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Review Paper

Review on Additive Manufacturing of Multi-Material Parts: Progress and Challenges

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Abstract: Additive manufacturing has already been established as a highly versatile manufacturing technique with demonstrated potential to completely transform conventional manufacturing in the future. The objective of this paper is to review the latest progress and challenges associated with the fabrication of multi-material parts using additive manufacturing technologies. Various manufacturing processes and materials used to produce functional components were investigated and summarized. The latest applications of multi-material additive manufacturing (MMAM) in automotive, aerospace, biomedical and dentistry field were demonstrated. Investigation on the current challenges was also carried out to predict the future direction of MMAM processes. It is concluded that the further research and development needed in the design of multi-material interfaces, manufacturing processes and material compatibility of MMAM parts are necessary.

Keywords: Multi-material additive manufacturing; Functionally graded materials; Conventional manufacturing; Interface issues

1. Introduction

Additive Manufacturing (AM) is an emergent technology already demonstrating its potential for functional end-use products. AM helps to reduce the need for tooling, provides flexibility in design, and product customization as compared to conventional fabrication processes [1–6] . Recently, advances in AM processes enable the fabrication of multi-material structures with complex geometry and parts with various materials that display different thermal, chemical, and physical properties [7–10] .

The advantages of manufacturing components with multiple materials with different chemical and physical properties are key for the successful production of customized mechanical components with tailored performance characteristics. Multi-material AM (MMAM) methods have recently been applied to fabricate complex structures in an efficient way to save production time and the cost of the materials used [11–16] . With the advantage of fabricating multiple materials in a single manufacturing process, it is possible to produce functionally graded materials (FGM) with improved material interfaces. With the help of MMAM, arbitrarily complex and locally controlled FGMs can easily be fabricated. A number of previous attempts have mainly focused on ceramic/metal structures [18] , metal composites fabricated by selective laser melting (SLM) [19, 20], wire-arc [21, 22] and other laser deposition processes [23, 24] . Recently, advances in material jetting processes have enabled the control of the material deposition on a voxel scale [25–27] With the help of these technologies, the spatial distribution of mechanical properties can be controlled over very small dimensions [28]. However, limitation of materials and cost of these technologies reduce the benefits of the current FGM fabrication. A simplistic outline highlighting the general material combinations based on suitable material type and possible material property improvement is presented in Figure 1.

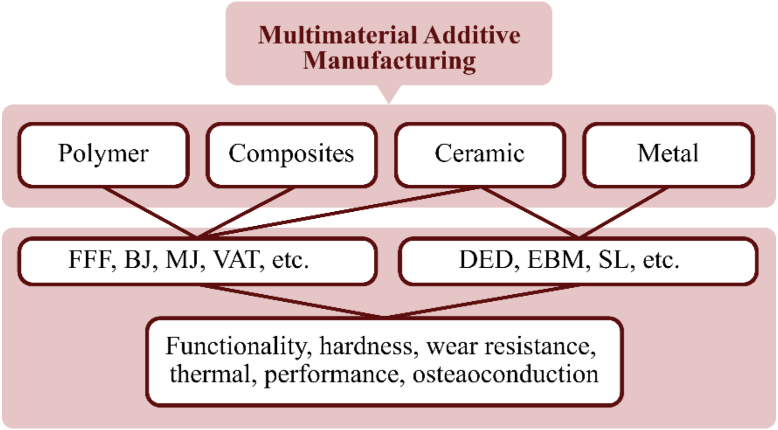

Figure 1. Overview of manufacturing and property enhancement possibilities of MMAM.

Multiple material combinations of the real structures widely exist in nature. Therefore, fabrication of multi-material parts using a low-cost manufacturing process is desirable. MMAM enables the manufacture of highly complex parts with site-specific properties without using costly and time-consuming conventional processes. Multi-material parts can be fabricated with graded regions which provide property gradients over the volume that can be used for damping, thermal gradients, fracture resistance, and construction materials. Based on these implementations, it is of great interest to fabricate multi-material parts using AM technologies. Therefore, investigation of the existing literature is an important step to identify current advantages and limitations of MMAM that enables prediction of the future trend of the technology and its possible applications. Figure 2 shows some example multi-material parts fabricated using various AM techniques.

MMAM has been explored in recent years with a variety of processes and methods. Recently, Ituarte et al. conducted research on the design and fabrication of functionally graded structures through multi-material binder jetting technology [28]. One unique research study performed by Garland et al investigated the fabrication of multi-material structures with optimal material distributions [29]. Another research study was performed by Dorcas et al. who used the voxel-based multi-material deposition process to fabricate FGM components for tensile tests [30]. Moreover, Doubrovski et al. manufactured a prosthetic socket that consisted of various material combinations [26] . Some research studies investigated multi-material parts made by AM technology which material joining region had a direct contact. Brischetto et al. conducted a research study to fabricate a sandwich panel using AM method [31]. In that study, external layers were produced with ABS, while an internal core was produced by PLA material with the help of multi-extruder fused filament fabrication process. Lopez et al. also investigated the mechanical behavior of tension test specimens made of PLA, ABS, and HIPS material combinations [32]. The results showed that producing sandwich structures with a PLA-ABS-PLA material arrangement led to a higher mechanical behavior than other design combinations. Some studies reported the combination of polymer-metal/ceramic multi-material parts via laser powder bed fusion technique [33, 34].

The purpose of the literature review is to explore the current research studies associated with the fabrication of multi-material parts using AM methods. In addition to the very latest published research, this review explores the conventional multi-material part fabrication techniques, potential materials used, AM processes, and their application areas. This paper also outlines the importance of FGM fabrication with the help of MMAM processes.

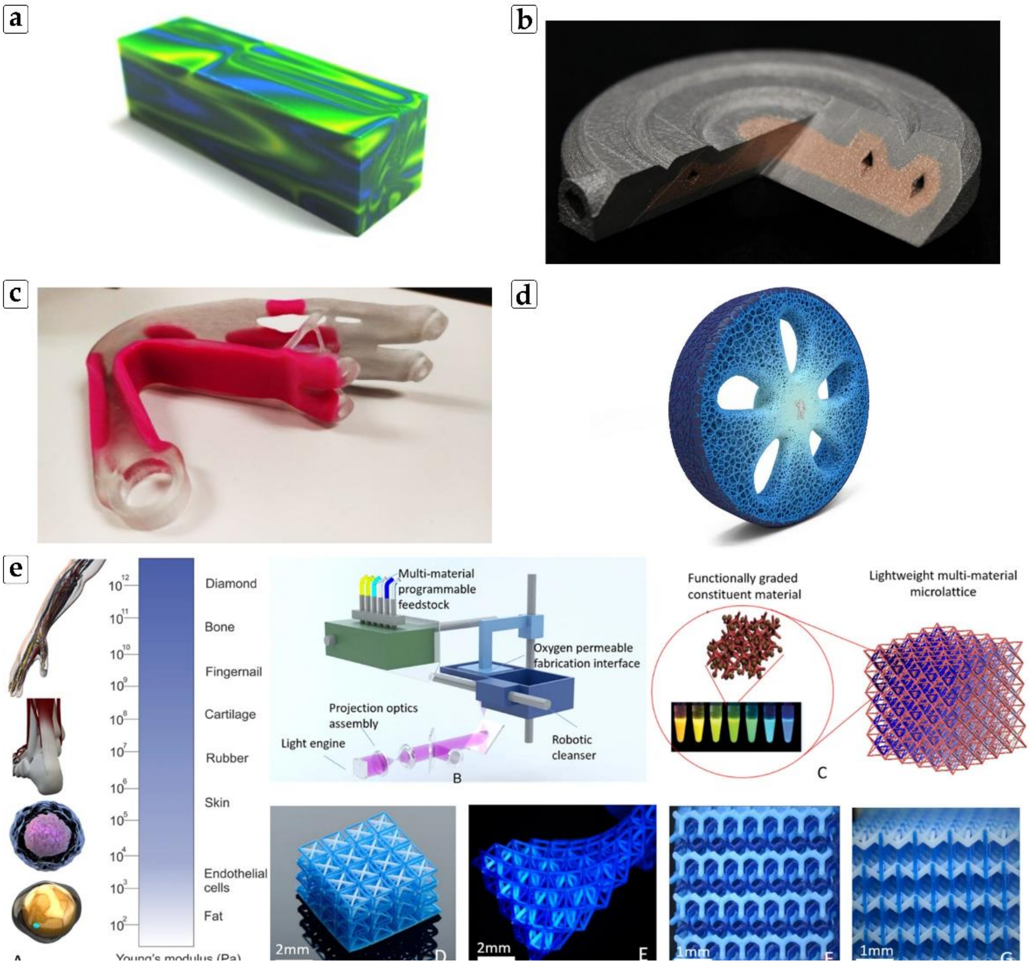

Figure 2. (a) Multi-material [27], (b) dual metal part created using Aerosint's recoater. Photo via Aerosint [36], (c) multi-material part generated by the Paramatters software and fabricated by the AM technology [37], (d) combine supple viscoelastic materials with stiff engineering polymers for application like airless tires [38], (e) fabrication of 3D multi-material microlattice with dissimilar constituent material. Images were reprinted for free with no permission required under http://creativecommons.org/licenses/by/4.0/through article [39].

