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Current and Potential Applications of Additive Manufacturing for Power Electronics

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ABSTRACT To meet the upcoming challenges of higher power density and higher efficiency for power electronics, a system level approach to the design of power electronic devices must be carried out. Higher system integration and packaging will allow for more compact designs but will also result in challenges for component manufacturing and thermal management. Additive manufacturing can potentially mitigate some of these challenges due to the design flexibility and intricate features that additive manufacturing methods can provide. This paper presents an overview of the additive manufacturing technologies currently in practice at the academic and industry level. A detailed review is presented of current applications of additive methods for the production of power electronic components, advanced heat exchanger designs and integrated power electronic systems.

INDEX TERMS Additive manufacturing, electrified transportation, passive component design, power electronics, thermal management.

NOMENCLATURE

ABS	Acrylonitrile Butadiene Styrene
AJ	Aerosol Jetting
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer Aided Design
CTE	Coefficient of Thermal Expansion
DED	Direct Energy Deposition
DLP	Digital Light Projection
ELDC	Electrochemical Double Layer Capacitors
FDM	Fused Deposition Modelling
FEA	Finite Element Analysis
GA	Genetic Algorithm
HX	Heat Exchanger
IGBT	Insulated-Gate Bipolar Transistor
ME	Material Extrusion
MJ	Material Jetting
NNS	Near Net Shape
PBF	Powder Bed Fusion
PCB	Printed Circuit Board
SL	Stereolithography
TM	Thermal Management
VP	Vat Photopolymerization
WBG	Wide Band-Gap

I. INTRODUCTION

As global trends in energy consumption continue to rise [1], there is a corresponding demand to exceed the current power, weight reduction, and efficiency limitations in technology sectors such as electrified transportation. A critical subsector of the transportation industry is manufacturing and due to the previously mentioned global trends, manufacturing of Original Equipment Manufacturer components with greater complexity, weight reduction, and cost effectiveness is required [2]. Since its development three decades ago, Additive Manufacturing (AM) processes have been progressively improved to produce complex light-weight structures in the automotive industry. Also known as 3-D printing, AM is the overarching term that encapsulates any form of component manufacturing that involves the layer by layer addition and joining of material from data created in CAD software [3]. The technology has made various recent advances in specific AM methods and material selection to be a feasible

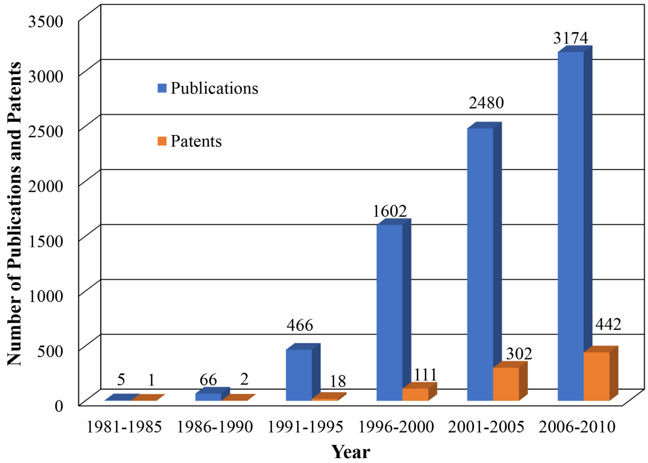

FIGURE 1. **Trend of research publications and patents related to AM from 1981–2010 (data from [5]).**

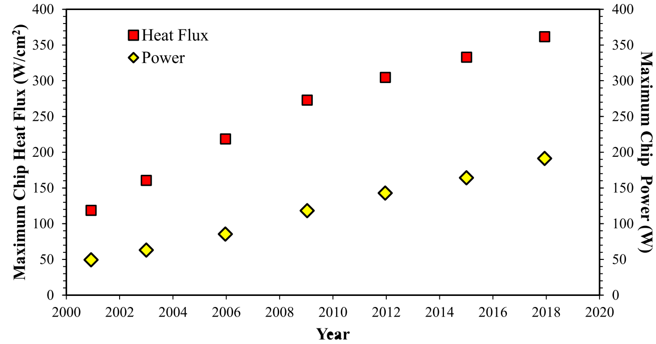

FIGURE 2. **Power trends of power electronics (data from [12]).**

option for researchers to implement in power electronic fabrication and solutions; advances examined throughout this review.

The first advancements of AM began in 1987 with the release of polymer based Stereolithography (SL), known as vat photopolymerization (VP), by 3D Systems company [4]. However, it was only in the past decade where an increased interest in AM applications, material capabilities and cost reduction allowed it to expand from a technology used in prototyping into a technology that can be leveraged for small to medium scale production. Fig. 1 shows the number of research publications that contribute to the AM technology in the last decade. These research pieces cover the fundamental engineering aspects and technical findings of AM processes. Therefore, AM processes can currently be implemented in several applications including the transportation industry.

For automotive technologies such as power electronics, the demand for power modules and converters with higher efficiency and power density are increasingly challenging to meet. The transition of power electronics (such as DC boost converters, rectifiers and traction inverters) to wide band-gap (WBG) devices is an inevitable change due to the higher operating temperature, breakdown voltage, and switching capabilities of WBG devices compared to their conventional silicon counterpart [6]. However, the reduced semiconductor package size results in elevated heat fluxes and power levels as displayed in Fig. 2. Correspondingly, WBG devices will require advanced thermal management (TM), reduced package sizes and integrated solutions to meet operational conditions [7], but current manufacturing methods are limited in geometric freedom, manufacturability, high turnover times and material selection.

Furthermore, the packaging and material selection for passive component manufacturing for power electronics is limited by conventional methods [8], [9], but with the implementation of AM, more efficient inductors with higher inductance capabilities are possible. Similarly, faster turnaround time of resistors and capacitors is possible with AM as studied by Yan *et al.* [10]. Additionally, the thermal bottleneck for power electronic devices is no longer the performance of the heat spreader/exchanger as discussed by Moreno [11]. Instead, the limitation is the thermal interface material or bonding between the power substrate and chosen cooling solution which contributes the largest thermal resistance of the entire device stackup. Thus, conventional packaging and cooling solutions will no longer suffice to meet the upcoming thermal demands.

Therefore, this paper presents a current review of AM for various aspects of power electronics, including the design and fabrication of passive components, packaging and TM solutions for power electronics. AM solutions for fabricating passive components which include resistors, capacitors, and inductors are reviewed in detail. Moreover, advanced heat sink designs and optimization that can only be achieved through AM practices are discussed. Likewise, with the inevitable demand for higher system integration and compact packaging [11], the preeminent solutions for higher system efficiency, improved thermal performance and increased power density that can be achieved through AM methods are reviewed. Additionally, the paper will also review the prominent AM processes that could be practical and applicable for power electronic design and manufacturing.

