Review

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Application of additive manufacturing in automobile industry: a mini review

Jian Yang , Bo Li , Jian Liu , Zhantong Tu , Xin Wu *

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Keywords: additive manufacturing; automobile industry; printable materials; product quality

Review

Application of Additive Manufacturing in Automobile Industry: A Mini Review

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Abstract: Automobile industry is recognized as one of the most influential sectors shaping the global economies, societies, and individual lifestyles. Therefore, fierce competitions among different companies are continuously undergoing, and innovations deserve special attention to improve the competitiveness. In the past several years, additive manufacturing (AM) is emerging as an innovative technology in the applications of automobile industry with significant advantages over traditional techniques. As a result, increasing attention has been attracted to combining AM technology with the development of automobile industry. Currently, many automobile players are optimizing their industrial layout by incorporating with innovative AM techniques, and meanwhile, many research progresses have been achieved to meet the market demand. This article aims at presenting a timely review to conclude the recent advances in the application of AM techniques in automobile industry, focusing on the available AM techniques, printable materials, and the industry applications. The future research opportunities and challenges are also outlooked. Hopefully, this work can be useful to the related researchers, as well as the game players in the industry of this field.

Keywords: additive manufacturing; automobile industry; printable materials; product quality

1. Introduction

The automobile industry, being vital to the global economy, is recognized as one of the most influential sectors shaping the economies, societies, and individual lifestyles globally. It was reported that the global automotive market could be expected to reach USD 3817171.94 million by 2030, growing at a Compound Annual Growth Rate (CAGR) of 3.01% [1]. The huge market thrives on the fierce competition among major players regarding the industry's innovation and growth. The automotive market is driven by demanding to develop along several directions including: 1) Innovation of the technology such as the development of electric and autonomous vehicles; 2) Environmental concerns such as the eco-friendly solutions for the environmental problems; 3) Urbanization for efficient transportation solutions; 4) Consumer preferences such as the design of the personalized, connected and safe vehicles. To grab the market share, breakthroughs in areas such as sustainable materials, energy storage, and autonomous systems are frequently proposed in automobile industry [2]. On the other hand, as the core of the automobile industry, manufacturing techniques dominate the market competitiveness of a car company [3,4]. Therefore, innovation in the manufacturing process is highly expected.

Conventional manufacturing techniques used in the automobile industry, such as casting and injection moulding, largely depend on the subtractive process, which are technically mature though, have a high buy-to-fly ratio [5]. Recently, the emerging additive manufacturing (AM) is reforming the automobile industry and receiving increasing attention from the auto companies worldwide. AM technique, also known as three-dimensional (3D) printing, is a relatively new technology creating 3D objects through gradually depositing the material in a layer-by-layer manner based on a computer designed model [6–13]. With the obvious advantages of design flexibility, reduced material waste,

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shortened lead time, and reduced tooling requirement, AM is recognized as a game-changer for the production process by replacing traditional manufacturing [14]. For automobile industry, AM technique is unprecedentedly adopted to explore new design and manufacturing opportunities throughout all the segments [15–17]. With the development in the manufacturing ability and manufacturing quality, AM can not only be used in rapid prototyping of automobile parts, but also in the production of high-quality end-use components. It was predicted that the 3D printing market in the automobile sector could reach a value of USD 9.7 billion by 2030 with a CAGR of 15.94% [18]. The major merit of employing AM in automobile industry is the ability to create lighter and more complex structures in a short amount of time, which can improve the energy efficiency, shorten the process chain and reduce the manufacturing cost in automobile industry [19].

There have different AM technologies been developed for the applications in automobile industry, including material extrusion, vat photopolymerization, binder jetting, powder bed fusion, sheet lamination and directed energy deposition [20–23]. Based on the different 3D printing technologies being involved, various materials including polymers, metals, ceramics, and alloys have been applied in the AM of automobile sectors [24,25]. Integration the advances in the 3D printing techniques with material development, many applications in the automobile industry have been demonstrated. For example, Honda realized a crankshaft with 50% weight reduction by using AM [26]. General Motors successfully consolidated eight pieces of components into one single seat bracket part though AM technique [27]. Ford adopted 3D printing technique to fabricate the aluminium inlet manifold, which was installed in a 1977 Hoonitruck [28]. Currently, this company has printed over 500,000 automobile components in the Detroit center. Volkswagen has been working with 3D printing techniques for more than 25 years, and BMW group also spent €15 million to build the Additive Manufacturing Campus. Obviously, more and more companies are investing into the AM techniques to maintain short development cycles and to achieve lower costs, and the application trend is extensively expanding.

Over the past several years, research into the application of additive manufacturing in automobile industry is experiencing exponential growth, as shown in Figure 1. Great achievements in the fields of advanced manufacturing technology, unique advanced printable materials, and high-performance end-use components have been made regarding automobile industry. Though there have been a few pieces of related work summarizing the current research status of the application of AM technique in automobile industry, they are either sort of superficial [5,16], or with partial content [29,30] (e.g., only the polymer-based components are discussed in Ref. [29], and only tooling manufacturing is described in Ref. [30]). In some other reviews such as Ref. [31,32], the focus is on cost control and production management, rather than the most important manufacturing parameters. For this article, we are aiming at presenting a timely and comprehensive review to conclude the recent advances in this field focusing on the AM techniques, printable materials, and the industry applications. Hopefully, this work can be useful to the academic researchers, as well as the game players in the industry of this field.

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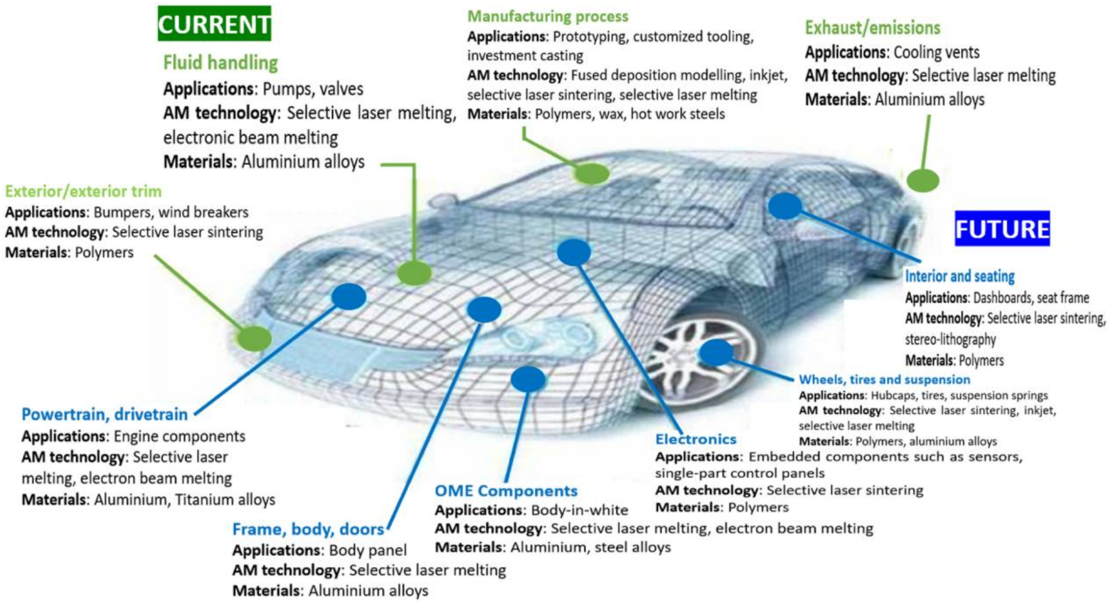

Figure 1. Current application of AM in automobile industry and future prospects [33].

2. Additive Manufacturing Techniques Used in Automobile Industry

According to the standard terminology of ASTM F2792-12a, AM used in automobile industry can be categorized into seven types: 1) material extrusion; 2) vat photopolymerization; 3) binder jetting; 4) material jetting; 5) powder bed fusion; 6) sheet lamination and 7) directed energy deposition. Table 1 summarizes the different types of AM processes and highlights the advantages and disadvantages for using in automobile industry.

Table 1. Different types of AM processes for using in automobile industry [34].