2. Conventional way of fabricating multi-material parts

Witnessing the advantages of multi-material approaches for part manufacture confirms that there is a need to generate different combinations of materials. These multi-material parts or structures need to be carefully designed and evaluated to take the full advantage of it. Various conventional manufacturing (CM) methods are available to join at least two different materials. They are still popularly practiced and have several advantages. Spot-welding, drilling, riveting, die casting, extrusion is some of the CM methods widely used in producing the multi-material parts [40] . CM processes presented in Figure 3 are significantly different to Additive Manufacturing (AM) processes due to their different shaping operations. In Casting, a hollow mold of the desired shape is filled with a molten metal or alloy. Machining produces workpieces made with subtractive steps through automation. In Forging, raw stock materials (also known as billets) are reshaped with compressive dies. In the case of Joining, process involves fusing or connecting two or more components for the purpose of making a new part.

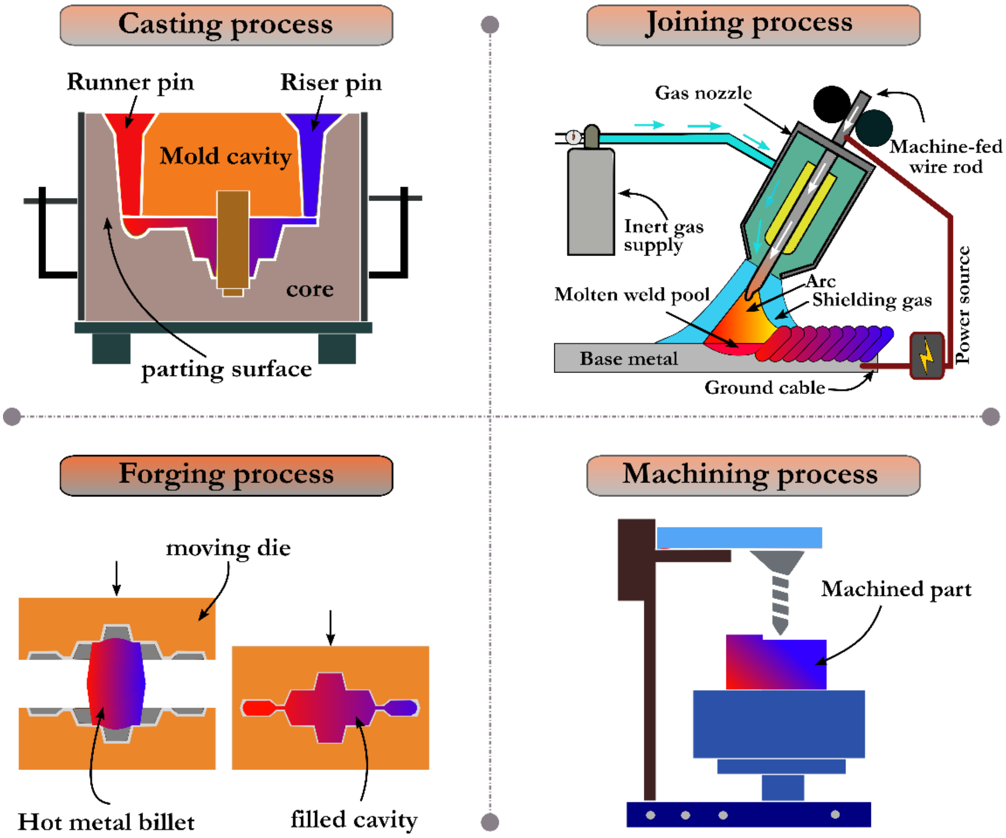

Figure 3. Schematic of casting, joining, forging, and machining processes.

2.1. Casting Process

Metal casting is one of the oldest and simplest processes for producing near net shape products. This process requires a mold cavity of the desired shape and molten metal to pour into the mold cavity, usually sand molds [41]. Classical foundry is still a relevant technique for producing large functional parts (e.g., engine blocks, gears, and chassis) despite advances in big area additive manufacturing [42]. The build parameters of currently available metal 3D printers and perhaps the physics behind the different AM processes also limit the production of large parts. Using a foundry will provide an advantageous solution if there is a need to produce multiple copies of parts. The cost of producing a large number of parts will equally reduce. In contrast, the use of AM could increase the production cost even with reduced labor. Priyadarshi et al. used the in-mold assembly technique to perform the multi-material part manufacturing. Multi-material molding is a technique to melt the different polymer material at their melting point and forced to place in a mold to get the desired shape as shown in Figure 4. Full assembly of the structure can be produced without the use of other joints like bolts, glue, welds, and fasteners [43][43][43][43][43][43][43][43][43]. Casting materials are usually metals or various time setting materials that cure after mixing two or more components together; examples are epoxy, concrete, plaster and clay.

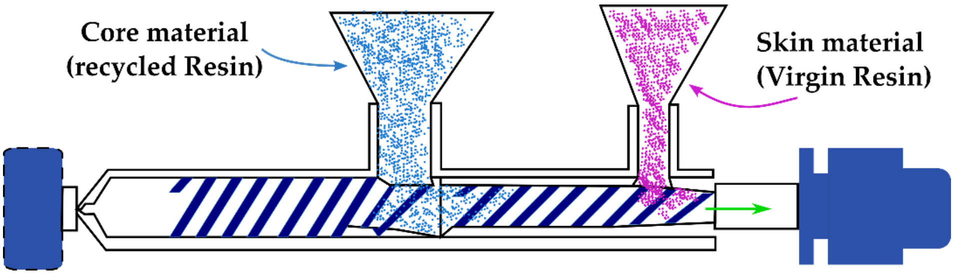

Figure 4. Multi-material molding process for multi-material part fabrication.

Casting is most often used for making intricate shapes that would be otherwise difficult or uneconomical to make by other methods. Heavy equipment like machine tool beds, ships' propellers, etc. can be cast easily in the required size, rather than fabricating by joining several small pieces [42]. Gouker et al. conducted a study on explaining the multi-material molding for making different types of compliant joints, successfully fabricating the compliant joints by combining mold pieces joints into an overall mold that can provide degree of freedom ranging from 1 to 3 [44].

2.2. Joining Process

Multi-material combination technique is considered to be very useful in automobile sectors. Due to more weight of steel which is a widely used material in car manufacturing, there is significant need to employ the different materials to reduce the weight. Joining processes are considered as one of the CM processes. They fuse or connect two or more components for the purpose of making a new part as shown in Figure 5. Overall, these processes connect two or more components permanently. They also require the use of separate tools. Some of the commonly used joining processes are welding and soldering. Joining two different materials is key technology that can play a significant role in developing the lightweight vehicles. Meschut et al. investigated the various welding technologies for combining the different materials to create multi-material structures, establishing the mechanical-thermal joining of dissimilar metals using resistance element and friction element welding [45]. Similarly, Dr. Uwe Alber (AUDI AG) presented the sound technique to fabricate the multi-material part using aluminum and hardened steel. High mechanical strength at the interface was achieved by mechanically joining the two-material using friction stir welding [46].

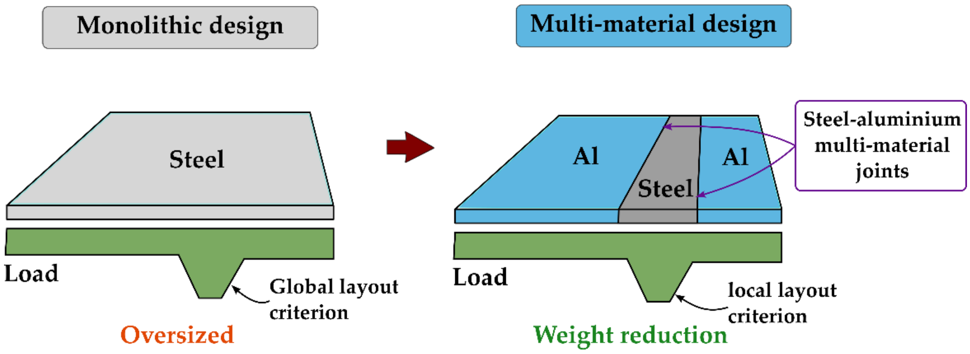

Figure 5. Example of a multi-material design using welding process

2.3. Forging Process

Complete material consumption, high strength, better surface quality, short lead times can be achieved using the forging technique for multi-material part fabrication. Forging is one of the oldest manufacturing processes that shapes the raw stock material by applying compressive dies on it. Based on the temperature at which the operation is performed, the process can be classified into "hot forging", "warm forging" and "cold forging". Wohletz et al. used the cold and warm forging technique to combine the steel and aluminum for manufacturing the multi-material products. The study concluded that the steel billet and aluminum billet up to an initial temperature of 450˚C and 100˚C respectively provided the significant bonding [47]. Forging process improves the mechanical properties of the raw stock material by refining its grain structure, providing a good grain flow, and at the end making it tougher and stronger. Another interesting study was performed by Behrens et al. on multi-materials, combining the two CM processes to fabricate the multi-material part. They performed the thermo-mechanical treatment in order to attain the grain refinement within the welded material using the forming process, which led to the enhancement of the mechanical properties of the final multi-material part [48] . The forging process can produce parts with superb mechanical properties with minimum waste. The basic concept is that the original metal is plastically deformed to the desired geometric shape—giving it higher fatigue resistance and strength. The process is economically sound with the ability to mass produce parts and achieve specific mechanical properties in the finished product [41].

