactured. The minimum feature thickness obtainable is dependent on the AM process and material used. Table 1 provides a summary of some of the smallest features manufactured for metal, polymer, and ceramic AM found in the literature. This provides a rough estimate of what the current technological limit is. A study by Arie et al. (2016a) suggests with current DMLS AM technology, the safe manufacturing limit of metal fin thickness is 0.3mm, the technological limit is 0.15mm, and the future technological projection is 0.05mm.

Table 1: Summary of Smallest Feature Thickness Attainable using AM for Varying Materials

Material	AM Process	Wall Thickness
Metal (Arie et al., 2017)	Direct Metal Laser Sintering (DMLS)	~150 μm
Polymer (Rua, et al., 2015)	Polyjet	~32-100 μm
Ceramic (Scheithauer et al., 2017)	Lithography-based Ceramic Manufacturing (LCM)	~100 μm

3. METAL HEAT EXCHANGERS

3.1 Laser Powder Bed Fusion

The most common and versatile AM method to create metal heat exchangers is Laser Powder-Bed Fusion (LPBF). Figure 1 shows a diagram of the process. There is a metal powder reservoir on one side and on the other side is the build platform. A powder scraper or roller moves the powder from the reservoir and creates an evenly distributed layer on the build platform. Then, a laser is directed at the powder to fuse or melt the powder to solidify it. The laser does this in the pattern of the cross section of the part for that specific layer of the part being built. The build platform is lowered, and a new powder layer is distributed, and the process repeats until the full part is built from the bottom up. LPBF is an umbrella term for Direct Metal Laser Sintering (DMLS) or Selective Laser Sintering (SLS), and Selective Laser Melting (SLM). All of which are just variants of the same process. PBF is one of the oldest metal AM methods on the market today; the first commercial metal sintering machine was introduced in 1995 by the EOS (Bhavar et al., 2014). Because of this, the cost and availability of the method is within reach for researchers to use to manufacture novel heat exchangers. Table 2 enumerates all studies that involve the use of LPBF processes to manufacture heat exchangers, heat sinks, or relevant components (such as tubing) and the major findings of each.

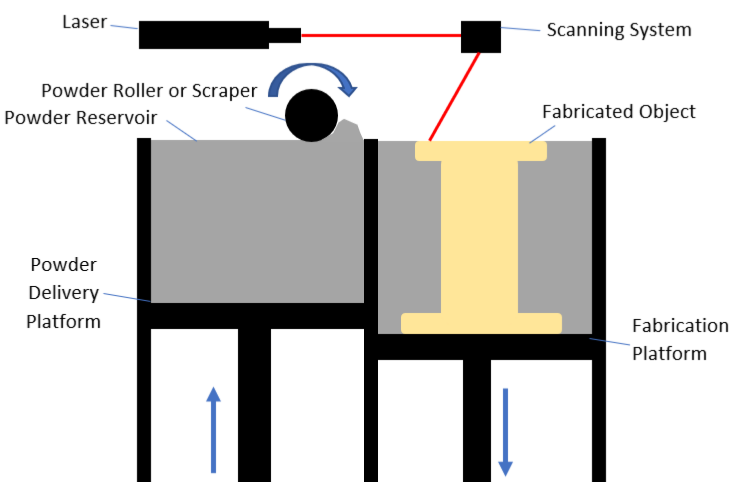

Figure 1: General Process of Laser Powder-Bed Fusion (LPBF)

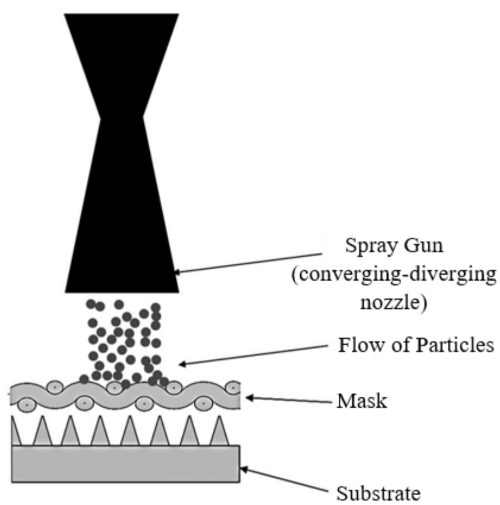

Figure 2: Schematic of the CGDS Process (Cormier et al., 2014)

