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Additive Manufacturing of Helicopter Transmission Components: A Review of Open Literature

prepared by Kyle Olchewsky
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under contract W15P7T-19-D-0126

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14. ABSTRACT
Additive manufacturing (AM) is being adopted by numerous industries to produce high-performance parts that are often unable to be created using legacy manufacturing methods. This review focuses on recent AM developments that have been published in open literature and their applications to rotorcraft transmission gears and housings. A background of AM processes and terminology is provided with a brief description of legacy transmission manufacturing methods for comparison. The aerospace industry is rapidly researching AM to meet the high-performance demands of future rotorcraft transmissions.

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Kyle Olchewsky	(520) 852-2945

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1. Introduction

Additive manufacturing (AM) is defined by ASTM Committee F42 as the process of joining materials layer by layer to make parts from a 3D model.[1] It is sometimes referred to as 3D printing with the part being "printed" layer by layer and the "ink" being a material ranging from plastics to metals.[2] AM can be a single-step process in which parts are fabricated to the desired geometry with acceptable material properties, or it can have postprocessing steps to improve the finished part's geometry and/or material properties. Improvements to AM technology have resulted in a shift from using 3D printing for rapid prototyping to designing and producing high-performance parts.[2] AM has the potential to revolutionize the power transmission industry because of its ability to enable complex designs that were previously impossible with traditional machining techniques.

2. Additive Manufacturing Processes

There are seven different AM technologies defined by deposition processes[1,2]: powder bed fusion (PBF), material extrusion, directed energy deposition (DED), binder jetting, material jetting, sheet lamination, and vat photopolymerization.[1] Each AM process has its own advantages and limitations, including production characteristics, compatible material types, and design requirements.[1,3] PBF is historically the most widely researched method for drivetrain applications due to the materials and geometric resolution required. PBF will be the focus of this review, although DED is being researched extensively as well. The PBF and DED processes are described below, along with a brief description of the other AM technologies for completeness.

1) Powder bed fusion (PBF) uses thermal energy to fuse specific regions of a powder bed.[1,2] PBF builds up material layer by layer by moving the build platform down in the "Z" direction, as shown in the process diagram in Figure 1 used to illustrate the construction of a gearbox housing. After the energy source selectively fuses regions of a layer, the platform moves down and a recoater bar applies a thin coating of powder at the start of each layer. PBF is often broken down into two separate processes based on the type of energy used.

   Laser powder bed fusion (LPBF) uses a laser of 100 to 1000 W with spot sizes of 30 to 100 μm (0.001 to 0.004 inch) to selectively fuse regions of a powder bed. It is also known as selective laser sintering, selective laser melting (SLM), and direct metal laser sintering (DMLS). LPBF produces high accuracy and low surface roughness parts with deposition rates up to 0.1 kg/h.

Electron beam powder bed fusion is similar to LPBF with the main difference being that the source of thermal energy is an electron beam as opposed to a laser. The part is also created within a controlled vacuum chamber.[2,4,5] Typical spot size ranges between 100 and 200 µm, and deposition rates can reach 0.2 kg/h, both slightly higher than LPBF.[5,6] The powder layer typically undergoes a preheating process to minimize electron accumulation and avoid powder spreading from electrostatic charging.[5,6] Components built with EPBF often do not require a postprocess stress relief and need fewer heat treatments because the build temperature is usually above the stress-relief temperature of the material.[2]

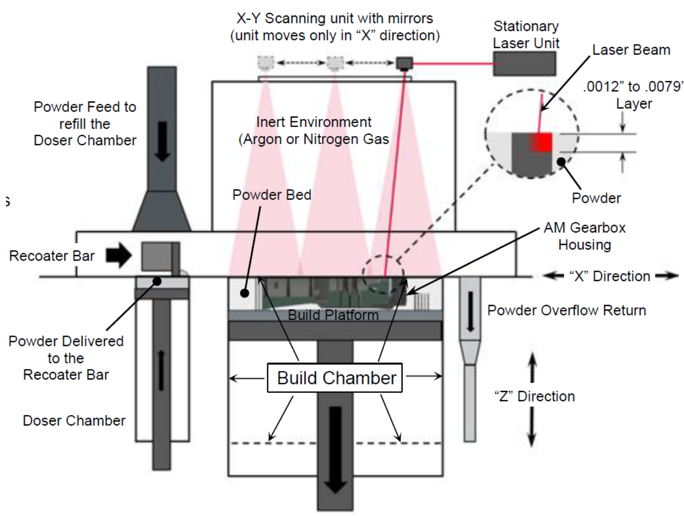


Figure 1. Laser powder bed fusion (LPBF) schematic.[7]

2) Directed energy deposition (DED) uses a high-energy-density heat source such as a laser, electron beam, or plasma/electric arc to form a small melt pool[8] to fuse material as it is being deposited. Laser directed energy deposition (LDED), illustrated in Figure 2, uses a coaxial nozzle to deposit powder particles. The nozzle uses a shield gas to separate the powder from the laser until it is deposited on the substrate. LDED has been shown to enable in situ formation of intermetallic structures and alloying of a wide range of alloys.[9,10] One of the main advantages of DED is deposition rate, with LDED reaching values up to 2 kg/h and electron beam DED ranging from 3 to 10 kg/h. However, high deposition rates can result in significant thermal stresses and high surface roughness that require secondary processing operations to achieve a final part.

