



METAL BINDER JETTING OF AUTOMOTIVE COMPONENTS

AZOTH INC.

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ABOUT US

Azoth is a world-class, vertically integrated manufacturing company founded in 2018, and headquartered in Ann Arbor, Michigan. We specialize in manufacturing small and complex parts leveraging production-capable additive (3D) manufacturing technology. We offer over 45 different polymers and metals to ensure the right material, process and technology is used in every application.

Azoth's additive technology is a disruptive force in traditional manufacturing through its quick production lead times and **TOMO®** (Take One Make One). The TOMO process is designed to convert physical inventory to digital inventory eliminating supply chain disruptions, inventory obsolescence and saving its partners significant inventory costs and cash flow.

Not just another service bureau – **Azoth is your dedicated manufacturing partner.**



AZOTH INC.

1099 Highland Drive
Ann Arbor, Michigan 48108

Phone: [734-669-3797](tel:734-669-3797)

Email: info@azoth3d.com



INTRODUCTION: METAL ADDITIVE MANUFACTURING

Metal Binder Jetting (MBJ) is a promising Additive Manufacturing (AM) technique as it can be used to form complex geometries out of powder metal without the use of direct heat input at high production rates and low manufacturing cost.

In this work Metal Binder Jetting is presented as a fabrication process for automotive components for vehicle interior applications.

The components are parts exposed in customer-facing automotive interior applications requiring cosmetic surface finishes and detail resolution superior to the capabilities of traditional fusion-based Additive Manufacturing techniques. For these reasons, the development of additive manufacturing intended designs and post-processing approaches using Metal Binder Jetting as fabrication method were investigated.

To validate the material and function of the components, various tests were performed to predict effects on part quality through long-term consumer use for the lifetime of the vehicles in which they are installed in. Many factors had to be taken into consideration to match the level of standardization and quality control required for automotive production. These components passed all automotive Production Part Approval Process (PPAP) quality requirements and are installed in production vehicles.

INTRODUCTION

REVIEW OF METAL ADDITIVE MANUFACTURING OF AUTOMOTIVE APPLICATIONS

The manufacturing industry has been revolutionized by the implementation of Metal Additive Manufacturing, also known as 3D printing, and its ability to create complex geometries. In recent years, the automotive industry has increasingly adopted Metal Additive Manufacturing technologies for a variety of applications. However, until recently the use of metal 3D printed components has been scarce with most additive manufactured automotive components being polymer based that are used for prototyping. The automotive industry is slowly beginning to transition the use of Additive Manufacturing from solely prototyping to production due to its advantages over traditional means of manufacturing. The most significant advantages of Metal Additive Manufacturing in the automotive industry is the ability to produce components that utilize designs that would not be possible to manufacture via traditional means. This has been demonstrated by Czinger's development of their hyper car, the 21C. Nearly the entire chassis and suspension system is completely created using Additive Manufacturing along with many other components of the car. While currently still limited in its application, the possibilities of incorporating Metal Additive Manufacturing into key components of a vehicle are displayed by the design and production of the Czinger 21C. Another benefit of Metal Additive Manufacturing in automotive applications is the ability to create customized high detail resolution components for vehicle interior applications. These smaller and more detailed components are created more quickly and cost-effectively using Additive Manufacturing opposed to traditional manufacturing methods. However, this transition of the automotive industry is not yet fully completed due to challenges like part size, build rates, and meeting the strict safety and performance standards. Components used for vehicle interior applications have already overcome many of these challenges and passed automotive Production Part Approval Process (PPAP) quality requirements.

REVIEW OF METAL BINDER JETTING

Additive Manufacturing, also known as 3D printing, is a manufacturing method of joining material together, usually layer by layer, to make objects from digital three-dimensional model data. Metal Binder Jetting is an Additive Manufacturing process characterized by the absence of thermal energy in the shaping process. Indeed, it is a two-step process where the manufactured objects are printed and densified in separate steps. The printing step consists of high-precision ink jet printing of binder on metal powder bed substrate. Metal powder is bonded together when binder is jetted on the powder bed in a selective manner, corresponding to the cross-sectional shape of the objects being manufactured. In a cyclical way, the powder bed is lowered and recoated with additional loose powder on top to form the next layer, to which the binder is printed. This is done layer by layer until the whole build box is used and filled with metal powder. The printed objects are now located in three dimensions inside the build box, supported by loose metal powder. In this stage, the objects are in a green state (consolidated powder forms, held together by binder, that have not yet been sintered for final strength). The green objects are then cleared from powder with vacuum and