Table 2: Studies using L-PBF to Manufacture Heat Exchangers, Heat Sinks, or Relevant Components

Researchers	AM Process	Summary/Major Findings
Tsopanos et al., 2006	SLM	• Micro scale heat exchangers and meso scale heat sinks were manufactured. • Micro scale heat exchangers demonstrated consistent performance with those considered in previous research. • Meso scale heat sinks did not perform as well as existing pin-fin designs.
Wong et al., 2007	SLM	• Heat transfer and pressure loss characteristics of four heat sinks experimentally studied. • Aluminum 6061 proven to as a viable material to be used with SLM.
Wong et al., 2009b	SLM	• Five heat sink geometries manufactured using Aluminum 6061. • Lattice-structure heat sink demonstrates that increasing surface area alone does not necessarily improve the overall heat transfer performance.
Wong et al., 2009a	SLM	• Three novel finned structures manufactured using Aluminum 6061 and Stainless Steel 316L. • Heat sinks produced showed superior performance to the conventional heat sinks. • New geometries incurred lower pressure drop.
Yan et al., 2014	DMLS	• Evaluates the manufacturability and performance of AlSi10Mg periodic cellular lattice structures. • DMLS can be used with this new alloy to produce porous lattice structures.
Ventola et al., 2014	DMLS	• When compared to smooth surfaces, rough flat surfaces and finned surfaces produced with DMLS respectively experienced on average 63% and 35% better convective heat transfer.
Pakkanen et al., 2016	SLM	• Cylindrical geometry for internal channels built at different angles using AlSi10Mg and Ti6Al4V and internal surfaces analyzed. • Surface roughness of internal channels evolve depending on building angle.
Arie et al., 2016a	DMLS	• Implementation of DMLS was studied on a manifold-microchannel heat exchanger. • Manifold-microchannel geometry using DMLS offers significant improvement over state-of-the art advanced fin technologies.
Arie et al., 2016b	DMLS	• Fabricated and experimentally tested a high-performance titanium alloy air-water heat exchanger that utilizes manifold-microchannel design. • Demonstrated a 45-100% increase in base conductance and 15-50% increase in heat transfer coefficient for the same pressure drop compared with wavy-fin surfaces.
Stimpson et al., 2016a	DMLS	• With decreasing hydraulic diameters, the friction factors increased as a consequence of higher roughness-to-hydraulic diameter ratios. • Channels made with DMLS have relatively comparable thermal performance to channels with grooves.
Kirsch and Thole, 2016	DMLS	• Three wavy channel coupons, each containing channels of varying wavelength, were designed and additively manufactured to evaluate pressure loss and heat transfer performance of the channels.
Snyder et al., 2016	DMLS	• Cylindrical-shaped channels built in three different orientations, while teardrop and diamond shaped channels built horizontally. • Vertically built channels had the lowest friction factor, while the diagonally built coupons had the highest friction factor.
Stimpson et al., 2016b	DMLS	• Developed correlations that relate the physical roughness measurements to the effect the roughness has on the flow friction and heat transfer. • Heat transfer correlation is presented which predicts Nusselt number of flow through DMLS microchannels using predictions or measurement of friction factor.
Bernardin et al., 2017	DMLS	• Presented a process to improve the thermal performance of a twisted shell-and-tube heat exchanger by leveraging CFD -modeling and expanded fabrication space of AM. • Modeled to have a 40% increase in heat transfer coefficient.
Bacellar et al., 2017	LPBF	• A new bare tube heat exchanger was designed and additively manufactured using laser powder bed fusion. • Achieved ~20%reduction in size, ~20% reduction in air pressure, ~40% reduction in material volume, and ~2% reduction in face area compared to a microchannel heat exchanger.
Ibrahim et al., 2017	LPBF	• L-PBF used to fabricate a multi-layered, Ti-6Al-4V oscillating heat pipe(ML-OHP) • Characterized the ML-OHP thermal performance.
Garde et al., 2017	SLM	• Additively manufactured oil cooler was designed and manufactured using SLM • Design is projected to transfer heat at 15kW at the design conditions
Gerstler and Erno, 2017	DMLS	• Novel heat exchanger designed to meet the heat transfer and fluid pressure drop requirements of a turbine engine fuel cooled oil cooler. • Mass and volume of the heat exchanger is 66% and 50% lower than the legacy fuel cooled oil cooler with similar performance.
Korinko et al., 2017	SLM	• Type 316 Stainless Steel printed tubing has a higher mechanical strength and lower ductility than annealed Type 316L Stainless Steel.
Arie et al., 2018	DMLS	• Three prototype heat exchangers were fabricated out of stainless-steel, titanium alloy, and aluminum alloy for power plant air-water heat exchangers. • Improvement in gravimetric heat transfer density compared to wavy fin heat exchanger.
Hathaway et al., 2018	SLM	• Commercial -scale tube bank oil cooler fabricated. • Unique features include, lenticular tubes with offset strip fins, and angled plate-fins.

