MULTIDISCIPLINARY SCIENTIFIC RESEARCH

BJMSR VOL 8 NO 1 (2023) P-ISSN 2687-850X E-ISSN 2687-8518

Available online at https://www.cribfb.com
Journal homepage: https://www.cribfb.com/journal/index.php/BJMSR
Published by CRIBFB, USA

USAGE OF ADDITIVE MANUFACTURING IN THE AUTOMOTIVE INDUSTRY: A REVIEW

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ARTICLE INFO

Article History:

Received: 18th August 2023
Revised: 26th November 2023
Accepted: 2nd December 2023
Published: 7th December 2023

Keywords:

Additive Manufacturing, Automotive Industry, 3D Printing, Metal Additive Manufacturing, Automobile.

JEL Classification Codes:

Y90

ABSTRACT

Additive manufacturing (AM), commonly known as 3D printing, is an emerging technology with immense potential across various industries, particularly in the automotive sector. It involves the layer-by-layer fabrication of parts by gradually depositing material, distinguishing itself from traditional manufacturing through various ways, including design flexibility, reduced material wastage, shorter lead time, and the absence of tooling requirements. It is still in its nascent phase, and several drawbacks, such as a lack of mechanical strength, limited material availability, and poor surface finish, still hinder its integration into the mainstream production workflow. As a result, further exploration is required to harness its potential along with traditional methods. The automotive sector is long known for its adoption of cutting-edge technologies. Due to the vast potential of AM, the automotive industry is actively trying to incorporate additive manufacturing into mainstream production processes. Consequently, the automotive industry continuously explores ways to enhance this process for seamless integration into product development. However, research elucidating different additive manufacturing processes used within the automotive industry, such as stereolithography (SLA), fused deposition modeling (FDM), and selective laser sintering (SLS), is limited. This paper aims to illuminate various additive manufacturing processes used by automotive companies worldwide. In addition to exploring different processes, the study delves into the advantages and limitations of additive manufacturing, contributing to a comprehensive understanding of its application in the automotive manufacturing landscape.

INTRODUCTION

Additive manufacturing (AM) is a relatively new technology that involves creating three-dimensional objects through the gradual deposition of material layer by layer. It is a straightforward process for creating intricate products from a CAD model using different types of 3D printers. AM differs from conventional manufacturing in several aspects, such as design flexibility, reduced material wastage, shorter lead time, reduced tooling requirement etc. Though initially embraced by hobbyists and researchers for making custom products, due to its immense potential, manufacturing industries are now seeking to harness its capabilities. It is thought to be a game-changer which may change the production process by replacing traditional manufacturing. However, AM is currently in its nascent phase, and its integration into the mainstream manufacturing process to replace traditional methods will require time. As a result, all the manufacturing industries, such as aerospace, automotive, consumer electronics, and healthcare, are exploring it. The automotive industry has a long history of adopting cutting-edge technologies to enhance vehicle design, production, and performance. AM offers a range of advantages, including rapid prototyping, design flexibility, and the capacity to produce complex, lightweight components. As a result, in recent times, all the major automotive companies have started using AM to some extent.

The field of manufacturing can be categorized into five fundamental processes: subtractive, additive, joining, dividing, and transformative (Abdulhameed et al., 2019). Subtractive manufacturing is the most common method, involving the removal of material to achieve the desired shape of the final product. Traditional manufacturing relies heavily on subtractive processes, such as machining with lathes or CNC machinery. With the advancements in computer numerical control technology, CNC has gained widespread adoption across all manufacturing industries. However, subtractive manufacturing suffers from significantly lower material efficiency when compared to additive manufacturing. Material efficiency directly impacts both the cost and energy consumption associated with the production process. Additive

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https://doi.org/10.46281/bjmsr.v8i1.2135

To cite this article: Nayeem, A. M., & Hossain, M. M. N. (2023). USAGE OF ADDITIVE MANUFACTURING IN THE AUTOMOTIVE INDUSTRY: A REVIEW. *Bangladesh Journal of Multidisciplinary Scientific Research*, *8*(1), 9-20. https://doi.org/10.46281/bjmsr.v8i1.2135

manufacturing offers a potential solution to improve material efficiency, thereby reducing energy consumption and costs. This enhancement of material efficiency can be quantified through a metric known as the "buy-to-fly ratio", which measures the ratio between the mass of the initial raw materials and the mass of the final product. In a specific case, it has been observed that the typical buy-to-fly ratio in traditional subtractive manufacturing is approximately 10:1(Kobryn et al., n.d.). This means that if the final product has a mass of 10 kilograms, the manufacturing process starts with a 100 kilogram material block. Consequently, a substantial portion of the material, 90 kilograms in this case, is discarded as waste, making it challenging to reuse directly. Furthermore, the energy consumed during the production process is higher due to the substantial waste percentage. So, the overall cost of manufacturing the product significantly increases when employing the traditional subtractive manufacturing approach.

Consideration is given to AM for its potential to reduce material waste and energy consumption while enabling the production of complex products. Its layer-by-layer gradual production process results in minimal waste. For complex designs, AM often requires support materials. Additionally, its buy-to-fly ratio is quite low, typically ranging from 1:1 to 3:1(Blakey-Milner et al., 2021). 3D printing is particularly valuable for creating complex products in small quantities, a process that typically involves extensive preparation, steps, and time in traditional manufacturing. As a result, it can significantly reduce lead times for both emergency and low-volume production. In the automotive industry, where product weight plays a crucial role in fuel efficiency, AM can produce lightweight parts without compromising desired properties. However, it's important to note that in most cases, the mechanical performance of 3D printed products still falls short of traditional manufacturing standards. Nonetheless, there is optimism that in the near future, AM may achieve mechanical properties similar to those of traditional processes, leading to more extensive use. Despite this potential, various regulatory bodies have not yet fully approved 3D printed parts for large scale production.

To comprehend the necessity of AM in the automotive industry, it is essential to analyze market trends. According to a recent study, the 3D printing market in the automotive sector is projected to reach a value of USD 9.7 billion by 2030 with a CAGR of 15.94% (Akre, 2023). The North American region is going to lead the 3D printing in automotive industry followed by Europe, Asia and other region. Over the past few years, research into 3D printing has experienced exponential growth, a trend expected to persist until the full potential of 3D printing is harnessed across various sectors. The advantages of 3D printing over traditional manufacturing methods, including cost-effectiveness, lead time reduction, the creation of lightweight complex parts, and the development of high-performance materials, collectively contribute to the expansion of AM in the automotive industry. Initially, AM was primarily employed for prototyping in the automotive sector, given its ability to swiftly produce accurate prototypes. However, automotive companies are progressively exploring the use of AM for manufacturing entire vehicles. Initially, polymers were the preferred materials for AM, but the use of metals, ceramics, and alloys has since gained traction (Herzog et al., 2016; Lakhdar et al., 2021).

Numerous research studies have already explored additive manufacturing processes within various industries. However, research addressing the AM processes within the automotive industry remains relatively limited. Approaches and procedures used in the automotive industry regarding AM are not well known, necessitating a comprehensive examination of status. This paper aims to comprehensively address various AM processes, advantages, and challenges utilized by automotive industry leaders. Initially, we will cover the fundamentals of the AM procedure. Then, we will focus on classifications of AM followed by a description of different processes such as SLA, FDM, SLS, etc. Finally, we will discuss AM trends in the automotive industry.

