



# Recent development in the additive manufacturing of polymer-based composites for automotive structures—a review

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Received: 27 September 2021 / Accepted: 14 December 2021 / Published online: 23 January 2022  
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## Abstract

Additive manufacturing (AM) of polymer-based composites in the automotive industry has enjoyed tremendous progress in recent times. The use of this manufacturing technique has made it possible for the manufacturing of cost-effective, single, complex and customized automotive components. Of all the available additive manufacturing techniques, stereolithography (SLA), selective laser sintering (SLS), fused deposition modelling (FDM), laminated object manufacturing (LOM) and inkjet are the most used in the creation of polymer composite parts in the automotive industry. In spite of the success recorded in the use of AM of polymer composites in the automotive industry, the technology is limited by the size and quantity of parts produced as some of the components are massive in size and often requires mass production. Hence, AM should be a complement and not a replacement to traditional manufacturing methods in the automotive industry. In this review, the progress made and some of the challenges that are associated with the use of AM of polymer-based composites in the automotive industry are presented.

**Keywords** 3D printing · CAD model · Filler · Powder · Thermoplastic · Prototypes · Feedstock

## 1 Introduction

The advent of additive manufacturing (AM) sometimes referred to as 3D printing has revolutionised the way complex components with special features are produced [1, 2], and tremendous success has been recorded in the use of this manufacturing technique in areas such as automotive, aerospace and packaging, just to mention a few [3–5]. In recent times, the AM of polymer-based composites in automotive structures has attracted significant attention because of the improved, modified, diversified generic material properties it promises through reinforcement introduction [3].

Since the first commercial introduction of AM with stereolithography (SLA) in 1987 by 3D systems, there has been a rapid evolution in AM especially in the last decade, as several techniques such as fused deposition modelling (FDM) (introduced and commercialised by Stratasys), solid ground curing (SGC) by Cubital and Helisys, digital light processing by Envision TEC, laminated object manufacturing by

Cubital and Helisys and selective laser sintering by DTM Corp. have been developed [1, 6]. Today, there are different classifications of printing technologies in AM. Some are based on the deposition methods while others are based on material selection [7–9]. Despite the fact that AM came into the limelight a few decades ago, the standardization of the different techniques in AM was done recently. Based on this recent standardization, AM processes were classified into seven major categories [10–12] namely.

- Binder jetting.
- Material extrusion (3D plotting, fused deposition modelling, micro extrusion).
- Direct deposition.
- Material jetting (polyjet printing).
- Powder bed fusion (selective laser melting, selective laser sintering, electron beam melting).
- Sheet lamination and.
- Vat photopolymerization (stereolithography or SLA, digital light processing (DPL), two-photon polymerization).

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Polymers as well as blends of polymer composites have been discovered to address some limitations like mechanical

and thermal performance associated with 3D printing or AM particularly in the automotive industry [13]. Tremendous research has been conducted on a number of polymers and polymer composites for use in the automotive industry. Polymers or engineering thermoplastics as it is sometimes called are some of the 3D printing materials that are available in commercial quantities. A number of these polymers provide high chemical stability and mechanical performance. The versatile nature of polymers made its use very popular particularly in the automotive industry [14] as they can be blended with other materials in the form of polymer composites to improve mechanical performance, bio-content during packaging and cost [15].

The fact that polymers are readily available in the form of a filament, resin and powder has made it a popular choice for AM processes because of the low manufacturing cost they prefer especially for some classes of low-range machines [16–18]. In recent years, additional advantages such as a smaller footprint and minimal to no maintenance have been achieved in a high-end professional system of polymers printers [1], thus increasing the popularity of AM. Nevertheless, system instability that requires frequent calibration is often experienced by some AM systems. Some of the thermoplastics polymer materials commonly used for AM or 3D printing are acrylonitrile butadiene styrene (ABS) and its derivatives [19–21], polylactic acid (PLA) [22], polyvinyl alcohol (PVA) [23, 24], thermoplastic polyurethane (TPU) [25, 26], nylon [27], polyamides (PAs), polyamides (PIs), polyetherimides (PEIs), polyether block amide [28] and polycarbonates (PCs) [29]. Furthermore, the use of different materials with stiffness that ranges from soft to rubber-like and then to hard plastic material is increasing in AM processes and could be used in automotive structures, the body of amour and shoe soles [30, 31].

In AM, the 3D extrusion printer can be categorised based on their size as either large-scale or small-scale printers. Prior to the trademarking, small-scale 3D printers were called FDM. This name has now been replaced with fused filament fabrication (FFF), and the thermoplastic polymer filaments are extruded by the desktop-sized printer through a heated nozzle, and the extrudate is deposited on a heated bed [32] such that a bottom-up method is used in the building of the components. The cost of the printer and the final product is comparatively low when compared to selective laser sintering (SLS) [33]. Nevertheless, the printer's limitations include a minimal filament diameter and a print area that is limited by the bed size of the printer.

During material development using 3D printing, the size of the filament influences the cost of manufacturing, as larger filament diameter increases the production cost and the time to optimize the processing conditions as more additives are needed. In a bit to overcome these, large-scale extrusion printers also known as big area additive manufacturing

(BAAM) [34–36] that allows the use of filament feed systems or pellets were fabricated. BAAM increases the rate of production and the expected time of mass production using 3D printing. In selective laser sintering sometimes called powder bed fusion [37], a powder bed and a laser are needed to melt the polymer in a way that each layer of the melted polymer connects to the surrounding ones. The parts created by powder bed fusion is larger than those created by FFF. Hence, more space and resources are required if powder bed fusion is to be used. Polylactic acid (PLA) is the most commonly used thermoplastic for FFF. However, the use of PLA in SLS is limited due to its mechanical properties and thermal stability [38]. Hence, the materials used in the SLS technique are limited to resins and other materials that give minimal performance variability [39].