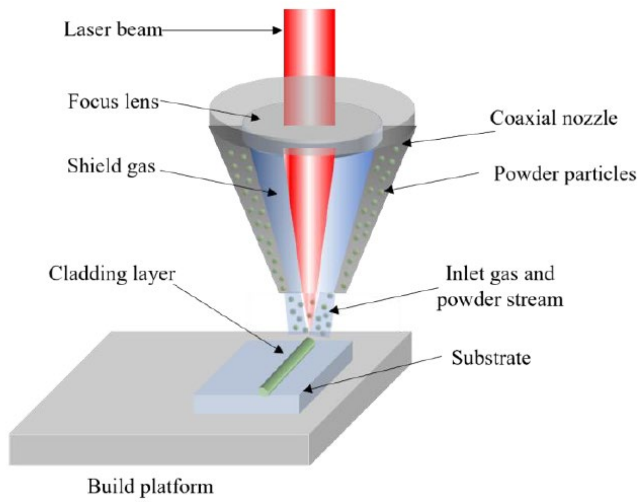


Figure 2. Schematic diagram of laser-directed energy deposition (LDED).[10]

3) Material extrusion (ME) uses a gantry-based motion system where material is fed through a heated nozzle and deposited layer by layer. ME has been used with plastics for several years, and it is a common process many people think of in relation to 3D printing. Recent improvements have also allowed for metals printing based on friction stir welding.[2]
4) Binder jet processing (BJP) selectively deposits a liquid bonding agent over a bed of powder material to form a part. BJP often requires a curing cycle to cross-link and cure the binder.[2,11]
5) Material jetting is a process in which droplets of build material are selectively deposited. It is limited to specific materials such as photopolymer and wax.[1]
6) Sheet lamination bonds sheets of material to form a part.[1] This can be done by gluing or adhesive bonding, thermal bonding, clamping, or ultrasonic welding.[12]
7) Vat photopolymerization selectively cures a liquid photopolymer by light-activated polymerization.[1]

While AM technologies are often able to produce near net shape components, each AM process and specific application has its own unique set of postprocessing requirements to achieve a final part. For drivetrain quality components produced by PBF, postprocessing steps typically include heat treatment to reduce residual stresses and machining of mating surfaces.

3. Traditional Manufacturing of Rotorcraft Transmission Housings

In the late 1950s and early 1960s, there was a significant change to the design and technology of helicopter transmissions with the advent of gas turbine engines. Drive speeds and power increased significantly, and the helicopter industry successfully utilized the manufacturing technologies available to produce reliable turbine-driven rotorcraft transmissions. Since then, emphasis has been placed on producing optimized designs from new technologies that include ways to reduce weight, decrease noise, increase survivability and safety, and lower life-cycle costs.[13]

Helicopter gearbox housings comprise 20% to 60% of the total transmission weight,[13] so lightweight materials of adequate strength are used. Magnesium casting alloys have become the material of choice for many housings due to their high strength-to-weight ratio.[7] Magnesium also has excellent vibration dampening, ease of machining, and electromagnetic shielding.[14] While magnesium alloys have many advantageous material properties, development of magnesium sand casted parts is costly with long lead times that can be prohibitive of design iterations.[14] Casting also requires several postprocessing steps, which include removal of significant amounts of material, straightening, and detection and reduction of defects though hot isostatic pressing and heat treatment.[15]

4. Additive Manufacturing of Transmission Housings

AM has the potential to make significant improvements to aerospace drivetrain components to meet the increasing design requirements of today's helicopter. AM gearbox housings offer the ability for rapid prototyping and increased performance due to the ability to incorporate complex geometries such as internal cooling passages, varied wall thickness, and selective removal of material in specified areas. One of the biggest limitations of aerospace AM gearbox housing development has been materials, as a suitable magnesium powder has not been commercially available.[14] However, gearbox manufacturing with aluminum alloys has shown promising results.

In 2013, the Boeing Advanced Drive Systems Engineering group in Philadelphia began a 4-year Independent Research and Development effort that focused on fabricating a rotorcraft engine nose gearbox housing using AM.[7] The AH-64 A/D nose gearbox (NGB) housing was selected as the AM housing prototype.