3.2 Cold Spray Additive Manufacturing

The second most common metal AM method found in this review to manufacture heat transfer devices is Cold Gas Dynamic Spray (CGDS) or just Cold Spray. This process is based on the addition of material to a substrate by the deposition of solid powder particles. This deposition is enabled by the acceleration of the powder particles by a high-pressure carrier gas flowing at supersonic speed (Cormier et al., 2014). The most common application of CGDS is the creation of pin fin heat exchangers. Numerous studies have suggested that wavy, or strip louvered fins have reached their limit of their performance and properly distributed pin fins with an optimal height to diameter ratio will further improve heat exchanger performance (Sahiti et al., 2005). Figure 2 shows a general schematic of how CGDS creates pin fin features. The use of the mask enables the creation of pin fins with varying cross-sectional geometry, such as pyramidal fins. Table 3 enumerates all studies that involve using CGDS to manufacture heat exchangers, heat sinks, or relevant components (such as tubing) and the major findings of each.

Table 3: Studies using CGDS to Manufacture Heat Exchangers, Heat Sinks, or Relevant Components

Researchers	AM Process	Summary/Major Findings
Jazi et al., 2009	Wire-Arc Spraying	• Dense, alloy 625 deposited on the surface of 10 pores per inch (PPI) and 20 PPI nickel foam sheets to fabricate compact heat exchangers. • 20 PPI foam showed higher resistance to flow and greater heat transfer than the 10 PPI foam because of its smaller pore size and larger internal surface area.
Cormier et al., 2013	CGDS	• Pyramidal fin array produced with CGDS outperformed traditional straight cut fins at the same fin density and hydraulic diameter due to fluid mixing increasing the convective heat transfer coefficient.
Cormier et al., 2014	CGDS	• Investigated the effect of varying the fin height and the fin density of pyramidal pin fins. • Increasing either fin height or fin density also increases the total thermal conductivity at the expense of a higher-pressure loss.
Dupuis et al., 2014	CGDS	• Two new geometric pin fin arrays manufactured; pyramidal and trapezoidal fin arrays. • Two new geometries have better heat transfer performance than traditional plain rectangular fins, but larger pressure loss.
Farjam et al., 2015	CGDS	• Pyramidal fin arrays with different volume fractions of aluminum-alumina were produced. • Use of Aluminum-Aluminum feedstock powder as an alternative to pure aluminum prevents the use of costly polymer nozzles that wear out quickly.
Cormier et al., 2015	CGDS	• Near-net-shaped pyramidal fin arrays of various materials were manufactured; including aluminum, nickel, and grade 34 stainless steel. • The aluminum powder outperformed the other materials.
Dupuis et al., 2016a	CGDS	• Pyramidal pin fins fabricated using CGDS. • Classic double recirculation structures, and flow bypass structures observed in wake regions of fins.
Dupuis et al., 2016b	CGDS	• Pressure losses and the convective coefficients of square base, round base and diamond base tapered pin fins. • Staggered configurations produce higher convective coefficients and higher-pressure losses.