1.4. Machining Process

Machining process goes back to ancient times. In fact, the original machining tools date back to 1200 B.C., and were carefully handcrafted [49] . Machining is a manufacturing process in which a raw stock material is cut to a desired final shape and size by a controlled material removal operation. Today, Computer Numerical Control (CNC) is more commonly used due to its advantages in precision, automation, and better surface finish. CNC manufacturing is the process of producing machined workpieces with computerized manufacturing techniques. Although numerical control is the original name given to this technology, it is still used interchangeably with CNC. These CM processes are the most common methods in subtractive manufacturing. In these processes, the final geometry of the workpiece is formed by removing material from the raw stock material. CNC operations use the same G code logic with AM processes. However, their function is to cut the object in order to shape the final geometry here [50] . CNC machine processes any kind of material (i.e. metal, plastic, wood, ceramic, or composite) to meet specifications by following a coded programmed instruction and without a manual operator directly controlling the machining operation [51].

1.5 Limitations of conventional manufacturing of fabricating multi-material parts

Not only advantages, various disadvantages also need to be addressed. Figure 6 shows the list of conventional methods with their corresponding issues. Cost and quality of the finished workpieces are the main factors that need to be considered while selecting the CM technique for multi-material part generation. Conventional methods require a lot of investment in terms of consumables or logistics. CMs also consume more energy to fuse the materials together which adds on to overall costs. Joining the materials with casting includes more cost because of heavy initial investment, consumables for post processing, etc [40]. Quality is also another factor to be considered for the case of multi-material. Welding the dissimilar materials leads to poor quality at the interface and hence needs to be addressed critically. The processing time is also a big issue in CMs. Most of the CMs involve the high set up time and movement of bulky devices which increases the processing time.

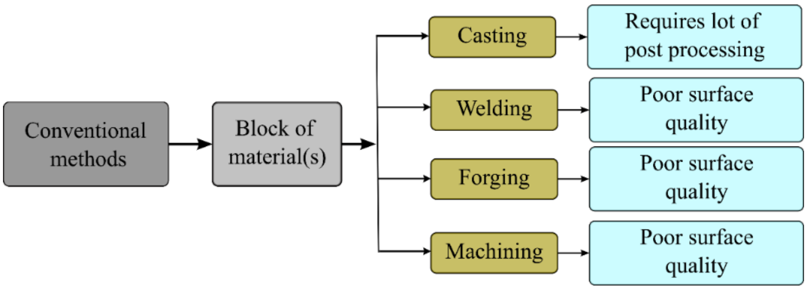

Figure 6. List of conventional methods with their associated limitations

3. Current multi-material Additive Manufacturing methods

Multi-material Additive manufacturing (MMAM) technology is becoming more and more popular in the industrial and research communities. This method is essentially unique from conventional subtractive manufacturing method. Layer by layer material is added to build the desired structure in the form of the solid 3D model. The raw material used to produce the parts are Metals, Thermoplastics, Hydrogels, Ceramics, Composites, Hybrids and Functionally Graded Materials and these raw materials are in the state of liquid, powder and solid. MMAM has several advantages over traditional manufacturing processes, i.e. no material wastage, parts are light in weight, manufacturing process is low cost, complex shapes can be easily fabricated, and they are affordable and environmentally friendly. Each MMAM technology has its own pros and cons. Low dimensional accuracy, size limitation of component, limited range of printable materials, post processing is required after completion of the print, inefficient for large volumes, some of MMAM technologies are required for specific environments. The technology is found in diverse applications for industrial sectors such as aerospace, automotive, healthcare, construction and food processing as well as in research and academic institutions. Broadly, MMAM technology is classified into seven catergories: Material Extrusion, Vat Photopolymerization, Powder Bed Fusion, Material Jetting, Direct Energy Deposition, Sheet Lamination, Binder Jetting Hybrid Additive Manufacturing (HAM) and Functionally Graded Materials.

3.1. Material Extrusion (ME)

FFF is one of the MMAM manufacturing method and also known as Material extrusion process. This process was invented in 1980's and commercialized in 1990 by Stratasys USA. Thermopolymer material is processed in this technique. Material is passed to FFF extruder through Feed mechanism. Where material melts in heating chamber and then deposited layer over layer. Subsequently material solidifies by cooling. Nozzle moves in three dimensions with G-codes. Extruded 3D object rest on build platform.

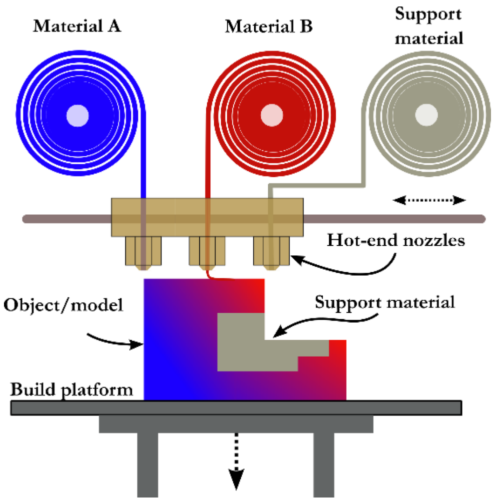

Figure 7. Process description of FFF process

Material Extrusion is one of the manufacturing methods is gaining traction among the academics and industry because of some unique features such as Easily portable, reliability, Numerous material options, compact design, dimensional stability. The major material used in this technique is thermoplastic filament i.e. Pure polymer with low melting point hence they are heat sensitive. This technique has several restrictions, low dimensional accuracy, low strength, printing time is long, warpage, Nozzle blockage etc. due to these shortcomings few materials are employed such as Nylon, Poly lactic acid (PLA), Acrylonitrile butadiene styrene (ABS). Many researchers have studied the different process parameters of Material Extrusion to enhance the product quality and performance. Some of the most often used process parameters viz. Layer height, Layer thickness, Raster plane orientation, Raster width, Infill density, Infill pattern, number of shells, build orientation, print speed, Traverse print speed, temperature of extrusion, diameter of nozzle, Air gap, Platform temperature. Feiyang He et al studied the impact of three printing parameters on the fatigue life. They examined the factors were Nozzle size, Building orientation and layer thickness. Plane of building orientation of the Standard test specimen in x-direction, y-direction and z-direction. The author has carried out Experimental Design. Analysis of variance (ANOVA) was used to examine their findings which revealed that Plane of orientation in x-direction was the most important factor in determining the longest fatigue life. Pavan Kumar et.al studied challenges involved in Material extrusion of thermoplastic polymer composites. To reduce the occurrences of voids during the printing process, weak adhesion between the layers which leads to delamination of long continuous fiber, limited strength in transverse direction of short fiber composites. Defects and voids are common concerns in material extrusion, and they should be taken into account when optimizing the process since they increase stress concentration.

3.2 Material Jetting (MJ)

Material Jetting is one of the most efficient and precise Additive manufacturing method. Some common names viz. Drop on Demand (DOD), Polyjet and Multijet. It was invented by object Ltd. In 1999 under the name of Polyjet later acquired by the Stratasys company in 2012. Some common names viz. Drop on Demand (DOD), Polyjet and Multijet. Working principle of MJ AM is same as conventional printing machines. Different colours with different materials are used in this technique. Components are multiple inkjet heads, UV light, Material container, Build platform, Elevator. Material in the form of ink comes to the inkjet heads through the Material container via tubes. Inkjet head has multiple nozzles. Micro droplets are deposited layer by layer on the build platform. Subsequently UV lights are used to solidify the material. Elevator is used to move the build platform in up and down directions only. Some common materials are employed for this process such as thermosetting, thermo-polymers, elastomers, waxes, vero cyan, vero clear and SUP 706 (liquid polymer) Ana Pilipovic et.al. conducted experimental analysis on Polyjet materials i.e.Vero Black, Vero Blue and Full core 720 investigated the mechanical properties of these materials.

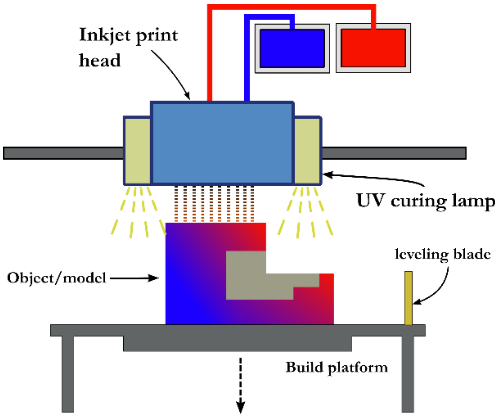

Figure 8. Process Description of MJ

Kesy et.al. examined the test bars on Full core 720 material (transparent resin) which revealed that the mechanical properties of test bars generated in the second orientation are best while those produced in the third orientation are the worst. Paul o'neal et al. compared the mechanical properties RGD 525. Bio-compatible MED 610 and RGD 835. Properties of High impact polystyrene (HIPS) and Acrylonitrile Butadiene styrene (ABS) are in line with RGD 835. Benefits of Material Jetting technique in contrast with other Additive Manufacturing techniques are: i) Easily fabricate complex geometries. ii) The key benefit is speed with which 3D model can be created along with different colors. iii) Parts can be built in a variety of materials with multiple inkjet nozzles. iv) Good dimensional accuracy v) Ability to distribute a large amount of material quickly and efficiently across a region. On the other hand, has some drawbacks including: i) Limited selection of materials. ii)Process is expensive so Product cost is more. iii) For large section parts quality is poor. Some studies carried out on the influence of process parameters on material jetting made parts to see what mechanical properties affect the surface roughness and dimensional accuracy. Most common process parameters are Plane of direction, layer thickness, surface finish and material type. J. kechagias et.al. studied the impact of 3 Process Parameters for surface measurements. The examined factors are built style, layer thickness and model scale and performed with experimental design. Results are compared with Analysis of Variance (ANOVA) and Analysis of Means (ANOM). Major findings are the optimal surface roughness results were achieved with layer thickness of 16 microns and glossy style, while scale factor is not a major influence.