The project progressed through all phases of design and manufacturing, including process and material selection, coupon testing, housing redesign to leverage AM benefits, component build, postprocessing, and final testing. Some of the redesigns are illustrated in Figure 3, and these included integrating oil passages and revising the cross-section geometry to decrease material and print time. Another significant redesign was replacing the external cooling "fins" with cooling "pins." The pins reduced weight and computational fluid dynamics (CFD) showed the pins were 45% more efficient than fins due to turbulent airflow that breaks up the boundary layer.[7] Although the production gearbox housing was made of ZE41A-T5 cast magnesium alloy, AlSi10Mg was used for the AM prototype because magnesium powder was not commercially available. Despite AlSi10Mg being approximately 35% more dense than magnesium alloys, the final NGB weight was only 6% heavier than the production housing due to selective material removal enabled by AM.

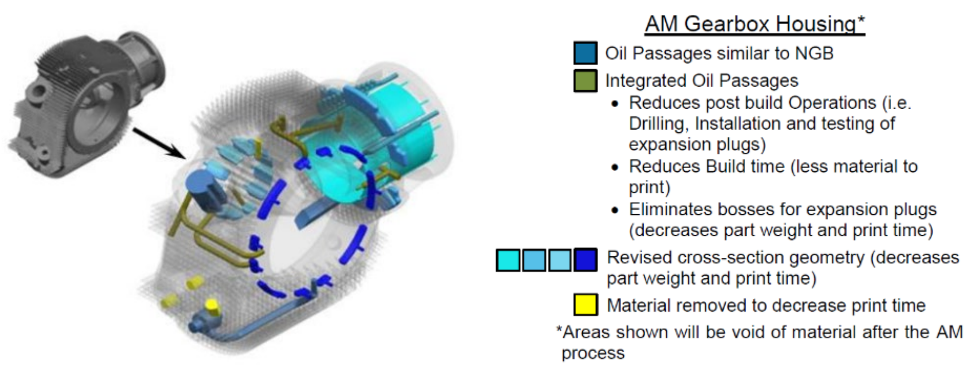
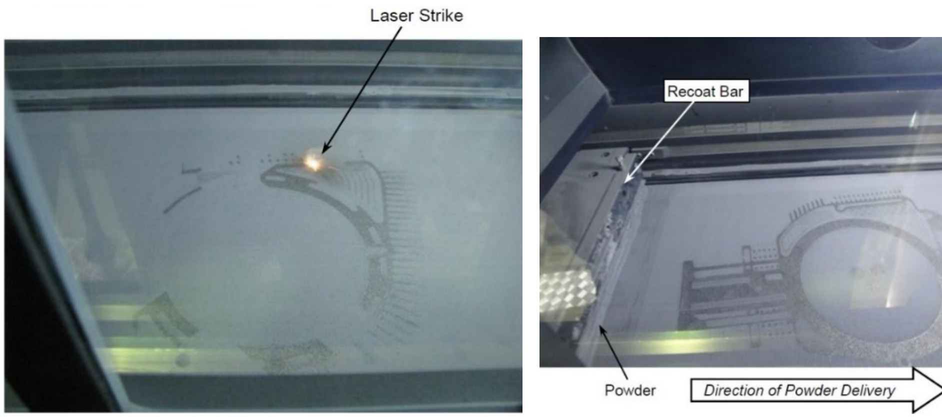


Figure 3. AM gearbox redesign with integrated oil passages and revised geometry to reduce weight.[13]

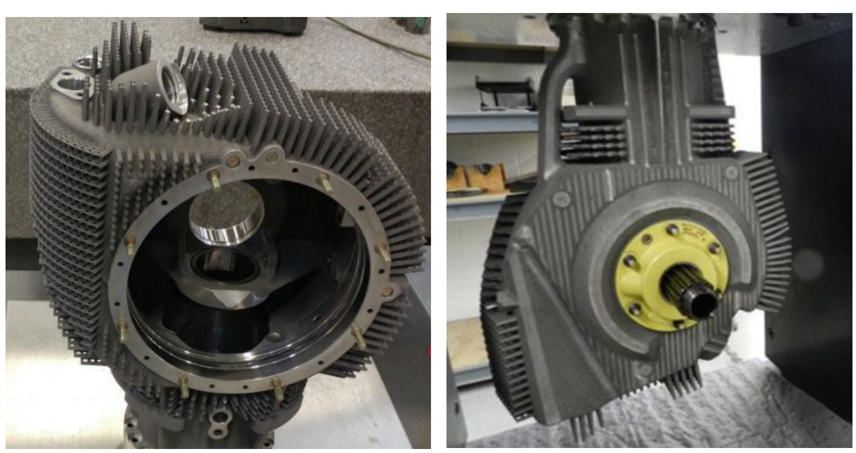
The housing was printed using LPBF SLM with a 60-µm (0.0024-inch) layer thickness. Figure 4 shows different steps in the build process. Figure 4a shows the laser strike as it selectively fuses powder to build up a layer of the housing. Figure 4b depicts a completed build layer and the location of the recoat bar that will spread a thin layer of new powder to begin the next layer. The dark gray regions are areas of fused powder that make up a cross section of the housing, and the light gray is unfused powder that will be removed.