compressed air in a closed environment. The green objects are then placed on ceramic plates and densified in the following sintering step. The objects shrink during the sintering. It is in this step that the metal particles fuse together, and the objects receive their strength, density, and material properties. After sintering, the objects can be subject to additional process and heat treatments as per conventionally manufactured counterparts. A schematic of the Metal Binder Jetting Process is shown in Figure 1. Since forming, or 3D printing, and sintering are separate, Metal Binder Jetting Additive Manufacturing allows for a wide materials selection, where the process can be optimized for each material selection. Virtually, all materials that can be sintered can be processed via Metal Binder Jetting Additive Manufacturing if they are available in powder form with properties within the limits suitable for the printing process. Powder characteristics such as particle size, powder morphology, density, and flowability affect the printing process, therefore limiting the range of powders that can be processed.

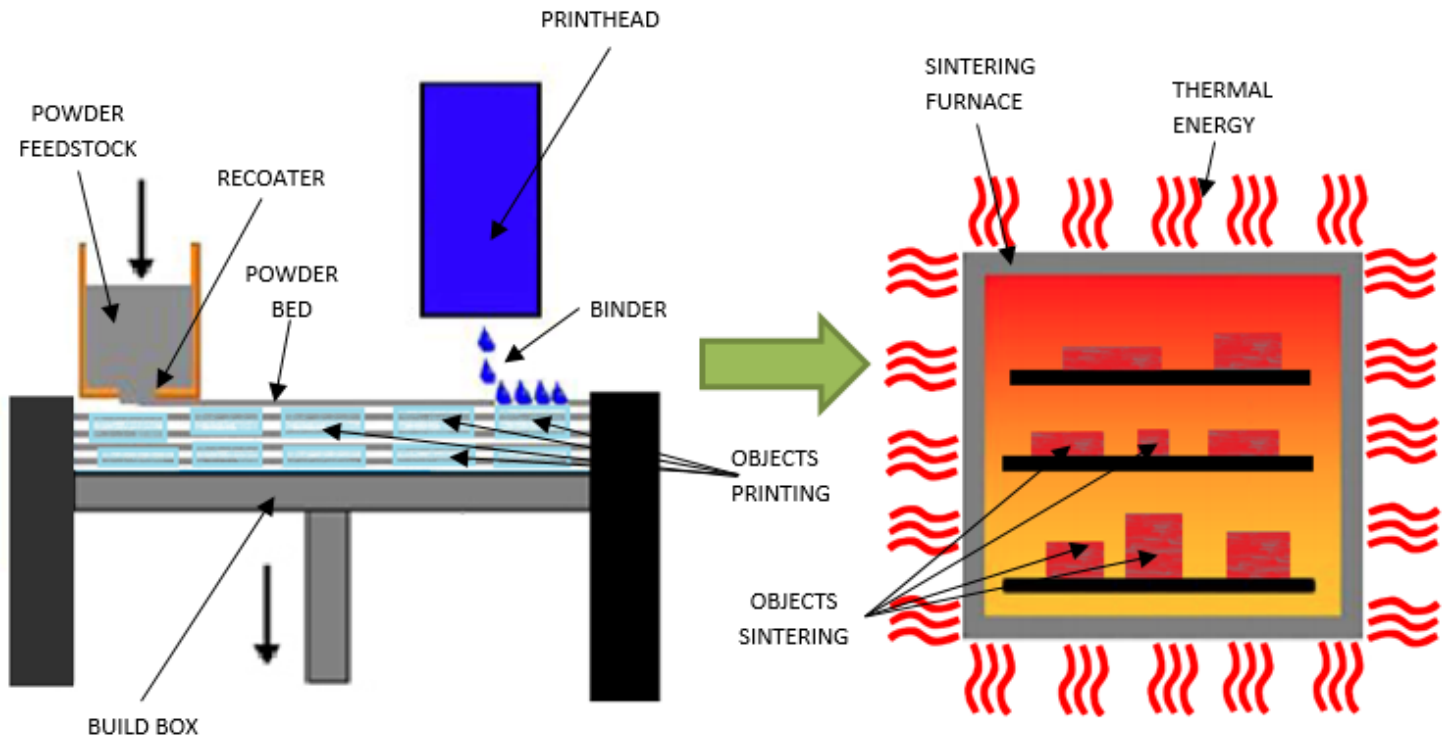


Figure 1 Schematic of Metal Binder Jetting Additive Manufacturing process, consisting of 3D printing at room temperature followed by sintering.