3.3 Direct Ink Writing (DIW)

The key contrast between FFF and DIW is that in FFF material melts in heating chamber. It passes though extruder then it builds 3D object on the platform where in DIW materials is in the form of liquid phase. Material mixes with help of rotating impeller and comes through nozzle by applied pressure [52]. Nozzle moves as per G codes. For MMAM can use various nozzles. DIW can create complex structure element with no use of dies and tools [53] .

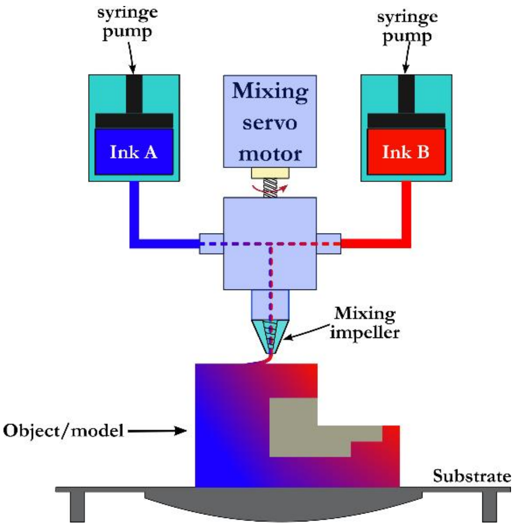

Figure 9. Process description of DIW

3.4. Vat photopolimerization (VAT)

It is also known as sterolithography (SLA), Digital Light Processing (DLP),. One of the most widely used additive manufacturing processes is vat photopolymerization (VPP). The term Vat photoploymerization coined by Dr. Hideo Kodama in 1981 [24] The process of curing is used to classify the Photopolymerisation.Cured with laser known as stereolithography (SLA), Cured with projector known as Digital ligth processing (DLP). Cured with LED and Oxygen known as continuous Digital light Processing (CLDP) and Continuous liquid inteerface production(CLIP)[54]. Material used for this process is photopolymer resin [55]. At certain extent resin fills in vat. A single monochromatic ray in Laser form directed on the resin by using computer control. Subsequently UV light solidifies the resin layer by layer and this process repeats itself until model is complete. Laser moves in XY directions. Platform moves in the downward direction as per layer thickness.

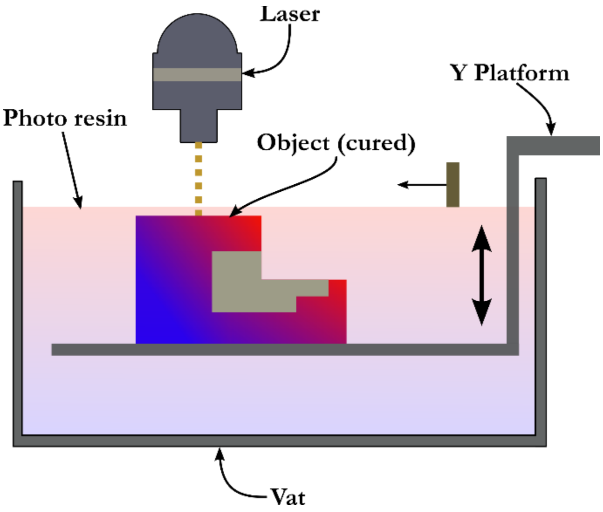

Figure 10. Process description of VAT

Photopolymerisation is the curing process, when UV light is exposed to deposited material, cross connections between polymer chains develop, causing the deposited material to transition from a liquid or semi-solid to a solid state [28].

The Resins of vat Photopolymerisations are Acrylate, [29] Epoxy, [30] Poly(D,l-lactide) (PDLLA)-acrylate [31] Polypropylene fumarate (PPF), Poly(trimethylene carbonate) (PTMC)-acrylate,[32] Polyvinylsilazane (PVSZ)-acrylate, [33] Vinylpyrrolidone (VP) [34] it has attracted substantial interest from both academics and industry.beacuse of High accuracy and speed, vat photopolymerization has high resolution rate and good surface finish. The limited material selection is one of the limitations of vat photopolymerization. The process is expensive and Printed parts post processing is essential.

3.5. Direct Energy Deposition (DED)

It is a type of metal Additive Manufacturing process [56]. It is aloso known as Laser Metal Deposotion (LMD), Laser Engineered Net Shaping (LENS) and Direct Metal Deposition (DMD). In this process material is used in the form of wire or powder. Material melts by Laser, Electron beam or Plasma arc but carries out in the controlled region. Inert gas is used to prevent the oxidation of molten pool. Material blown through nozzles. It melts and deposited layer by layer on substrate where it solidifies. Nozzle has multi axis arm and moves around the object [57]. This procedure includes the use of a variety of materials. Metal Wire and Powder, with Ceramics, functionally graded materials (FGM), metal-matrix composites (MMC), and coatings[41].

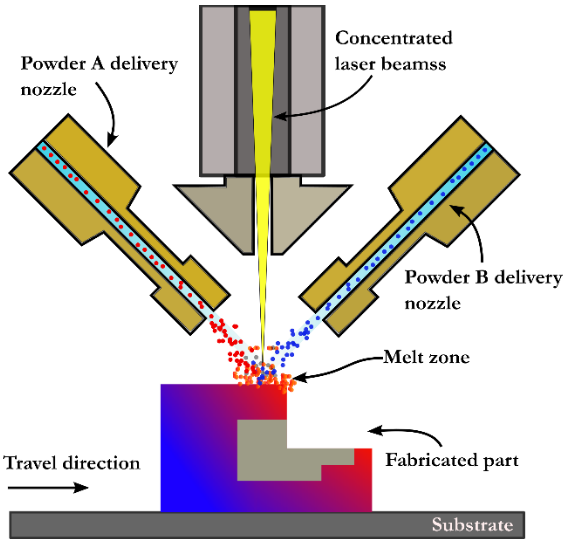

Figure 11. Process description of DED

DED systems classified in a variety of forms.Powder feed and wire feed based on the type of feedsick.kinetcic energy and Heat energy bsed on the type energy Heat energy DED subclassified as Laser DED, Plasma DED,Electron Beam DED and Electric arc DED [41] Zheng, B et.al.investigated mechanical properties.The impact of Laser-deposited IN625 Metal Matrix Composites with Ni-Coated TiC. In the deposited MMCs, the microstructures and spatial distribution of TiC particles were studied. The findings reveal that Using Ni-coated TiC particles, the mechanical Properties of LENS-deposited MMCs were significantly enhanced.[42]. Ke, D et al studied on Laser and Plasma Spray Coating of Compositionally Graded Doped Hydroxyapatite. Laser engineered net shaping (LENS) and plasma spray deposition were used to create a hydroxyapatite (HA) coating on Ti6Al4V. The findings reveal that to enhance strength and osteoconductivity of metallic implants [43]. Yan, J et al optimized the process parameters on multimaterials i.e. fabrication of cermet composite using Inconel 718 and ceramic powders. Mode FRONTIER software used for computation with MATLAB code. Results shows that FRONTIER softare helped to reduce energy usage and material waste while increases powder melting. [44] Niu, F et al predicted laser power for different processing conditions of Al2O3 ceramic parts and processing conditions are nozzle travel speed, powder flow rate and physical properties of deposited material. The suggested model was then validated by fabricating Al2O3 ceramic parts with varying laser powers. Result demonstrate that The model's estimated laser power is correct for various processing conditions,[45].

3.6. Hybrid Additive Manufacturing

The term Hybrid Additive Manufacturing describes the combination of two or more different processes and machines. Primary goal of this method is to overcome the limitations of MMAM techniques and to improve the part quality and productivity [58]. Figure 12 shows that AM techniques combining with FFF, DIW, Ink jet (IJ) and Aerosol Jetting (AJ). By using this design objects are manufactured more efficiently rather than current manufacturing strategies which employ different methods [59] .