Additive manufacturing material capabilities are frequently changing, specifically for challenging materials such as copper and soft magnetic alloys. It is important to highlight current applications that could potentially improve with the development of new processes with enhanced material properties for applications such as inductor manufacturing as discussed by Ding *et al.* [13]. Additionally, all the literature reviewed in this paper currently lack the capabilities for mass production and are solely for proof of concept and performance comparison to conventional methods for determining feasibility. Thus, the literature surveyed are defined as potential applications of AM, as the methods, materials and solutions still require further research and development before larger scale implementation is achievable.

Previous reviews of AM applications for certain aspects or components of power electronics have been published, however this review examines multiple facets of power electronic design and manufacturing including the current and potential applications for power electronics. Zhakeyev *et al.* [14] reviewed multiple applications and developments of AM within energy devices and energy storage. However, they do not focus on the AM applications that pertain to power electronics, and instead highlighted the general TM solutions for a variety of applications. Conversely, Jafari *et al.* [12] reviewed the use of AM for heat transfer devices in energy conversion applications. However, their focus was on the application of a single method of AM, powder bed fusion. Muthu *et al.* [15] reviewed similar technologies and AM methods, but there have been recent advancements in areas such as composite manufacturing, packaging and TM applications. Lastly, Espera Jr. *et al.* [16] provides a detailed review on the application of various AM for electronics, including passive component and printed circuit board manufacturing. However, Espera Jr. *et al.* [16] do not specifically focus on power electronics, thermal management for power electronics or integrated solutions for power electronics using AM. Thus, there is a need for an up-to-date review of diverse AM methods focused on power electronics for electrified transportation that includes the information that is lacking in the previously mentioned reviews.

The following review will commence with an introduction of general additive manufacturing methods to understand the different process set ups and how the individual process determines the allowed materials and final product quality (dimensional tolerance, material properties). The following sections individually present current AM solutions and technologies for distinct aspects of power electronics: design and manufacturing of passive components, TM solutions and higher system integration and packaging. Finally, a conclusion is made, stating the necessity of AM to penetrate various solutions for power electronics to meet future performance and volume requirements at large scale production.

II. ADDITIVE MANUFACTURING METHODS

According to the ISO/ASTM52900 - 15 Standard [3], AM can be classified into seven distinct methods: Material Extrusion, Vat Photopolymerization, Powder Bed Fusion, Direct Energy Deposition, Binder Jetting, Material Jetting and Sheet Lamination. This section is divided into the method's material capabilities: metal and non-metal. The details of each process are briefly elucidated and the key differences between AM methods are outlined.

A. METAL AM METHODS

Although Binder Jetting has the capability to manufacture solid metal parts, the required post-processing techniques (lengthy curing, sintering, infiltration) to achieve high material densities is too complex and often results in deformed, non-conforming finished parts [17]. Additionally, it is seldom applied in power electronic applications, thus Binder Jetting is omitted from this overview. On the other hand, Direct Energy Deposition (DED), Powder Bed Fusion (PBF), Material Jetting (MJ) and Sheet Lamination have been widely used in power electronics and various methods and solutions are described in the subsequent sections. Fig. 3 depicts a schematic

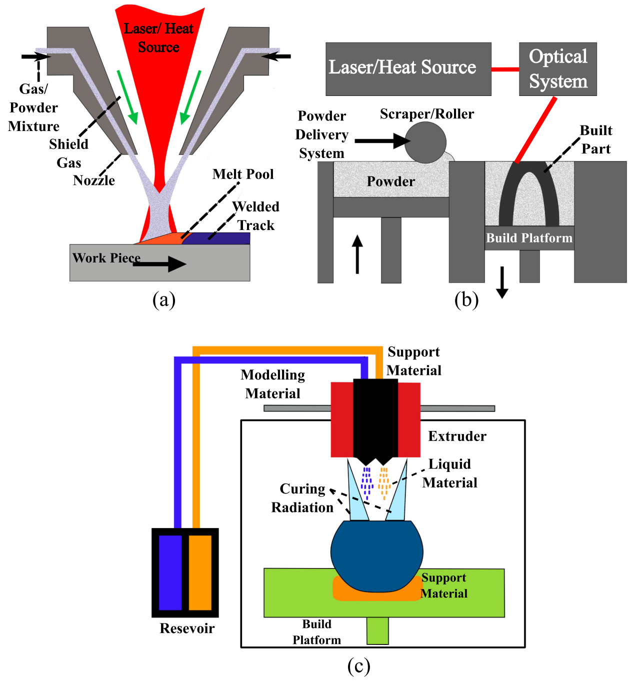

FIGURE 3. Visual schematic of three reviewed methods of metal AM - (a) Direct Energy Deposition [18]; (b) Powder Bed Fusion [19]; (c) Material Jetting [20].

for the DED, PBF and MJ. In DED, heat energy (typically laser, electron beam, or arc plasma energy) is directly deposited to the feedstock being simultaneously delivered to the work piece through a nozzle as shown in Fig. 3(a) [18]. Similarly, PBF uses a heat source to fuse powder particles; however, the powder is first deposited onto a build platform to form a layer where the heat source (usually a laser or electron beam) will selectively melt a specific region as depicted in Fig. 3(b) [19]. MJ instead selectively deposits droplets of the material onto the workpiece that is subsequently cured or solidified through a specific process (radiation, cooling or evaporation) as demonstrated in Fig. 3(c) [20]. DED and PBF utilize solid metal feedstock (possibly wire for DED); however, liquids are used as feedstocks in the MJ process.

Significantly distinct from these processes, sheet lamination utilizes thin material sheets/foils as feedstock, subsequently joining the adjacent layers through various processes including ultrasound (welding), polymer adhesion and diffusion binding [21]. The variation in material joining allows sheet lamination to have a wider range of material selection in comparison to PBF, DED and MJ [21]. Therefore, these processes will differ according to their limitations and benefits. This review will not go into further detail as to the exact process of each method (as they are already well defined by the ASTM standards for AM and previous reviews [3], [18], [19], [22], [23]). Zhang *et al.* [21] provide a detailed review of commercially available systems and their respective print parameters, allowing researchers to compare the solution's parameter to the user requirements. Lastly, it should be noted that with the exception of DED, these methods are also capable of producing non-metallic parts [3].