### 1.1 Fused deposition modelling

Of all the AM techniques listed above, FDM is one of the most used [40–43], as products created using this technique account for 41.5% of the market share and about 15,000 FDM machines already sold out at the end of 2010 [44], and as of July 2018, the market share grew to 69% [45]. Currently, the total sale of FDM cannot be accurately estimated as various firms have started production of cost-effective FDM printers. Initially, FDM was designed for pure thermoplastics or polymers; however, the advancement of technology has made it possible for the commercial availability of reinforced feedstock FDM although the authenticity of the developed feedstock is not guaranteed as most users customize their feedstock using suitable processing routes [46]. The availability of reinforced feedstock FDM in commercial quantity has further popularised the use of FDM in the automotive industry particularly in the production of polymer composite parts.

### 1.2 Selective laser sintering

With the aid of high laser power, the polymeric powder particles are fused in the SLS technique [47, 48]. Just like the other AM technologies, the polymer powders are laser fused at specific locations for each of the specified layers in the design [49] such that the quality of the final print is dependent on the processing conditions such as the scan speed and laser power [50, 51]. Also, the SLS technique allows the usage of blended polymers as well as polymer composites [52–55]. The advancement and use of this technique in the automotive industry have led to a drastic reduction in the cost and time of part production [56, 78]. Also, the polymer/polymer composite powder used in this technique makes it possible to print fine and exact part details as compared to the other printing methods as a fine layer of the powder polymer/polymer composite is produced by the printer sets

using a laser to produce a second layer. This process continues until the desired part with a much smoother finish as compared to the other AM method is achieved.

### 1.3 Stereolithography

In terms of high resolution, watertight mechanical channel creation using liquidized photo-curable resin feedstock that is cured by ultraviolet (UV) light [57, 79] and mechanical stability, the stereolithography (SLA) has an edge when compared to the other AM techniques [58, 59]. Nevertheless, the photopolymer resin or UV resin used in this technique needs to be properly cured under ultraviolet light as the uncured or not properly cured resin is toxic and can be harmful to the user (as it could lead to severe health issues) and environment [60, 61]. When the resin is properly cured, it hardened and thus no longer toxic. The SLA technique has proven to be a fast, maskless, stable and layer-by-layer AM process with exceptional ability to build a 3D, high aspect ratio, lightweight microscale and mesoscale components [62]. Just like the SLS technique, SLA can utilize both synthetic and natural polymers; as such, they have areas of noticeable scope of application [63], particularly in the automotive industry. The successful use of SLA in the automotive industry has allowed AM or 3D printing to gain industrial status, and more innovative use of the technology is currently a top priority in many fields of study [64, 65]. One of such innovative studies conducted was the attempt made towards the development of mathematical models and the design of algorithms for the stereolithography process to determine if a proposed object or part could be created using 3D printing [66].

### 1.4 Laminated object manufacturing or sheet lamination

The laminated object manufacturing (LOM), sometimes addressed as sheet lamination, is the least explored and least popular AM technique. With the help of polymeric films, metal, foils and paper laminates as feedstock, this technique is used in the production of prototypes [67–69]. In this AM technique, the use of different combinations of the feedstocks helps in the creation of parts with improved mechanical properties [70]. Three major steps, namely, adhesion joining, clamping and ultrasonic welding, are involved during LOM-based printing. As such, there is a compromise between strategies of additive and subtractive manufacturing when this technique is adopted in building a 3D structure. Just like FDM, a prestep is required in LOM during the fabrication of fibre-reinforced composites and laminated before printing [71]. This technique offers a convenient and cost-effective way of producing millimetre to metre-sized parts such as automobile parts while

incorporating micrometre-sized features. There has been significant improvement in the modern LOM machine as compared to the one patent by DiMatteo [72]. The modern LOM machine allows for a continuous material feed which makes it possible for a continuous strand of polymer tape, metal foil or paper to run through instead of the tedious manual layer stacking associated with the old LOM machines [72]. The application of multiple sensors and a CO<sub>2</sub> laser in the modern LOM machine has drastically improved its cutting technique [72].

### 1.5 Inkjet

Inkjet printing differs from the other AM techniques in terms of its high resolutions and its ability to allow drop-on demand of different types of feedstocks such as hydrogels, liquid polymers, ceramics, metallic solutions and bio-inks [73–75]. Aside from the conductive interfaces which have been widely practised with inkjet printing, the technology has also been successfully used for building electrical devices, sensors in automotive and biomedical devices etc. [74–77, 80–82].

Depicted in Table 1 is a schematic description of the AM techniques of polymer composite frequently used in the automotive industry. In the table, used polymer matrix, filler and area of application in automotive is presented.