MATERIALS AND METHODS

This section will outline the typical additive manufacturing procedure, followed by categorizations. Subsequently, we will explore some commonly used processes and methods of AM implemented across different industries. This comprehensive overview aims to provide insights and understanding of the key AM processes.

Fundamentals of Additive Manufacturing

AM differs from traditional manufacturing processes, which often involve complex tooling and extensive preparation. In common machining operations such as turning, facing, drilling, and milling, material is gradually removed from the workpiece. For molding or casting, specific tools tailored to each product are necessary, rendering the development process complex, costly, and time-consuming. In contrast, the AM process is largely uniform across different products. By following a set of basic steps, AM can create complex parts by gradually depositing material. This stands in contrast to traditional processes, which tend to generate substantial material waste that requires extra effort to reuse. A typical AM process can be divided into four fundamental steps:

- CAD modeling of product
- Preprocessing
- 3D printing
- Post processing

The AM process begins with the modeling of the product in CAD. The current advancements in 3D printer technology are closely connected with CAD, CAM & CAE processes. Following the design and analysis of the product, the final CAD model undergoes a series of steps for 3D printing. This step is called preprocessing which includes creating STL file from the CAD model, fixing the STL file in case of any issue, adding support structure of the part to tackle overhanging geometry, and slicing the model into layer by layer. The STL format, a specialized file type, represents the shell of the product using triangular facet data. Each facet consists of a unit normal and three vertices which are specified by three coordinates each (Chen et al., 1999).

An STL file can be generated directly from all the common CAD packages such as Solidworks, CATIA, Creo or special extension can be used to convert to STL if required. Each CAD system has its own file format to represent parts, assemblies and drawings. However, for 3D printing, a uniform format is required to make manufacturing independent of CAD packages. As a result, most available 3D printers use STL file format for manufacturing. There are some other file formats available, but slicing STL format is easier comparing to other formats like B-rep, CSG (Liou, 2019). Though some resolution is lost due to the use of triangles, still most CAD systems support STL (Ahn et al., 2002).

STL file is then sliced into a series of 2D layers which is served as a tool path or path for layer-by-layer deposition of materials. User has the freedom of controlling slice number which ultimately control the layer thickness of part. Orientation of printing part is selected before slicing which helps the user optimize best possible way to print the part with least overhanging portion. Support structure is created for overhanging portion during slicing that ensures printing of whole part without failure. Slicing parameters has effect on the part strength, build time, wight & surface finish (Liou, 2019).

Finally, this sliced file is sent into the printer for 3D printing. All kinds of 3D printing technology automatically build the part according to the sliced file. Support is also created during printing, which is removed during post processing step. Depending on the printing technology, different materials are used. Some printers can create support using separate material, while most printers use same material for printing both part and support. After printing, the post-processing process includes removing support materials, cleaning, polishing etc. according to the design requirement. Overall AM process is outlined as below:

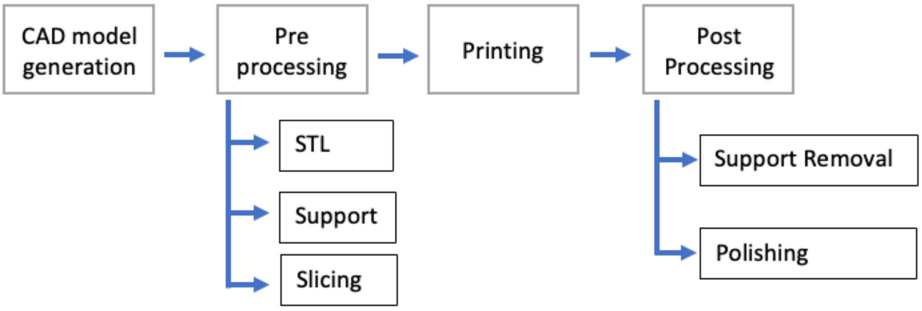

Figure 1. Typical Additive Manufacturing Process

Most Common Additive Manufacturing Processes

AM can be classified based on several aspects, but most popular classification is based on the state of printing material. Considering the state of material, it can be classified into three types. A classification tree of some common AM methods is given below:

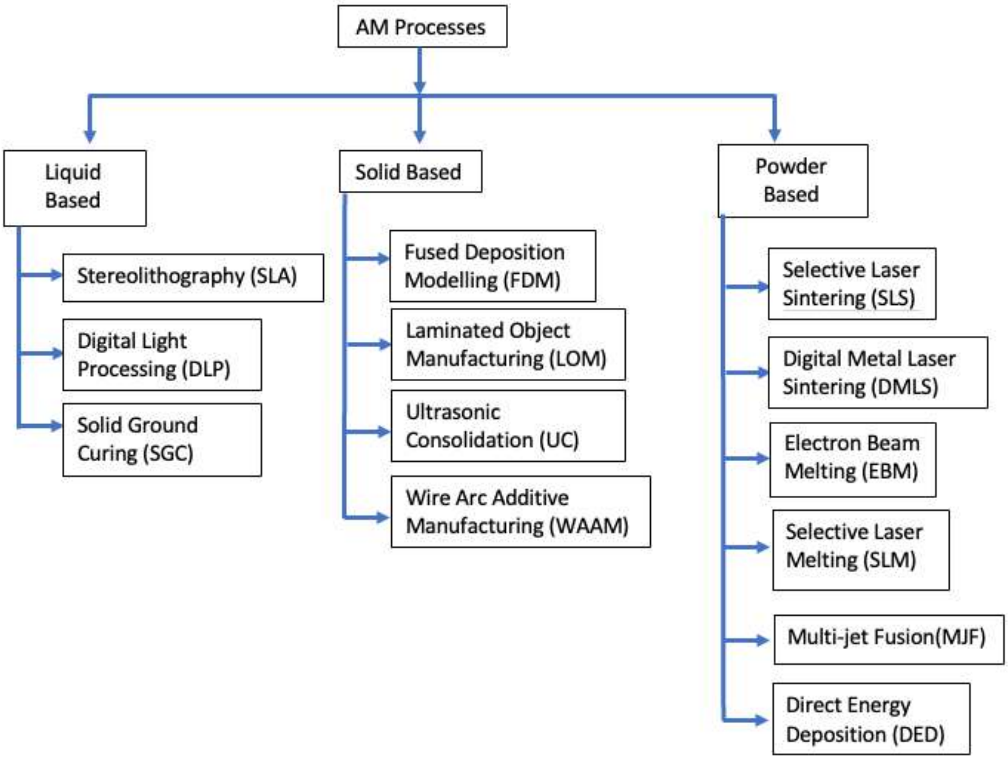

Figure 2. Classification of different AM processes

Stereolithography (SLA)

AM began with stereolithography (SLA) around 1980. It is a liquid-based 3D printing process founded on the principle of photopolymerization. Mainly, photosensitive resin is cured using UV laser light layer-by-layer to create 3D objects. Two types of approaches are available for SLA printing: 1) bottom-up approach, and 2) top-down approach. In the top-down approach, the printing platform is lowered into the vat during printing, while platform is raised during printing in the case of bottom-up process (Khadilkar et al., 2019). A vat of photosensitive resin, typically epoxy, vinyl ether, or an acrylate, contains a platform that can vertically up or down during printing. The printed part is created on this moving platform layer by layer. During slicing, STL file is sliced in thousands of layers which are used by UV laser light to trace the part. The polymer is hardened by laser light due to its photosensitive nature. A sweeper is used after every layer to relocate the liquid resin, continuing from starting to finish. As liquid resin cannot provide support to the overhanging portions of the parts, a support structure is also created during laser scanning (Liou, 2019; Khadilkar et al., 2019).