3.3 Other Notable Metal Additive Manufacturing Methods

One other notable AM process found in the literature is Ultrasonic Additive Manufacturing (UAM). The UAM process involves building up solid metal objects through ultrasonically welding a succession of metal tapes into a 3D shape, with periodic machining operations to create the detailed features of the resultant object (Norfolk and Johnson, 2015). The vibrations of the transducer are transmitted to the aluminum tape, which create an ultrasonic solid-state weld between the thin metal tape and base plate. The advantages for heat exchanger manufacturing are that it can use thermally conductive materials such as copper and aluminum and the finished surfaces are not as rough as LPBF surfaces. Norfolk and Johnson (2015) present a case study involving printing of 3D complex thermal management structures using this method.

4. POLYMER HEAT EXCHANGERS

Even though polymers have a very low thermal conductivity, polymer heat exchangers manufactured using AM methods are being considered for heat exchanger applications. The benefits of using polymer heat exchanger include low weight, low manufacturing cost, antifouling, anticorrosion, and are electrical insulators (Deisenroth et al., 2017). Another benefit, not related to the material properties of polymers, is that polymer AM is older and, in many ways, better understood than metal or ceramic AM. Indeed, there are other ways to mitigate the low thermal conductivity of including approaching extremely thin wall thickness (Arie et al., 2017) and adding fillers to the polymer matrix

(Deisenroth et al., 2017). Care must be taken as well when designing polymer heat exchangers due to its lower structural strength and lower melting temperatures. One AM polymer recently developed for high temperature applications is ULTEM 9085 (Nordin et al., 2017). AM techniques to manufacture polymer heat exchangers include Fused Deposition Modeling (FDM) (Singh and Garg, 2016), Laser Polymer Welding (LPW) (Denkenberger et al., 2012), PolyJet (Stratasys, 2018), and Lithography, Electroplating, and Molding (LIGA) (Malek and Saile, 2004). Table 4 enumerates all studies that involve AM of polymer heat exchangers or heat sinks and the major findings of each.

Table 4: Studies of Additively Manufactured Polymer Heat Exchangers or Heat Sinks

Researchers	AM Process	Summary/Major Findings
Harris et al., 2000	LIGA	• Cross-flow micro heat exchanger was developed to provide function similar to a car radiator. • Micro heat exchanger demonstrated good heat transfer rate/volume ratio.
Deisenroth et al., 2017	LPW	• Provides a thorough review of polymer heat exchangers. • Case study presented of an air-to-water heat exchanger constructed using Laser Polymer Welding. • Polymer heat exchanger required 85% less mass, but 35% more volume than a metallic wavy fin heat exchanger of the same capacity. COP also increased by 27%.
Rua et al., 2015	Polyjet	• Aimed to quantify the limitations of the AM process when used for printing microfluidic channels in heat exchanger fins. • .032mm-.1mm walls were possible to clean with care, but deformed slightly under pressure.
Arie et al., 2017	LPW	• LPW or layer-by-layer line welding by laser was used to fabricate an air-to-water heat exchanger. • Extremely thin walls (150 μm) reduced the thermal resistance of the wall to only 3% of the total thermal resistance.
Felber et al., 2016	FDM	• Prototype air-to-water heat exchanger designed and printed using FDM. • Improving the thermal conductivity for the printed polymer directly affects the heat exchanger performance, but this is a non-linear relationship.
Cevallos, 2014	FDM	• Novel polymer composite heat exchanger, called a webbed-tube heat exchanger. • Design shown to have similar performance to a plate-fin heat exchanger but used less material volume.