## 2 AM procedure in automotive applications

Over the years, the procedures used in AM have been improved and the applied techniques have ensured the production of precise component parts. The following are the AM procedure currently in use:

- I. Computer-aided design (CAD): In AM process, the first step is the design of a digital model of the component to be produced [47, 57]. This procedure is not peculiar to the design of automotive parts alone but to all components that need to be produced using AM. The most common and perhaps the easiest method for developing the digital model is through CAD [83]. It is worth noting that the use of reverse engineering through 3D scanning has enjoyed patronage in the generation of digital models in the automotive industry [84].
- II. Conversion of CAD model to STL file and the manipulation of the file: After the development of the CAD, there is a need to convert the CAD model to STL (stereolithography) file since the AM process varies from the traditional manufacturing methodology [85]. The surfaces of objects to be developed using AM whose CAD model has been converted to STL file are described using polygons [84]. Based on this, several model limitations such as the physical size of the model, the polygon count and the water tightness are considered before the developed

CAD models are converted into STL files [84, 86]. Once the CAD model is converted into the STL file, the file is imported into a slicer program where it is converted into a G-code (a numerical control (NC) programming language) used in computer-aided manufacturing (CAM) to control the automated machine tools such as the computer numerical control (CNC) and 3D printers [84]. With the help of the slicer program, the designer can customize the build parameters such as layer height, support and the orientation of the parts of the components.

III. Printing: Often, the 3D printing machine comprises several small and complicated parts that require appropriate calibration and maintenance in order to create and print accurate parts [84]. After these are considered, the print material is carefully loaded in the printer having in mind that most of the used raw materials in AM often have a limited shelf life and thus require careful handling, although some AM processes allow for the recycling of excess build materials. Repeated reuse often results in a significant reduction in the properties of the produced component [84]. Most of the newly produced AM machines do not require monitoring once the print has been initiated as the machine would follow an automated process and only requires attention when the machine runs short of materials or encounters software errors.

IV. Print removal: The removal of parts for some AM technologies is as simple as just separating the printed part from the build platform while for others, it involves a highly technical process that requires precise extraction of the print while it is still attached to the build plate or encased in the build material. Thus, a complex removal procedure requires a highly skilled machine operator, controlled environments and the use of safety equipment [84].

V. Post-processing: Just like print removal, the post-processing procedure in AM varies from one printer technology to another. Stereolithography (SLA) requires the printed component to cure under ultraviolet (UV) light before handling [60]. Also, metal parts are often subjected to a stress relief procedure in an oven while parts produced using FDM can be handled immediately after printing [84]. For AM technologies that use support, the print is removed at the post-processing stage and most 3D printing materials are sanded while other post-processing techniques such as high-pressure air cleaning, tumbling, polishing and colouring are implemented to get the print user ready [83].

### 3 Meeting the requirements in automotive industry using AM

In the automotive industry, fuel economy and speed are very important factors that are considered during component/material selection, hence the need to develop lightweight

components with intricate parts that allow for significant fuel economy. In order to fabricate these automotive components with high complexity in shapes, AM has been at the forefront for several years now and the following are required:

I. Weight-final parts: Weight reduction, in a bid to reduce fuel consumption, is one of the most critical aspects of the automotive industry [87]. In an attempt to improve performance, automotive applications use advanced engineering components with complex geometries. Creating these complex components using the traditional methods is tedious and time-consuming. Hence, AM is capable of producing these lightweight polymer parts that are useful in weight reduction in the automotive industry in the shortest possible time [87].

II. Complex geometry prototypes and final parts: Some parts of automotive are complex in geometry. A number of them require internal channels for conformal cooling, thin walls hidden features, complex curve surfaces and fine meshes [87]. Using AM of polymer composite, these complex structures can be manufactured such that they possess the needed lightweight and stability that is required of them [88], as this manufacturing technique provides a high degree of design freedom that is optimized by integrating the functional features in the components. Employing this manufacturing technique gives room for the cost-effective manufacturing of small batches of components/products with a high degree of customization. Also, the more complex the shape of the component is, the better it is to have it printed in 3D because the energy and cost for printing are independent of the complexity of the shape [89]. Thus, several parts can be integrated into one complex shape through redesigning, and the need to assemble or dismantle several components would be reduced [90].

III. Temperature testing and final parts: Some automotive application requires components to show a significant level of minimum heat deflection. A number of AM processes produce materials that are capable of withstanding temperatures well above 105°C, which are often maintained in the engine compartment of automotive [87]. The SLS-produced nylon as well as UV light-cured polymer are some of the AM-produced components suitable for high-temperature applications [84].

IV. Moisture testing and final parts: Most of the components of automobiles are moisture proof or moisture resistant, and this gives AM an edge over other manufacturing processes as printed parts can be post-processed to create a part that is watertight and moisture resistant [87].

V. Consolidation of parts, prototyping and final parts: With AM, the herculean task of item/part assembly that is associated with other manufacturing techniques can

be drastically reduced since a single complex component can be produced in AM [83]. When considering how to reduce material usage, consolidation of parts is a major factor to consider in AM, as it helps in weight and cost reduction [84, 87]. Through part consolidation, inventory is reduced since many assemblies can be replaced with a single part. This helps in the reduction of repair/maintenance time in the automotive industry.

#### 4 Benefits of AM in the automotive industry

The concept/usage of AM has benefited the automotive industry in more ways than one, and some of the benefits are.

**Communication:** In the automotive industry, design often begins with a scaled model that showcases the form of the vehicle or component of the vehicle that needs to be manufactured. After which a high detailed, smooth and scaled model of the automotive component is produced. In the automotive industry, these smooth, detailed and scaled components are usually produced using SLA and material jetting such that the intention of a design is clearly communicated, and the overall concept is showcased if the component is accurately modelled [84, 87].

**Validation:** The use of prototyping in AM is becoming more popular in the automotive industry as it allows the fast printing of a full-sized wing mirror using the low-cost FDM for the printing of a high-detailed full-coloured dashboard [87]. So far, there is a suitable AM technology for every needed prototype, and some of the available AM materials allow for full testing and prototype validation.