MATERIALS AND METHODS

MATERIAL

The most common materials used for automotive components created using Metal Binder Jetting are 316-L and 17-4PH stainless steel. This is due to the ability to achieve near fully dense parts and material properties that are close to traditionally manufactured parts. A great example of the use of Metal Binder Jetting in an automotive application is the Transmission Shift Knob component that has been in production vehicles for General Motors since 2021. The shift knob emblem is created using 316-L stainless steel, chosen for its final appearance and corrosion properties. The 316-L stainless steel is commonly used for customer-facing automotive interior applications like the shift knob emblem, while 17-4PH is a stronger and more wear resistant material that could be used for load bearing applications in the automotive field. While the transition to using Binder Jetted 17-4PH components in production within key mechanisms of a vehicle is still in its early phases, the increasing success in other industries has proven that it is very likely that more Metal Binder Jetted components in both 316-L and 17-4PH will be seen in production vehicles soon.

Table 1 Material properties of 316-L and 17-4PH stainless steel manufactured via Metal Binder Jetting Additive Manufacturing

Material	316-L	17-4PH
Yield Strength	180 MPa	730 MPa
Tensile Strength	520 MPa	950 MPa
Elongation	50%	4%
Hardness	HRB 55	HRC 27
Density	97%	97%

Also, with the automotive industry placing a heavy focus on electric vehicles there is an increase in demand for copper components needed for automotive applications. Many original equipment manufacturers and powder suppliers have recently developed materials, equipment, and processes to manufacture such components utilizing Metal Binder Jetting additive manufacturing. Early industrial adopters are working towards the extended characterization of key properties such as electrical and thermal conductivity, and towards the qualification of components suitable for production.

PRINTING

In Metal Binder Jetting 3D printing, as with most additive manufacturing technologies, components are created layer by layer. Components are printed based on their 3D CAD models, however, to account for the shrinkage that occurs during sintering, parts are scaled up using a volumetric scaling factor. For example, the shift knob emblems that are manufactured on a Digital Metal P2500 machine are scaled up using a volumetric scaling factor of ~1.7. Following this, the component models are positioned in 3D space to align with the build box, and then sliced into two-dimensional files that correspond to the cross-sectional layers of the build. With Metal Binder Jetting as many parts as can fit in the build box can be printed at the same time, this is a great advantage when it comes to manufacturing small components. Also, expendable sintering setters are typically additively manufactured within the same build. In the case of the shift knob emblem, printing parameters are set using the proprietary Digital Metal Build Preparation software, using 42µm layer height, with a printing speed correspondent to 100 cm³/hour, 316-L stainless steel powder commercialized by Höganäs AB and water-based organic binder commercialized by Digital Metal as C-20 ink as raw materials. The binder-powder saturation is about 69%.

After components are printed, the entire build box is placed in an oven and cured at 200 °C (392 °F) in air atmosphere to evaporate the solvent present in the ink and crosslink the binder. Next the entire build box is moved into a de-powdering cabinet where all the loose powder enclosing the printed components is blown off and separated from them. This loose powder is collected during de-powdering and is available to be reused in future print jobs.

DEBINDING AND SINTERING

After the parts are removed from the de-powdering cabinet, they are staged on ceramic plates in preparation for the debinding and sintering process. First, the parts are debinded with the primary debind being in air atmosphere at 345 °C (653 °F) and the secondary debind being in partial pressure hydrogen and the temperature incrementally increased up to 550 °C (1022 °F). This debind is done to begin to evacuate the binder holding the powder together but not completely remove the backbone binder component. The parts are then placed in a batch sintering furnace as an Elnik MIM 3015 where they are sintered in Hydrogen atmosphere at 1365 °C (2489 °F). Many parts from multiple print builds can be sintered at the same time, with total processing time for the parts to go through debinding and sintering being about 24 hours. However, the debinding and sintering temperatures, number of parts, and total sintering and debinding time varies depending on the material and geometry of the component.