These methods all share similar material capabilities, build envelope [3] and post-processing requirements before achieving desired dimensional tolerance. Thus, selection of the appropriate AM method is typically based on the dimensional capabilities. If resolution or minimum feature size is the primary concern, PBF and MJ would be the the preferred choice due to the way the material is implemented. For DED the powder or wire is fed through a nozzle to subsequently come in contact with the energy source. This process will result in higher layer thickness but inherently lacks the precision to achieve the same resolution as PBF, where the powder is deposited on top of a substrate prior to the energy deposition. This allows for more selective laser melting and consequently better feature size. Moreover, the following studies have compared these methods in finer detail [24], [25], comparing complexity, volume of production, lead times and other associated factors. Furthermore, sheet lamination offers a significantly cost-effective solution with comparable densities to the previous methods but lacks the capability to produce internal features typically required for heat exchangers [26] available in PBF and DED systems. This is due to the joining process for metal sheets requiring ultrasonic welding at high pressures; internal features are hollow and do not give a normal reaction force to the pressure causing welding defects and discontinuities in the region nearby the feature [26].

B. NON-METAL AM METHODS

Material extrusion (ME) and vat photopolymerization (VP) encompass the most well-known and commercially available AM solutions, with significant market penetration even at the average consumer level. ME uses a filament feedstock extruded through a heated nozzle; the liquefied filament passing through the nozzle is then deposited onto a build platform where subsequent deposited layers fuse to the previous layer until the final form is achieved [27]. VP implements laser or digital light processing to selectively radiate a layer of photopolymer resin. This radiation causes the resin to cure and solidify forming a layer of the intended part; the build platform lowers, allowing the layer to be re-coated with resin and the process continuous [28]. Commonly used technologies from ME and VP are Fused Deposition Modelling (FDM) and Stereolithography (SLA) respectively.

Both processes offer low-cost and fast turnaround time with little required post-processing. Additionally, SLA has the highest accuracy of the presented AM processes [28], making it well suited solution for small scale applications such as passive component manufacturing in power electronics. However, the inherent process of SLA significantly limits the material selection to only photopolymer resins. Moreover, FDM technology offers a printing solution with multi-material capabilities suitable for parts such as magnetic components, typically comprised of two dissimilar materials. However, FDM's accuracy is limited by the extrusion diameter, much coarser than the light source in the SLA process [27].

III. AM APPLICATIONS FOR PASSIVE COMPONENTS

Transitioning from current silicon IGBT devices to WBG devices is an inevitable change in the power electronics field. Similarly, so is the change in design of power electronic components in WBG devices for conventional manufacturing methods into designing for additive manufacturing. Dede *et al.* [29] points to the possibility to miniaturize components within power electronics due to the impedance of the magnetic components being proportional to the operational frequency (WBG enables devices to operate at significantly higher frequencies of 100 kHz to 10 MHz).

Individual passive components within power electronics, such as capacitors, resistors, inductors, are also candidates to be completely fabricated through current AM methods. Conventionally, passive and other electronic components are produced through a mix of subtractive and additive manufacturing including lamination, ablation, photolithography and additive methods (limited to material deposition) [30]. Although this mixture suits mass production, it contains disadvantages such as slower prototyping, design limitations and material waste. Naturally, this warrants further investigation on the feasibility of implementing AM processes for passive components.

According to Khan *et al.* [31], the finished resolution of an electrical component significantly influences its electrical performance. Thus, Tan *et al.* [32] determined that aerosol and ink jetting AM processes were the best candidates to manufacture advanced passive components due to the high resolution and thin layer thickness (10 μm and 0.1 μm for aero jet printing respectively). However, both processes have low throughput due to their low print speed compared to other discussed techniques (offset lithography) [32]. Implementing an inkjet process, Yang *et al.* [10] printed three different passive components made of two different polymers, a sacrificial material representing the hollow channels and the other for the encasing. Upon post-processing to remove the sacrificial material, the remaining material acting as a cast, is injected with a conductive liquid silver suspension, displayed in Fig. 4. Yang *et al.* [10] discovered that the injected silver was almost 90% of the ideal conductivity of solid silver paste, thus validating the feasibility of this new method of print-injection passive component manufacturing. However, void formation was present in the injected silver but could be addressed through optimization of the silver suspension concentration, curing process and filling operations.

Correia *et al.* [33] attempted to gauge the feasibility of tailored passive components (inductors, resistors, capacitors), implementing inkjet printing and comparing the results to the theoretical equivalent RLC circuit. Correia *et al.* [33] determined that the capacitor and resistor both successfully resulted in nearly identical capacitance and resistance to the ideal equivalent circuit values. However, poor dimensional tolerancing of the planar inductor's coils (coil line width and spacing) resulted in non-uniformities that negatively impacted the inductor's electrical properties. Thus, Correia *et al.* [33] demonstrated the feasibility to additively

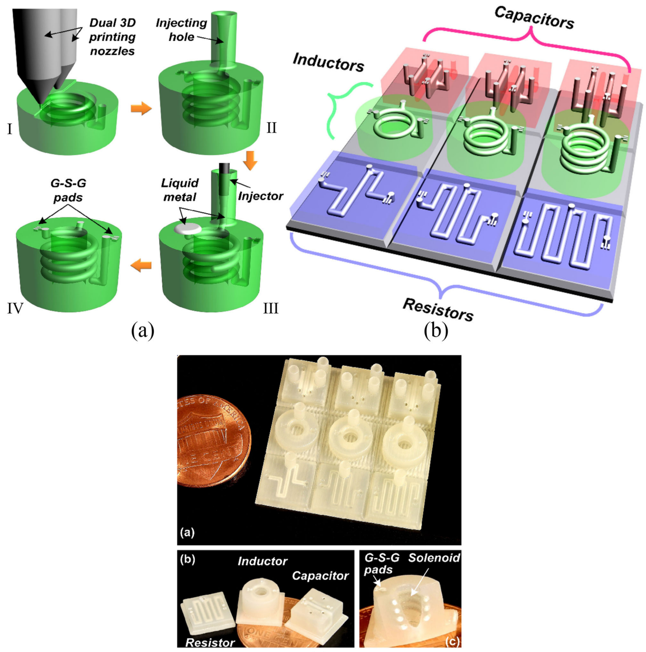

FIGURE 4. (a) Two stage printing process for each component where the polymer negative is built first, followed by the liquid metal filling and remaining post processing: (b) Component schematic: (c) Finished component compared to a US coin after printing and curing [10]. (Photo courtesy of University of California, Berkeley, CA.).