**Pre-production:** Although AM has been a bit disruptive in the area of production of low-cost rapid tooling for injection moulding, jig and thermoforming fixtures [84, 91]. However, in the automotive industry, low-cost toolings are allowed to be quickly manufactured and used to produce parts with low to medium runs [87]. Nonetheless, this pre-production prevents the risk associated with investing in high-cost tooling during the production stage.

**Production:** Owing to the large volume (greater than 100,000 parts per year) of production required in the automotive industry [92, 93], AM is mostly used as a prototyping solution rather than the manufacturing of end parts [94]. Also, due to the constant improvement in the speed and size of industrial printers, and the available materials, AM has enjoyed high patronage in medium-sized production runs, especially for higher-end automobile manufacturers with a restricted number of productions below average [87]. Since AM technique can be used to produce multiple design iteration within a short period, although with a little increment in production cost, the technique (3D printing or AM) serves as an effective tool for the development of products. Also, the technique provides a comparative speed in terms

of production time as other typical techniques would have to go through several cycles before agreeing on the final design [84]. In addition to the comparative advantage in the area of speed, the technique is cost-effective in the event of any need to modify any design since expensive tools are not required to produce prototypes in AM.

**Tooling:** The use of tooling in the automotive industry is very extensive because it aids the production of high-quality products. Employing AM as a complement to this process has helped in the creation of jigs, complex features and other customized tooling equipment that are needed in the automotive industry. Already, an in-house AM-produced tooling equipment is been used at the Volkswagen Europa assembly [84], and this has discouraged sourcing of tooling equipment from third-party providers. The use of AM has drastically reduced the turnaround time and has proved to give a cost-effective return on investment through the enhancement of the overall production process [95, 96].

**End-part production:** The recent advancement in AM technology and materials has made it possible for the production of medium and small parts although this technology was initially designed as a prototype tool. The current use of AM in the automotive industry ranges from the production of interior components such as bellows, mounting brackets, complex dunting and engine parts to exterior components. A typical example is the use of 3D printing by Bugatti (a luxury car manufacturing company) in the production of a fully functional brake caliper [84]. With this success, 3D is set to be at the forefront of the production of this component.

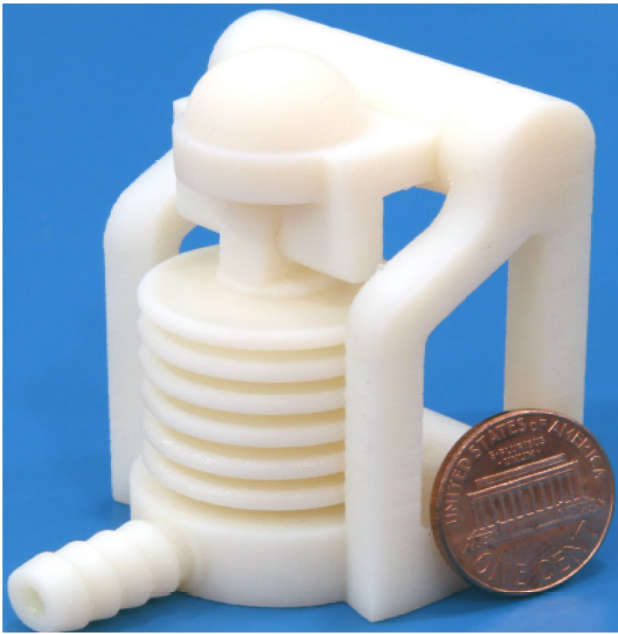
**Spare parts:** By leveraging the advantages of AM, automakers can create spare parts upon demand and this will help in the reduction of inventory costs associated with part storage, improve the delivery time of produced components and simplify the supply chain.

#### 5 Common automotive applications of AM of polymer composites

Owing to the near neat component produced and its flexibility, AM technique has found serious patronage in the automotive industry [97, 98]. Some of the common applications of AM of polymer composite in the automotive industry are.

I. **Bellows:** A semi-functional bellow piece that requires some level of flexibility in its mating or assembly can be produced using AM. In general, AM is suitable for applications that require the produced parts to be exposed to limited repetitive flexing motions. If the component to be produced requires significant flexing, other polyethylene-based SLS materials like Duraform Flex are more