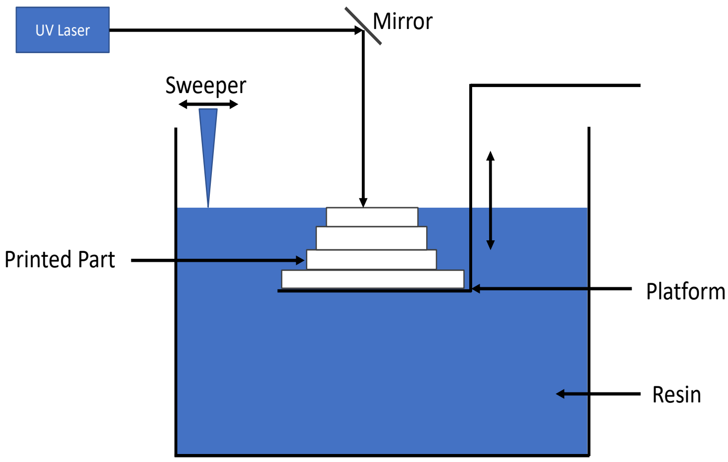

Figure 3. Top-down SLA 3D printing process

SLA printing is fully automated, meaning that external assistance is not required once the printing begins. The SLA process can build parts with any geometrical shape with up to 0.05mm accuracy. Due to liquid printing material, the printed part has a very good glass like finishing. However, material options are limited for SLA process and printed parts are relatively brittle and prone to curling and warping. Additionally, several studies have shown that uncured resin can be toxic and harmful for user and surroundings (Kostoryz et al., n.d.; Wendel et al., 2008). As a result, SLA printing process needs special care and is not suitable for in desktop printing.

Solid Ground Curing (SGC)

Another liquid-based AM process is solid ground curing (SGC), which is even suitable for batch production. It is also very similar to the SLA process, but the whole layer can be made simultaneously using mask. In this process, a photosensitive resin is sprayed on the building platform. Then, a mask is generated electrostatically using an electron gun and toner on a glass plate, which is a negative image of part cross section. As a result, light can pass through the transparent area, which is exactly the cross-section of the part. Then the mask is placed between UV light source and the photosensitive resin layer. UV light passes through the mask and cures the resin layer. The whole layer is fully cured due to the intensity of the UV light. Glass mask is cleaned to make the next layer, and the uncured resin is cleared using a vacuum cleaner. Then, the void of the layer is filled using hot liquid wax, which works as a support. After the wax solidifies, a milling cutter is used to machine the extra wax from the above layer of photosensitive resin so that the next layer can be printed on it. This process is repeated continuously until the full part is made. Advantage of this process is high throughput as each layer can be printed at the same time. However, secondary operation is needed, such as wax for support, which can be melted or washed away after the operation. This method has a high accuracy and fabrication rate but suffers considerable operation costs(Liou, 2019; Gu et al., 2001) .

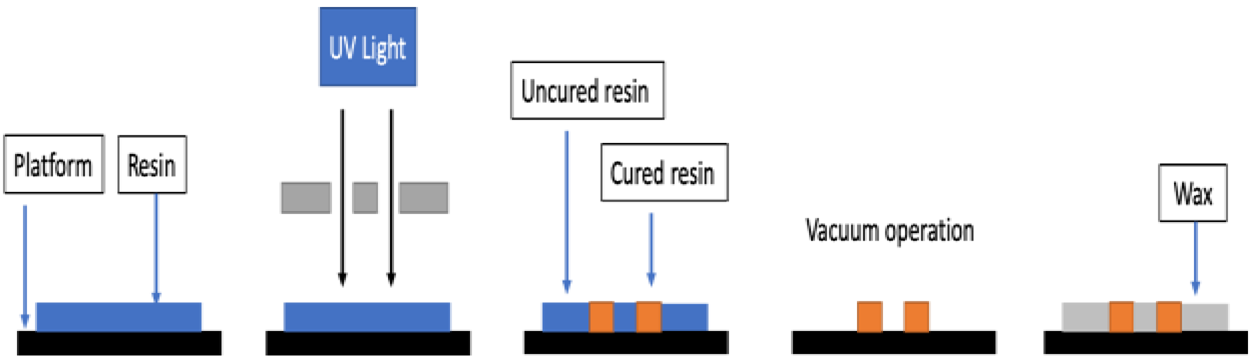

Figure 4. SGC 3D printing process

Fused Deposition Modeling (FDM)

FDM is the most widely used AM process, which uses thermoplastic material that is extruded from the bottom up using a heated nozzle in a printing platform. FDM was first developed by Advanced Ceramics Research in Tucson, Arizona, but it was significantly advanced by Stratasys (Liou, 2019). Materials are in the form of solid filament, which is fed through the nozzle. Nozzle temperature is maintained very close to the melting temperature of printing material (usually 2°C high) so that molten material can solidify as early as possible (Prakash et al., 2018). According to the part design, nozzle moves over the printing platform and deposits the first layer of the part. Materials solidify almost instantly, so the second layer can easily be deposited on top of the first layer. Extra support is also needed based on the part design. Some FDM 3D printers use separate nozzles and materials for making support structures, but using the same material and nozzles is also very common for support. After printing each layer, the nozzle changes vertical position, which ensures the deposition of the next layer on top of the previous layer. The FDM process is hassle-free and harmless, so it can be easily used in an office environment. Layer height of 0.1mm can be achieved with FDM, while wall thickness can be around 0.5 mm.