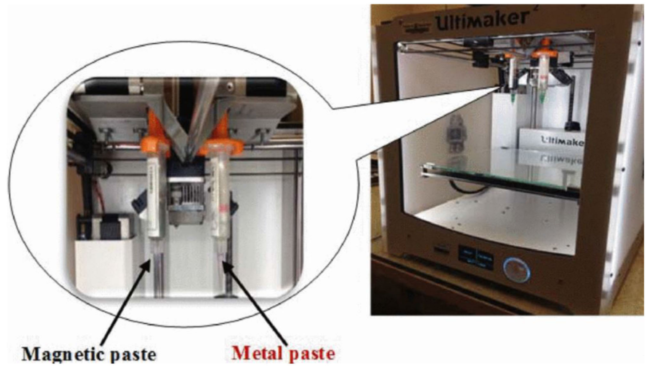

FIGURE 5. Multi-material extrusion of magnetic and metal pastes [9]. (Photo courtesy of Virginia Tech, Blacksburn, Virginia).

manufacture application-specific capacitors and resistors with inkjet printing; however, higher resolution AM methods (such as aero jetting) should be investigated for inductor coil manufacturing. Lastly, passive component manufacturing is not limited to solely inkjet solutions. Through a novel process combining SLA and copper electroless plating, Salas-Beranys *et al.* [34] demonstrated that the manufacturing of RF passive components are comparable to the best off-the-shelf inkjet solutions. Measuring a resistivity of 9-20 $\mu\Omega$cm compared to Optomec's inkjet system of 5 $\mu\Omega$cm. Additionally, this novel method is less than 5% of the cost of the Optomec system [34], making it a feasible option for RF passive component manufacturing and research.

The fabrication of magnetic components, specifically inductors, within power electronics is an important process currently limited by conventional manufacturing techniques [35]. Typically, the core and winding for magnetic components are manufactured separately resulting in larger package size, longer lead times and performance limitations of the component [8], [9]. Proposed geometries, such as Cui and Ngo's [36] constant flux inductor, can reduce package size and increase component efficiency but require advanced methods of fabrication to be feasible, an opportunity where AM can be effectively applied. In addition to the methods of additive manufacturing, Ding *et al.* [13] state that the AM methods are limited by the implemented feedstock material, rather than the specific manufacturing process for soft magnetic alloys. Few publications have successfully printed soft magnetic components with an acceptable relative permeability, typically less than 10 [13].

Based on a similar process created by Yan *et al.* [9] using an FDM printer as shown in Fig. 5, Ding *et al.* [37] developed a constant-flux inductor with a novel multi-material magnetic paste with comparable relative permeability (of 35) to commercially available powder-iron cores. In addition, the FDM manufacturing process permits the ability to consistently produce complex coil designs with varying line thickness to an accuracy of 0.2 mm, a capability conventional powder methods and inkjet printing process [33] lack. Furthermore, Ding *et al.* [38] analyzed the reliability of the manufactured constant-flux inductor through lengthy temperature cycling and high temperature storage testing. It was determined that after extensive testing, there was negligible change in winding resistance and less than 5% change in inductance, indicating an acceptable reliability for the production of Ding *et al.*'s magnetic feedstock and AM process [38].

Conventional air-core inductors for transformers such as wire-wound and solenoid inductors have various constraints such as limited available geometry and unpredictable inductance. These limitations stem from the conventional process having high turnaround cost/time and the inaccuracy of the copper winding process [39]. Tong *et al.* [39] eclipses these limitations through the design and manufacturing of various 3D printed transformers through a combination of SLA and electroplating technique, similar to that used by Salas-Barenys *et al.* [34]. Although Tong *et al.* [39] determined that printed transformers had various drawbacks such as limited inductance and poor field confinement, the implemented process offers significantly improved design freedom, predictable inductance and considerably lower cost.

Lastly, integrated magnetic components for power electronic converters offers smaller package sizes, lower production costs and higher efficiency. Fukuoka *et al.* [40] studied the feasibility of these benefits for converters using a multi-material sheet lamination process as opposed to the previously used and more common material extrusion and vat polymerization techniques. The manufactured converter was found to have a fast load transient response of 2.6 μs and 86% max efficiency, comparable to state-of-the-art technology parameters provided by Fukuoka *et al.* [40]. Additionally, the produced converter achieves a smaller footprint at lower cost due sheet lamination (as discussed in Section II) being a cheaper option to other AM techniques. Thus, manufacturing passive components using AM is highly feasible and offers significant benefits compared to conventional methods, and with future improvements in materials, process resolution and cost, larger scale implementation will become achievable.

IV. AM FOR THERMAL MANAGEMENT OF POWER ELECTRONICS

The limitations of current TM using conventional manufacturing methods can be offset through the implementation of AM. As previously mentioned, increased heat flux and reduced WBG device packaging pushes power electronic technology to implement more effective TM solutions with tighter volume and weight constraints. The AM methods presented in Section II have the capability of producing optimized surface area for heat sinks, heat pipes and cold plates. Historically, PBF methods are generally limited to producing copper alloy parts as opposed to pure copper due to copper's high reflectivity and thermal conductivity preventing the appropriate beam power deposition onto the material [41]. However, this is only a minor drawback as the material properties for the copper alloys and aluminum used for AM heat exchangers present a marginal difference in performance (max allowable temperature) compared to their pure counterpart [42]. This performance discrepancy can be further reduced with the addition of thermal annealing to the printed part, the overall performance of the printed part can match the conventional material HX [42].

Theoretically, complex heat sink geometries have proven to have lower thermal resistances and weight while maintaining feasible pressure drops [43]. Additionally, with the design freedom provided by AM, the appropriate methodology for heat sink design optimization can be implemented. Using the genetic algorithm and real time FEA feedback, Wu *et al.* [44] were able to converge to an optimized heat sink and subsequently manufacture the final model through PBF. Testing their product with a 50 kW inverter, the optimized heat sink design thermally outperformed the conventional pin fin heat sink with nearly a 30% volume reduction. This is a significant increase in performance and efficiency, however these studies that optimize heatsink geometry using GA typically focus on 2D cross section or grid optimization [44]–[46]. Thus, there is significant potential to further exploit the benefits of AM for heatsink design with future developments of 3D optimization while staying within computational capabilities. Substantially more complex designs with higher heat transfer coefficients and surface areas are achievable, as is the case with Dede *et al.* [47], displayed in Fig. 6, and in the following resources [48], [49].