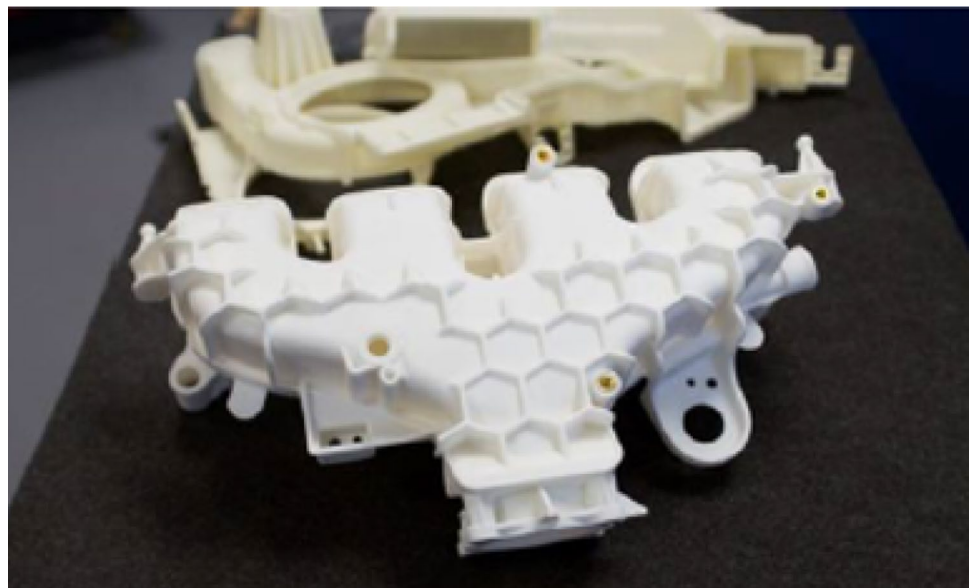


**Fig. 1** Three-dimensional printed bellows using inkjet [99]

suitable. Depicted in Fig. 1 is a 3D printed bellow using inkjet technique.

**II. Complex ducting:** The use of SLS additive manufacturing technique for the manufacturing of non-structural low-volume ducting like the environmental control system (ECS) ducting used for performance racing in automobiles and cabin pressurization in aerospace, one can as well design a highly optimised but very complex single-piece structure. Depicted in Fig. 2 is an SLS 3D printed complex functional ducting of an automobile.

**Fig. 2** Three-dimensional printed complex functional ducting using SLS [84]



Through the use of the SLS additive manufacturing technique, it is possible to vary the wall thickness, which in return helps in the increase of the strength-to-weight ratio through structural application of optimized surface webbing. It is worth noting that this procedure is quite expensive if the conventional manufacturing technique is used, but with the SLS technique, the complexity of the part has no cost implication on the prints as parts are printed with a high level of accuracy and without any support.

**III. High detailed visual prototype:** Some AM processes, unlike the traditional prototyping methods, are capable of producing multicolour designs with a surface finish similar to those produced via injection moulding. Using these models or AM processes, designers get a better understanding of how parts are formed and how they can perfectly fit. These highly accurate prototyping methods are ideal in the analysis and testing of aerodynamics. In automotive, AM is frequently used in the manufacturing of components that depends on aesthetics such as wing mirror, steering wheels, light housing and full interior dashboard. Of all the AM methods, SLA printing and material jetting are the most used for producing aesthetic prototype parts from a photo-activated resin. A full-coloured texture visual prototype centre console of automobile produced using AM technique is shown in Fig. 3.

**IV. Functional mounting brackets:** The ability to manufacture a lightweight, complex bracket within a short period is synonymous with AM industry. Aside from the simplicity in manufacturing organic shapes and designs, AM requires minimal input from operators as the technique is very fast in taking a design from the computing stage to the assembly stage, a procedure that is almost impossible with the traditional manufacturing methods such as CNC machining



**Fig. 3** Full-coloured, textured visual prototype centre console produced using AM [84]

which requires the services of a skilled operator during part production. For the production of functional parts, powder bed fusion technologies such as SLS nylon and metal printing that allows a range of materials from nylon to titanium are more suitable. Through the use of SLS nylon, a functional alternator bracket of an automobile shown in Fig. 4 is 3D printed.

**Fig. 4** Three-dimensional printed functional alternator bracket using SLS nylon [84]



## 6 Current uses of AM of polymer/polymer composite in automotive

**Fluid handling:** Currently, electron beam and selective laser melting are used with polymer composites to make the fuel pumps and valves of the fluid handling system of automobiles [84].

**I. Automobiles exterior:** With the help of selective laser technique, polymers have been successfully used in the manufacturing of windbreakers and bumpers of automobiles [100].

**II. Manufacturing process:** The use of polymer and hot worked steel in conjunction with the available AM techniques like selective laser melting, selective laser sintering and fused deposition modelling, the creation of prototypes, customized tooling and casting are possible, and these techniques can be used in both small and big automotive industry [83].

**III. Seating and interior:** The use of polymers/polymer composites and AM techniques such as laser sintering and stereolithography (STL), seat frames and dashboards could be easily manufactured [84].

**IV. Suspension, tyres and wheels:** With the use of AM techniques such as selective laser melting, laser sintering and inkjet technology, polymers and polymer composites can be manipulated to produce hubcaps, suspension springs and tyres [84].

**V. Electronic components:** The use of selective laser sintering on polymers/polymer composites has made it possible for the manufacturing of a range of delicate com-