(a) (b)

Figure 4. View looking into LPBF build chamber showing (a) build layer in progress and (b) completed build layer awaiting new layer of powder applied by recoat bar.[13]

Four separate housings were printed, and difficulties were experienced at various stages during build up with each of the four builds. These included a failed layer due to software glitches and misalignments after the build was paused for machine maintenance. All four final builds contained cracks and other defects that would have likely been rejected in a production environment. However, some of the printed housings were able to be machined and repaired, and one of the original four housings was selected to go through the full machining and assembly process to produce a complete gearbox. Figure 5a shows the AM gearbox housing after postprocess machining during sub-assembly to clean up mating surfaces. Figure 5b shows the completed gearbox assembly including installation of shafts and bearings.



(a) (b)

Figure 5. AM gearbox housing at different stages during assembly: (a) after machining and hardware installation and (b) completed gearbox assembly.[7]

Another AM opportunity arose during assembly when the steel input bearing liner's lead time was projected to be 28 weeks. The bearing liner's tight tolerances and thin-walled geometry resulted in a difficult-to-manufacture part that is typically produced from steel bar in which 95% of material would be removed. The liner was instead manufactured using AM with postprocess machining and completed in 2 weeks, which highlighted the ability of AM to rapidly produce high-quality parts.[7]

After assembly, the NGB was tested to prove its ability to withstand aircraft flight loads. Testing included a 50-h endurance experiment with a final inspection. The housing successfully completed the experiment, and the posttest inspection did not detect cracks or unusual wear of internal components. These experiments demonstrated the feasibility of an AM rotorcraft drivetrain housing and signified a milestone in the application of AM components to the aerospace industry.[7] However, the numerous difficulties encountered as well as the sub-optimal build quality and repeatability offer many opportunities for further research and process improvements.

Boeing went on to design and manufacture a Chinook AM flight-critical transmission housing in 2021, seen in Figure 6, that successfully completed test flights. Although little is published in open literature regarding the design and manufacturing of this housing, Boeing was able to build upon past prototypes and create a repeatable process that met flight-worthy component requirements. AM allowed for lower lead times as well as design improvements for the Chinook test flights.[16]

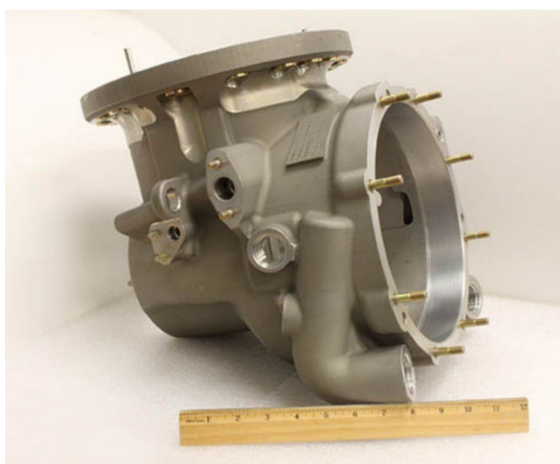


Figure 6. Boeing Chinook 3D-printed transmission housing that withstood the stress of rotorcraft flight.[16]

The automotive industry has also been proving the flexibility and applicability of AM for gearbox housings. Hypercar maker Czinger developed a gearbox case printed in a proprietary aluminum alloy that the company claims is the first 3D-printed automotive gearbox case.[17] Rodin cars 3D printed an eight-speed gearbox out of titanium LaserForm Ti Gr23 (A).[18] The automotive industry–based research and applications can offer new insights into designs and materials that can be refined to the aerospace industry.

5. Traditional Manufacturing of Rotorcraft Transmission Gears

Rotorcraft drivetrain gearing has had numerous advancements in recent decades to keep up with improvements in engine speed, power, and requirements for reliability and durability. The main gearbox is responsible for taking the high-speed low-torque power from the gas turbine engine and converting it to lower speed and higher torque applied to the main rotor. Many helicopter transmissions have reduction ratios on the order of 80:1 to 100:1 and often achieve this through several stages of gearing including spiral bevel gears and planetary gears.[13] Contact stresses can be upward of 1.5 GPa (220,000 psi) and bending stresses can be 0.4 GPa (60,000 psi).[13] Overall specific weights are typically around 0.30 to 0.50 lb/hp.[13] Reliability and weight far outweigh cost as the dominant factors for aircraft applications.[19] Gears make up a substantial portion of the overall aircraft weight, and their reliability is essential for flight.