Categories	Technologies	Power Source	Materials	Advantages	Disadvantages
Material extrusion	Fused deposition modeling	Thermal energy	Thermoplastics (ABS, PLA, PC, nylon)	Inexpensive, multimaterial, easy to operate	Poor resolution and surface finish, poor bonding
Vat photopolymerization	Stereolithography, digital light processing, continuous liquid interface production, daylight polymer printing	Ultraviolet light	Photosensitive resin, ceramics	High accuracy, good resolution, fully automation	Overcuring lengthy post-processing, single composition, high cost of materials
Binder jetting	Binder jetting	Binder/thermal energy	Polymer/ceramic/metal powder	Wide material selection,	Lengthy postprocessing, porosities within parts

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				relatively fast printing	
Material jetting	Drop on demand, PolyJet, nanoparticle jetting	Thermal energy	Photopolymer resins, metals, ceramics	High accuracy, smooth surface finish, multimaterial	Low mechanical strength
Powder bed fusion	Direct metal laser sintering, electron beam melting, selective laser melting, selective laser sintering	Laser, electron beam	Polymer/ ceramic/metal powder	High accuracy, high resolution, fully dense parts, high strength	Powder recycling, support structures, single material, residual stress
Sheet lamination	Laminated object manufacturing	Laser	Plastic/metal/ceramic foil	High surface finish	Material limitation
Directed energy deposition	Laser engineered net shaping, direct metal deposition, laser metal deposition, laser cladding, laser consolidation	Laser	Metal/ceramic/powder	Repair of worn components, multimaterial (functionally graded materials)	Low accuracy, low surface finish, residual stress, require postmachining

2.1. Material Extrusion

As a widely used printing process based on thermoplastic polymer materials, material extrusion realizes the fabrication of polymer filament by continuously feeding materials into the printing area through extruding nozzles where it would be heated and then deposited onto the substrate layer by layer [35,36]. The most widely used material extrusion technique is fused deposition modeling (FDM). As shown in Figure 2, the thermoplastic filament is driven by a stepper motor towards the extrusion head, where high temperature would melt and fuse the filament, and the material would be extruded out of the nozzle to make a pre-defined section layer. Additional layers would then be deposited on top of the previous ones to make the final 3D products. Owing to the merits of abundant of available materials, low maintenance costs, good production efficiency, easy material change, low operation temperature, etc., FDM is widely applicated for fabricating automobile components.

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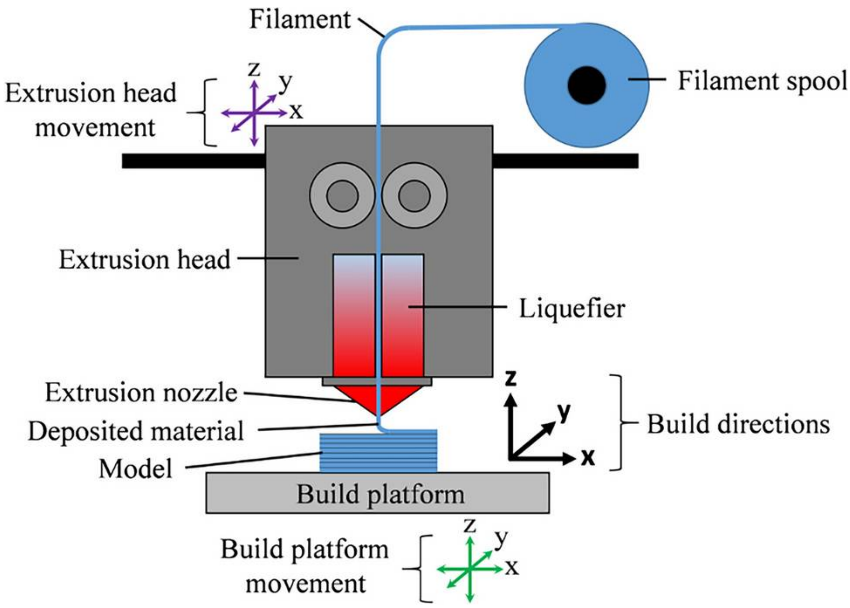

Figure 2. Schematic diagram of the FDM printing process [37].

In 2010, Ryan et al. designed and manufactured an intake system for a 600cc Formula Society of Automotive Engineers engine. In this work, FDM was used to create an intake system which consists a plenum, plenum elbow and cylinder runners, as shown in Figure 3. FDM allows for the geometric design freedom, which could create a unique intake geometry featuring tapered plenum and tapered runners, generating reduced weight (22% decrease) for the system and enhanced performance. Then in 2020, Sakthivel et al. optimized the process parameters of FDM used for manufacturing automotive components using Grey based Taguchi and TOPSIS methods. The results can advance the FDM manufacturing of automotive parts with extreme quality and less wastage. Other automobile components, such as bumper and pillar trim, have also been demonstrated using FDM process [40,41]. Recently, the usage of FDM in manufacturing unmanned aerial vehicles has drawn great attention [42]. FDM emerges as a robust technology to provide good opportunities for fabricating compact, strong, lightweight functional parts.

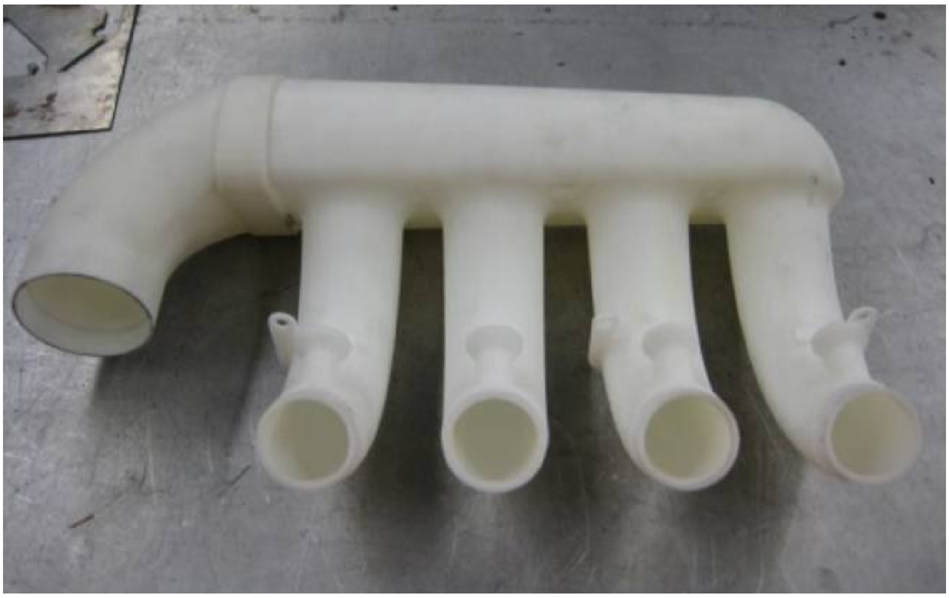

Figure 3. Assembly of the 3D printed intake manifold [38].

2.2. Vat Photopolymerization

Vat photopolymerization is a liquid-based 3D printing process based on photopolymerization which selectively cures the photosensitive resin using source like UV light in a layer-by-layer manner.

Based on the difference in light source and printing setup, vat photopolymerization can be classified into stereolithography (SLA), digital light processing (DLP), continuous liquid interface production (CLIP) and daylight polymer printing (DPP) [43,44]. Take the SLA process as an example, the focused laser beam is guided by galvanometers to scan onto the liquid resin according to the predefined trace, which would then cure the resin into designed morphology, as shown in Figure 4. With the advantages of high accuracy, good resolution, fully automation, vat photopolymerization technique is also popular in application in automobile industry.