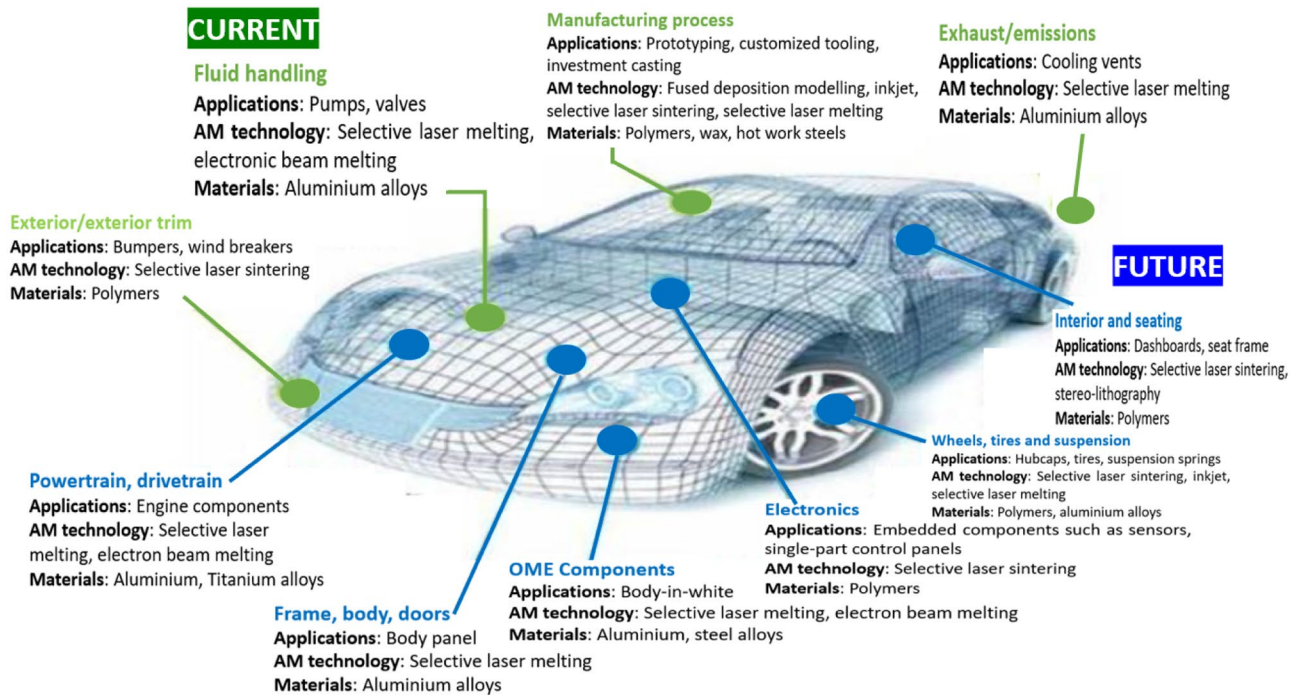


Fig. 5 Current and future use of AM in the automotive industry [100]

ponents such as embedded parts like sensors and single control panel parts [84, 101].

VI. Frameworks and doors: The use of selective laser melting has made it possible for polymer composite to be used in the creation of lightweight body panels such as doors and frameworks [102].

VII. Engine components: AM techniques such as selective laser melting and selective sintering [103, 104] have made it possible for reinforced polymer composite to be used in the creation of automotive engine components such as the crankshaft bearings, camshaft gear, crankshaft gear and timing gears. Figure 5 shows the current and future general use of additive manufacturing technology in the automotive industry while depicted in Fig. 6 are some of the parts/components of the automobile that are currently enjoying the usage of polymer/polymer composites in their production. The use of these polymer/polymer composites in the production of the parts/components is reported to have improved heat resistance, better durability and are less susceptible to shrinkage when compared to the previously used components [105].

## 7 Current challenges facing the use of AM in the automotive industry

I. Mass production: Although there is a fast acceptance and incorporation of AM by automotive original equipment manufacturers (OEMs) in the development and production

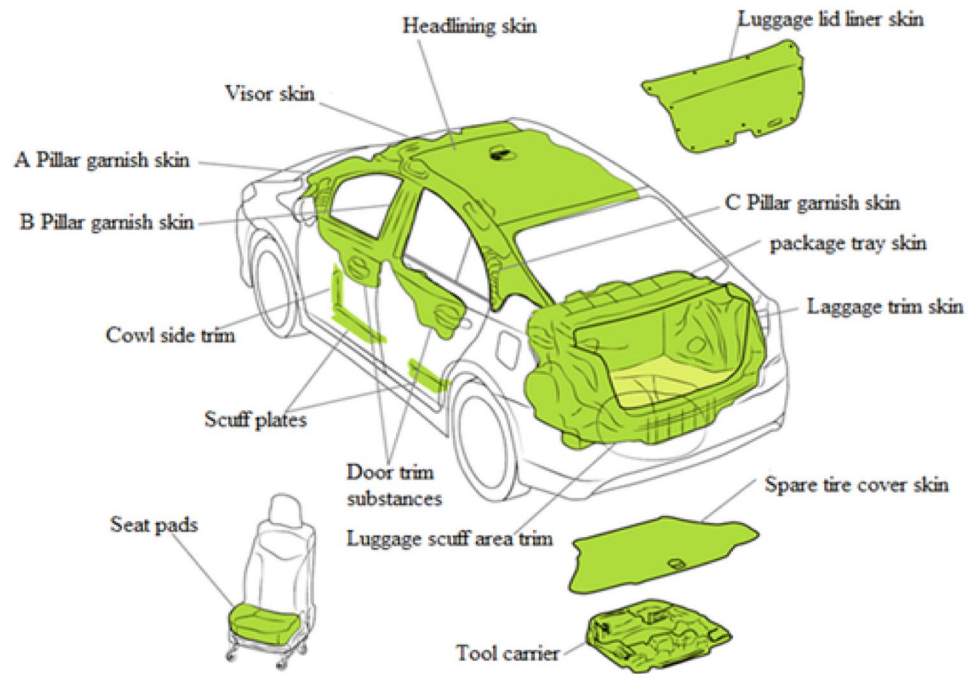
of parts. However, general acceptance of this method is faced with the volume of production. In 2017 alone, over 80 million cars were produced [84], thus making the automotive industry dependent on mass, series production. Hence, AM should not be seen as a total replacement for the traditional manufacturing methods known for their mass or high volume production but as a complement for the production of low volume, customised automotive components or parts [106].