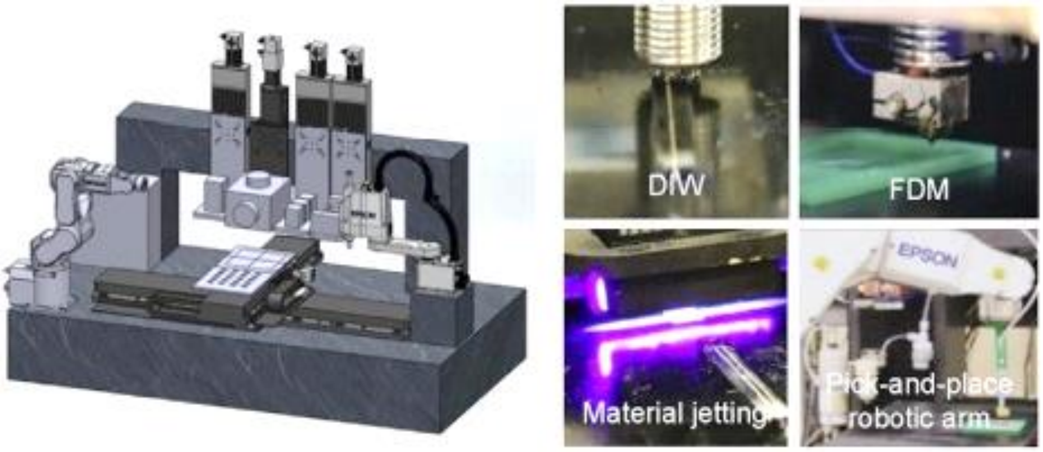

Figure 12. Hybrid AM system combining DIW, FDM, IJ and AJ [54, 59][54, 59][54, 59][54, 59][54, 59][54, 59][54, 59][54, 59][54, 59]

Based on literature view Hybrid Additive Manufacturing technology includes Hybrid Machines, Process and materials [46-49] Chu W. et al addressed the term hybrid process based on traditional manufacturing processes are additive, subtractive, transformative, joining and dividing.[49] Ugur M et. al. provides a comphrensive review on Opportunities for hybrid additive manufacturing research and important features are Hybridization of AM techniques, process planning of integrated technologies and current prospectus of Hybrid AM industry.[50] Wang, Z et al described the process conversion of SCARA robot into Hybrid manufacturing workstation. Aid of equipments.motors, kinematics, controllers turned SCARA robot into Hybrid Machines. M codes and extra functionalities make operations for varied manufacturing processes easier [51]. K. P. Karunakaran et. al. presented HM strategy, integration of Additive and Substractive processes for Hybrid manufacturing. The initial layer is deposited in the form of weld beads by GMAW equipment. The scallops make the deposited layer uneven and subsequently finish with face milling opertation. In the second stage, the finished product is machined. ArcHLM combines the advantages of both additive and subtractive manufacturing [52].

3.7 Functionally Graded Additive Manufacturing (FGAM)

The interface of multi-material structures can be fabricated by varying volume concentrations of the materials in a continuous step using a single machine, which enables the fabrication of composite parts to go directly from the design stage to the final functional components [15]. The unique ability to combine various materials in a single manufacturing process enable the mixture of materials to produce polymer to polymer, metal to metal and polymer to composite material combinations at desired locations [8]. Instead of manufacturing two materials using conventional techniques, FGMs could be fabricated by depositing two different materials at a specific area to locally enhance the performance of the component .FGMs are advanced engineering materials that present complex spatially varying material properties in the structure [24].

MMAM is a revolutionary approach and broad range of applications can also provide new opportunities in the fabrication of advanced FGMs as structural material with new forms of functionalities and properties in aerospace, automobile, and medical industries [18, 19, 60]. Functionally Graded Additive Manufacturing (FGAM) is a layer-by-layer fabrication process that intentionally modifies the processing parameters and gradually changes the spatial of material distribution within one component to meet the intended function [61]. The main goal of using FGAM is to produce performance-based freeform components driven by their gradual change in the material properties. Another unique method for the fabrication of FGMs is now possible with the help of the FFF process. FFF is one of the AM methods that is based on layer-by-layer deposition of semi-molten materials for object buildup. The advantage of this process is the availability of a large selection of materials (thermoplastics, metal-infused thermoplastics, fiber reinforced composites, thermosets, wood etc.), low-cost technology, and inexpensive materials. The workflow of FGAM is shown in Figure 13.

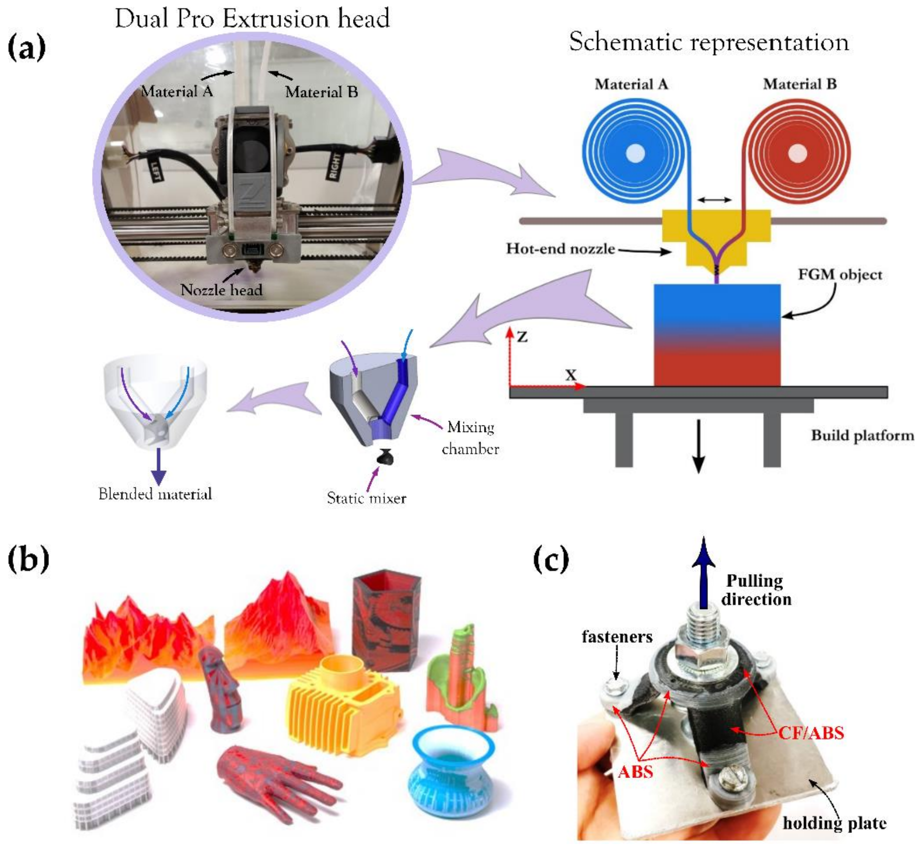

Figure 13. Functionally Graded Additive Manufacturing Workflow, (a) process description of fabricating FGM parts, (b) Zmorph multi-material and multi-color 3D printer parts [62], (c) multi-material FGM mounting bracket part fabricated by the Zmorph technology [63] .

Currently, the fabrication of multi-material parts using the traditional method which utilizes separate nozzles for each of the material limiting the capability of printing FGM components. This is because conventional FFF techniques produce multiple-material component with direct interface transition. Since sharp transition at material joints can show high stress concentrations, the part will show weaknesses under various stress states. In order to solve this issue, FFF technology advances its multi-material printing capability to fabricate components by utilizing a single nozzle extruder which enables the change of composition continuously while printing based on the adjustable ratio of the extruder motor. The advantage of the FGAM process over conventional AM is swapping materials without changing the extrusion head.

4. Materials used to fabricate multi-material parts with AM technologies

Several material types were investigated in the literature to fabricate multi-material parts using AM processes. In one such study, additive manufacturing by DIW was applied to fabricate multi-phase carbide specimens with tailored composition and mesostructure. A custom DIW system was developed to allow simultaneous extrusion and mixing of multiple inks, comprised of ceramic particulate suspensions, through a single nozzle. Boron carbide (B4C) and silicon carbide (SiC) were chosen for this study due to their excellent mechanical properties [64]. The influence of three multi-material FDM processing parameters, i.e. nozzle temperature, building stage temperature and printing speed, on the interfacial bonding strength of thermoplastic polyurethane (TPU)/acrylonitrile butadiene styrene (ABS) bi-material structures was experimentally investigated [65]. N.E. Putra has presented the viable options of the state-of-the-art multimaterial AM for Ti-, Mg-, and Fe-based biomaterials to be used as bone substitutes [66]. Joshua S. Pelz applied direct ink writing (DIW) to fabricate multi-phase carbide specimens with tailored composition and mesostructure. A custom DIW system was developed to allow simultaneous extrusion and mixing of multiple inks, comprised of ceramic particulate suspensions, through a single nozzle. Boron carbide (B4C) and silicon carbide (SiC) were chosen for this study due to their excellent mechanical properties [64] . Zhangwei Chen has given a review on various ceramic materials, their properties and applications [67] . Farhan Cecil has explored multi-material 3D printing to fabricate an integrated photometric flow cell design containing an opaque fluidic channel along with cavities for LED and photodiode combined with windows created from a visibly transparent material to allow for the light to travel between light source and detector.

4.1 Materials

To build objects using MMAM technologies, multiple materials must be delivered during the fabrication processes, and strong bonding between materials of different types or compositions must be ensured. Multiple material delivery systems and their bonding processes vary, depending on the particular AM technology used. Meeting these two requirements is essential for successful multi-material fabrication, as they strongly influence the performance of the resulting multi-materials. For the MMAM, various materials can be used by applying different AM techniques. As per materials properties different AM techniques are chosen. The materials used in MMAM are given in Figure 14.