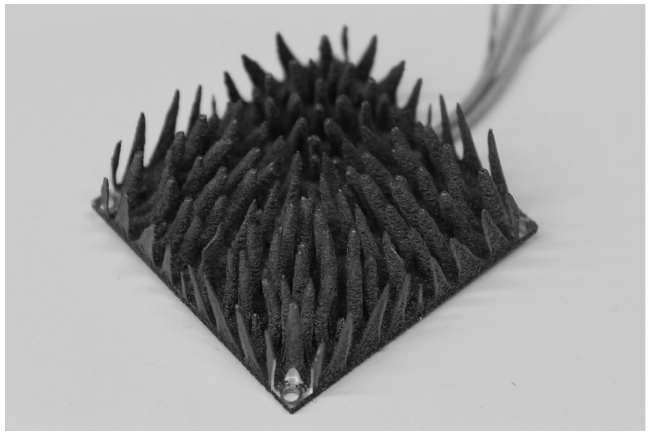

FIGURE 6. **3D optimized topology of AlSi12 heat sink [47]. (Photo courtesy of Toyota Research Institute of North America, Ann Arbor, Michigan).**

In addition to conventional materials used in heat transfer devices, AM has a considerable potential to incorporate composite materials into TM applications for power electronics. Generally, polymer materials are lightweight and have high flexibility, but their low thermal conductivity and high CTE leads to reduced performance and durability. However, utilizing the concept of materials such as reinforced concrete or fibre glass, additive manufacturing for TM can leverage the material benefits of polymers as a composite solution. Thus, certain fillers or additives can be combined to polymer matrices to mitigate the drawback of polymers and produce a composite material suitable for TM applications [50]–[52]. Typical fillers (and their concentration) depend on the specific application, though commonly used fillers are nanostructures (carbon nanotubes, graphene), metals and ceramics [53]. Guo *et al.* [54] reviews the most recent advances for printing of graphene-based composites and found various AM methods such as SLA, SLS and FDM are currently implemented and feasible options for composite manufacturing combined with the appropriate post-processing such as annealing. However, Guo *et al.* [54] concludes that improvements of void percentage, graphene orientation, and filler/matrix mixture quality are vital for the future of the technology. Additionally, the MJ methods used in these multi-material processes have lower cost compared to other AM methods. This is due to the reduced cost of SL, direct ink writing, inkjet and FDM (as discussed in [9]) systems and their corresponding materials (ink/chemical solution) in comparison to PBF and DED methods and powder materials. Thus, with the ability to produce these hybrid materials, HXs can be manufactured at lower cost and reduced weight in comparison to traditional materials [53], [55].

Implementing an FDM method, Wei *et al.* [56] successfully printed the first polymer composite using ABS with a 5.6 wt% concentration of graphene filler that exhibited improved electrical and thermal properties compared to the standalone polymer. However, higher concentrations of graphene resulted in discontinuous extrusion of the composite material through the printer nozzle [56] and thus other AM methods for polymer composites have been investigated. Additionally, the appropriate concentration of the filler requires optimization before the apical performance improvements can be observed. Using a low cost SL printer, Kalsoom *et al.* [53] found that a 30% concentration of a diamond micro-particles resulted in the ideal thermal conductivity and CTE for a pin fin heat sink. Subsequently, Kalsoom *et al.* [53] also applied the same material to manufacture a heat pipe that demonstrated a 50% temperature drop in the applied fluid.

Lastly, AM of composites can be integrated with existing HX design. A prime example of how traditional HX design for power electronics can be upgraded, Hymas *et al.* [57] successfully manufactured a metal/polymer radiator integrating aluminum transverse fins and polymer liquid cooling channels using a novel combination of FDM and Embedded Fiber Composite Additive Manufacturing (EFCAM). The produced HX performed nearly identically to the target values set by Hymas *et al.* [57], establishing the feasibility of composite HX for TM of power electronics. There is significant potential for AM of composites to further penetrate the field of TM of power electronics. However, this requires placing focus on shorter lead time processes, lower cost materials, advanced/functional fillers (magnetic fillers [58]), and post processing techniques that improve durability and reliability without significant cost or lead time increases [53], [55], [57].

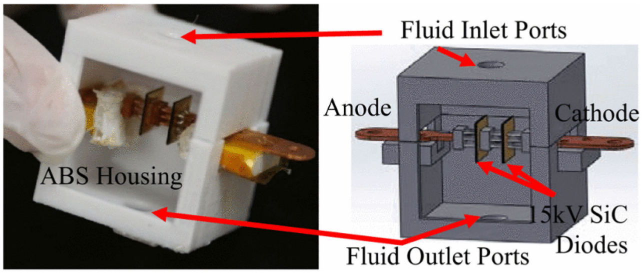

FIGURE 7. Fabricated high voltage module with integrated cooling [60]. (Photo courtesy of U.S. Army Research Laboratory, Adelphi, Maryland).

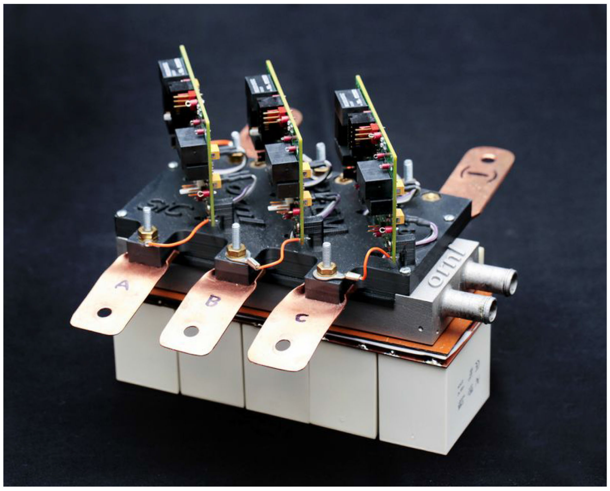

FIGURE 8. AM prototype of 10 kW inverter [61]. (Photo courtesy of Oak Ridge National Laboratory, Oak Ridge, Tennessee).

V. AM FOR HIGHER SYSTEM INTEGRATION AND PACKAGING

Additionally, AM can provide substantial benefit for the packaging and system integration of power electronics. In order to manage the increased heat flux with smaller packaged WBG devices, integrating the mechanical enclosure with the electronics is a vital step needed to improve the efficiency and power density of WBG devices [59]. Therefore, implementing the method of SL to manufacture a polymer enclosure, Ke *et al.* [59] were able to successfully produce a module that allowed the electronics and interconnects to be embedded within the structure resulting in smaller packaging size and better thermal performance. Due to the high entry and material cost, AM for mass produced components remains unfeasible, however Ke *et al.* [59] acknowledge that the eventual cost-reduction will allow for commercial adaptation in power electronics.

Furthermore, compact packaging for WBG devices poses a significant challenge for high voltage applications due to the failure locations (wire bonds, DBC, and heat sink interface) associated with standard packaging techniques. Thus, Boteler *et al.* [60] implemented an integrated AM ABS housing for the WBG (GaN) devices, displayed in Fig. 7, that not only allowed the produced module to operate $>$20 kV, but significantly reduced the cost, weight, and lead time of the module compared to conventional methods.

