Materials Science & Engineering R 129 (2018) 1–16

Contents lists available at ScienceDirect

Materials Science & Engineering R

journal homepage: www.elsevier.com/locate/mser

Additive manufacturing of multi-material structures

Amit Bandyopadhyay*, Bryan Heer

W. M. Keck Biomedical Materials Research Laboratory, School of Mechanical and Materials Engineering, Washington State University, Pullman, WA 99164-2920, USA

ARTICLE INFO

Keywords:
Additive manufacturing
3D printing
Multi-material structures

ABSTRACT

Additive manufacturing (AM) or 3D printing has revolutionized the manufacturing world through its rapid and geometrically-intricate capabilities as well as economic benefits. Countless businesses in automotive, aerospace, medical, and even food industries have adopted this approach over the past decade. Though this revolution has sparked widespread innovation with single material usage, the manufacturing world is constantly evolving. 3D printers now have the capability to create multi-material systems with performance improvements in user-definable locations. This means throughout a single component, properties like hardness, corrosion resistance, and environmental adaptation can be defined in areas that require it the most. These new processes allow for exciting multifunctional parts to be built that were never possible through traditional, single material AM processes. AM of metals, ceramics, and polymers is currently being evaluated to combine multiple materials in one operation and has already produced never-before-produced parts. While multi-material AM is still in its infancy, researchers are shifting their mindset toward this unique approach showing that the technology is beginning to advance past a research and development stage into real-world applications. This review is intended to highlight the range of 3D printed polymer-based, metal-metal, and metal-ceramic applications while discussing advantages and challenges with additively manufactured multi-material structures.

1. Introduction

Additive Manufacturing (AM) or 3D printing encompasses three essential concepts for a revolutionary idea: universal, practical, and efficient. When you consider how “universal” 3D printing is and what areas it has already influenced, the impact is quite remarkable. As it may be quite the leap from metal, polymer, and ceramic materials, imagine being able to 3D print something that everyone on the planet has at one point desired: food. Having the ability to think of your food, upload it to a printer, and see it automatically print your meal directly in front of you is no longer a thought for the future. Pizzas, intricately-shaped chocolates, and even cakes have been printed using 3D printing with little to no material waste, demonstrating the practicality and efficiency of the process. With 3D printing being a fully customizable process, even a simple trip to the kitchen would be influenced by the ability to print unique, mouthwatering meals at any time (Table 1).

While this customization is appealing to food-based application, 3D printing has generated a large appeal throughout the STEM field for designing personalized parts. Nike completely changed the way customers think about shoe performance when it unveiled a 3D printed football cleat that optimized cleat traction while decreasing weight [1]. General Electric created its new CFM LEAP aircraft engine with additively manufactured fuel nozzles, which reduced the component to only one part that was 25-percent lighter than the entire 18-part system previously used [2]. Even the medical industry and its patients have largely benefitted from the technology with 3D printed implants being tailor-made to specific patients to reduce surgery and recovery times. Tailoring these implants to patients also allows for a better-fitting product, which can reduce cosmetic defects and increase overall implant performance [3].

With its obvious universal practicality and efficiency, it is challenging to predict how the process will advance in the coming years. Multi-material additive manufacturing (MM-AM) is taking that first step forward by surpassing single material products to multi-material components that hold innovative promise. With all the advantages of 3D printing (material and resource efficiency, part and production flexibility, reduced production lead time, increased performance, etc. [4]), these components can have multiple materials with complex geometries and added functionality [5].

Take an ordinary chocolate bar. 3D printing the bar on demand in the size you’d like is rather intriguing but imagine taking it a step further. With MM-AM, you could take the same bar and introduce caramel, nougat, and maybe even a peanut butter coating to create a personalized candy bar with different flavors across the candy. By personalizing a candy bar to your specific taste through MM-AM, you can see the direct appeal of adding multiple materials into the same

---

* Corresponding author.
E-mail address: amitband@wsu.edu (A. Bandyopadhyay).

https://doi.org/10.1016/j.mser.2018.04.001
Received 27 March 2018; Accepted 3 April 2018

Table 1
Acronyms.

Acronym	Meaning
AM	Additive manufacturing
CAD	Computer-aided design
CBAM	Composite-based additive manufacturing
DED	Directed energy deposition
DLD	Direct laser deposition
DLF	Directed light fabrication
DMD	Direct metal deposition
DMLF	Direct metal laser fusion
DMLM	Direct metal laser melting
EBAM	Electron beam additive manufacturing
EBF	Electron beam freeform fabrication
EBM	Electron beam melting
FDM	Fuse deposition modeling
FGM	Functionally gradient materials
FRPC	Fiber-reinforced polymer composites
HAM	Hybrid additive manufacturing
IJP	Inkjet printing
LC	Laser cladding
LENS	Laser engineering net shaping
LMD	Laser melting deposition
LMWD	Laser-based metal wire deposition
MM-AM	Multi-material additive manufacturing
MMC	Metal matrix composites
MJP	Multi jet fusion
SLA	Stereolithography
UAM	Ultrasonic additive manufacturing
WAAM	Wire and arc additive manufacturing