II. Build size: Currently, the build size of AM systems is limited [107] and is faced with the challenge of appropriately accounting for the needed sizes required by automakers. Although 3D printing technology allows for the production of larger parts, this needs to be created in modular parts after which other coupling technologies such as welding are used to assemble the parts. Nonetheless, there is growing research in the creation of large-scale AM technologies such as big area additive manufacturing (BAAM) [108] and wire additive manufacturing (WAAM) that can support larger built sizes similar to those required in the automotive industry [84].

III. AM skill gap: So far, there is still a wide gap between the available and needed skills required for AM technology to gain the required patronage expected of it [109, 110]. Important skills in the area of AM design, operation, systems maintenance, AM materials and post-processing must be developed and fostered. Also, the automotive industry must create a strong collaboration with universities and AM experts in order to improve



**Fig. 6** Some of the polymer/polymer composites manufactured parts of automobiles [105]



and increase the pool of skilled talent in the use of AM technology.

IV. Some of the current applications of AM of polymer composites, material systems and the techniques used in the production of the component/part in the automotive industry are highlighted in Table 2.

## 8 Economic feasibility/sustainability and environmental impacts of AM in the automotive industry

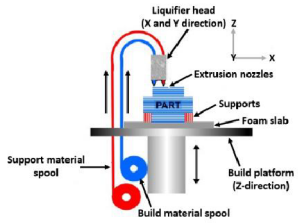
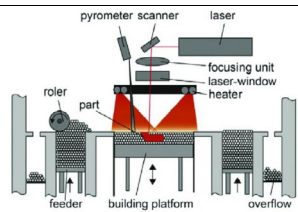
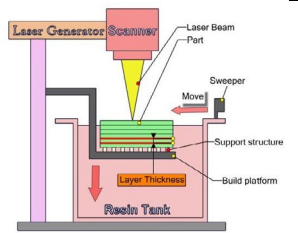
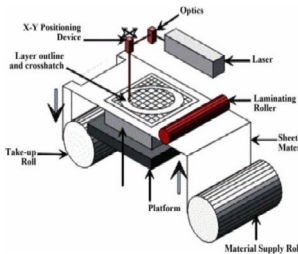
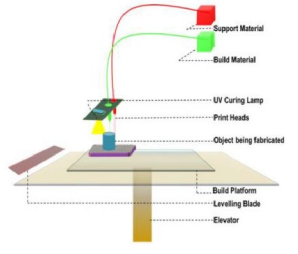
The economic impact of AM in the automotive industry was noticed during the days of rapid prototyping on product development, where its usage was limited to the production of prototypes to minimize cost and speed up the production rate [113, 114]. Ranging from soft tooling to hard tooling or supporting the assembly line, AM has proved to be an unavoidable process due to its flexibility and ability to produce optimized automotive components [115]. In the automotive industry, mass customization plays a major role and the possibility of manufacturing a customized vehicle upon request has enhanced the customer-manufacturer collaboration, hence simplifying or shortening the supply chain. Also, the use of AM technique in the automotive industry allows customers and manufacturers to codesign products in such a way that their mutual requirements are met. Based on this flexibility, the range of the products can grow almost infinitely, and the cost of manufacturing is not increased significantly, except the customer needs and additional features which may require an additional price. Hence, AM is indeed a powerful tool capable of achieving

a high level of product customization, and with unlimited market potential [116].

In a bid to estimate the economic feasibility and sustainability of AM in the automotive industry, a cost modelling of conventional manufacturing techniques and additive manufacturing techniques were used as the basis, and the material, machine and labour cost of the two manufacturing processes were used for the evaluation [117, 118]. Different variations of couplings ranging from single variation to 10 variation couplings were used to calculate the production cost for the two manufacturing techniques (conventional and additive), and it was discovered that the cost of AM produced parts is constant irrespective of the number of variation couplings used. However, the final cost of the component produced using the conventional technique (i.e. injection moulding) is dependent on the number of moulds used to produce the part variations [117, 119]. A breakeven point of both techniques for a single-type variation is the same, but differs as the number of variations increases, with the AM technique being a more cost-efficient way in the production of parts with multiple variations [119], and preferable in the production of very small series components, as this makes it possible to keep inventories low or solve unexpected gripper configuration.

For the automotive manufacturers, AM offers a different approach for stocks management and the chain of supply. It is worth noting that automotive manufacturers are mandated to keep spare parts for the different models of vehicles manufactured for a legal duration of 10 years. Based on this, a number of the automotive industries depends on a third party for the manufacturing of these components and thus supports