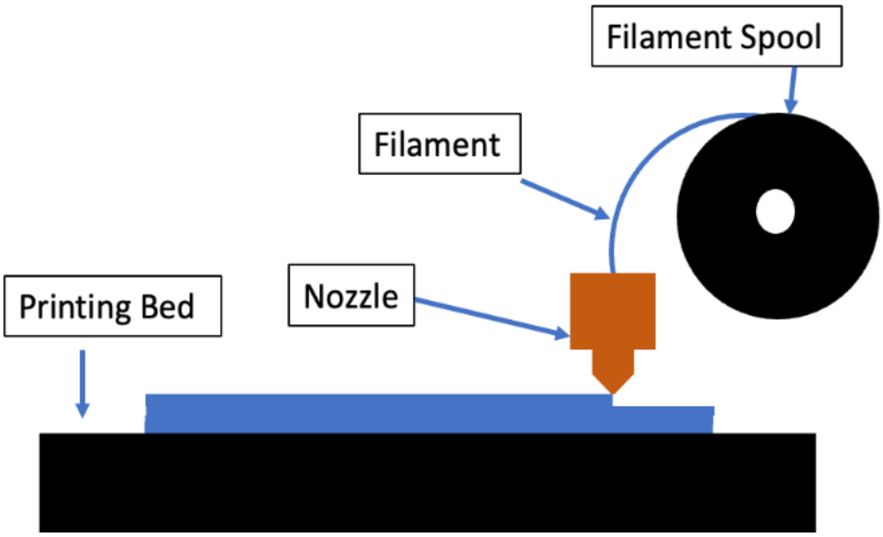

Figure 5. FDM 3D Printing

Typically, polymer materials like ABS, PLA, Polycarbonate, and various versions of those materials are used in FDM printing. Besides, polymer/ceramic, ceramic/metal, polymer/metal, etc. materials are continuously being explored for FDM printing. Compared to other technologies, FDM is very inexpensive. The surface finish of FDM technology is not very good compared to other 3D printing technology, but improvement is going on to get a smooth surface. Typically, the stair-stepping problem is pervasive for FDM 3D printing. Extra post-processing is necessary to make the surface smooth, which can increase the cost. Besides, the removal of support material is another major drawback of FDM technology. Due to poor resolution, surface finish FDM is not directly used in the automotive industry. Still, FDM can be used for producing molds of different parts that can be used in the automotive industry (Romero et al., 2021). For example, FDM can be used to make a mold for polyurethane (PUR) parts widely used in automotive. Chemical finishing using acetone vapors or similar chemicals is used to polish the rough surface of those molds.

Laminated Object Manufacturing (LOM)

LOM is one of the fastest 3D printing technologies used to manufacture 3D objects using the sheet lamination process. It can make complex geometrical shapes with less printing time and less cost. This process uses layers of sheet materials, such as paper, plastics, composites, etc., to complete the printing process. LOM was first developed and introduced by Helisys Inc. in 1985. The thickness of the layer in the LOM process depends on the printing sheet, which can be 0.001-0.005 in thick (Liou, 2019). Printing involves cyclic stacking, bonding, and cutting sheets to the desired shape. At first, a roller stacks adhesive-coated paper sheets on the printing platform. Another hot roller or pressurized hot plate melts the plastic-coated paper to the bottom surface, creating bonding. Finally, a laser cut the sheet according to the design to remove excess material from the layer, which gives the layer the desired shape. This completes the layer, and the platform moves vertically to make the next step. Again, it starts from the first step, and the same process continues until the entire part is made (Mekonnen et al., 2016). The LOM process can make very large parts, and no support is needed for this process. Also, the finished part does not experience shrinkage, warpage, or other deformation. However, surface finish and accuracy are not very good compared to other 3D printing processes. Nevertheless, the produced part can be machined to get the desired finish. Laser is used to cut the paper sheet so smoke can be generated, which requires a smoke filtration system and a sealed chamber. Besides paper material, metallic material can also be used in this process, but laser cutting induces a high amount of thermal energy that weakens the bond between sheets (Mekonnen et al., 2016).

Wire Arc Additive Manufacturing (WAAM)

WAAM is a popular AM technique that is different from powder-based printing techniques like SLS or EBM. Instead of a laser or electron beam, a welding arc is used for melting and depositing metal wire layer by layer. In the building platform, the welding torch is moved by a robot or any other axis system to deposit molten wire according to the part design. WAAM can again be divided into three types based on the heat source: metal inert gas (MIG), tungsten inert gas (TIG), and plasma arc welding (PAW). MIG is the most common welding process that creates an electric arc between the wire electrode and the workpiece. As a result, consumable wire is melted.

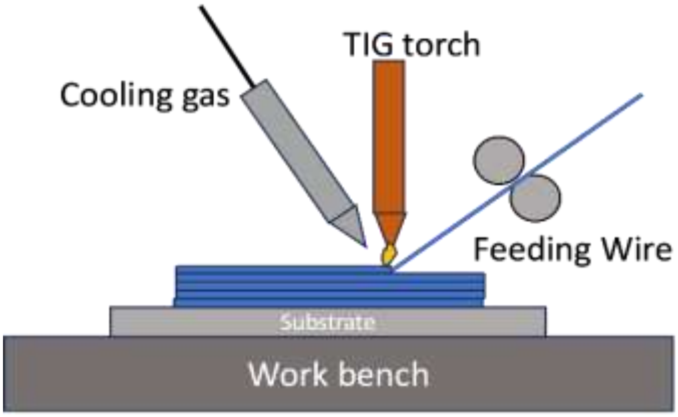

Figure 6. WAAM Printing

There could be a lot of variation in the WAAM system as advanced systems can be equipped with various sensors to measure welding signals, deposited bead geometry, temperature of molten metal, interpass cooling, etc. A schematic diagram of a WAAM system equipped with gas cooling process is presented. In this system, a moveable gas nozzle, which provides argon, nitrogen, or CO2 gas, is used to provide active cooling during the fabrication process. WAAM process can achieve a deposition rate of 50-130 g/min compared to electron beam or laser power sources, which can get a maximum deposition rate of up to 2-10 gm/m. A lot of metal material in the form of wire, such as Ti6Al4V, copper-coated steel, Inconel 625, Steel-bronze bimetal, etc, can be used as a feeding material in the WAAM process (Singh et al., 2020). WAAM does not require a vacuum environment, and components for making the WAAM system are cheap compared to other fusion-based methods, as welding instruments can be used to make the WAAM system. Besides, the electric arc-based system offers higher efficiency than the laser-based method (Cunningham et al., 2018).

Selective Laser Sintering (SLS)

SLS is one of the most important and earliest powder-based AM processes, which was patented in 1989. Almost any material in the form of powder, such as polymer, metal, ceramic, or composites, can be used in the SLS process (Kruth et al., 2003). The SLS process is similar to SLA in several aspects, but powder of the intended material is used in SLS. A laser is used in SLS to sinter material powder to make the final product. Whole process is completed in a building chamber, which is kept at a specific high temperature based on the printing material. As a result, the laser can instantly sinter the material. The SLS process consists of a few cyclic steps. There are separate beds for printing and powder materials. Bed containing powder material rises according to the layer thickness (typically 0.1-0.3 mm). A roller is used for successive deposition of metal powder to the printing bed. Excess powder is also removed with the roller. After powder deposition, a laser sinters the material based on the part's design. Each layer is sintered to the previous layer which creates a final solid part based on the supplied design. When sintering is done, printing bed goes down based on layer height for making the next layer. Powder containing bed again goes up, and roller is ready for making the next layer of the part. In SLS process, unsintered powder is used as support, so extra support is not required for overhanging portion. SLS process is normally operated in an inert gas environment. This process can produce parts with very high mechanical strength; in fact, the material properties of the printed part are very close to the used material. However, the SLS process has some disadvantages, such as the surface finish and lower density, and the printed part suffers from porosity as the material is sintered using a laser.

Digital metal laser sintering (DMLS) is very similar to SLS, but only metal alloys can be used in DMLS process (Joshi & Sheikh, 2015). DMLS gives excellent part accuracy due to full control over the temperature and atmosphere of the building chamber (Atzeni & Salmi, 2015). In this process, fully dense metal parts can be made (Atzeni & Salmi, 2015). Multi-jet fusion (MJF) printing is also close to the SLS process but uses infrared lamps as the energy source with a fusing agent that can absorb radiation energy to fuse the material (Cai et al., 2021).