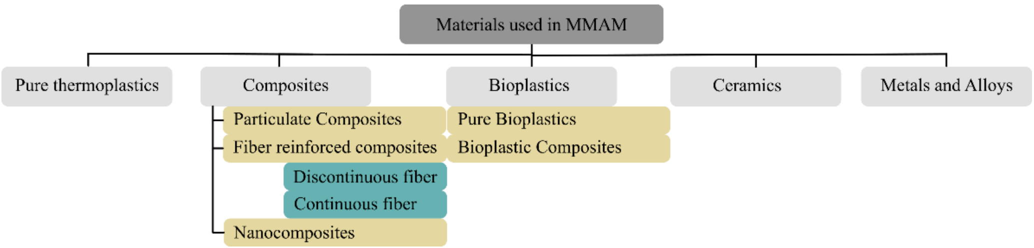

Figure 14. Material categories used in MMAM

4.1.1 Pure Thermoplastics

The following materials were extensively used to fabricate multi-material parts using AM technology.

Acrylonitrile butadiene styrene (ABS) is a common thermoplastic polymer. ABS provide favorable mechanical properties such as impact resistance, toughness, and rigidity when compared with other common polymers. A variety of modifications can be made to improve impact resistance, toughness, and heat resistance.

Poly (lactic acid) or polylactide (PLA) is the most extensively researched and utilized biodegradable and renewable aliphatic polyester. The production of PLA has numerous advantages including - it is Eco-friendly, biodegradable, recyclable, and compostable. Its production also consumes carbon dioxide. It is Biocompatible as well. PLA is the most widely used plastic filament material in 3D printing. PLA is sensitive to humidity over 600C.

Polycarbonates (PC) are a group of thermoplastic polymers containing carbonate groups in their chemical structures. Polycarbonates used in engineering are strong, tough materials, and some grades are optically transparent. Polycarbonate is a durable material. Although it has high impact-resistance, it has low scratch-resistance. Therefore, a hard coating is applied to polycarbonate eyewear lenses and polycarbonate exterior automotive components.

Polyether ether ketone (PEEK) is a colorless organic thermoplastic polymer in the polyaryletherketone (PAEK) family. PEEK is a semi crystalline thermoplastic with excellent mechanical and chemical resistance properties that are retained to high temperatures. The processing conditions used to mold PEEK can influence the crystallinity and hence the mechanical properties.

PEI is a lightweight thermoplastic and has good mechanical properties, like heat, and smoke resistance. It is a biocompatible polymer with a high glass transition temperature. However, FFF parts build from PEI have poor surface finish and poor dimensional accuracy. When looking at the weight to strength ratio, it would be a good option for rapid prototyping applications in several industries such as aerospace and automotive.

Nylon is a generic designation for a family of synthetic polymers composed of polyamides. Nylon is a silk-like thermoplastic, generally made from petroleum, that can be melt-processed into fibers, films, or shapes. Nylon polymers can be mixed with a wide variety of additives to achieve many different property variations.

HIPS is a biodegradable polymer that is a low strength thermoplastic with good machining characteristics. The advantages of using this FFF filament are its good flow characteristics, impact resistance, and low cost. However, it is prone to wear, and it requires a high printing temperature and a heated build platform. The properties of HIPS are similar to ABS, but it is lighter than ABS.

Table 1. Thermo-mechanical properties of various materials used in MMAM

Material	**Density (g/cm3)**	**Youngs Modulus (GPA)**	**Tensile Strength (MPA)**	**Glass Transition Temperature (^{0}C)**	**Melting Temperature (^{0}C)**	**Printing Temperature Range**
ABS		2.28	43		200-250	210-250 [68]
PLA	1.21–1.25 [69]		21–60 [69]	45–60 [69]	150–162 [69]	190-230 [68]
PC	1.21 [70]	2.57 [70]	-	140 [70]	270 [70]	260-310 [68]
PEEK	1.32 [71]		90-100 [71]	143 [71]	343 [71]	360-420 [68]
PEI	1.27 [72]			217 [72]		340-380 [68]
Nylon	1.15 [73]				190-350 [73]	240-270 [68]
HIPS						220-250 [68]

4.1.2 Composite

Composite materials are a class of advanced material, made up of one or more materials combined in solid states with distinct physical and chemical properties. Composite materials offer an excellent combination of properties which are different from the individual parent materials and are also lighter in weight.

Pure metals are of little use in engineering applications because of the demand of conflicting property requirement. For example, an application may require a material that is hard as well as ductile, there is no such material existing in nature. To solve this problem, combination of one metal with other metals or non-metals is used [74.

Not only pure metals but also pure thermoplastic filaments have limitations such as low strength and stiffness in meeting the improved performance of built parts. Thermoplastics become soft and fail to retain their original shape at high temperatures. In many cases, a product produced from thermoplastic filaments cannot meet a set of specific functional requirements. The properties of built parts are often inadequate when compared to the properties of injection molded parts [68] . Thus, the composite materials are viewed as the viable option to meet these requirements.

4.1.2.1 Particulate Composites

To fabricate particulate composite filaments, the reinforcement materials in the form of particles are incorporated in a polymer matrix and further extruded into filaments. The properties of particulate composites depend on the particles' size, shape, orientation, and volume fraction and the interfaces between particles and polymers matrix.

4.1.2.2 Fiber reinforced Composites

Natural or synthetic fibers are used as reinforcement materials instead of particles with polymer matrices in fiber composites. Different fibers such as glass, rice husk, and carbon with different lengths are mixed with polymers for composite filament preparation. The properties of a fiber composite depend on the properties of fibers and matrix, fiber volume fraction, alignment of fibers, the interfacial bond between fibers and matrix, and void content [68][68][68][68][68][68][68][68][68].

- *Discontinuous/Short Fiber* - Short fibers are blended with matrix prior to developing the short fiber composite filaments. In short fiber composites, the fibers are homogeneously dispersed on a matrix
- *Continuous Fiber* - Matrix polymer and fibers are deposited from two separate spools for continuous fiber composite filaments in the FFF process.

4.1.2.3 Nanocomposites

Similar to other composite materials, nanocomposites consist of more than one constituent or phase, forming a unique property. The difference is that at least one material dimension is below 100 nm [68][68][68][68][68][68][68][68][68].

4.1.3 Bioplastics

There are two types of bioplastics that have used in the fabrication of multi-material parts.

- Biobased and Biodegradable Bioplastics
- Bioplastic Composites

4.1.3 Ceramics

Owing to their various excellent properties, ceramics are used in a wide range of applications, including the chemical industry, machinery, electronics, aerospace and biomedical engineering. The properties that make them such versatile materials include high mechanical strength and hardness, good thermal and chemical stability and viable thermal, optical, electrical and magnetic performance [67, 75][67, 75][67, 75][67, 75][67, 75][67, 75][67, 75][67, 75][67, 75].

4.1.3 Metals and Alloys

Table 2 shows the various materials used in MMAM processes. The table also highlights the material properties as well.

Table 2. Materials and their mechanical properties used in MMAM

Material	**AM Technology**	**Elastic Modulus GPa**	**Yield Strength MPa**	**Hardness HV**
Ti6Al4V/TiC (From 0% to 50% Ti)	LMD			380-737
TA15/TiC (From 0% to 50% TiC)	LMD		806-925	
Ti6Al4V/TiC (From 0% to 30% Ti)	DED	108-164		300-600
Ti6Al4V/SS304 L/V	DED			220-850
From pure TiAl4V to 50%V/50% SS304 L	DED			190-900
TiAl4V/Invar (From Ti6Al4V to pure Invar with 3% increment)	DED			350-858
Ti6Al4V/Mo (From Ti6Al4V to pure Mo with 25% increment)	DED			250-450
Ti6Al4V/Al_2O_3	LENS			350-2365
400W/1000W/400W SS 316L	SLM			150-220
SS 316L/Stellite12 with few millimeter transition zone	LDM			200-650
SS 316L/Stellite12 with alternating layers	LDM			300-400
SS 316L/Cu bimetallic	SLM			259±7-74±5
SS 316L/P21 with 25/50/75% graded layers	DED			200-440
SS 316L/P21 + 316L SS/P21	DED			210-330
SS 316L/NiCr with Cr/Ni ratio varying from 1.4 to 1.7 to 2.3 to 3.7 to 9.7	LMD			
SS 316L/IN718 bimetallic	EBD			148+-11 – 241+-12
SS 316L with 25/50/75% graded layers	LDMD			155.6-186.1
SS 410/NiCr/Ti6Al4V	LENS			115-275
SS 316 L/SS316L + Fe3Al/Fe3Al	LENS			500-400
SS 304 L/IN625 with 1 vol% change per layer	DED			210-240
Fe-16Cr-8Ni/Fe-14Cr-16Ni/Fe-12Cr-23Ni/Fe-9Cr-28Ni	DED			110-250

4.2 *AM technique selection on the basis of materials*

As per the material properties, and its characterization, various additive manufacturing technologies should be used as given in the following table [76].

Table 3. Surface roughness values of multi-material parts fabricated by MMAM

Technology	Materials	Surface roughness
Laser based process	Metals Hybrid	Less than 10 μm
SLA process	Polymers Ceramics Composites	10 μm -100 μm
Material Jetting Process	Polymers Ceramics Composites Hybrid Metals	Around 0.1mm
FDM Process	Polymers Composites	Around 0.1mm

5. Applications of MMAM

Through MMAM, single and multifunctional structures are built to meet requirements for complexity and improved performance for applications in industries that include aerospace, soft robotics, medical, electronics, automotive, and food processing [77–79].