SECONDARY OPERATIONS AND FINISHING

After Sintering the manufactured objects can be subjected to secondary operation as any other metal component traditionally manufactured. Secondary operations are typically done to provide an aesthetically pleasing look to the component. Although there are many post-processing options like traditionally manufactured components in terms of surface finishing methods, the

Metal Binder Jetting of Automotive Components

approach for Metal Binder Jetted parts can differ from traditionally manufactured parts due to the nature of the process. Metal Binder Jetted parts have a typical surface roughness of $\sim 6\mu\text{m Ra}$ ($39\mu\text{in}$), which can require specialized finishing techniques to achieve a smooth surface. The use of automated abrasive blasting or tumbling methods can help to smooth and improve the surface finish of parts. Other common approaches for finishing that improve the overall surface finish of Metal Binder Jetted parts include various hand grinding and buffing techniques for polishing. Additionally, applying a sealant or coating to the surface of Metal Binder Jetted parts is a common method to enhance its aesthetic appearance. The shift knob emblem is again a great example of the possibilities of Metal Binder Jetting within interior automotive applications. The finished part requires 4 different surface finishes: “high luster” (a.k.a. mirror finish) on the outside and top ring features, “blasted” surface in the background deep features, “brush” finish on the center bridge, and “as printed” inside the debossed letters on the outside as shown in Figure 2.



Figure 2 Concept artwork from General Motors design studio



Figure 3 Example of finished automotive shift knob emblem

VALIDATION

In order for parts to be viable for automotive applications, Metal Binder Jetted components must meet strict automotive qualification standards. Components intended to be used in automotive applications must pass all automotive Production Part Approval Process (PPAP) quality requirements. The Production Part Approval Process (PPAP) is in accordance with the Automotive Industry Action Group (AIAG) manual, ISO 9001 quality management systems, and Customer-specific requirements (GMW standards). The shift knob emblem used in example was the first metal additive manufactured part via Metal Binder Jetting to pass all automotive Production Part Approval Process (PPAP) quality requirements and be installed on a production volume vehicle by General Motors. Since the component is an exposed customer facing part within the interior of a vehicle 316-L was the chosen material for this product, as mentioned above, due to its final appearance and corrosion properties. Many tests are conducted to validate both the material and the desired function of a part, including effects of cleaners and lotions, scratch and mar resistance (before and after heat aging), effects of sunscreen and insect repellent, perspiration resistance, impact resistance, thermal shock resistance, Copper Accelerated Acetic Acid Salt Spray (CASS) corrosion resistance, and Cyclic Corrosion resistance. These tests were conducted to replicate long-term customer use and predict the effects on quality throughout the vehicle's lifetime. These tests are just a few of the common tests performed that are vital to validate a part for automotive applications.

RESULTS: EXAMPLE APPLICATIONS

INTERIOR COMPONENTS PRODUCTION

Again, the shift knob emblem can be used as an example of Metal Binder Jetting additive manufacturing for automotive interior components. The shift knob emblem was designed by General Motors with additive in mind, who leveraged the expertise of Azoth's team of engineers to refine the design and create an automotive production part. The part itself is made up of many complex features that pose a challenge in the manufacturing process. The features include: 7 debossed numerical or alphabetic characters as thin as 0.2mm in width and 1.0mm in depth, concave, and convex surfaces to provide a sense of depth visually, M4x0.7mm threads that are printed on the part, and a geometric concave removal pattern on the back of the part that goes into the part for heat dissipation. Other than the features themselves being a manufacturing challenge, the dimensional tolerances of these features and the part itself are critical, as each shift knob emblem is installed on a serial production line. The outside diameter, for example, is an important dimension as the emblem must fit within the mating component with a very small tolerance. If the emblem is smaller than the lower tolerance limit there would be a gap between the part and the shift knob tower which would not be up to visual quality standards. Oppositely, if the emblem is larger than the upper tolerance limit than the part simply wouldn't fit within the mating component. The outside diameter of the emblem must be 34.00 +/- 0.25mm which is a tolerance of +/- 0.7% of the diameter. Another key dimension is the height of the part as this ensures alignment with the shift knob tower, the height must be 5.1 +/- 0.1mm. To ensure these dimensions are within tolerance the control plan includes direct measurement of X, Y, and Z dimensions and indirect measurement of other features as well. The threads are also to be verified using a standard thread gauge. These are all part of a nine-point critical inspection included within the production control plan. The challenges and validation of this component demonstrates the capabilities Metal Binder Jetting has within the automotive industry.