AISI 9310 and X53 are the most commonly used gear steels in current U.S. helicopter transmissions.[13] Other materials such as Vasco X2, CBS 600, and CBS 1000 have also been incorporated or researched historically. Gear manufacturing is a multistep process that begins with casting, forging, or drawing. The gear is then machined through hobbing and/or grinding, is heat treated, and surface finished.[20] One of the most significant advancements to improve the quality of gearing materials is the use of double vacuum melt steel. This process uses vacuum-induction-melt (VIM) in combination with vacuum-arc-remelt (VAR) to produce a homogenous material with reduced inclusions and superior cleanliness. VIM VAR has been shown to increase fatigue strength and fracture toughness of gear steels and other metals.[13,21]

6. Additive Manufacturing of Rotorcraft Gears

AM has the potential to significantly change the gearing industry, with options for better materials and complex geometries. These new design opportunities can lead to lower weight gears with as good or even better reliability than current standards. AM can also enable enhanced gear performance characteristics such as improved cooling and reduced vibration with new designs that are unachievable using standard machining methods.[22]

6.1 Additive Manufacturing Gear Materials

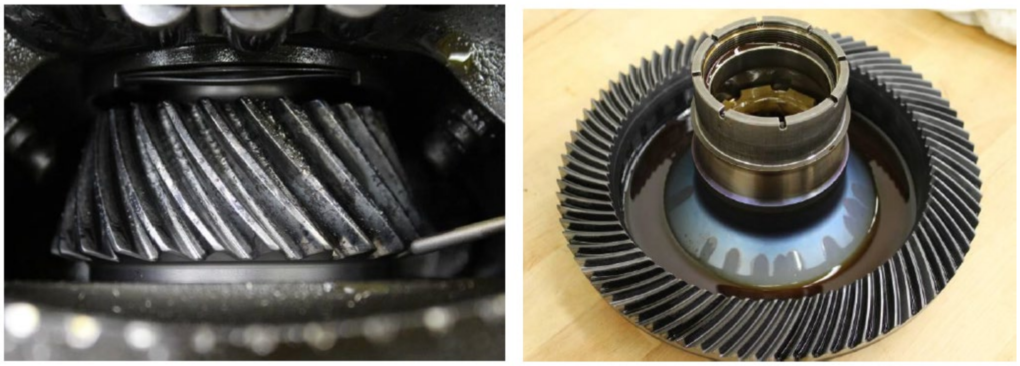
One of the biggest challenges with adapting AM to gears has been availability of suitable materials. Common gear steels such as AISI 9310 and X53 had not been readily available in the particle size range required for AM.[23] However, AISI 9310 has recently been atomized and is now commercially available, along with several other common gear steels such as AISI 8620, 20MnCr5, and 16MnCr5.[2]

AM powder deposition has the potential to replace traditional forging, casting, or drawing. However, current AM methods such as LPBF have print resolutions that still require machining and other postprocessing for adequate material properties and surface finish. Figure 7 provides an example of the different production steps for an LPBF-produced gear, including initial deposition, copper plating, carburization, initial and final machining, and shot peening to produce a final gear.

(a) (b) (c) (d)

Figure 7. Images of Ferrium C64 steel gears through postprocessing steps: (a) after deposition and hot isostatic pressing, (b) after copper plating and initial machining, (c) after carburization and final machining, and (d) after shot peening.[24]

The Army released a Small Business Innovation Research (SBIR) solicitation in 2015 to find an alternative gear steel to X53 that is able to achieve similar properties via AM.[25] This SBIR was awarded to QuesTek Innovations based on their innovative Ferrium C64 steel. C64 steel is an ultrahigh-strength, high-toughness, case-hardenable, secondary-hardening steel that was designed as an upgrade to legacy gear materials such as 9310.[26] Its high tempering temperature enables elevated temperature performance, including superior loss of lubrication performance.[27] Both Bell and Sikorsky / Lockheed Martin selected wrought C64 as the gear material in the Future Advanced Rotor Drive Systems (FARDS) program, whose main objectives included increasing power density and increased oil-out performance.[25] The FARDS main rotor gearbox (MRGB), an enhanced version of a Bell 407, similar to the OH-58D Kiowa Warrior, successfully completed the Technology Readiness Level–6 testing, which included the 30-min loss of lubrication (LOL) requirement.[23] Figures 8a and 8b show Ferrium C64 Bell FARDS input pinion (left) and gearshaft (right) with minor scuffing but no indication of surface damage or failure after a 85-min loss of lube operation, which significantly outperformed the 30-min requirement. These gears were produced using wrought C64 and traditional machining methods, and the test demonstrated the viability and enhanced oil-out performance of the material.