Other extensively used metal 3D printing technologies, such as Electron beam melting (EBM) and Selective Laser Melting (SLM), are also very similar to SLS but use higher energy density than SLS. In EBM, instead of a laser, the electron beam is used to melt powder metal. Its ability to make complex parts with excellent mechanical properties made it a dependable metal manufacturing technology. Zinc, Bronze, Steel, Titanium alloy, etc. can be easily used as a material to produce complex, high-density parts (Biamino et al., 2011; Liou, 2019).

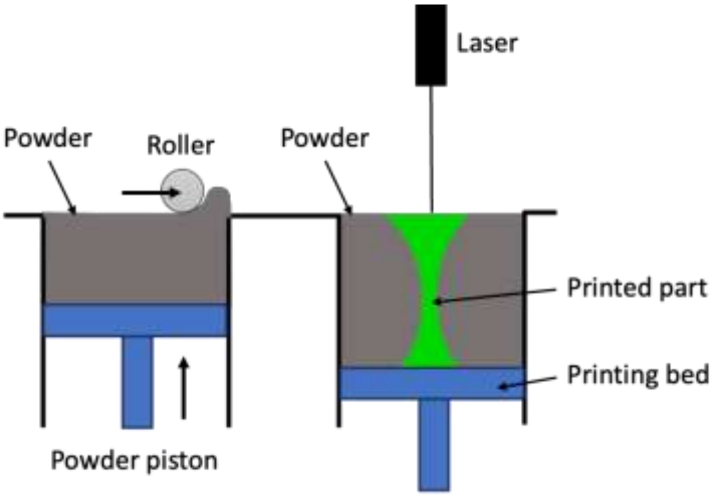

Figure 7. SLS printing process

DISCUSSIONS

All the major automotive companies are exploring AM to utilize its advantages in the main production line. BMW is one of the pioneers of additive manufacturing in the automotive industry. They started their 3D printing research in 1990 (BMW Group, 2015). Initially, the BMW group started using 3D printing for prototyping car parts due to the fast availability of components, flexible design requirements, and no tooling requirements. However, they are working toward systematic integration of 3D printing at the industrial level. In 2018, BMW announced that they had produced one million 3D-printed parts (BMW Group, 2018). In different sites across the global production network, BMW is using both metal and polymer 3D printing. Polymer parts are generated using multi-jet fusion and selective laser sintering, while metal parts use laser beam melting technology (BMW Group, 2020). They have printed mounting for the top cover and window guide rail for the BMW i8 Roadster using HP jet Multi Jet Fusion technology (BMW Group, 2018). Those components are complex in design and would not be possible using traditional casting process. Material is another concern for AM as minimal materials are available for different processes. For those parts, BMW used aluminum alloy, which weighs even less than injection-molded plastic parts.

Audi uses AM as a quick solution for on-demand auxiliary tools, prototyping, and spare part development. Due to the quick and inexpensive nature of AM, Audi's production department regularly prints positioning guides, safety devices, and casting molds. 3D printers give Audi the power of precision, simplicity, and user-friendliness, which is very complex and time-consuming with traditional methods. Audi is preparing to achieve the capability of applying 3D-printed parts directly on cars in the future. They are currently focusing on both polymer and metal AM technology. For polymer 3D printing, they extensively use printers made by Ultimate & Makerbot with PLA material (Vialva, 2019). On the other hand, for metal 3D printing, Audi uses the SLM 3D printing-based printer SLM280 made by SLM Solutions (Petch, 2018). Recently, Audi has partnered with EOS to make some selected tools entirely using metal 3D printing EOS M 400 system (EOS, 2021).

Another prominent automotive industry leader, Toyota, also uses AM continuously. Though they have not started using AM directly in manufacturing production parts, they use it for tool making and prototyping. On Toyota Motor North America Research & Development (TMNA R&D), Toyota regularly uses FDM, SLS, SLA, MJM, and DLP-based 3D printers (SAE International, 2021). Toyota Racing Development (TRD) has partnered with a polymer 3D printing leader, Stratasys, to make production-ready parts for Toyota GR86 (Stratasys, 2022).

Ford is using autonomous technology in addition to 3D printers to take advantage of advanced manufacturing. They have already made an autonomous robot named Javier, which can operate a Carbon 3D printer precisely, on time, and continuously throughout the day (Redford, 2022). Autonomous system integration gives the power to run a 3D printer continuously without human interaction, decreasing cost while increasing throughput. Ford has used this system to produce parts such as brake line brackets for the Mustang Shelby GT 500 (Cune, 2018). Ford also extensively uses FDM 3D printers, such as Prusa and LulzBot, with thermoplastic material to solve various problems in their production process. They have used those printers to print assembly line pucks, which has saved around $394,000 per year (Donaldson, 2021). Besides polymer, Ford is also working with metal AM. They are now working toward full-scale production of parts with the ExOne metal binder jet printer, which can produce metal parts using aluminum 6061(Molitch-Hou, 2021). Physical properties of those printed parts are comparable to the die casting process. Ford is more interested in binder jet instead of laser powder bed fusion because binder jet does not need any support material as the loose powder can support the part.

Volvo uses AM technologies to produce tools and fixtures in their Dublin New River Valley plant (NRV). They use around 500 manufacturing tools and fixtures in the NRV plant made by 3D printing. As the quality and precision of 3D printers are increasing day by day, Volvo is focused on utilizing the unique abilities of 3D printing in their production. They are using Selective laser sintering (SLS) to produce production-related tools and solve sudden problems uniquely. They developed a one-piece diffuser for paint atomizer cleaning process that saves $1,000 for each part. Besides, they are printing roof seal gauges, fuse installation platens, drilling fixtures, brake piston gauges, etc. (Volvo Group, 2019)

Other automotive companies are also gradually adopting AM and setting goals to incorporate it as much as possible in prototyping, tool development, and spare parts development.

Table 1. Automotive companies and their corresponding AM approach

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	Fused Filament Fabrication (FFF) (The Manufacturer, 2021) Selective Laser Sintering (SLS) (3D Systems, 2015) Multi Jet Printing (MJP)(3D Systems, 2015)
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)

Advantages of Additive Manufacturing in Automotive Industry

Additive manufacturing gives numerous advantages over traditional manufacturing. Though both processes have their strengths and weaknesses, additive technologies can be useful for specific scenarios when traditional methods are not very useful. Below, we have mentioned a few advantages of additive manufacturing:

- **Design Flexibility:** Traditional manufacturing methods impose constraints on the shape and structure of the product design. As a result, manufacturing complex parts is difficult. But additive manufacturing offers design flexibility due to layer-by-layer design capability. Internal channels and features can be made gradually, which gives unparalleled freedom in additive manufacturing design. Moreover, complex parts can be designed as a single part, which gives better freedom during design and performance.

- **Rapid Prototyping:** Rapid prototyping facilitates making workable designs directly from digital files, which is one of the best traits of additive manufacturing. Traditional manufacturing requires tooling or molds for prototypes, while additive manufacturing can make that without any complex tool requirements. This saves time and money during the production phase. Due to the speed of rapid prototyping, additive manufacturing is particularly beneficial to the automotive industry, where time-to-market is critical.