Metal Binder Jetting of Automotive Components

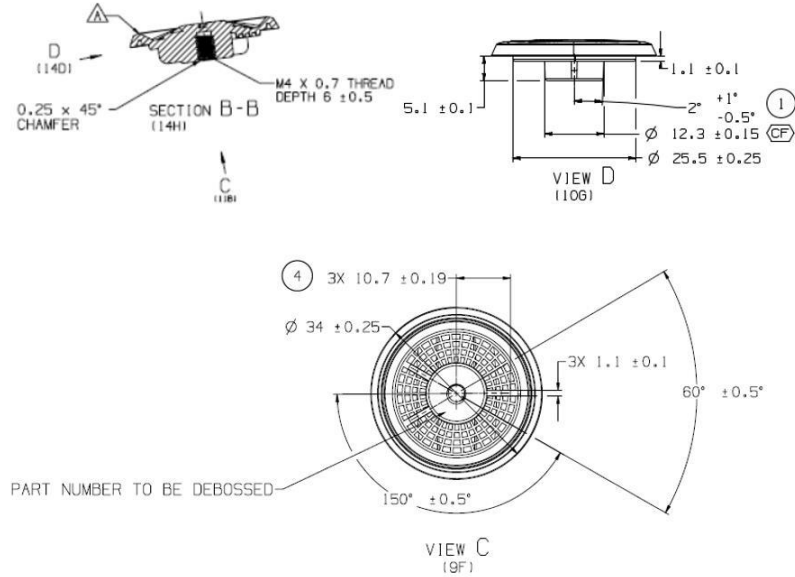


Figure 4 Extract of drawing of shift knob emblem with dimensions

TOOLING, JIGS, AND FIXTURES

The creation of tooling, jigs, and fixtures is a proven additive manufacturing application and is something Azoth is executing on. Due to the ability to create complex parts, Metal Binder Jetting is a great Additive Manufacturing method for creating tooling, jigs, and fixtures as it allows for the manufacturing of unique and application specific components. Also, the ability to establish an online inventory where parts are printed when needed. For example, Azoth's implementation of the Take One Make One (TOMO™) system maximizes the abilities of Metal Binder Jetting. Adopting a TOMO™ model for any components, specifically tooling, jigs, and fixtures, can generate cost savings in inventory management. The main downside to using Metal Binder Jetting for tooling, jigs, or fixtures applications is that possibilities are limited due to tolerance requirements. In many designs tolerances are only achievable through traditional milling with today's state of sinter-based Additive Manufacturing not being up to the same standard.