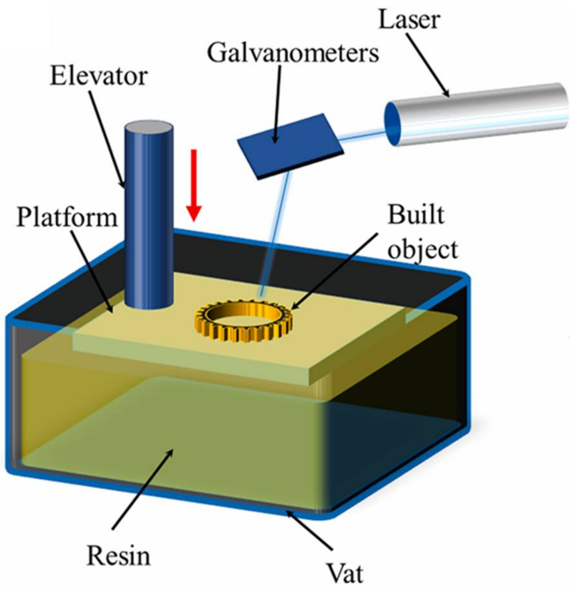

Figure 4. Schematic illustration of the traditional SLA process [45].

More and more car manufactures are making use of SLA 3D printing for rapid prototyping and final parts as well. Car companies such as BMW, Lamborghini and Jaguar Land Rover have all been involved into this new trend. For example, Great Wall Motors printed the front-left door panel and speaker mesh using a ProtoFab SLA600 machine with Formula W Resin [46]. Figure 5 shows the as-printed complex grill structure. DLP technique, based on the digital micromirror device to project full pixel-patterned light images of each layer at once, can provide fast printing speed with high resolution. Therefore, DLP process is more suitable for printing large automobile parts. For example, Porsche used DLP process to produce a new type of bucket seat. McLaren applied DLP to produce titanium wheels with incredible strength. Bugatti used DLP to manufacture its brake calipers [47]. The CLIP technology, as one type of DLP processes, could deliver much higher production speed combining with multiple programmable resins to form functional end-use parts in automobile such as personalized side scuttles, brake bracket, air duct split, and fuel tank cap [48].

Figure 5. A complex grill structure manufactured by the SLA technique [46].

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2.3. Material Jetting

In material jetting (MJ), the liquid materials are delivered into the extruder from which the liquid is sprayed to form numerous tiny droplets. After being exposed to light, the droplets would be solidified [49–51], as shown in Figure 6. Several techniques including drop-on-demand, PolyJet, and nanoparticle jetting belong to the material jetting technique. Material jetting has the advantages of high accuracy, smooth surface finish. Since it allows different materials to be jetted within the same object, material jetting is often used for the scenario with the request of multilaterals or gradient functional materials. Lots of applications in automobile industry have also been demonstrated using this technique.

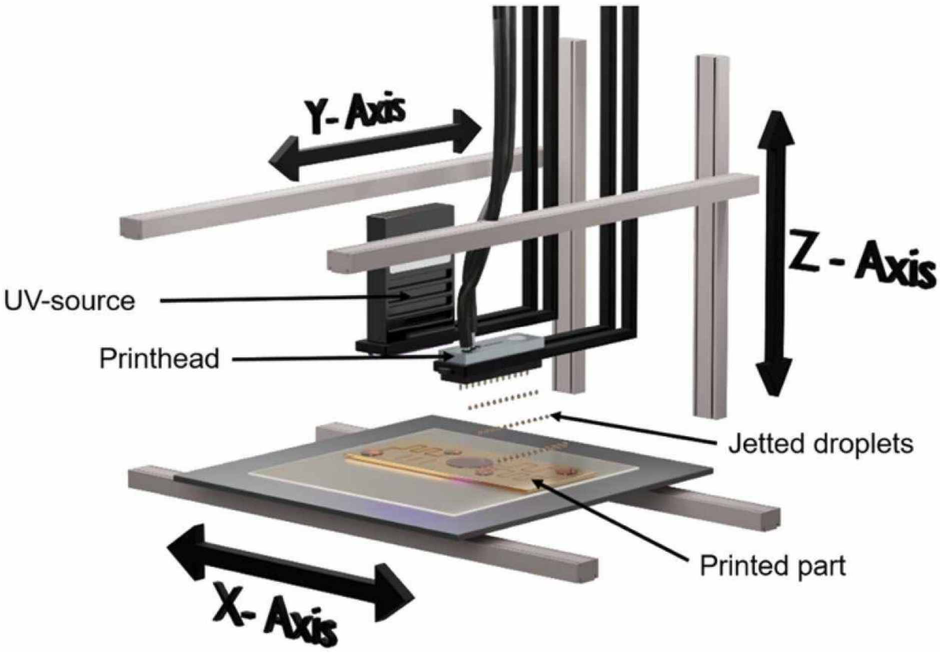

Figure 6. Schematic of the material jetting process [51].

Maurya et al. compared MJ technique with FDM in terms of form error, surface roughness, dimensional accuracy, tolerance grade and cost by taking the engine connecting rod of the car as a research object. They concluded that the MJ printed parts present lower average percentage error in circular dimensions, as well as lower form error and lower surface roughness, while higher cost when compared to FDM technique. Wang et al. [53,54] produced an automobile component with a height of 70 mm by using the PolyJet technique, and used a finite element model to simulate this manufacturing process. Figure 7 depicts the prototype of an additive manufactured jounce bumper compared to the traditional one.

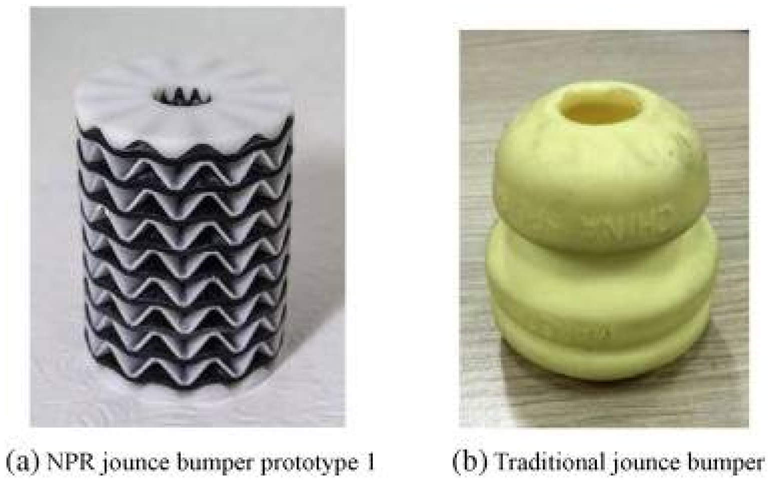

Figure 7. (a) Additive manufactured jounce bumper prototype and the traditional bumper [53].

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2.4. Binder Jetting

For the binder jetting process, powder is first sprayed onto the build table by a roller. After then, the liquid binder is injected from the print head and selectively deposited onto the powder sites to bind the powder together [55,56]. Therefore, the difference between the material jetting is that binder jetting process injects the auxiliary adhesive binder rather than the as-printed host material. After the manufacturing of the green part, sintering process in a furnace would be used to burned out the binder material. This two-step process is illustrated in Figure 8. Compared with other metal AM process such as DED, binder jetting process has wider material selection, and doesn't rely on the heating energy for printing the green parts, which would minimize the detrimental residual stress in the objects.

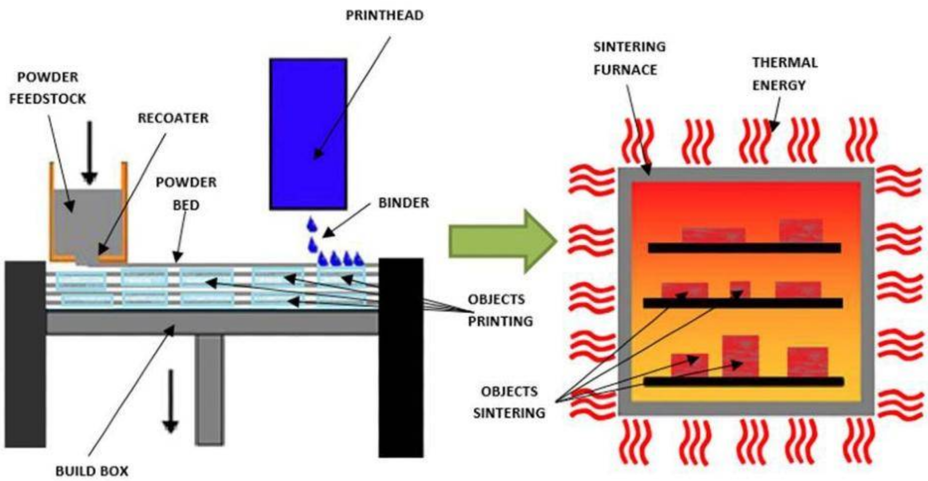

Figure 8. Two-step process of binder jetting [57].