**Table 1** Description of AM of polymer composite used in automotive industry

Schematics of techniques	Polymer matrix	Fillers	Application	Ref
<b>Fused Modelling Deposition (FDM)</b>				
 <p>[77]</p>	Thermoset (EVA)	Graphite	Electrical	[47]
	Thermoplastic (PLA)	Bronze	Structural	[46]
	Thermoplastic (ABS)	Iron/Copper	Thermal	[48]
	Thermoplastic (ABS)	Carbon fibre	Load bearing	[46]
	Thermoplastic (ABS)	Graphene	Structural and thermal	[51]
	Thermoplastic (PLA)	Graphite	Electrical and thermal	[46]
	Thermoplastic (ABS)	Multiwall carbon-nanotube	Structural and thermal	[46]
	Thermoplastic (PPR)	Graphene oxide	Electrical	[55]
	Thermoplastic (PLA)	Montmorillonite	Electrical	[46]
	<b>Selective Laser Sintering (SLS)</b>			
 <p>[78]</p>	Thermoplastic (PA-11)	Silica	Mechanical	[46]
	Thermoplastic (PA-12)	Carbon fibre	Mechanical	[46]
		Carbon black	Mechanical	[46]
		Carbon nano-fibre	Mechanical	[46]
<b>Stereolithography (SLA)</b>				
 <p>[79]</p>	Thermoset (Polyamic (SPR-212))	SiOC and SiC	Mechanical	[80]
	Thermoplastic (PMMA)	Urea, ammonium chloride and resorcinol Graphene	Smart materials	[81]
	Thermoset (Envision-TEC)		Electrical	[46]
<b>Laminated Object Manufacturing (LOM)</b>				
 <p>[82]</p>	Thermoset (PI film)	Graphene	Energy and electronics	[46]
<b>Inkjet Printing</b>				
	Thermoset (PVA)	CdTe nanocrystals	Electrical	[46]
	Thermoset (Poly-isobutylene)	Quantum dots	Electrical	[46]
	Thermoset (Polyacrylate)	Alumina nanoparticles	Mechanical	[46]
	Thermoset (Poly(2-methoxyaniline-5-sulfonic acid))	Single wall carbon nanotubes	Electrical	[46]
	Thermoset (Polyaniline)	Graphene	Electrical	[46]

**Table 2** Current applications of AM of polymer composites

Application	Material system	AM technique used	Key outcomes	Ref
Smart devices	Photoinitiator, polyurethane acrylate oligomers, rheology modifier, reactive diluents and the alumina platelets	Direct ink writing	It assists in the manufacturing of functional heterogeneous materials	[111]
	Polyethylene glycol diacrylate and barium titanate nanoparticle	3D optical printing	When the composite is loaded with 10% mass of the chemically modified barium titanate nanoparticle, the manufactured component shows piezoelectric coefficients of $\sim 40$ pC/N suitable for use in various applications including the automotive industry	[112]
	Polymorph and carbon black	FDM	The material developed and unmodified FDM system is suitable for printing electronic sensors capable of sensing mechanical flexing and capacitance changes	[46]
Energy	ABS/graphene	3D printer HOF1-X1	The composites formed have linear thermal coefficient was lower than $75 \text{ ppm } ^\circ\text{C}^{-1}$ from room to glass transition temperature, thereby making it crucial when minute thermal stress components are needed to be built	[46]
Automobile	Nylon and carbon fibre	SLS	The printing gives a product with suitable tolerances	[46]
Aerospace	PLA/ABS and short carbon microfibers	FDM	Short carbon microfibers embedded filaments show better print capabilities for automotive and aerospace industry	[46]

the spare part supply chain. This helps to reduce downtime as the AM provides the possibility of reproducing parts without specific and expensive tools which allow the stock of physical parts to be converted to a digital warehouse, such that the files of the 3D model, manufacturing methods/strategies are stored and can be used when needed [114, 116, 120]. On an industrial scale, the feasibility of using AM in the automotive industry is on the increase due to the entry of third-party suppliers of raw materials, and this enables the user to be independent of proprietary materials as the manufacturers of AM equipment are forced to make their equipment third-party material compatible. Hence, reducing the cost of raw materials required for the production of parts and also increasing competition in the market [120].

In the area of manufacturing and environment, the use of AM in automotive has a significant economic impact as it allows for the decentralization of manufacturing; and through digitalization, logistics can be simplified such that manufacturing of the automotive parts will be independent of location. Thus, there is a substantial reduction in the physical flow of materials and products which results in a significant reduction of emissions [113, 116, 121].

In spite of the vast benefits provided by the use of AM especially in materializing a digital product, critical issues such as the respect for the property of products designed have seriously affected the usage of this manufacturing technique, and this has been discovered to be one of the most severe economic consequence of additive manufacturing

[114] because the 3D model of the developed or designed products are transmitted for end-user or industrial purpose base on the established contractual confidence between the supplier and the customer, and the transmitted files often contain not only the geometry of the designed product but also the material information, building strategies and parameters among other details that are needed to produce a product with high quality, which indeed needs to be protected [122]. In a bid to protect these AM files, a special security feature has been proposed to be incorporated in the files for the protection of the files and ease of identification of genuine products [123].

## 9 Conclusion

In this review paper, the recent progress made in the use of additive manufacturing of polymer and polymer composite in the automotive industry is presented. The different AM techniques that are available and those that are suitable for use with polymers and polymer composites are also presented. The enormous volume of parts, relatively slow speed of production and sometimes the massive size of some of the components were identified as the major challenge of the use of AM of polymer composite in the automotive industry. Nevertheless, there is tremendous research geared towards increasing the production speed in AM and the improvement

in large-scale AM technologies such as BAAM and WAAM that are capable of supporting the massive sizes peculiar to the automotive industry. Lastly, the use of conventional manufacturing methods cannot be wished away because of the advent of AM but should serve as a complement to the already existing conventional manufacturing methods.

**Acknowledgements** This research has been supported by Tshwane University of Technology and the University of Pretoria, South Africa. Also, the authors greatly appreciate the support of Eskom Power Plant Engineering Institute (Republic of South Africa).

**Author contribution** Smith Salifu: conceptualization, writing—original draft. Dawood Desai: conceptualization, writing—review and editing. Olugbenga Ogunbiyi: writing—review and editing. Kampamba Mwale: writing—review and editing.

**Data availability** Not applicable.

**Code availability** Not applicable.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** The author agrees to publication in the International Journal of Advanced Manufacturing Technology and confirms that the work described has not been published before, and its publication has been approved by all coauthors.

**Competing interests** The authors declare no competing interests.

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