(a) (b)

Figure 8. FARDS MRGB Ferrium C64 components after LOL: (a) input pinion and (b) gearshaft.[23]

QuesTek successfully atomized C64 steel into powder form and demonstrated that AM components manufactured via DMLS have material properties that meet or exceed those of wrought C64.[2,25] Recently, they investigated the recyclability of LPBF Ferrium C64 powder. Powder waste has been one of the major downsides of LPBF since large volumes of un-sintered power are necessary during buildup to support the component. QuesTek developed six different powders based on increasing ratio of recycled powder to virgin powder, with an illustration of material composition provided in Figure 9a. The yield strength, percent elongation, and S-N curve were determined for each build material using LPBF to produce test specimens. The data is shown in Figures 9b–d. Notably, the AM builds outperformed the wrought steel for each of the respective material properties studied, and there was consistency across the different builds.[24] QuesTek is currently conducting research to expand C64 to other AM processes, including DED and binder jet, and has demonstrated that various processes are able to produce similar properties to those of wrought, including yield strength and elongation.[24,26] Open literature does not indicate QuesTek has as of yet produced gears for contact fatigue testing.

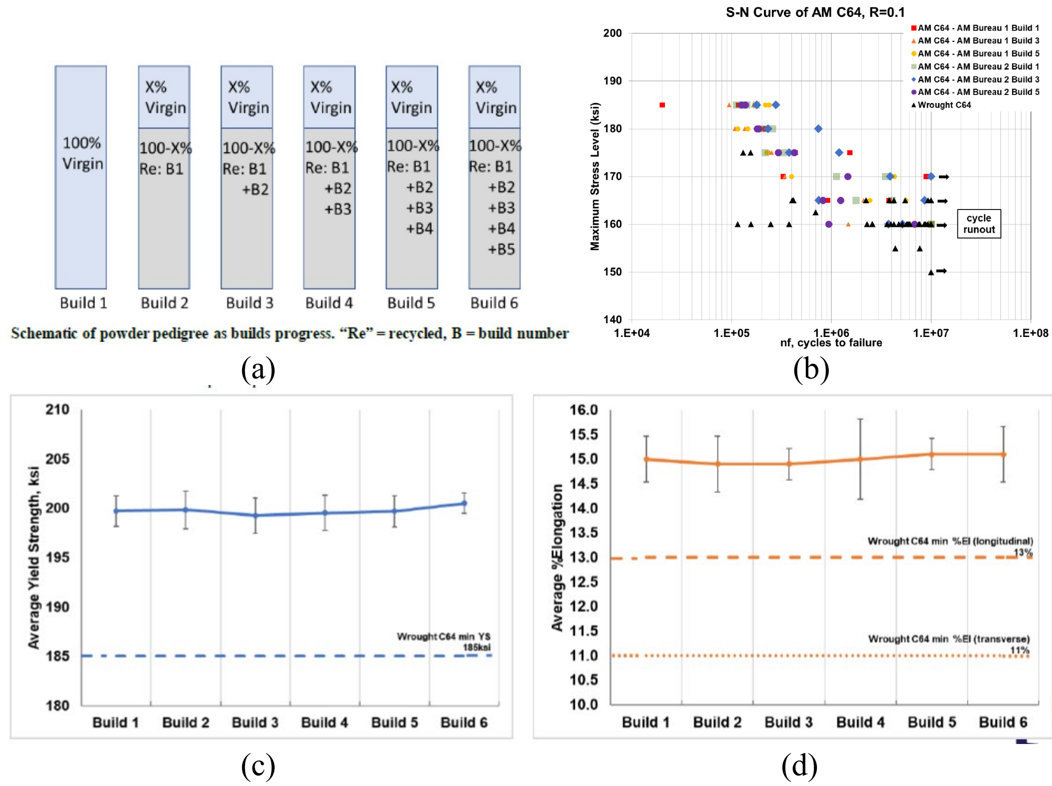
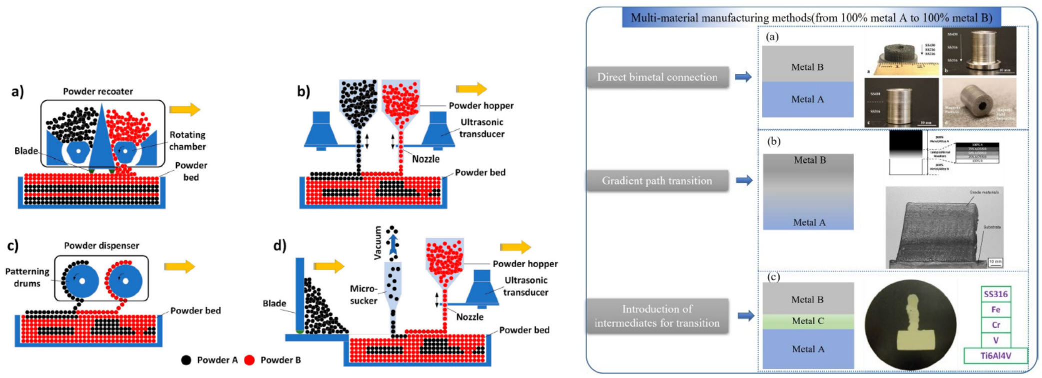