Markus et al. discussed the process chains of using powder-bed-based metal AM in automobile industry, and compared the binder jetting process with selective laser melting for using in automotive production. The individual process procedures and the related properties were discussed based on evaluation criteria to support the determine of the optimized process chain in automobile industry. Amy et al. developed a binder jetting process to rapidly manufacture moderately sized injection molding tools for automotive lamps. Metal powders were used as the source material, and the influence of finishing process on the performance of the printed mold was discussed. Cooperating with ExOne, Ford developed the binder jetting technology for printing aluminum 6061 automobile components. The printed parts can achieve a density of 99% and great mechanical properties as well [60]. Solgang et al. discussed the influence of different sintering agents for binder jetting of aluminum alloy in the applications of automobile components. Figure 9 shows the ICC radar mounting brackets manufactured by a binder jetting process.

Figure 9. Binder jetting printed ICC radar mounting brackets [62].

2.5. Powder Bed Fusion

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Powder bed fusion (PBF), which includes direct metal laser sintering (DMLS), selective laser melting (SLM), selective laser sintering (SLS), and electron beam melting (EBM), relies on high energy source (laser source or electron beam source) to directly and selectively sinter or melt powder materials layer by layer to generate a solid part [63,64], while the unused feedstock could reused, making it be a cost-effective technique, as shown in Figure 10. For laser-based PBF process, an inert atmosphere such as argon or helium would be adopted to prevent the material oxidation. While for electron beam-based PBF process, the vacuum atmosphere is generally used. Owing to the merits of high accuracy, high resolution, fully dense parts, and high strength, PBF printing process has more applications in automobile industry.

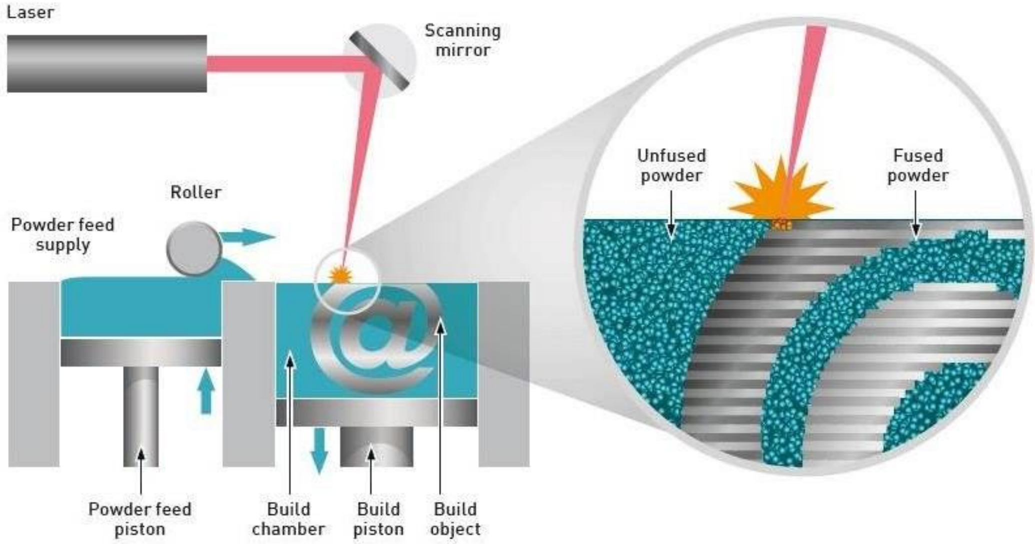

Figure 10. Schematic illustration of the laser-based PBF process [65].

Morteza et al. revealed the applications of PBF technique in tool and die making in automotive industry. AISI H 13 tool steel was chose as the research object. They focused on the method around eradication of cracks, building the process-structure-property relationship, understanding the residual stresses, developing functionally graded materials, which could provide important information for the application of PBF technique in automobile industry. Jorge et al. tested the mechanical and electrical insulation of the specimens manufactured by SLS and HP-Multi Jet Fusion process in three building orientations and compared to the specimens generated by injection molding. The applications of the PBF techniques in high voltage electric vehicle applications were evaluated. Figure 11 shows some products manufactured by PBF technique for automobile industry [68]. It was claimed that PBF could help reduce 80% of the manufacturing time for some industries when compared to traditional manufacturing techniques.

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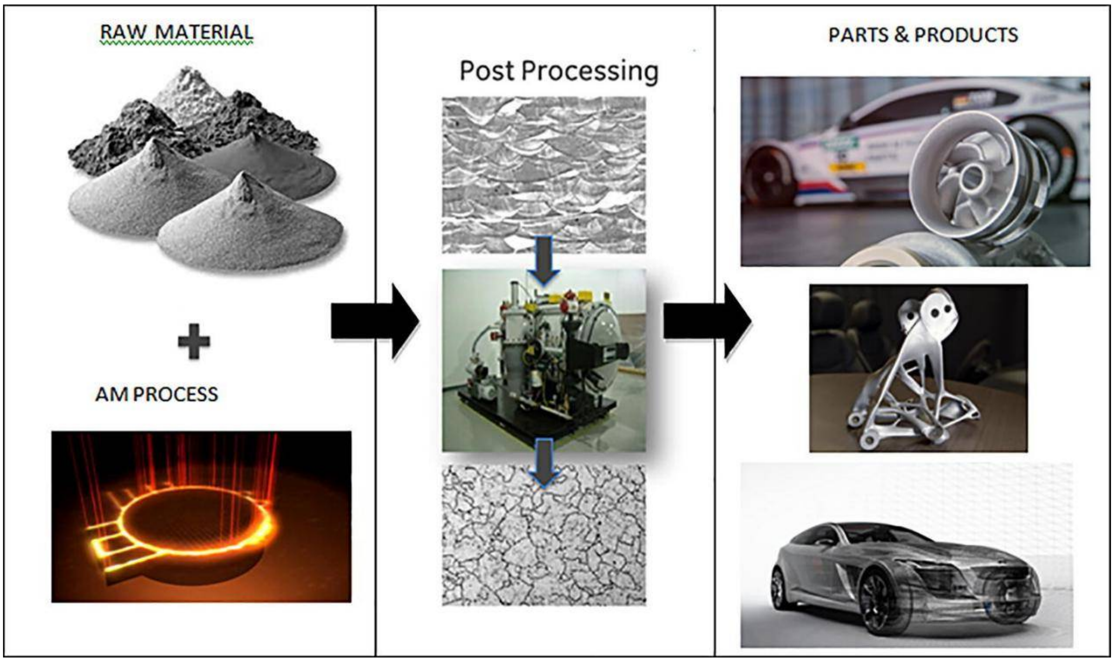

Figure 11. Processing map for the application of PBF technique in automobile industry [68].

2.6. Sheet Lamination

Sheet lamination, also known as laminated object manufacturing (LOM), uses thin foil as the raw material. The sheets of materials, including adhesive-coated paper, plastic, and metal laminates, are selectively cut into desired shape using a knife or laser energy, and then glued together by a compression roller layer by layer [69–71], as shown in Figure 12(a). LOM can produce objects of different sizes, shapes and colors in a relatively cheap and fast way.

Because the main printed material is paper and plastic, LOM has less been demonstrated in the applications of automobile industry except for some conceptual models [72], as shown in Figure 12(b). The recent development in high performance ABS/TPU multimaterial and ceramic-based materials has brought more potential for the application of LOM process in automobile industry [73,74].