- **Reduced Material Waste:** Additive manufacturing significantly reduces waste material compared to traditional manufacturing. Conventional manufacturing largely depends on the subtractive process, which has a higher buy-to-fly ratio. However, additive manufacturing has a higher buy-to-fly ratio, which generates very low waste. Typically, based on the design, the material used for support material is the only waste in the additive manufacturing process.

- **Light Weight:** Additive manufacturing can produce lightweight products through topology optimization, hollow sections, and lattice structures. Topology optimization is the process of analyzing internal and external structures based on performance requirements. The lattice structure makes geometric patterns with a high strength-to-weight ratio. Due to distinctive manufacturing freedom, additive manufacturing can produce parts designed using topology optimization having lattice or hollow structures. This reduces weight significantly without sacrificing performance requirements.

- **Consolidation of Parts:** Additive manufacturing has the strength to produce complex parts at the same time, which reduces assembly requirements. In the automotive industry, complex parts are required, especially in the engine. Integration of multiple components into a single structure gives multiple production benefits. Finally, consolidating parts gives better performance within a limited budget without additional materials.

Due to simple part design using topology optimization and the capability to produce lightweight parts, fuel-efficient design is possible using additive manufacturing. Moreover, no tooling requirement alters the supply chain during the product development phase, which enables rapid deployment of the final product. Even low-volume production is possible using additive manufacturing, which significantly benefits the workflow. Finally, additive manufacturing facilitates the repair and replacement of parts within a short time, which would not be possible without the development of additive manufacturing.

Challenges of Additive Manufacturing in Automotive Industry

In recent years, additive technologies have been incorporated into almost all major industries. There are a number of advantages of additive methods that come due to the inherent nature of the technology. Still, it has many drawbacks that deter its rapid acceptance in mainstream production. Almost all AM processes suffer from significant weaknesses that have to be removed before using AM in the primary production. In this section, we will discuss some common drawbacks of additive manufacturing.

- **Product Quality:** While AM offers excellent flexibility in product manufacturing, product quality is still one of the most critical drawbacks when considering traditional manufacturing. In many cases, additively manufactured products suffer from a lack of mechanical strength and distorted geometry. After manufacturing, the material property is changed under cyclic thermal loading conditions (Volvo Group, 2019). In the case of metal printing, anisotropy and heterogeneity in microstructure are also seen (Kok et al., 2018). Besides voids, porosity is very common on additively printed products, which creates a severe alteration in main product design and hampers accuracy. For example, extrusion-based processes such as FDM create voids inside the layers that result in anisotropic mechanical properties and delamination (Abdulhameed et al., 2019).

- **Low Volume Production:** Build volume is a major challenge in additive manufacturing process. As product is built in layer-by-layer fashion, it takes a long time for making parts that ultimately results low product volume. It is true that additive does not require excessive tools and fixtures for individual design, but when still AM lags behind of traditional methods comes to large scale production. While traditional methods capable of produce thousands of parts in a fraction of time, still AM takes long time for making any types of products. Even cutting down large product into small parts cannot increase the production volume.

- **Limited Material:** The quality of 3D printed products depends on the material significantly. Almost all technologies have limited materials for printing parts. For example, FDM 3D printing depends on thermoplastic material, and SLA needs resin that can be photocurable; for metal 3D printing, stainless steel, gold, silver, Inconel, copper, titanium, and nickel-based alow are preferred. However, many materials with remarkable mechanical properties cannot be used in AM. So, AM cannot be considered when parts require high mechanical properties. Advanced research is being conducted to develop high-entropy alloys, magnetic alloys, functionally graded materials, novel material composites, etc (Scott, 2018).

- **Post-processing:** The requirement of excessive post-processing is one of the main hurdles of additive manufacturing. Firstly, the surface finish of additively manufactured products may not meet industry standards, necessitating labor-intensive processes, such as sanding, polishing, or chemical treatments, to achieve a smooth finish. The surface finish also affects dimensional accuracy, which may constrain the usage of 3D-printed parts in low-accuracy-related applications. Moreover, removing support materials can be a daunting task, requiring extra time and money.

- **Lack of Standards:** The need for standardized processes and materials in AM poses significant challenges. The absence of universally accepted standards can lead to inconsistencies in part quality, making it challenging to ensure uniformity and reliability across different AM technologies. Variability in material properties and printing parameters can affect printed objects' mechanical strength and performance. This lack of standardization complicates interoperability between 3D printers and software, limiting design portability. Moreover, the absence of standardized testing protocols makes it difficult to validate the quality and safety of 3D-printed components. These issues hinder widespread adoption, particularly in industries such as aerospace and healthcare, where adherence to strict standards is critical.

CONCLUSIONS

In summary, additive manufacturing brings game-changing abilities in design freedom, rapid prototyping, waste reduction, and lightweight constructions to the automotive space. In its initial stages, Additive Manufacturing (AM) was primarily used for prototyping. Over time, AM is progressively securing its position on the primary production line with each passing day. As technology and materials advance, 3D printing can solve more complex engineering problems cost-effectively. Automakers worldwide are increasingly investing in industrial 3D printers and leveraging this cutting-edge method for design iterations, tooling, jigs and fixtures, and end-use parts production.

However, issues around inferior quality, slow build speeds, limited material selection, and lack of standards need resolution for extensive incorporation along automotive assembly lines. As printers and allied systems grow more sophisticated, component quality and volumes should reach levels acceptable for full-scale manufacturing. With ongoing R&D, additive techniques are poised to complement conventional automotive manufacturing in the years ahead. For the ongoing analysis of tracking Additive Manufacturing (AM) progress in the automotive industry, our primary data collection was from company websites. Occasionally, we had to resort to internet sources, the verification of which posed challenges. Nonetheless, we maintain confidence that this study successfully identified the most prevalent processes employed in the automotive industry. In future research endeavors, there is potential to enhance the current study by incorporating upcoming AM technologies used in automotive and conducting a thorough analysis of the challenges in Additive Manufacturing (AM) during that time.

Author Contributions: Conceptualization, A.M.N. and M.M.N.H.; Data Curation, A.M.N.; Methodology, A.M.N.; Validation, A.M.N.; Visualization, M.M.U.; Formal Analysis, A.M.N. and M.M.N.H.; Investigation, A.M.N.; Resources, A.M.N. and M.M.N.H.; Writing - Original Draft, A.M.N., M.M.N.H.; Writing - Review & Editing, A.M.N. and M.M.N.H.; Supervision, M.M.N.H.; Software, A.M.N.; Project Administration, A.M.N.; Funding Acquisition, A.M.N. and M.M.N.H. All authors have read and agreed to the published version of the manuscript.
Institutional Review Board Statement: Ethical review and approval were waived for this study because the research does not deal with vulnerable groups or sensitive issues.
Funding: The authors received no direct funding for this research.
Acknowledgement: Not applicable.
Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.
Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to restrictions.
Conflicts of Interest: The authors declare no conflict of interest.