Figure 9. **QuesTek recyclability study using LPBF builds of different recycled composition ratios: (a) illustration of powder pedigrees for Builds 1–6, (b) S-N curves, (c) yield strength data, and (d) percent elongation.[24]**

Also studied as a possible material for AM gears is 17-4 PH stainless steel.[22] Concli et al. investigated 17-4 PH gears produced by LPBF (PBF-LB/M) that were then machined with traditional machining tools.[22] This study was intended to serve as a baseline for evaluating heat and surface treatments, so these gears did not have any mechanical or heat treatment postprocessing. The fatigue limit was determined at 50% failure probability, and the results showed the tested material's properties are similar to those of common gear steels. However, the importance of reducing AM defects was noted.[22]

Multimaterial hybrid AM is a developing technology that utilizes two or more powder materials deposited at specific locations within a build to improve performance and functional properties such as wear, temperature, and corrosion resistance.[10,28] Multimaterial AM has significant potential within gear technology to allow selection of different desired mechanical properties at various parts on a gear. For example, multimaterials can be incorporated to design a gear with a high-tensile-strength material for the tooth core and a high-hardness material for the tooth surface. Another application could be a lightweight gear hub material combined with a higher tensile strength gear tooth material to reduce overall weight.

Multimaterial AM has several challenges. One challenge is accurately depositing the correct material at a high resolution to meet design requirements. Figure 10a illustrates some methods investigated for material deposition using LPBF, including a) blade based recoaters, b) ultrasonic powder dispensers, c) electrophotgraphic powder dispenser, and d) a combination of blade and ultrasonic powder dispensing.



(a) (b)

Figure 10. Multimaterial challenges and potential solutions: (a) LPBF material deposition processes[28] and (b) material transition strategies.[10]

The transition between two materials has also been challenging as it is prone to high stress concentrations and can lead to fracture or delamination. A direct connection, gradient interface transition, and the introduction of intermediates, as shown in Figure 10b, have been researched as ways to transition from one material to another. However, additional research is needed to fully understand and optimize the process and the interface between the materials.

6.2 New Gear Designs Enabled by Additive Manufacturing

Significant research is being performed to leverage AM gear designs to reduce weight, enhance durability, and increase performance of rotorcraft transmissions. The ability to manufacture previously impossible geometries has opened the door to new designs that can help improve or solve fundamental rotorcraft problems.

Historically, noise has been a parameter of concern in helicopter design and development, since noise levels in the cabin reach upward of 100–120 dB.[29] Coy et al. determined a large portion of cabin noise is associated with the gear mesh behavior, with the largest contributors being the spiral bevel gear mesh and the planetary gear train.[29] Helicopter noise has continued to increase with decreased weight of gearboxes and increased power-to-weight ratio of the transmissions.[29] Thus, noise reduction technologies continue to be an important design consideration with growing power-to-weight capabilities.

AM can provide a potential solution to decreasing gear vibration and noise due to its ability to create complex structures that previously were unable to be manufactured. Ramadani et al. investigated cellular lattice gear structure as a design to reduce the mass and vibration of the gear.[30] The 90-mm tip diameter gear was fabricated by SLM using Ti-6Al-4V alloy. It was designed with a cube diagonal lattice cell chosen for the inner part of the gear body and a plane diagonal lattice cell for the outer part of the gear body. Three gear designs were tested: a solid–solid gear pair, solid–lattice gear pair, and a solid–lattice polymer-filled gear pair in which the void regions between lattices were filled with a polymer. The three designs are shown in Figure 11.

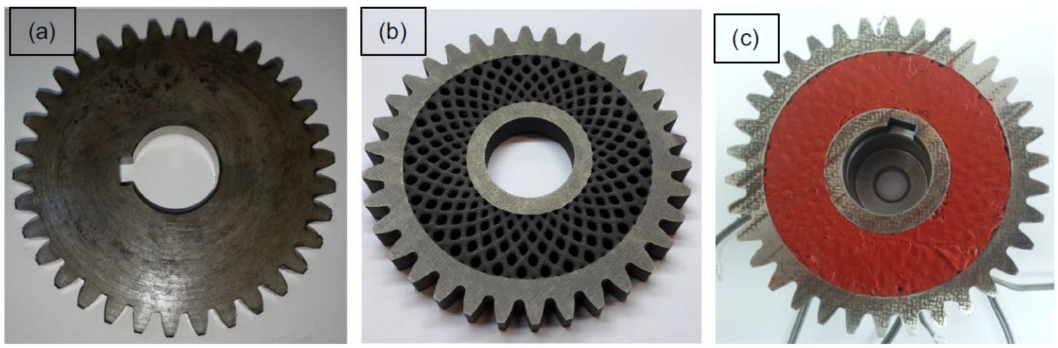


Figure 11. Gears used for sound pressure measurement experiments: (a) solid body gear, (b) lattice structure gear, and (c) lattice structure with a polymer inserted.[30]