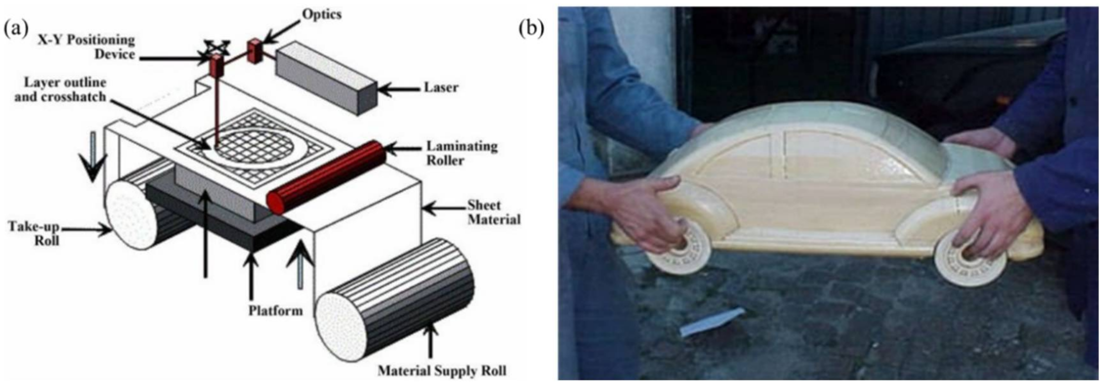

Figure 12. Schematic illustration of LOM process [75], and the printed automobile model [72].

2.7. Directed Energy Deposition

Directed energy deposition (DED) is a powder-based AM technique typically used to directly melt the metal particles using a laser system and deposit them onto a metal substrate layer by layer [76–78]. Many AM processes, including laser engineered net shaping, laser metal deposition, direct metal deposition, laser deposition welding can be classified into the category of DED. Similar to PBF process, spherical powder is used as the material source. While for the PBF process, powder is sprayed onto the platform before the printing, different from the DED process for which metal powders are injected into the molten pool through nozzles simultaneously with the emission of laser

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energy. This feature enables DED process the ability for repairing of worn components [79], and manufacturing of functionally graded materials [80]. Figure 13 gives the schematic diagram of DED process. Many applications of the DED process in the automobile industry have been demonstrated because of the unique feature.

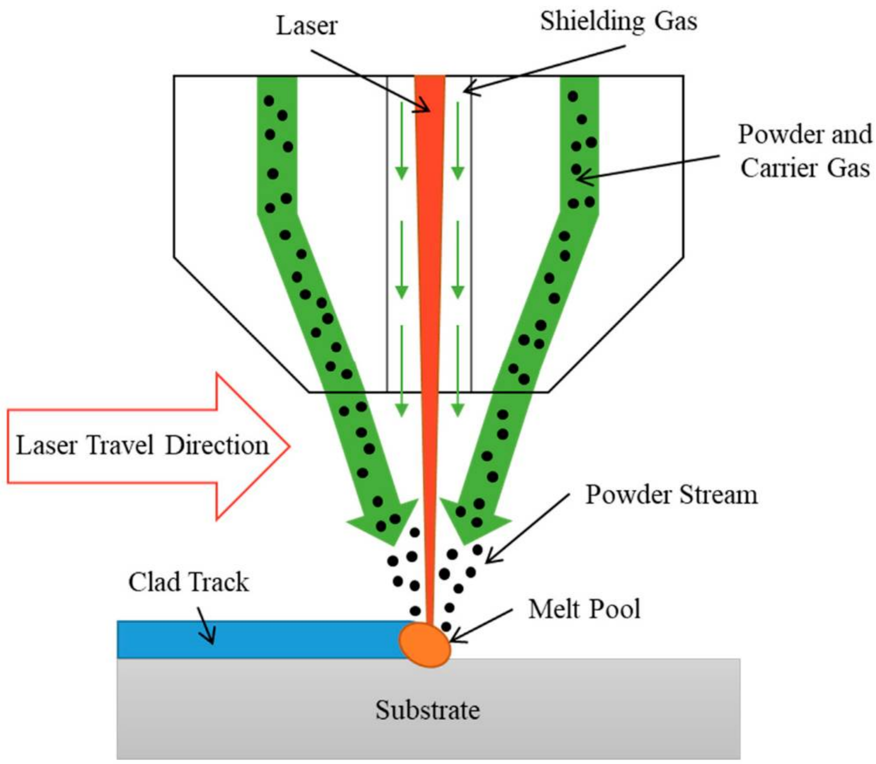

Figure 13. Schematic diagram of the DED process [81].

Jennifer et al. used the DED technique to repair the automotive dies and evaluated the performance of the repaired dies regarding life cycle analyses and environmental impacts. They concluded that the DED repair process could significantly reduce the damage from the environmental impacts when compared to the traditional welding repair. Later on, Nitul et al. demonstrated that by using a DED technique, the repair of crankshafts and pistons, gears and pinions, engine turbocharger blades, drive axles of dumpers, hydraulic distribution valves can be easily realized. The ability to manufacture functional gradient materials also provides great potential for the application in automobile industry [84]. Moreover, DED process can also be used in the surface treatment which is important in some core automobile parts. For example, Diana et al. employed the DED technique to clad the surface of gray cast iron brake discs with Inconel 718 alloy, as shown in Figure 14. After cladding process, the mechanical properties, hardness, anti-friction performance, and corrosion resistance of the brake discs was demonstrated with great improvement.

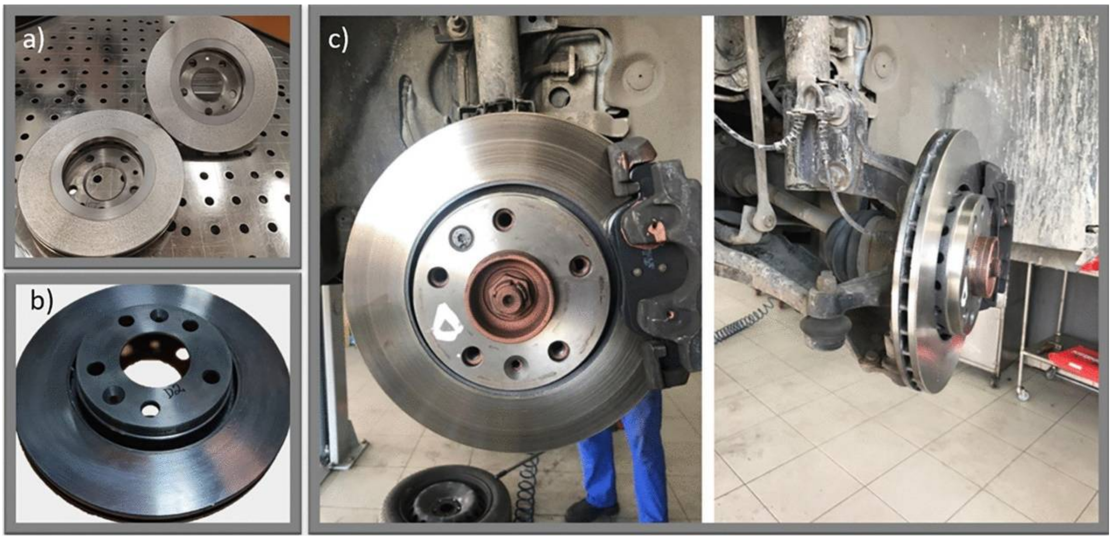

Figure 14. (a) Coating the brake discs with IN718 using DED process. (b) Final product. (c) Functionally tested on a car service unit [85].

Table 2 summaries the AM techniques used in different automobile companies, from which it can be seen that all the major automobile companies are integrating AM into their production line to increase the innovation and competitiveness.

Table 2. The AM techniques used in different automobile companies [86].