As previously discussed, current power electronics are thermally managed through HXs directly attached (soldered, brazed, mounted with TIM) to the power module but conventional manufacturing methods limit the device's ability to withstand the higher operational temperatures of WBG devices. Thus, in order to fully take advantage of the capabilities of WBG devices, integrated cooling for power electronics is required, realizable through AM methods. In collaboration with Oak Ridge National Laboratory, Chintavali *et al.* [61], [62] developed two (10 kW air-cooled and 30 kW liquid-cooled) SiC inverters integrated with an PBF manufactured aluminum alloy heat sinks, the 10 kW inverter displayed in Fig. 8. Additionally, Chintavali *et al.* [61] demonstrated how AM aluminum alloy performs equally to normal 6061 aluminum at the operational temperatures expected in the inverter, thus performance of the device is not negatively affected by the new AM material. Consequently, the capability of 3D printing the HXs allowed more compact packaging of the inverter for both air and liquid cooled inverters while still maintaining acceptable pressure drops and operational efficiency [61], [62].

Similarly, integration of heat pipes into power electronics has also shown to have potential as heat pipes consume less volume and do not require complex designs to meet surface area requirements. Therefore, embedding heat pipes into power electronics is a feasible alternative to attaching heat sinks to a pre-assembled module. Theoretically, Muthu *et al.* [63] demonstrated how the implementation of additively manufactured PCBs, through future use of systems such as Nano Dimension's Dragonfly [64], would permit the embedding of heat pipes between individual layer printing sequences. This concept is subsequently simulated in the absence of a commercial system and found to exhibit significantly improved thermal distribution across the PCB layers, reduced thermal resistance and more efficient thermal dissipation [63]. In addition to integrating thermal solutions into a PCB assembly, various studies have investigated the feasibility of directly printing copper traces and heat sinks onto the dieletric material of the power substrate. Implementing a PBF method of selective laser melting, Stoll *et al.* [65] demonstrated that an acceptable shear strength of 44 N/mm^2 between the ceramic and copper layers can be achieved compared to conventional direct bonded copper substrates. Additionally, Stoll *et al.* [66] investigated the influence of preheating the base ceramic material and discovered that the common challenges of delamination, high residual stresses and oxidation can be minimized through preheating. However, fatigue analysis, electrical conductivity measurements and post-processing techniques of the print were not performed and should be investigated in future studies. Although partial integration of additively manufactured TM solutions for power electronics is possible as discussed in the previous examples, future progress with more commercially available systems and materials will allow higher levels of integration, reduced package sizes and improved TM for WBG devices within power electronics.

VI. CONCLUSION

The penetration of additive manufacturing in the vehicle industry is significant for both automotive and aerospace applications. Progression into lower entry cost AM systems, faster production times and wider material selection will permit AM to establish itself more commonly in large scale production. Additionally, the inevitable transition from traditional IGBTs to WBG devices requires a corresponding change in current solutions for power electronics. Conventional methods and designs will not be able to match the complexity, weight reduction, and level of integration of potential AM solutions in power electronics. As a result, advanced solutions such as AM of magnetic and other passive components, integrated cooling, polymer composite HX, and AM enclosures/structures will be required in order to meet these thermal, mechanical, and volume demands. Although, several reviewed methods and technologies are at a developmental stage, the results and characterization demonstrate similar or superior performance to their conventionally manufactured counterparts. Consequently, it is no longer a question whether AM methods can successfully be implemented for power electronics applications, but rather how it can be done at a mass production level. Current limitations of AM methods such as lack of commercially available systems, narrow material selection and high production/entry cost pose a challenge to AM implementation for power electronics at a large scale. Nonetheless, thermal and packaging demands from WBG devices will eventually exceed conventional solutions and require OEMs to integrate AM into their design and fabrication process for power electronics.

REFERENCES

[1] S. Ma, A. Pitman, M. Hart, J. P. Evans, N. Haghdadi, and I. MacGill, "The impact of an urban canopy and anthropogenic heat fluxes on sydney's climate," *Int. J. Climatol.*, vol. 37, no. 1, pp. 255–270, Feb. 2017.

[2] L. Monostori, "AI and machine learning techniques for managing complexity, changes and uncertainties in manufacturing," *IFAC Proc. Volumes (IFAC-PapersOnline)*, vol. 15, no. 1, pp. 119–130, 2002.

[3] ISO/ASTM52910-18, "Additive manufacturing - design - requirements, guidelines and recommendations," West Conshohocken, PA, 2018. [Online]. Available: www.astm.org

[4] T. Wohlers and T. Gornet, "History of additive manufacturing introduction of non-SL systems introduction of low-cost 3D printers," Wohlers Report 2012, 2012, pp. 1–23.

[5] A. D. Lantada and P. L. Morgado, "Rapid prototyping for biomedical engineering: Current capabilities and challenges," *Annu. Rev. Biomed. Eng.*, vol. 14, no. 1, pp. 73–96, 2012.

[6] A. Bindra, "Wide-bandgap-based power devices reshaping the power electronics landscape," *IEEE Power Electron. Mag.*, vol. 2, no. 1, pp. 42–47, Mar. 2015.

[7] L. Marlino, "FreedomCAR and DOE roadmap for automotive power electronics 3/4 DOE and FreedomCAR partnership 3/4 program packaging challenges 3/4 roadmap overview 3/4 power electronics in the program 3/4 government/industrial partnerships and opportunities," Dept. Energy, Fort Worth, TX, USA, Tech. Rep. 1, 2011.

[8] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2237–2245, Jun. 2008.

[9] Y. Yan, K. D. Ngo, Y. Mei, and G. Q. Lu, "Additive manufacturing of magnetic components for power electronics integration," in *Proc. Int. Conf. Electron. Packag.*, Sapporo, Japan: The Japan Institute of Electronics Packaging, 2016, pp. 368–371.

[10] C. Yang, S. Y. Wu, C. Glick, Y. S. Choi, W. Hsu, and L. Lin, "3D printed RF passive components by liquid metal filling," in *Proc. IEEE Int. Conf. Micro Electro Mech. Syst.*, Estoril, Portugal, 2015, pp. 261–264.

[11] G. Moreno, "Thermal performance benchmarking annual report," Tech. Rep. 1, Apr. 2016.

[12] D. Jafari and W. W. Wits, "The utilization of selective laser melting technology on heat transfer devices for thermal energy conversion applications: A review," *Renewable Sustain. Energy Rev.*, vol. 91, no. 1, pp. 420–442, Aug. 2018.

[13] C. Ding, L. Liu, Y. Mei, K. D. Ngo, and G. Q. Lu, "Magnetic paste as feedstock for additive manufacturing of power magnetics," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, San Antonio, TX, 2018, pp. 615–618, doi: 10.1109/APEC.2018.8341075.

[14] A. Zhakeyev, P. Wang, L. Zhang, W. Shu, H. Wang, and J. Xuan, "Additive manufacturing: Unlocking the evolution of energy materials," *Adv. Sci.*, vol. 4, no. 10, 2017, Art. no. 1700187.