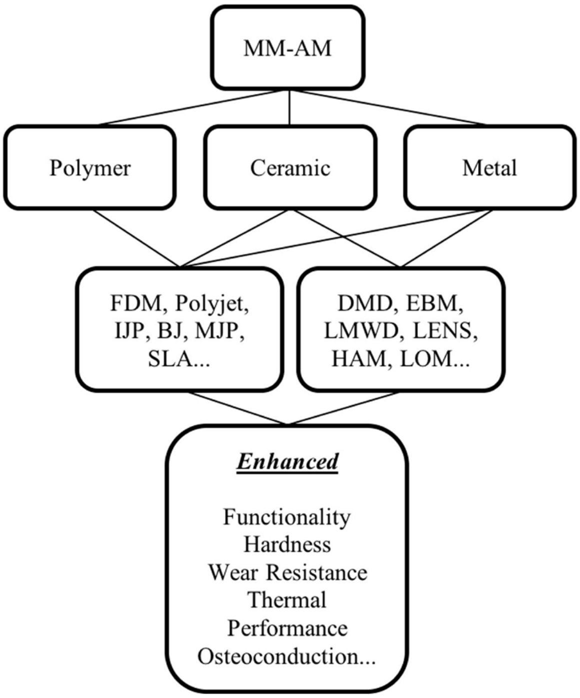

Fig. 1. Overview of some manufacturing and enhancement possibilities for MM-AM.

structure to get the most desirable combination. This same idea is being implemented into MM-AM of engineering materials, where instead of caramel in a chocolate bar to add sweetness, it could be a ceramic material in a metal bar to increase wear and corrosion resistance. The nougat could even be a harder metal to increase surface hardness, and the peanut butter coating could be a biocompatible coating for bone implant applications. This added functionality is the driving factor behind MM-AM processes, where region-specific functionalities can be placed in user-definable locations to create high-performance systems. A simplistic outline highlighting the general material combinations which make up these systems, what AM processes are most suitable based on material type, and possible material property improvements is presented in Fig. 1.

As shown in Fig. 2, traditional manufacturing processes must make system components separately and join them post-fabrication to create a composite part. The same goes with the chocolate bar analogy; the traditional bar has to go through multiple machines along the assembly line before the final product is made. With MM-AM, composite structures with graded or separate regions of differing materials can be built in one continuous step in a single machine, which enables composite parts to go directly from the design stage to the final part. Polymeric 3D printing was one of the first processes that advanced to MM-AM due to its simplicity and widely compatible material choice. Multi-colored components such as bike helmets, football helmets, and wearable gloves have been made with a very realistic appearance, shown in Fig. 3, as well as multi-functional smart polymer composites that change their geometry as a function of a changing environment, called 4D Printing. Although multi-material polymeric parts are exciting, they mostly serve as proof-of-concept prototypes that show the possibility of functional, multi-material systems.

To grow past this prototype stage and truly start to see a real-world application, 3D printing of metals has started to adapt to MM-AM of metallic composites. Single material 3D printing is what most industries are currently implementing into their products yet limiting the design to a single material holds back potential improvements that could increase the lifespan and performance of the part. Unique bonding styles of MM-AM processes can make a superior bond between multiple metals when compared to conventional processes because there are no weld seams to cause stress concentrations. And, with both materials starting in powdered form, multiple metals that are inherently difficult to combine via conventional methods can be more easily combined.

The unique ability of MM-AM, though, is that it cannot only combine two different materials at 100% composition but can create homogeneous areas of predesignated mixtures. This idea has led to combining multiple materials such as Inconel 718 and copper alloy GRCop-84, non-magnetic and magnetic stainless steels, and niobium on Ti6Al4V in various mixtures and are shown in Fig. 4. MM-AM processes have also shown that they can change metal properties by adding different phases, such as a secondary metallic phase, to new or pre-existing structures [23]. Furthermore, by controlling the amount of these phases the metal's properties can additionally be manipulated [24].

While combining multiple materials is influential, generating property-specific areas is likely the most significant ability of MM-AM as it can produce the part and its property variations in a single manufacturing operation instead of multiple steps. This advances metal MM-AM since homogenous mixtures can be made with metal-metal and metal-ceramic combinations at desired locations, just like in the chocolate bar analogy with chocolate and caramel combinations. Instead of being limited to conventionally welding two alloys together, functionally gradient materials (FGM) can be made by depositing metal or ceramic materials at a specific location to locally increase performance. When these material design choices are properly addressed, MM-AM can give more control over material properties when compared to conventional manufacturing processes to create these never-before-seen structures [25]. Metal-ceramic parts have been combined through AM processes to create metallic structures with high-performance coatings such as silicon carbide composite coatings onto Ti6Al4V [26]. Similarly, Vanadium Carbide (VC) was fabricated onto stainless steel for increased wear resistance (Fig. 5r–t), and an FGM consisting of Ti6Al4V transitioning to 100% alumina (Al_2O_3) was created to significantly increase hardness (Fig. 5o). Deposition of 100% alumina on an alumina substrate and graded alumina on stainless steel/titanium have also been demonstrated for multiple applications [29,30]. Reactive processes have been completed to create ceramic regions depending on the environment such as with *in situ* synthesized TiB-TiN-reinforced coatings