Company	AM processes
BMW	Fused Deposition Modeling (FDM) (Davies, 2023)
	Selective Laser Sintering (SLS) (Ricoh 3D, 2020)
	Multi Jet Fusion (BMW Group, 2020)
	Laser Beam Melting (BMW Group, 2020)
Audi	Selective Laser Melting (SLM) (Petch, 2018)
	Stereolithography (SLA) (Krassenstein, 2015)
	Fused Deposition Modeling (FDM) (Krassenstein, 2015)
	Multi Jet Fusion (MJF) (Krassenstein, 2015)
Toyota	Selective Laser Sintering (SLS) (SAE International, 2021)
	Fused Deposition Modeling (FDM) (SAE International, 2021)
	Stereolithography (SLA) (SAE International, 2021)
	Multi Jet Modeling (MJM) (SAE International, 2021)
	Digital Light Processing (DLP) (SAE International, 2021)
Honda	Liquid Deposition Modeling (LDM) (Everett, 2021)
Ford	Selective Laser Sintering (SLS) (Ford Motor Company, n.d.)
	Stereolithography (SLA) (Ford Motor Company, n.d.)
	Fused Deposition Modeling (FDM) (Cune, 2018)
	Metal Binder Jet Printing (Molitch-Hou, 2021)
Volvo	Selective Laser Sintering (SLS) (Volvo Group, 2019)
	Fused Deposition Modeling (FDM) (Pearson, 2020)
Rolls-Royce	Electron Beam Melting (EBM) (Molitch-Hou, 2015)
	Selective Laser Melting (SLM) (Tyrrell, 2022)

	Direct Energy Deposition (DED) (Kingsbury, 2019)
Chevrolet	Selective Lase Sintering (SLS) (General Motors, 2020)
	Selective Laser Melting (SLM) (General Motors, 2020)
	Fused Deposition Modeling (FDM) (General Motors, 2020)
Nissan	Selective Lase Sintering (SLS) (General Motors, 2020)
	Selective Laser Melting (SLM) (General Motors, 2020)
	Fused Deposition Modeling (FDM) (General Motors, 2020)
Tesla	Sand Binder Jetting (Madeleine P., 2023)
	Fused Deposition Modeling (FDM) (3D printing.com, 2020)
Mercedes-Benz	Selective Laser Melting (SLM)(Additive News, 2017; Moore, 2020)
	Fused Deposition Modeling (FDM)(Moore, 2020)
	Stereolithography (SLA)(Moore, 2020)
	Selective Laser Melting (SLM) (Moore, 2020)
Volkswagen	Binder Jetting (Volkswagen AG, 2021)
	Fused Deposition Modeling (FDM) (Jackson, 2017)

3. Printable Materials for Automobile AM Applications

To achieve the application potential of AM technology in automobile industry, the core aspect is the development of diverse printable materials. From the thermoplastics, metals to advanced composites, the types of materials applicable in AM of automobile parts continue to expand [87]. The following section summaries some of the key materials utilized in the applications of AM automobile components.

3.1. Polymer Additive Manufacturing

Polymers are generally recognized as the primary and most commonly used materials for additive manufacturing. Polymers can address some limitations such as mechanical and thermal, electrical properties associated with 3D printing in automotive applications [88]. The versatile nature of polymer materials makes it popular in the automobile industry, and the functionalization potential to generate polymer composites further improves the mechanical performance, biodegradability during the automobile packaging and operation [89]. Figure 15 shows some of the automobile components manufactured with polymer/polymer composites [90].

Among the AM techniques described above, SLA, SLS, FDM, LOM and inkjet printing technologies are most often used for creating polymer composite components in automobile applications [91]. Based on the methods being used, different polymer materials are adopted in AM process. For example, the commonly used thermoplastics polymer materials applied in AM process include acrylonitrile butadiene styrene (ABS) [92], polylactic acid (PLA) [93], polyvinylalcohol (PVA) [94], thermoplastic polyurethane (TPU) [95], nylon, polyamides (PIs) [96], and polycarbonates (PCs) [97], etc. Table 3 lists the different polymer composites used in the AM application of automobile industry [29].

Based on the various polymer materials and the associated AM techniques, some application examples in automobile industry were realized. Such as the producing of three-dimensional bellows using inkjet [98], SLS manufacturing of three-dimensional complex functional ducting [99], the manufacturing of a full-coloured visual prototype for the centre console of automobile [99], and the printing of functional alternator bracket using SLS nylon [99].

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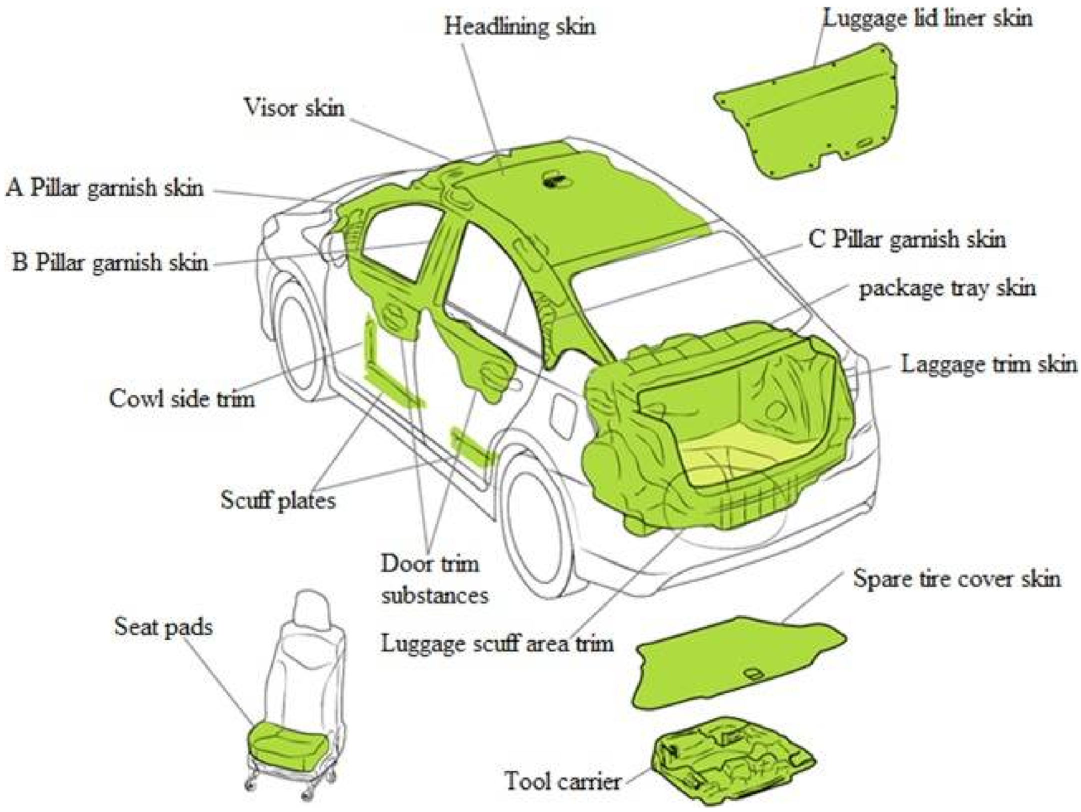
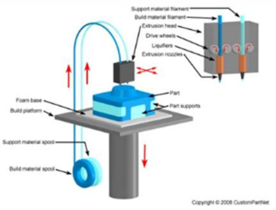
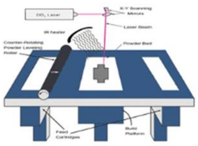
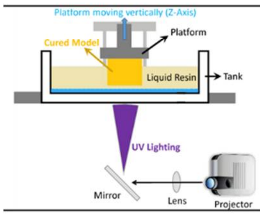
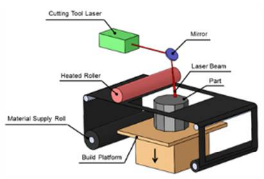
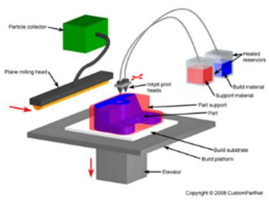


Figure 15. Some of the automobile components manufactured with polymer/polymer composites [90].

Table 3. Description of the different polymer composites used in the AM of automobile industry [29].