Within the aerospace industry, MMAM is used to achieve complex shapes and processing that are not possible by conventional methods. Electric motors and turbine engines with integrated sub-elements of different materials and structures are examples of components that are built with the aid of MMAM to attain unique and superior properties (e.g., microstructure, mechanical, electrical, thermal, and magnetic) [80]. Laser-based powder bed fusion is one of the AM processes that can be used or combined with another AM process to build metallic and non-metallic materials (e.g., metal–metal, metal–ceramic, and metal–polymer components) with high geometrical resolution [81].

Soft robots are inherently compliant and exhibit large strains in normal operation compared to conventionally rigid robots [82]. As depicted by their name, they are elastically soft and capable of safely cooperating with humans or steering through constrained environments [83]. 3D printing of soft robotic systems is now popular due to improvements in the materials available, as well as compatible AM processes (fused deposition modelling, stereolithography, direct ink writing, selective laser sintering, inkjet printing), offering the flexibility to use MMAM to directly fabricate components, particularly from elastomeric material, to mimic the complex motion such as jumping, complex 3D movements, gripping and releasing [84]. The printing process is mainly comprised of direct printing of smart materials, and 3D printing of molds for soft robotics suitable for medical and other industrial applications [83].

In biomedical engineering, MMAM has proven relevant in the design and manufacturing of hand orthoses using polylactic acid (PLA) and thermoplastic polyurethane (TPU) with comparable results to conventional plaster casts [85]. In dental technology, support structures of castable devices built by material jetting process can be melted away easily in a heated oven [86]. Similarly, polymeric end-use devices do not require compulsory and harsh postprocessing like those built by vat-photopolymerization and the support structures are easily removed with a water jet or by hand [87]. 3D printed medical models for training and educational purposes (Figure 8) exhibit unique and real-life appearance in terms of color and material transitions when built with MMAM [88]. Among other unique applications are the possibility to print dual functional scaffolds through direct incorporation of antibiotics [89] and dental resins with antibacterial monomers to prevent the formation of secondary caries [90].

In general, multi-material AM systems form essential aspects of 3D bioprinting for tissue engineering and regeneration: precise layering of cells, biologic scaffolds, and biologic factors with the goal of recapitulating a biologic tissue [91] and associated innovative research [92]; pharmaceutical development of customized pills [93]; 4D printing of structures or pre-programmed ‘smart materials’ to assume different shapes and forms when subjected to different stimuli such as magnetic field, ultrasound, light, temperature, water, pH, mechanical, solvent [94, 95]; 3D electronic devices of dissimilar materials [96]; metal material extrusion [97] and fiber-reinforced composites [98–100].

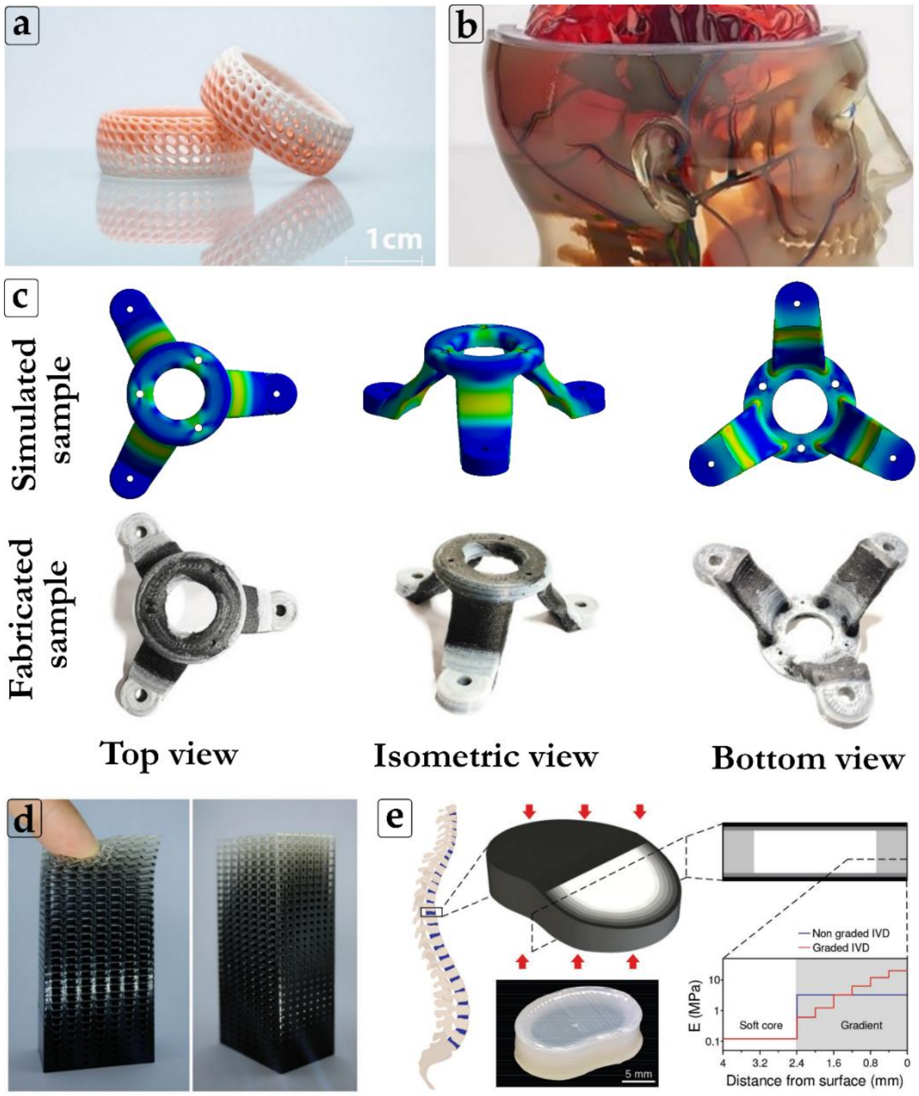

Figure 15. (a) Multi-material ceramics 3D printing using CeraFab Multi 2M30 printer [101],(b) 3D printed medical model for educational purposes [88], (c) optimized material distribution of FFF-made multi-material mounting bracket [63], (d) multi-material functionally graded lattice structure produced on the Stratasys J750 with GradCAD Voxel Print [102], (e) illustration of the loading condition as well as the gradient design of the printed human intervertebral disk. Reproduced with permission, Copywrite © 2018 [103].

6. Critical issues and challenges associated with MMAM

MMAM is the process of joining the materials with different thermo-mechanical properties to enhance the overall performance of the entire structure. There are limitations of this process whether it combines multiple polymers, metals, or metal and ceramics. Another material and process related limitation might be the real-world applications such as dimensional accuracy and size, need for post-processing, the lack of processability to combine different materials at the same time under the same environment, etc.

MMAM has been explored in recent years with a variety of processes and methods, but majority still tends to produce multiple material structures by assigning materials to different layers. This approach experiences issues associated with the difficulty of bonding dissimilar materials. This is because joining process occurs at the layer-to-layer contact area of two materials as shown in Figure 16. It can be seen from the graph that the strength of joining process depends on the intermolecular diffusion quality between PC and ABS polymer chains.

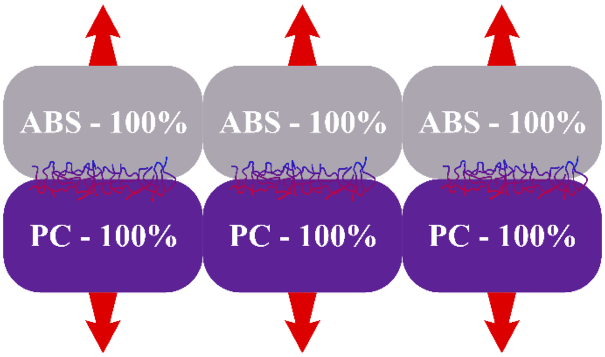

Figure 16. Interface of fused filament fabrication made multi-material part which has a direct transition from ABS to polycarbonate (PC) material. Red arrows indicate the tension loading direction

Several research investigations addressed the strength of multi-material interfaces. Lumpe et al. conducted a research study on the tensile properties of multi-material interfaces manufactured by the material jetting processes [104]. In this study, it was found that interfaces had strong dependencies on material combination and print orientation. Rigid and compliant material interfaces were mostly found to be strong as compared to the soft material itself. In another study, rigid-soft material combinations were applied for robotic applications [105]. The elastic modulus of the multi-material part was varied from 1 MPA to 1GPa, which allowed it to soften external impacts while maintaining a semi-rigid overall shape and survive longer than its purely rigid or flexible counterparts. Vu et al. performed the interface characterization of soft (TB) and stiffer (VW) material combinations using several test methods. Authors found that fracture failures nominally occurred at the interface zones [106]. They have performed a T-peel test which demonstrated that the gradient pattern yielded much better peel resistance than the direct transition interface (62% higher in terms of both average peel force and energy release rate). Mirzaali et al. [12] investigated the fracture behavior of bio-inspired functionally graded rigid-soft composites with the help of material jetting technique. It was found that the fracture properties of multi-material gradient specimens were significantly influenced by the longer transition zone.