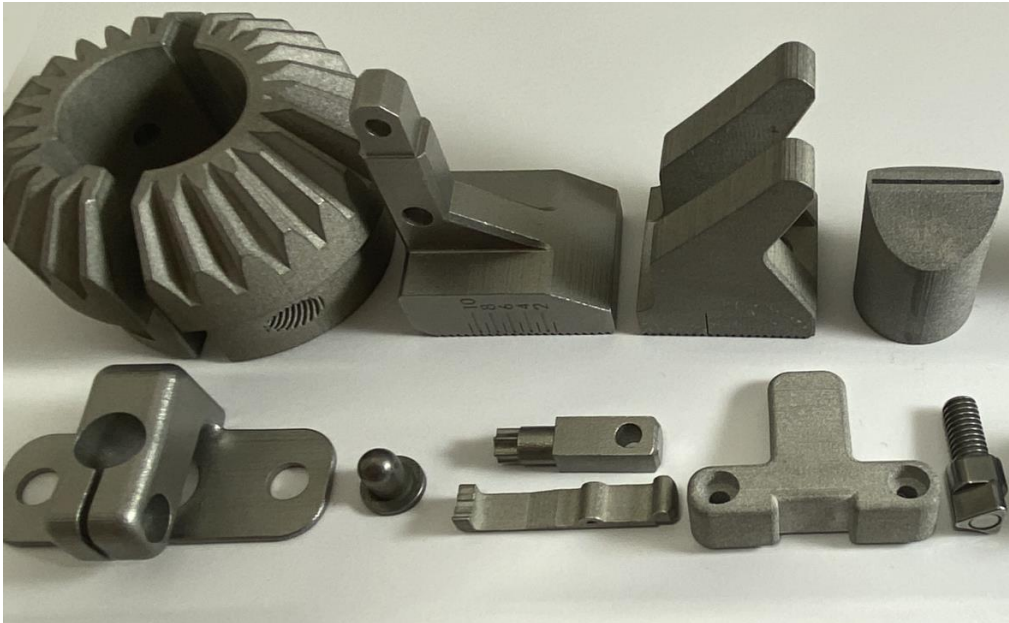


Figure 5 Examples of automotive tooling

BESPOKE AUTOMOTIVE COMPONENTS

Additive Manufacturing of interior automotive components, specifically using Metal Binder Jetting, is able to thrive in creating bespoke automotive components. Azoth is implementing, and has implemented, multiple examples of high value metal components which enable a better end-user experience through customization and high-quality feel. A great example of this is General Motor's 120th anniversary edition emblem that is a limited-edition version of the existing design. The Metal Binder Jetting process simplifies the customization of parts, requiring minimal requalification to achieve the desired specifications. With Metal Binder Jetting, parts can be easily customized by modifying the digital design files, allowing to produce unique parts with minimal additional cost or lead time. Moreover, Metal Binder Jetting can produce complex geometries that would be difficult or impossible to achieve with traditional manufacturing methods. This makes it particularly useful for creating customized parts with intricate designs or functional features, which has already been proven to be beneficial in the jewelry and medical industries. Additionally, Metal Binder Jetting is a scalable technology, which means that it can be used to produce small runs of customized parts cost-effectively, making it an ideal option for applications that require high degrees of customization but low production volumes.



Figure 6 Left: General Motor's 120th anniversary edition shift knob emblem, manufactured as single edition of only 120 vehicles total. Right: General Motor's special edition competition package vehicle, manufactured in limited edition.

AFTERMARKET PRODUCTS

As a result of the possibilities created using Additive Manufacturing in automotive applications, Azoth has been able to expand servicing the aftermarket. A great user application demonstrating this is Jeep's Graphic Studio. Metal Binder Jetting allows for the unique customization of transfer cases and shift knob inserts. These customizations include unique designs or patterns, different finishes, and many color coating options. This direction was found and expanded upon as a direct result to the implementation of Metal Binder Jetting in production automotive applications. The idea of implementing a digital inventory allows the many different combinations and customizations to be stored digitally. This can help prevent long lead times and overproductions as parts are only printed when needed, in line with Azoth's TOMO concept. These customizations are made easy due to Metal Binder Jetting, making it a great option for aftermarket parts in automotive applications.



Figure 7 Different Jeep transfer cases and shift knob emblems

DISCUSSION AND CONCLUSION

To the author's knowledge, the shift knob emblem for the General Motors Cadillac V-series Blackwing used as an example throughout this paper is the first metal additive manufactured part via Metal Binder Jetting to pass all automotive Production Part Approval Process (PPAP) quality requirements and be installed on a production volume vehicle (excluding low volume supercars and hyper cars). General Motors knew that they wanted to implement metal additive technology into their vehicle production and were looking for options within the additive space. This application has been specifically designed for Additive Manufacturing, with features that are impossible or highly inconvenient via traditional manufacturing methods. After initial design validation in 2020, Azoth began manufacturing the shift knob emblem in the first quarter of 2021 and has been in full production ever since, with monthly delivery quantities based on market demand forecast. This part specifically gained a significant promotional value in the media. First, it was used in 2020 by the Cadillac Marketing team as the main teaser image to reveal the V-series Blackwing, which will be the last manual transmission manufactured by General Motors. Moreover, the part was picked up by multiple automotive networks and journals, even being defined as the vehicle's "Hidden Gem" by Car and Driver Magazine published by Hearst Digital Media on Apple News (Fig. 5). Finally, this media exposure shined good light on the additive manufacturing and powder metallurgy industry, with many industry-specific networks sharing the news as well.

This component and the other applications mentioned prove that Metal Binder Jetting can be successful within automotive applications, specifically interior automotive applications. While the introduction of Metal Binder Jetting to the automotive industry is in its early phases, it seems to be more than capable of meeting the standards in place. The use of Additive Manufacturing, specifically Metal Binder Jetting, for other automotive applications like engine components is still scarce due to the lack of confidence in the parts and the lack of cost advantages over traditional manufacturing methods. However, rather than replacing traditional components as gears and shafts, the authors predict the use of Additive Manufacturing, and specifically Metal Binder Jetting in automotive application to drastically increase in the next few years for components designed to take advantage of additive technology design freedom, as parts with internal features, complex surfaces, combining multiple components in single parts, or using new forms of energy conversion to power automotive vehicles.

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