5. CERAMIC HEAT EXCHANGERS

Additively manufactured ceramic heat exchangers have not received as much attention as metal and polymer heat exchangers, but have potential to thrive in various situations. One of the reasons AM of ceramics as lagged behind the development for metals and polymers due to the challenges of adding and densifying ceramics in layers (Ross, and Shulman, 2015). Ceramics stand out based on their excellent reliability regarding high temperatures, abrasion, and extreme chemical environments (Scheithauer et al., 2017). Among engineering ceramics, silicon carbide, silicon nitride, aluminum oxide, and stabilized zirconia are materials that have appropriate physical and mechanical properties and manufacturability (Liu et al., 2005). Like for metals and polymers heat exchangers, AM techniques allow for novel geometries and monolithic builds that can boost thermal performance. AM techniques to manufacture ceramic heat exchangers include Lithography-based Ceramic Manufacturing (LCM) (Schwentenwein, 2014), Mould Shape Deposition (Liu et al., 2005), and Laminated Object Manufacturing (LOM) (Ross and Shulman, 2015). LCM is the most common of these methods. Table 5 enumerates all studies that involve AM of ceramic heat exchangers or heat sinks and the major findings of each.

Table 5: Studies of Additively Manufactured Ceramic Heat Exchangers or Heat Sinks

Researchers	AM Process	Summary/Major Findings
Liu et al., 2005	Mould Shape Deposition	• Fabricated micro heat exchanger with four and 40 channels out of silicon carbide.
Ross and Shulman, 2015	LOM	• Demonstrated complex ceramic heat exchangers can be built using LOM processes. • Ceramic heat exchanger could be manufactured at a reasonable cost.
Schwarzer et al., 2017	LCM	• Demonstrated the creation of complex designs using LCM. • Components with densities after sintering higher than 99% were achieved.
Scheithauer et al., 2017	LCM	• LCM allowed the production of alumina and zirconia components. • A heat transfer surface of more than 3500mm^2 and holes with a diameter if 0.2mm can be realized.

6. COST COMPETITIVENESS

The question posed is whether AM can be as cost effective as traditional manufacturing methods. AM offers many advantages over traditional manufacturing. The absence of tooling takes away a significant cost in the product development process at an early stage and changes to a part geometry may be applied without the need to incur the times and costs of producing new tooling (Hopkinson and Dickens, 2003). Also, by fabricating parts on demand using AM, holding stock can be reduced and consequently reduce cost. Raw materials for AM production are the only stock required (Atzeni and Salmi, 2012). Multiple models have been proposed predicting and comparing the cost of AM to traditional manufacturing methods. The first notable model is by Hopkinson and Dickens (2003). Figure 3 shows the cost comparison for a part using SLS and the conventional manufacturing method, high pressure die-casting. The initial start-up cost of traditional manufacturing methods, such as injection molding allows AM to be much more cost effective below a certain production volume. However, the opposite is true as the production volume increases further. A study by Laureijs et al. (2016) showed that additively manufacturing a GE engine bracket is cheaper than the traditionally manufactured forged part for a wide range of scenarios at high production volumes. Thomas and Gilbert (2014) provides a thorough review of the cost advantages of AM and explains multiple different cost models. Heat exchangers are very complex parts and many of these studies only provide cost analyses for simple parts or assemblies. It would be beneficial to know how the complexity of the part affects the cost competitiveness of using AM versus traditional manufacturing. Fera et al. (2017) propose a new model which uses complexity of the part being manufactured as a decision driver for the use of AM and not the number of products to manufacture. Most of the models presented do not take into full account the benefits AM has to offer and models still have progress to be made to better predict the economic competitiveness of AM. From the models discussed, the production volume and part complexity can be used to determine whether manufacturing a heat exchanger with AM methods can be cost competitive to traditional manufacturing methods.