[15] V. Muthu, P. Chatterjee, and T. K. Jet, "Review on application of additive manufacturing for electrical power converters," in *Proc. IEEE Region 10 Annu. Int. Conf., Proc./TENCON*. Singapore, 2017, pp. 2327–2333.

[16] A. H. Espera, J. R. C. Dizon, Q. Chen, and R. C. Advincula, "3D-printing and advanced manufacturing for electronics," *Prog. Additive Manuf.*, vol. 4, no. 3, pp. 245–267, 2019.

[17] M. Ziaee and N. B. Crane, "Binder jetting: A review of process, materials, and methods," *Additive Manuf.*, vol. 28, no. Dec. 2018, pp. 781–801, 2019.

[18] ASTMF 3413–19, "Guide for additive manufacturing - design - directed energy deposition," West Conshohocken, PA, 2019. [Online]. Available: www.astm.org

[19] ISO/ASTM52911-1-19, "Additive manufacturing - design - Part 1: Laser-based powder bed fusion of metals 1," West Conshohocken, PA, 2019. [Online]. Available: www.astm.org

[20] E. Taneva, B. Kusnoto, and C. A. Evans, "3D scanning, imaging, and printing in orthodontics," in *Proc. Issues Contemporary Orthodontics*, 2015, pp. 147–187.