REFERENCES

3D printing.com. (2020). *The Mysterious 3D Printed Part in the Tesla Model Y - 3D Printing*. Retrieved from https://3dprinting.com/automotive/the-mysterious-3d-printed-part-in-the-tesla-model-y/

3D Systems. (2015). *Australia's Nissan Motorsports Uses Additive Manufacturing to Rev Up Performance | 3D Systems*. Retrieved from https://www.3dsystems.com/learning-center/case-studies/australias-evok3d-uses-direct-digital-manufacturing-rev-performance

Abdulhameed, O., Al-Ahmari, A., Ameen, W., & Mian, S. H. (2019). Additive manufacturing: Challenges, trends, and applications. *Advances in Mechanical Engineering*, *11*(2), 1-27. https://doi.org/10.1177/1687814018822880

Additive News. (2017). *Mercedes-Benz Trucks starts 3D printing metal spare parts - Additive News*. Retrieved from https://additivenews.com/3d-printing-metal-parts-mercedes-trucks/

Ahn, S. H., Montero, M., Odell, D., Roundy, S., & Wright, P. K. (2002). Anisotropic material properties of fused deposition modeling ABS. *Rapid Prototyping Journal*, *8*(4), 248–257. https://doi.org/10.1108/13552540210441166

Akre, S. (2023). *3D Printing in Automotive Market Size, Share Analysis Report 2030*. Retrieved from https://www.marketresearchfuture.com/reports/3d-printing-automotive-market-4207

Atzeni, E., & Salmi, A. (2015). Study on unsupported overhangs of AlSi10Mg parts processed by Direct Metal Laser Sintering (DMLS). *Journal of Manufacturing Processes*, *20*, 500–506. https://doi.org/10.1016/j.jmapro.2015.04.004

Biamino, S., Penna, A., Ackelid, U., Sabbadini, S., Tassa, O., Fino, P., Pavese, M., Gennaro, P., & Badini, C. (2011). Electron beam melting of Ti-48Al-2Cr-2Nb alloy: Microstructure and mechanical properties investigation. *Intermetallics*, *19*(6), 776–781. https://doi.org/10.1016/j.intermet.2010.11.017

Blakey-Milner, B., Gradl, P., Snedden, G., Brooks, M., Pitot, J., Lopez, E., Leary, M., Berto, F., & du Plessis, A. (2021). Metal additive manufacturing in aerospace: A review. *Materials and Design*, *209*. https://doi.org/10.1016/j.matdes.2021.110008

BMW Group. (2015). *25 years of 3D printing at the BMW Group: Pioneers in additive manufacturing methods*. Retrieved from https://www.press.bmwgroup.com/global/article/detail/T0243462EN/25-years-of-3d-printing-at-the-bmw-group:-pioneers-in-additive-manufacturing-methods?language=en

BMW Group. (2018, November). *A million printed components in just ten years: BMW Group makes increasing use of 3D printing*. Retrieved from https://www.press.bmwgroup.com/global/article/detail/T0286895EN/a-million-printed-components-in-just-ten-years:-bmw-group-makes-increasing-use-of-3d-printing?language=en

BMW Group. (2020). *Industrial-scale 3D printing continues to advance at BMW Group*. Retrieved from https://www.press.bmwgroup.com/global/article/detail/T0322259EN/industrial-scale-3d-printing-continues-to-advance-at-bmw-group?language=en

Cai, C., Tey, W. S., Chen, J., Zhu, W., Liu, X., Liu, T., ... & Zhou, K. (2021). Comparative study on 3D printing of polyamide 12 by selective laser sintering and multi jet fusion. *Journal of Materials Processing Technology*, *288*, 116882. https://doi.org/10.1016/j.jmatprotec.2020.116882

Chen, Y. H., Ng, C. T., & Wang, Y. Z. (1999). Generation of an STL file from 3D measurement data with user-controlled data reduction. *The international journal of advanced manufacturing technology*, *15*, 127-131.

Cune, R. (2018). *Ford Mustang Shelby GT500 Gets 3D Printed Brake Line Brackets – 6th Gear Automotive Solutions*. Retrieved from https://www.6thgearautomotive.com/2018/12/08/ford-mustang-shelby-gt500-will-get-3D-printed-brake-line-brackets/

Cunningham, C. R., Flynn, J. M., Shokrani, A., Dhokia, V., & Newman, S. T. (2018). Invited review article: Strategies and processes for high quality wire arc additive manufacturing. *Additive Manufacturing*, *22*, 672-686. https://doi.org/10.1016/j.addma.2018.06.020

Davies, S. (2023). *"They listened to everything we asked for." – How Toyota helped shape the Stratasys F3300 FDM 3D printing system - TCT Magazine*. Retrieved from https://www.tctmagazine.com/additive-manufacturing-3d-printing-industry-insights/technology-insights/how-toyota-helped-shape-stratasys-f3300-fdm-3d-printer/

Donaldson, B. (2021). *Ford is Saving Millions through 3D Printing (But Maybe Not How You Think) | Additive Manufacturing*. Retrieved from https://www.additivemanufacturing.media/articles/ford-is-saving-millions-through-3d-printing-but-maybe-not-how-you-think

EOS. (2021, March 18). *EOS and Audi expand range of applications for metal 3D printing*. Retrieved from https://www.eos.info/en/presscenter/press-releases/cooperation-audi-tooling-2021

Everett, H. (2021). *WASP and Honda advance industrial clay motorcycle modeling with 3D printing - 3D Printing Industry*. Retrieved from https://3dprintingindustry.com/news/wasp-and-honda-advance-industrial-clay-motorcycle-modeling-with-3d-printing-197746/

Ford Motor Company. (n.d.). *Building in the Automotive Sandbox*. Retrieved November 24, 2023, from https://corporate.ford.com/articles/products/building-in-the-automotive-sandbox.html

General Motors. (2020). *General Motors Increases Agility and Speed by Opening All-New Additive Industrialization Center Dedicated to 3D Printing*. Retrieved from https://news.gm.com/newsroom.detail.html/Pages/news/us/en/2020/dec/1214-additive.html

Gu, P., Zhang, X., Zeng, Y., & Ferguson, B. (2001). Quality analysis and optimization of solid ground curing process. *Journal of manufacturing systems*, *20*(4), 250-263. https://doi.org/10.1016/S0278-6125(01)80045-5

Herzog, D., Seyda, V., Wycisk, E., & Emmelmann, C. (2016). Additive manufacturing of metals. *Acta Materialia*, *117*, 371–392. https://doi.org/10.1016/j.actamat.2016.07.019

Jackson, B. (2017). *Volkswagen saves $160k in tooling costs using desktop FDM 3D printers - 3D Printing Industry*. Retrieved from https://3dprintingindustry.com/news/volkswagen-saves-160k-tooling-costs-using-desktop-fdm-3d-printers-116640/

Joshi, S. C., & Sheikh, A. A. (2015). 3D printing in aerospace and its long-term sustainability. *Virtual and Physical Prototyping*, *10*(4), 175–185. https://doi.org/10.1080/17452759.2015.1111519

Khadilkar, A., Wang, J., & Rai, R. (2019). Deep learning–based stress prediction for bottom-up SLA 3D printing process. *International Journal of Advanced Manufacturing Technology*, *102*(5–8), 2555–2569. https://doi.org/10.1007/s00170-019-03363-4

Kingsbury. (2019). *Rolls Royce embraces additive manufacturing in its aircraft engines | Kingsbury*. Retrieved from https://kingsburyuk.com/how-rolls-royce-is-embracing-additive-manufacturing-in-its-aircraft-engines/

Kobryn, P. A., Ontko, N. R., Perkins, L. P., & Tiley, J. S. (n.d.). *Additive Manufacturing of Aerospace Alloys for Aircraft Structures*. Retrieved from http://www.rto.nato.int/abstracts.asp.