Schematics of techniques	Polymer matrix	Fillers	Applications
	Fused Deposition Modelling (FDM)		
	Thermoset (EVA)	Graphite	Electrical
	Thermoplastic (PLA)	Bronze	Structural
	Thermoplastic (ABS)	Iron/Copper	Thermal
	Thermoplastic (ABS)	Carbon fibre	Load bearing
	Thermoplastic (ABS)	Graphene	Structural and thermal
	Thermoplastic (PLA)	Graphite	Electrical and thermal
	Thermoplastic (ABS)	Multiwall carbon-nanotube	Structural and thermal
	Thermoplastic (PPR)	Graphene oxide	Electrical
	Thermoplastic (PLA)	Montmorillonite	Electrical
	Selective Laser Sintering (SLS)		
	Thermoplastic (PA-11)	Silica	Mechanical
	Thermoplastic (PA-12)	Carbon fibre	Mechanical
		Carbon black	Mechanical
		Carbon nanofibre	Mechanical
	Stereolithography (SLA)		
	Thermoset (Polyramic (SPR-212))	SiOC and SiC	Mechanical
	Thermoplastic(PMMA)	Urea, ammonium chloride and resorcinol	Smart Materials
	Thermoset (Envision-TEC)	Graphene	Electrical
	Laminated Object Manufacturing (LOM)		
	Thermoset (PI film)	Graphene	Energy and electronics
	Inkjet Printing		
	Thermoset (PVA)	CdTe nanocrystals	Electrical
	Thermoset (Poly-iso-butylene)	Quantum dots	Electrical
	Thermoset (Polyacrlate)	Alumina nanoparticles	Mechanical
	Thermoset (Poly(2-methoxyaniline-5-sulfonic acid))	Single wall carbon nanotubes	Electrical
	Thermoset (Polyaniline)	Graphene	Electrical

3.2. Metal Additive Manufacturing

Metal AM process has gained significant attention across various industries including automobile owing to the numerous advantages like the outstanding mechanical strength, great thermal conductivity and heat resistance of the printed parts [100–103]. The most often used metal materials in AM processing include steels, titanium alloys, aluminum alloys, nickel-based alloys, and cobalt-based alloys [104]. Based on the difference in feedstock and thermal source, common metal AM processes include material extrusion, VAT photopolymerization, lamination, material/binder jetting, powder bed fusion and direct energy deposition, among which the powder bed fusion and direct energy deposition processes dominate the automobile market [30]. The advances in metal AM has enabled the ability to produce the automobile components with more flexible, customized, and

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topologically optimized design (Figure 16 shows the topology optimization workflow of the mounting bracket for intelligent cruise control radar sensor); lightweight, stronger, and safer products; and reduced lead time and cost [105,106]. As a result, many automobile companies are engaging in metal AM for their products.

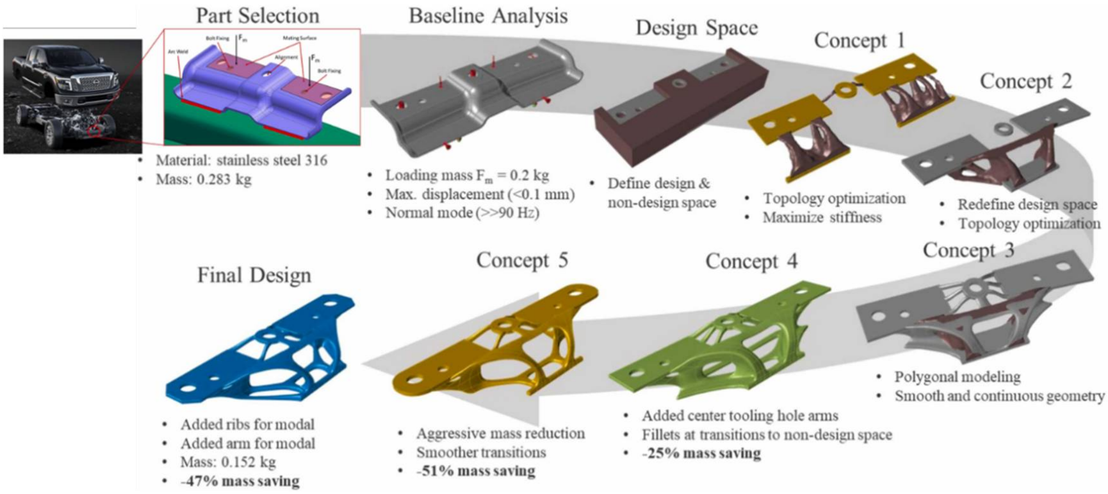

Figure 16. Topology optimization workflow of the mounting bracket [19].

For example, Formula Student Germany 2012 applied EOS DMLS technique to fabricate a light-weighted upright, which could reduce the mass by 35% when compared to the traditional cast-manufactured parts [107]. BMW group manufactured a window guide rail in the i8 Roadster employing the multi jetting fusion metal printing process. 100 rails can be finished in 24 h. Another component, a fixture for the soft-top attachment, was also printed, which could achieve a weight reduction by 44% and stiffness increase by 10 times. The innovation in engine manufacturing has also been achieved by using PBF metal AM process [108–110]. In 2018, Bugatti produced a Ti6Al4V brake caliper for future car models using SLM printing method. Being one of the largest calipers in the world, the as-manufactured caliper can reach a tensile strength of 1225 MPa, with a weight reduction of 40% [111]. Combining with topology optimization, Bugatti Chiron also manufactured the optimized bracket with integrated water cooling circuits [111]. Audi is also collaborating with SLM Solution to manufacture customized products and spare parts such as the water adapter for the Audi W 12 engine [112]. Figure 17 depicts some of the automobile components manufactured by metal AM process, which clearly indicate the high quality and complexity.

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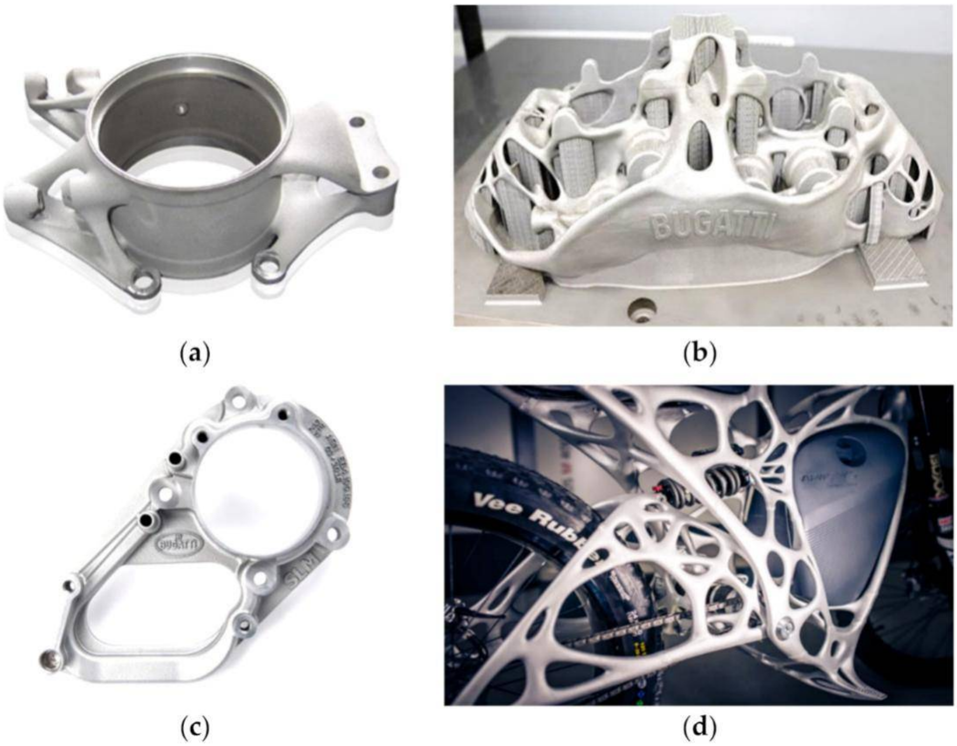

Figure 17. Some of the automobile components manufactured by metal AM process. (a) Steering knuckle. (b) Brake caliper. (c) Topology optimized bracket. (d) Aluminum lightweight structure [102].

3.3. Ceramic Additive Manufacturing

Ceramic materials present special features such as high hardness, heat resistance, wear and corrosion resistance, which make them suitable for high-temperature applications and electrical insulating components of automobile industry [113,114]. The ceramic composites, which combining the ceramic matrix with different additives [115], can endow the materials with more outstanding physical, chemical and mechanical properties for using in automobile parts. While the intrinsic nature of brittleness and high melting point limit the applicable AM processes for printing the ceramics-based products. Currently, the ceramics are incorporated into AM techniques through different forms of feedstocks like slurry-based, powder-based and bulk solid-based [116,117]. For the slurry-based process, liquid solution would be used and fine ceramic particles are dispersed. And for powder-based process, the solid loose ceramic particles are mixed with additives as the feedstock. For the solid-based process, it is inspired from the LOM process, and tapecast alumina, zirconia green sheets, silicon carbide, silicon-silicon carbide composites are used as the feedstock.