Lately researchers have investigated the efficient use of multi-material parts using gradient approach [7, 8, 12, 16, 19, 23, 24, 107, 108] These structures with graded regions of varying materials can be built in a continuous step using a single AM machine which combines various step and eventually reduce the manufacturing time and cost. MMAM is a revolutionary approach and broad range of implementations can also generate new opportunities in the fabrication of advanced FGMs as structural material with new forms of functionalities and properties in aerospace, automobile, and medical industries[18–20,29,39–41]. Influencing factors of AM processes were investigated on the strength of interfaces. Freund et al [111] conducted a research study to find the effect of factors in the interface strength of AM-made components. Ezair et al. [112] developed a software interface that allows designers to volumetrically apply material choices to their designs. Within this framework, authors fabricated multi-material structures that demonstrated control of porous regions and deposition of differing materials with repeatable patterns. Similarly, Vu et al. [106, 113] investigated the interface characteristics of soft (TangoBlackPlus, TB) and stiffer (VeroWhitePlus, VW) material combinations using various test methods. The study revealed that the fracture failures nominally occurred at the interface zones. The T-peel test also showed that the gradient pattern at the boundary region yielded much better peel resistance than the direct transition interface (62% higher in terms of both average peel force and energy release rate). Guessasma et al. [11] conducted a research study on tensile properties of the interfaces between two dissimilar polymers (ABS and TPU) printed using the droplet-based AM process. In this research, porosity analysis was done using a 3D imaging technique. It was found that the pore connectivity inside the components was surprisingly low compared to the filament-based extrusion processes.

Overall, several research studies investigated the interface characteristics of AM-made parts that consisted of different material combinations. Table 4 showed the literature review of multi-material AM research studies based on methods used to fabricate multi-material parts and the properties that were investigated. Based on the literature reviews, most of the research investigations were conducted on the interface characterization of rigid-soft material combinations with the help of the material jetting process.

Table 4. Literature review of multi-material AM research studies

Authors/reference	Methods (AM technique)	Investigated properties
Garland et al. [29]	Bi-level topology optimization (FFF)	Flexural behavior, Optimization of material distribution
Hasanov et al. [8, 63, 108]	Tensile, flexural, compression (FFF)	Numerical and experimental investigation of FGM parts
Brischetto et al. [31]	External layer ABS, while internal layer with PLA sandwich structure (FFF)	Bending properties
Lopez et al. [32]	Tensile specimen of sandwich structures (FFF)	Tensile behavior of various material combinations of sandwich structures
Kim et al. [114]	Tensile test (FFF)	Tensile behavior
Roger et al. [115]	Topology Optimization (TO), FEA (FFF)	Selectively material placement based on FEA results
Singh et al. [116]	Tensile tests (FFF)	Tensile behavior of specimens with different printing speed and infill density
Sudbury et al. [107]	Development of BAAM system for FGM fabrication (BAAM)	Cost, weight analysis
Bracket et al. [117]	Repeatability of mixing and printing process (BAAM)	Fabrication of FGM sandwich structure

Zheng et al. [6]	Compression test, Dynamic Material Analysis (SLA)	Energy dissipation characterizations, damping
Ituarte et al. [28]	Tensile test, FEA, TO (MJ)	Tensile behavior
Dorcas et al. [118]	Tensile test (MJ)	Tensile behavior
Doubrovski et al. [26]	Voxel-based design, bitmap printing (MJ)	Generation of FGM distribution on prosthetic socket
Freund et al. [111]	Peel test, plasma treatment (FFF)	Peel resistance
Lopes et a. [119]	Tensile test (FFF)	Interface strength of zebra like patterns
Guessasma et al. [11]	Tensile test, DIC (BJ)	Strength of different interface patterns, porosity analysis using CT scan
Vu et al. [106]	Interface characterization, tension test (MJ)	Fracture resistance
Bartlett et al. [105]	FEA simulation, experiments (MJ)	Fabrication of robotic rigid-flex legs for jumping applications
Lumpe et al. [104]	Tensile test (MJ)	Tensile properties of interfaces
Mueller et al. [120]	Hardness test (MJ)	Stiffness properties of various concentrations of rigid-soft composites
Mirzaali et al. [27]	Tensile test (MJ)	Fracture resistance properties

7. Future trends

MMAM has a future potential in the fabrication of multi-functional parts that are made of multi-material combinations. MMAM processes are already grabbing a lot of attention to academic and industrial environments. Among the other AM processes, HAM combined with prefabricated parts in a 3D printer could potentially manufacture the dimensionally accurate smart systems in a continuous single process. MMAM provides the capability to make parts that were previously unheard of. It allows for adaptable designs to be made as well as materials with superior properties in comparison with traditional manufacturing methods. AM technologies join materials to make composites, change their thermo-mechanical properties, or create new materials completely. The future of this technology will advance the polymer materials with functional materials, fiber reinforced composites, metal-matrix composites, and metal-ceramic composites.

3D printing is suitable for manufacturing various smart structures because of its multi-material compatibility and capacity for personalized customization and integrated fabrication. Although 3D printing of multi-material parts promise useful applications in the future, there are certain issues that need to be addressed. There are a wide range of functional materials having excellent properties which are not printable because they have unsuitable thermal and rheological properties. Moreover, albeit several enhanced AM methods have been proposed, effective methods for many materials remain lacking. Overall, the potential future work can adhere to the following directions.

Developing software capabilities

Improving software capabilities to design highly complex FGM patterns is desirable. More control on gradient transition direction and transition length is an essential step to model FGM designs. Current commercial slicers are limited to slice and export FGMs to fabricate using FFF technology. Although there are some attempts performed to design multi-material components with gradient regions, most of them use in-house computer codes [29, 121–123] and defining locally varying material properties on CAD models is a tedious and time-consuming process. There is a need for future developments in the design of computer programs to interactively and intuitively define material properties at specified regions of the components. GraMMaCAD is one of the computer programs that have been released from Computer Graphics Research of Fraunhofer Institute which can be used to design multi-material parts with locally defining material properties. Figure 17 shows a sample part, with custom designed interface from hard to soft material, designed using GraMMaCAD and fabricated with the help of multi-material 3D printer [124].

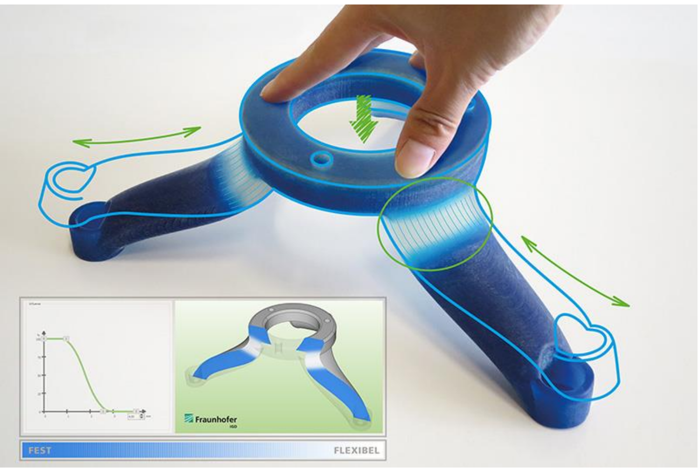

Figure 17. Interactively designed multi-material sample part using GraMMaCAD software developed by the Fraunhofer Institute [124].

Thermo-mechanical characterization of material interfaces

The defects and interface bonding strength of 3D printed structures significantly reduce their strength and durability. Since multi-material parts have potential wide range of application areas, there is need to produce reliable components with stronger interface joint. And the interface can also be affected under various temperature conditions and multi-material parts can be used for energy conversion devices and other energy related applications. Multi-material parts can effectively provide thermal barrier and can be used as a protective coating in specific applications. Although there are some research studies performed to characterize the mechanical strength of the interfaces, the characterization of thermal properties at material joints is an essential step for designing multi-functional products with improved thermo-mechanical properties.

Fabrication of multi-material parts using large-scale additive manufacturing processes

The large-scale manufacturing process would allow the fabrication of functional parts for aerospace, construction, and some other fields. Furthermore, multi-material structures remain in the demonstration stage with no specific application scenario. Accordingly, further research on this field is necessary.

New extruder designs for better material mixing

Fused filament fabrication is a low-cost process with a large selection of material possibilities which grabs attention of designers, researchers, and engineers. However, material mixing capability of this technology limits its potential. In this context, the design of a nozzle geometry and mixing chamber with an effective mixing method can be investigated. Since consistent and uniform mixing of two materials is highly dependent on the nozzle geometry and design of the mixing chamber, computational fluid dynamic methods could be applied for the new nozzle design possibilities. In addition, depositing FGMs using dynamic mixers could also be investigated, especially for BAAM, to improve the uniformity of the material mixing.

8. Conclusion

In this review paper, the latest developments, challenges, and future potential of MMAM were summarized in terms of various types of materials and their potential applications ranging from biomedical field to robotics. Different categories of materials with specific properties were utilized in MMAM which broaden the applicability of the multi-material objects to electronics, biomedical field, tissue engineering, and soft robotics.

The paper also outlined the future challenges and outlook based on the current state-of--art of this technology. In future, with the improvement of printing hardware, new types of materials applicable for multi-material printing and accurate prediction of interface properties based on numerical and theoretical analysis, it would broaden the fast development of MMAM. Overall, despite the challenges that remain, it is evident that the field of AM and more specifically as applied to multi-material fabrication, offers almost unlimited potential.

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