Kok, Y., Tan, X. P., Wang, P., Nai, M. L. S., Loh, N. H., Liu, E., & Tor, S. B. (2018). Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review. *Materials and Design*, 139, 565–586. https://doi.org/10.1016/j.matdes.2017.11.021

Kostoryz, E. L., Tong, P. Y., Chappelow, C. C., Eick, J. D., Glaros, A. G., & Yourtee, D. M. (1999). In vitro cytotoxicity of solid epoxy-based dental resins and their components. *Dental Materials*, *15*(5), 363-373. https://doi.org/10.1016/S0109-5641(99)00058-5

Krassenstein, B. (2015). *Automobile Manufacturer Audi Discusses Their 3D Printing & 4D Printing Ambitions With Us - 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing*. Retrieved from https://3dprint.com/79839/audi-3d-printing/

Kruth, J. P., Wang, X., Laoui, T., & Froyen, L. (2003). Lasers and materials in selective laser sintering. *Assembly Automation*, *23*(4), 357–371. https://doi.org/10.1108/01445150310698652/FULL/XML

Lakhdar, Y., Tuck, C., Binner, J., Terry, A., & Goodridge, R. (2021). Additive manufacturing of advanced ceramic materials. *Progress in Materials Science*, *116*, 100736. https://doi.org/10.1016/j.pmatsci.2020.100736

Liou, F. F. (2019). *Rapid Prototyping and Engineering Applications: A Toolbox for Prototype Development* (2nd ed.)

Madeleine P. (2023). *Tesla Turns to 3D Printing to "Reinvent Carmaking" - 3Dnatives*. Retrieved from https://www.3dnatives.com/en/tesla-turns-to-3d-printing-to-reinvent-carmaking-190920234/#!

Mekonnen, B. G., Bright, G., & Walker, A. (2016, January). A study on state of the art technology of laminated object manufacturing (LOM). In *CAD/CAM, Robotics and Factories of the Future: Proceedings of the 28th International Conference on CARs & FoF 2016* (pp. 207-216). New Delhi: Springer India. https://doi.org/10.1007/978-81-322-

2740-3_21

Molitch-Hou, M. (2015). *Rolls-Royce Flies Largest 3D Printed Part Ever Flown*. Retrieved from https://3dprintingindustry.com/news/rolls-royce-flies-largest-3d-printed-part-ever-flown-61608/

Molitch-Hou, M. (2021). *Ford to Mass Produce Metal 3D Printed Part for Popular Car - 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing*. Retrieved from https://3dprint.com/284045/ford-to-mass-produce-metal-3d-printed-part-for-popular-car/

Moore, S. (2020). *Mercedes-Benz Offers 3D Printing Capabilities for Medical Devices*. Retrieved from https://www.plasticstoday.com/3d-printing/mercedes-benz-offers-3d-printing-capabilities-medical-devices

Pearson, A. (2020). *Why Volvo Trucks Chose Additive Manufacturing for 30 Engine Assembly Tools*. Retrieved from https://www.stratasys.com/en/resources/blog/volvo-trucks-additive-manufacturing/

Petch, M. (2018). *AUDI gives update on use of SLM metal 3D printing for the automotive industry - 3D Printing Industry*. Retrieved from https://3dprintingindustry.com/news/audi-gives-update-use-slm-metal-3d-printing-automotive-industry-129376/

Prakash, K. S., Nancharaih, T., & Rao, V. V. S. (2018). Additive Manufacturing Techniques in Manufacturing -An Overview. *Materials Today: Proceedings*, *5*(2), 3873–3882. https://doi.org/10.1016/j.matpr.2017.11.642

Redford, M. (2022). *Geared for Success: Ford Now Operates 3D Printers Autonomously, Increasing Efficiency and Reducing Cost | Ford Media Center*. Ford Motor Company. Retrieved from https://media.ford.com/content/fordmedia/fna/us/en/news/2022/03/16/ford-now-operates-3d-printers-autonomously.html

Ricoh 3D. (2020). *Ricoh 3D - Case Studies - 3D Printing In The Automotive Industry*. Retrieved from https://rapidfab.ricoh-europe.com/resources/3d-print-experience-case-studies/helping-toyota-get-products-to-the-market-quicker/

Romero, P. E., Arribas-Barrios, J., Rodriguez-Alabanda, O., González-Merino, R., & Guerrero-Vaca, G. (2021). Manufacture of polyurethane foam parts for automotive industry using FDM 3D printed molds. *CIRP Journal of Manufacturing Science and Technology*, *32*, 396–404. https://doi.org/10.1016/j.cirpj.2021.01.019

SAE International. (2021, July 16). *Toyota RnD ups its additive manufacturing game*. Retrieved from https://www.sae.org/news/2021/07/toyota-rnd-ups-its-additive-manufacturing-game

Scott, C. (2018). *BMW Impresses with 3D Printed Roof Bracket for BMW i8 Roadster - 3DPrint.com | The Voice of 3D Printing / Additive Manufacturing*. Retrieved from https://3dprint.com/222268/bmw-3d-printed-roof-bracket/

Singh, S., Sharma, S. K., & Rathod, D. W. (2020). A review on process planning strategies and challenges of WAAM. *Materials Today: Proceedings*, 47, 6564–6575. https://doi.org/10.1016/j.matpr.2021.02.632

Stratasys. (2022). *Stratasys Named Official 3D Printing Partner of Toyota Racing Development: Stratasys Ltd. (SSYS)*. Retrieved from https://investors.stratasys.com/news-events/press-releases/detail/785/stratasys-named-official-3d-printing-partner-of-toyota

The Manufacturer. (2021). *Nissan accelerates assembly line with 3D printing solution - The Manufacturer*. Retrieved from https://www.themanufacturer.com/articles/nissan-accelerates-assembly-line-3d-printing-solution/

Tyrrell, M. (2022). *Rolls-Royce orders two more industrial 3D printers from SLM - Aerospace Manufacturing*. Retrieved from https://www.aero-mag.com/rolls-royce-slm-solutions-01092022

Vialva, T. (2019). *Audi expands 3D printed production for tooling*. Retrieved from https://3dprintingindustry.com/news/audi-expands-3d-printed-production-for-tooling-153007/

Volkswagen AG. (2021). *Volkswagen plans to use new 3D printing process in vehicle production in the years ahead | Volkswagen Newsroom*. Retrieved from https://www.volkswagen-newsroom.com/en/press-releases/volkswagen-plans-to-use-new-3d-printing-process-in-vehicle-production-in-the-years-ahead-7269

Volvo Group. (2019). *Volvo Trucks Improves Quality with 3D Printing Technology | Volvo Group*. Retrieved from https://www.volvogroup.com/en/news-and-media/news/2019/sep/printing-technology.html

Wendel, B., Rietzel, D., Kühnlein, F., Feulner, R., Hülder, G., & Schmachtenberg, E. (2008). Additive processing of polymers. In *Macromolecular Materials and Engineering*, *293*(10), 799–809. https://doi.org/10.1002/mame.200800121