7. RESEARCH TRENDS AND GAPS

Surface roughness is a consequence of the AM process and researchers are taking advantage of the increased design freedom with potential benefits of increased net transfer at the same time. More research is needed on how to mitigate porosity in additively manufactured parts to increase the thermal conductivity and improve the mechanical properties. There is still a need to further quantify the material properties of additively manufactured parts. NIST is developing new characterization methods in order to qualify and quantify attribute of AM materials. Increased knowledge of AM materials will increase quality control (NIST, 2018). New and complex geometries are being proposed, but there are still hurdles that need to be overcome with regard to reliability and fatigue life. AM has issues with accuracy and repeatability/consistency, and there is a lack of qualification and standards for critical parts. Accuracy and consistency issues pose an issue for potentially clogging heat exchanger tubes. Typically, after a metal part is fabricated, the surface is polished to remove geometry imperfections that could cause unwanted stress concentrations. Heat exchangers contain complex internal geometries that cannot undergo post-processing. For example, the internal tubing of microchannel heat exchangers cannot undergo any surface polishing or post-processing. Hence, more research is needed before additively manufactured parts can be considered finished products. Very few AM methods use copper, which traditionally is the best materials for heat exchangers due to its high thermal conductivity. Indeed, material selection needs to be expanded and better understanding of the interactions between the process parameters and materials is needed to produce better quality parts. Ceramic heat exchangers produced with AM have seen the smallest amount of attention even though LCM has been proven to be an effective method to produce complex geometries. Lastly, models have shown that AM can be more cost competitive than traditional manufacturing methods, but more accurate models are still needed to predict realistic cost benefits.

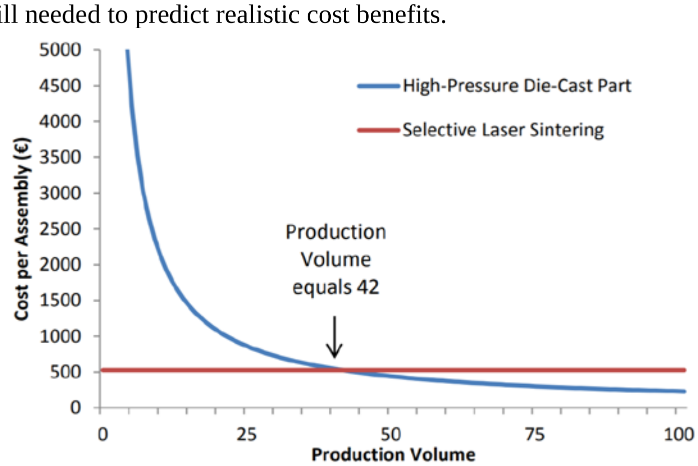

Figure 3: Cost Comparison of AM to Conventional Manufacturing Methods (Thomas and Gilbert, 2014)

8. CONCLUSIONS

Metal, polymer, and ceramic heat exchangers are being fabricated using AM technologies at an increasing rate for research purposes. AM facilitates the manufacturing of new and complex geometries than can enhance the performance of heat exchangers and has other physical property implications as well. Metal heat exchangers manufactured using LPBF processes was the most common process found in the literature of any material followed by CGDS. Many polymer and ceramic heat exchangers were also studied using various AM methods such as FDM and LCM, just to name a couple. Features, such as wall thicknesses, are reaching extremely small dimensions of ~100 μm. Surface roughness caused by AM is an area of ongoing research due to its enhancement of heat transfer surfaces. However, its advantages are offset by the increase in pressure drop. Porosity of the manufactured material can decrease the thermal conductivity and tensile strength. There are numerous challenges still to be addressed. Including, material characteristics, part quality and reliability, and AM models have demonstrated that it can be cost competitive with traditional manufacturing methods, but more accurate models are still needed. The production volume and part complexity can be used to determine whether manufacturing a heat exchanger with AM methods can be cost competitive to traditional manufacturing methods.

NOMENCLATURE

AM	Additive Manufacturing
CAD	Computer Aided Design
CGDS	Cold Gas Dynamic Spray
DMLS	Direct Metal Laser Sintering
FDM	Fused Deposition Modeling
LCM	Lithography-based Ceramic Manufacturing
LIGA	Lithography, Electroplating, and Molding
LOM	Laminated Object Manufacturing
LPBF	Laser Powder bed Fusion
LPW	Laser Polymer Welding
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
UAM	Ultrasonic Additive Manufacturing

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