For the usage of ceramics in 3D printing for automobile industry, Steinbach AG claimed that they used lithography based ceramic manufacturing (LCM) to produce a variety of heat-resistance components based on ceramic materials. The components in engine compartment such as valves and fuel pumps exhibit lower noise level, higher efficiency and less abrasion [118]. They also revealed other 3D printed ceramics in the automobile applications including: slide rings, storage, sealings, constituents of vent valves, components for fuel pumps, constituents of exhaust gas flaps, plain bearings, components for rolling bearings, shafts, supporting bodies in the crankcase, components for water pumps, constituents for valves, components for analyses in research laboratories, sensors. Figure 18 shows one of the 3D printed ceramic automobile components.

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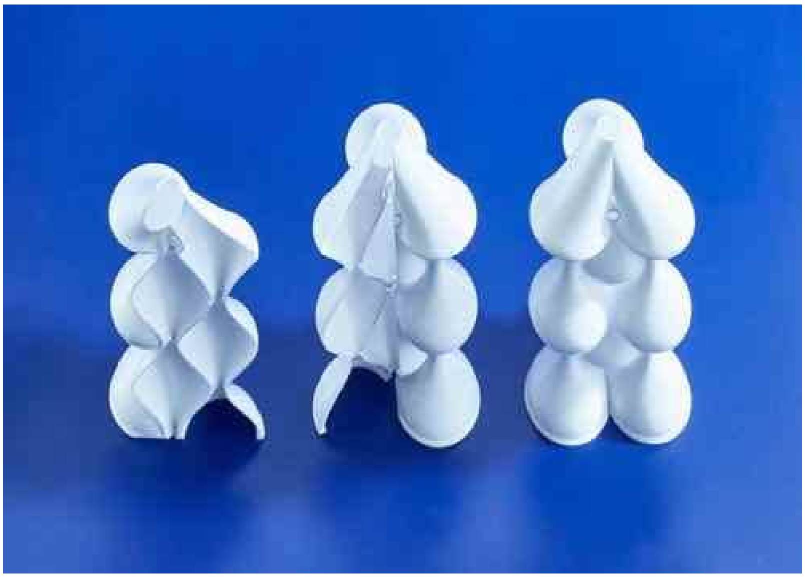

Figure 18. 3D printed ceramic automobile component [118].

Table 4 presents a summary of various printable materials used in the AM of automobile industry, with an emphasis on the advantages and disadvantages. It can be seen that each material has its own merits for a specific application regarding the required performance and working condition.

Table 4. Summary of the materials used in the AM of automobile industry [119].

Materials	Automobile application	Advantages	Disadvantages
Polymers	- Rapid tooling and fixture production - Functional prototypes and testing parts - Customized automotive Parts - Composite materials with polymers	- Low cost and ease of processing - Lightweight, suitable for interior components - Excellent design flexibility and complexity - Good impact resistance and vibration damping	- Limited mechanical strength and load-bearing capacity - Limited thermal stability and chemical resistance - Limited dimensional accuracy and potential for warping or distortion during printing - Limited recyclability and environmental concerns
Metals	- Engine parts and components - Transmission components and gears - Suspension systems and chassis components	- High strength-to-weight ratio - Excellent mechanical properties - High thermal conductivity	- High material and processing costs - Limited design complexity and intricate features - Limited availability of AM-grade materials for

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	- Exhaust systems and engine components - Braking components and systems	- Good wear resistance and fatigue resistance - High resistance to extreme temperatures and harsh environments	high-performance applications - Potential for microstructural defects in printed parts - Post-processing may be required to achieve desired mechanical properties
Ceramics	- High-performance brake components - Engine components and exhaust systems - Bearings and wear resistant components - Spark plugs and ignition systems - Electrical insulators and components - Sensors and electronic components	- High-temperature resistance and thermal stability - Excellent mechanical properties - Low density, lightweight - Good chemical inertness and resistance to corrosion	- Limited design complexity - High processing temperatures required for sintering - Cost and availability of specialized ceramic powders - Challenging to achieve dense and void-free prints due to high processing temperatures

4. Challenges and the Future Opportunities

AM technologies have the potential to revolutionize design capabilities and manufacturing processes in automobile industry. There are a number of advantages of AM process due to the inherent nature. However, the acceptance of AM as the mainstream production technology to replace traditional manufacturing technique is still debatable owing to the obvious drawbacks and challenges.

The first challenge is the material limitation. Even though each AM technique has its own material system, and there has been significant process in developing printable materials, many AM applications are still restricted by the available materials. For automobile industry, specific properties such as the temperature-controlled behavior with reduced cost are often expected [120,121], while the current material database can hardly meet the requirement. Therefore, the developing of high-quality printable materials with more functions would provide many opportunities in the AM of automobile industry.

Second, the control of product quality. Although AM process can sometimes achieve good product quality such as high mechanical strength and good surface finish, defects such as voids, porosity, cracks commonly exist for the AMed products [122,123], which would largely weaken the application properties. For the AM process involving with heat history, the uneven temperature field would induce residual stress and distortion [124], which are harmful for the actual automobile applications. Besides, as a layer-by-layer process, AM products would generally face the problem of anisotropy and heterogeneity, both in microstructure and macro performance [125]. Anyway, how to control the manufacturing process to get the products with desired quality is a big challenge for the AM application in automobile industry, while on the other hand, provides vast opportunities.

Third, the requirement of excessive post-processing. The as-printed products generally need time-consuming and costly post-processing such as smoothing surfaces, removing support structures, finishing details, releasing residual stress by heat treatment, etc., to meet the application

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standards [126,127]. Even for some scenarios, the post processing procedure is impossible to conduct, which would restrict the application of AM process. Developing of a technology reducing the amount of post-processing is highly expected.

Forth, improvement of the product volume. As the product is built layer by layer, it takes a long time for fabricating any object, which would ultimately lead to low product volume [128]. For traditional methods, the mature product line allows thousands of components to be fabricated in a short time. While for AM process, the merit in generating customized products does not apply to the large volume of production. Developing of the ways to increase the manufacturing speed, and expand the production efficiency by lowering the machine price would be helpful, still more research efforts are expected to improve the product volume.

Lastly, the lack of standards. For the application of AM in automobile industry, standardized processes and materials are required [129]. The lack of universe standards could impede the interoperability between different 3D printers and software, making it difficult to achieve the same performance even under identical process parameters. Therefore, a large amount of efforts would be waste to repeatedly validate the quality of the products. Universally accepted standards in AM techniques, materials, 3D printers and software are extremely significant for the applications of AM techniques in automobile industry.

Undoubtedly, there are some other challenges needed to be overcome for AM in automobile industry. With the rapid development in technology and the increased attention in environment crisis, other research opportunities include multi-material printing, large-scale AM, sustainability and recycling in AM, automation and AI integration would also arise great interest in the following years [130,131].

5. Conclusions

In conclusion, the automotive market is in the midst of a transformative journey. Additive manufacturing could bring in new blood to the automobile space owing to the abilities in design flexibility, rapid prototyping, waste reduction and lightweight production, which give the ability acting as a game-changer in automobile industry. Therefore, automakers worldwide are increasingly investing in AM technique and making use of this technology in their design interactions, tooling and end-use component production.

This work reviewed the recent advances in the application of AM technology in automobile, focusing on the most important aspects, i.e., the applicable AM techniques, and the printable materials. With the advantages and disadvantages being compared, we hope more progress in developing new AM techniques and associated materials would be stimulated. Current challenges including the material limitation, the inferior product quality, excessive post-processing, small product volume, and lack of standards are outlooked for extensively incorporating AM into automobile production line.

The automobile industry is shifting towards sustainable and green solutions by advancing in the battery system and the associate electrical cars [132]. Therefore, more opportunities would be exposed for the AM researchers regarding this new trend. With ongoing R&D, AM techniques are poised to complement traditional automobile manufacturing in the coming future.

Data Availability: The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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Competing Interests: The authors declare that there are no competing interests.

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