[21] F. Zhang *et al.*, "3D printing technologies for electrochemical energy storage," *Nano Energy*, vol. 40, pp. 418–431, Aug. 2017.
[22] W. E. Frazier, "Metal additive manufacturing: A review," *J. Mater. Eng. Perform.*, vol. 23, no. 6, pp. 1917–1928, 2014.
[23] M. K. Thompson *et al.*, "Design for additive manufacturing: Trends, opportunities, considerations, and constraints," *CIRP Ann. - Manuf. Technol.*, vol. 65, no. 2, pp. 737–760, 2016.
[24] K. Vartanian, L. Brewer, K. Manley, and T. Cobbs, "Powder bed fusion vs. directed energy deposition benchmark study: Mid-size part with simple geometry," *Optomec, Tech. Rep*. 1, 2016.
[25] T. DebRoy *et al.*, "Additive manufacturing of metallic components—process, structure and properties," *Prog. Mater. Sci.*, vol. 92, no. 1, pp. 112–224, 2018.
[26] M. Norfolk and H. Johnson, "Solid-state additive manufacturing for heat exchangers," *J. Operations Manage.*, vol. 67, no. 3, pp. 655–659, 2015.
[27] G. D. Goh, Y. L. Yap, H. K. Tan, S. L. Sing, G. L. Goh, and W. Y. Yeong, "Process-structure-properties in polymer additive manufacturing via material extrusion: A review," *Crit. Rev. Solid State Mater. Sci.*, vol. 45, no. 2, pp. 113–133, 2020.
[28] J. V. Crivello and E. Reichmanis, "Photopolymer materials and processes for advanced technologies," *Chem. Mater.*, vol. 26, no. 1, pp. 533–548, 2014.
[29] E. M. Dede, M. Ishigaki, S. N. Joshi, and F. Zhou, "Design for additive manufacturing of wide band-gap power electronics components," in *Proc. 3D-PEIM Int. Symp. 3D Power Electron. Integr. Manuf.*, Raleigh, NC, 2016, pp. 1–20.
[30] X. Zhang, T. Ge, and J. S. Chang, "Fully-additive printed electronics: Transistor model, process variation and fundamental circuit designs," *Org. Electron.*, vol. 26, no. 1, pp. 371–379, 2015.
[31] S. Khan, L. Lorenzelli, and R. S. Dahiya, "Technologies for printing sensors and electronics over large flexible substrates: A review," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3164–3185, Jun. 2015.
[32] H. W. Tan, T. Tran, and C. K. Chua, "A review of printed passive electronic components through fully additive manufacturing methods," *Virtual Phys. Prototyping*, vol. 11, no. 4, pp. 271–288, 2016.
[33] V. Correia *et al.*, "Design and fabrication of multilayer inkjet-printed passive components for printed electronics circuit development," *J. Manuf. Process.*, vol. 31, no. 1, pp. 364–371, 2018.
[34] A. Salas-Barenys, N. Vidal, J. Sieiro, J. M. Lopez-Villegas, B. Medina-Rodriguez, and F. M. Ramos, "Fabrication of Full-3D printed electronics RF passive components and circuits," in *Proc. PRIME 14th Conf. on Ph.D. Res. Microelectron. Electron.*, Prague, 2018, pp. 265–268.
[35] L. Liu, T. Ge, Y. Yan, K. D. Ngo, and G. Q. Lu, "UV-assisted 3D-printing of soft ferrite magnetic components for power electronics integration," in *Proc. Int. Conf. Electron. Packag.*, Yamagata, Japan, 2017, pp. 447–450.
[36] H. Cui and K. D. Ngo, "Constant-flux inductor with enclosed winding for high-density energy storage," *Electron. Lett.*, vol. 49, no. 13, pp. 841–843, 2013.
[37] C. Ding *et al.*, "Additive manufacturing of spiral windings for a pot-core constant-flux inductor," *IEEE Trans. Emerg. Sel. Top. Power Electron.*, vol. 8, no. 1, pp. 618–625, Mar. 2020.
[38] C. Ding, L. Liu, J. Moss, J. Mullenix, K. D. Ngo, and G. Q. Lu, "Reliability assessment of magnetic cores and 3-D-Printed constant-flux inductors," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 10, no. 10, pp. 1693–1699, Oct. 2020.
[39] Z. Tong, W. D. Braun, and J. M. Rivas-Davila, "Design and fabrication of three-dimensional printed air-core transformers for high-frequency power applications," *IEEE Trans. Power Electron.*, vol. 35, no. 8, pp. 8472–8489, Aug. 2020.
[40] T. Fukuoka, Y. Karasawa, T. Akiyama, R. Oka, S. Ishida, and T. Shirasawa, "Converter with magnetic core inductor embedded in interposer fabricated by epoxy/magnetic-filler composite build-up sheet," in *Proc. IEEE Appl. Power Electron. Conf. Expo.*, Anaheim, CA: IEEE, 2019, pp. 1561–1566.
[41] M. M. O. F. Singer, D. C. Deisenroth, D. M. Hymas, "Additively manufactured copper components and composite structures for thermal management applications," in *Proc. 16th IEEE Intersoc. Conf. Thermal Thermomech. Phenomena Electron. Syst*., Orlando, FL: IEEE, 2017, pp. 174–183.
[42] T. Wu, A. A. Wereszczak, H. Wang, B. Ozpineci, and C. W. Ayers, "Thermal response of additive manufactured aluminum," in *Proc. 3D-PEIM Int. Symp. 3D Power Electron. Integr. Manuf.*, Raleigh, NC, 2016, pp. 1–15.
[43] S. Otake *et al.*, "Heatsink design using spiral-fins considering additive manufacturing," in *Proc. Int. Conf. Electron. Packag.*, Niigata, Japan, 2019, pp. 46–51.
[44] T. Wu, Z. Wang, B. Ozpineci, M. Chinthavali, and S. Campbell, "Automated heatsink optimization for air-cooled power semiconductor modules," *IEEE Trans. Power Electron.*, vol. 34, no. 6, pp. 5027–5031, Jun. 2019.
[45] D. Bacellar, V. Aute, Z. Huang, and R. Radermacher, "Design optimization and validation of high-performance heat exchangers using approximation assisted optimization and additive manufacturing," *Sci. Technol. Built Environ.*, vol. 23, no. 6, pp. 896–911, 2017.
[46] C. B. Dokken and B. M. Fronk, "Optimization of 3D printed liquid cooled heat sink designs using a micro-genetic algorithm with bit array representation," *Appl. Thermal Eng.*, vol. 143, pp. 316–325, May 2018.
[47] E. M. Dede, S. N. Joshi, and F. Zhou, "Topology optimization, additive layer manufacturing, and experimental testing of an air-cooled heat sink," *J. Mech. Des.*, *Trans. ASME*, vol. 137, no. 11, pp. 1–9, 2015.
[48] R. Smith, "Thermal Testing of a 3D printed super dense mesh heatsink against State-of-The-Art finned geometry," 2015. [Online]. Available: www.qualifiedrapidproducts.com
[49] H. Keramati, F. Battaglia, M. A. Arie, F. Singer, and M. M. Ohadi, "Additive manufacturing of compact manifold-microchannel heat exchangers utilizing direct metal laser sintering," in *Proc. InterSoc. Conf. Thermal Thermomech. Phenomena Electron. Syst., ITHERM*, Las Vegas, NV, 2019, pp. 423–429.
[50] C. P. Wong and R. S. Bollampally, "Comparative study of thermally conductive fillers for use in liquid encapsulants for electronic packaging," *IEEE Trans. Adv. Packag.*, vol. 22, no. 1, pp. 54–59, Feb. 1999.
[51] J. P. Hong *et al.*, "High thermal conductivity epoxy composites with bimodal distribution of aluminum nitride and boron nitride fillers," *Thermochimica Acta*, vol. 537, Dec. 2018, pp. 70–75, 2012.
[52] J. W. Zha, Y. H. Zhu, W. K. Li, J. Bai, and Z. M. Dang, "Low dielectric permittivity and high thermal conductivity silicone rubber composites with micro-nano-sized particles," *Appl. Phys. Lett.*, vol. 101, no. 6, 2012, Art. no. 062905.
[53] U. Kalsoom, A. Peristyy, P. N. Nesterenko, and B. Paull, "A 3D printable diamond polymer composite: A novel material for fabrication of low cost thermally conducting devices," *RSC Adv.*, vol. 6, no. 44, pp. 38 140–38 147, 2016.
[54] H. Guo, R. Lv, and S. Bai, "Recent advances on 3D printing graphene-based composites," *Nano Mater. Sci.*, vol. 1, no. 2, pp. 101–115, 2019.
[55] N. Nguyen, E. Melamed, J. G. Park, S. Zhang, A. Hao, and R. Liang, "Direct printing of thermal management device using low-cost composite ink," *Macromol. Mater. Eng.*, vol. 302, no. 10, pp. 1–6, 2017.
[56] X. Wei *et al.*, "3D printable graphene composite," *Sci. Rep.*, vol. 5, no. 1, pp. 1–7, 2015.
[57] D. M. Hymas, M. A. Arle, F. Singer, A. H. Shooshtari, and M. M. Ohadi, "Enhanced air-side heat transfer in an additively manufactured polymer composite heat exchanger," in *Proc. 16th InterSoc. Conf. Thermal Thermomech. Phenomena Electron. Syst.*, Orlando, FL, 2017, pp. 634–638.
[58] K. Gaska, G. Kmita, A. Rybak, R. Sekula, K. Goc, and C. Kapusta, "Magnetic-aligned, magnetite-filled epoxy composites with enhanced thermal conductivity," *J. Mater. Sci.*, vol. 50, no. 6, pp. 2510–2516, 2015.
[59] H. Ke, A. Morgan, R. Aman, and D. C. Hopkins, "Investigation of rapid-prototyping methods for 3D printed power electronic module development," in *Proc. 47th Int. Symp. Microelectron.*, IMAPS, San Diego, CA, 2014, pp. 887–892.
[60] L. M. Boteler, M. Hinojosa, V. A. Niemann, S. M. Miner, and D. Gonzalez-Nino, "High voltage stacked diode package with integrated thermal management," in *Proc. 16th InterSoc. Conf. Thermal Thermomech. Phenomena Electron. Syst.*, Orlando, FL, 2017, pp. 913–920.
[61] M. Chinthavali, C. Ayers, S. Campbell, R. Wiles, and B. Ozpineci, "A 10-kW SiC inverter with a novel printed metal power module with integrated cooling using additive manufacturing," in *Proc. 2nd IEEE Workshop Wide Bandgap Power Devices Appl.*, Knoxville, TN: IEEE, 2014, pp. 48–54.

[62] M. S. Chinthavali and Z. J. Wang, "30-kW All-SiC inverter with 3D-printed air-cooled heatsinks for plug-in and full electric vehicle applications," *Mater. Sci. Forum*, vol. 924 MSF, pp. 845–848, 2018.
[63] V. Muthu, C. Koh, J. Suan, A. Devinda, and P. Chatterjee, "Embedded thermal management solution for power electronics PCB using additive manufacturing," in *Proc. Asian Conf. Energy, Power Transp. Electrific. (ACEPT)*, Singapore, 2017, pp. 1–6.
[64] N. Dimension, "Dragonfly LDM," 2019. [Online]. Available: https://www.nano-di.com/
[65] T. Stoll, M. Kirstein, and J. Franke, "A novel approach of copper-ceramic-joints manufactured by selective laser melting," in *Proc. SPIE Opt. Eng. Appl.*, San Diego, CA, USA, 2019, Art. no. 1110109.
[66] T. Stoll, M. Kirstein, and J. Franke, "Additive manufacturing of 3D-copper-metallizations on alumina by means of selective laser melting for power electronic applications," in *Proc. 10th Int. Conf. Integr. Power Electron. Syst.*, Stuttgart, Germany, 2018, pp. 337–342.

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