The gears were run on a spur gear rig in mesh with a solid gear. Sound pressures were measured using a microphone at test conditions of 340, 630, and 950 rpm and a torque of 40 Nm. The results are shown in Table 1. Compared with the solid–solid gear mesh, the solid–lattice structure gear mesh showed an average decrease of sound amplitude of roughly 30% and the solid–lattice with polymer mesh decreased the amplitude by an additional 20% at the three speeds. Although the amplitude reductions varied with speed, it was shown that the lattice structure consistently decreased sound amplitude compared with a solid gear, and inserting a polymer in the lattice provided additional sound dampening. It was also noticed that the amplitudes of all notable harmonics were more equilibrated.[30]

Table 1. Sound pressure of different gear designs for three speeds at torque T = 40 Nm.[30]

Gear design	340 rpm (Pa)	630 rpm (Pa)	950 rpm (Pa)
Gear with a solid body (Figure 14a)	0.32	0.9	1.2
Gear with a lattice structure (Figure 14b)	0.13	0.71	0.97
Gear with a lattice structure with a polymer inserted (Figure 14c)	0.11	0.42	0.8

Another growing trend in the aerospace drivetrain industry is condition-based monitoring via integrated sensors.[31] This creates new requirements for sensors to be positioned closer to the source. Binder et al. investigated an AM 16MnCr5 gear that was designed to include a tri-axis accelerometer and cavity for sensor integration of the antenna.[31] During fabrication, the AM process was paused and an electronic printed circuit board (PCB) was inserted. The antenna was manually soldered to the sensor board in the cavity. Fabrication continued to close the cavity and complete the gear. The antenna location can be seen in Figure 12a. A CT scan, shown in Figure 12b, verified electrical contact between the antenna and RFID transponder, and the functionality was checked by the readability of the data. At slow speeds (1 rpm) and close distance (1 cm) between the reader and gear, data was collected and successfully verified operation of the system. This research provided insight that integrated sensors within a gear may be a viable process to monitor gear conditions. However, more work is needed to address the inability of PCB to withstand heat treatment required for production gears, as well as the need for higher data transmission rates and increased readout range.[31]

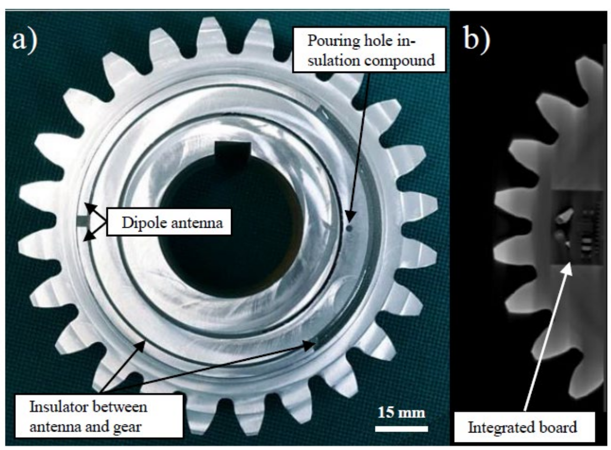


Figure 12. AM gear with integrated sensors: (a) dipole antenna and insulation location and (b) CT scan verifying correct positioning of integrated PCB.[31]

Objectives to reduce energy consumption and increase power have led to research focused on increasing transmission efficiency. Siglmüller et al. investigated AM gears with integrated cooling channels to decrease gear temperature and study the effects on efficiency.[32] The internal channels allowed a cooling fluid to flow through the gear teeth close to the gear flank to dissipate heat from the inside of the gear. Gears were tested on a FZG efficiency test rig at different operating conditions. Temperature data was recorded for two different loads, 1022 N/mm^2 and 685 N/mm^2, and plots of the data are shown in Figure 13. The gears without internal cooling channels are represented as solid lines, and the gears with cooling channels are shown as dashed lines. At a load of 1022 N/mm^2 the temperature was roughly 40 °C lower with active cooling than without. This trend was common across all speeds and loads recorded, with the internal cooling effectively reducing pinion tooth bulk temperature at all test conditions. The study also noted that initial results showed at a no-load condition the gear loss increased with decreasing coolant temperature, but it was believed this was due to higher effective oil viscosity in the mesh.[32]

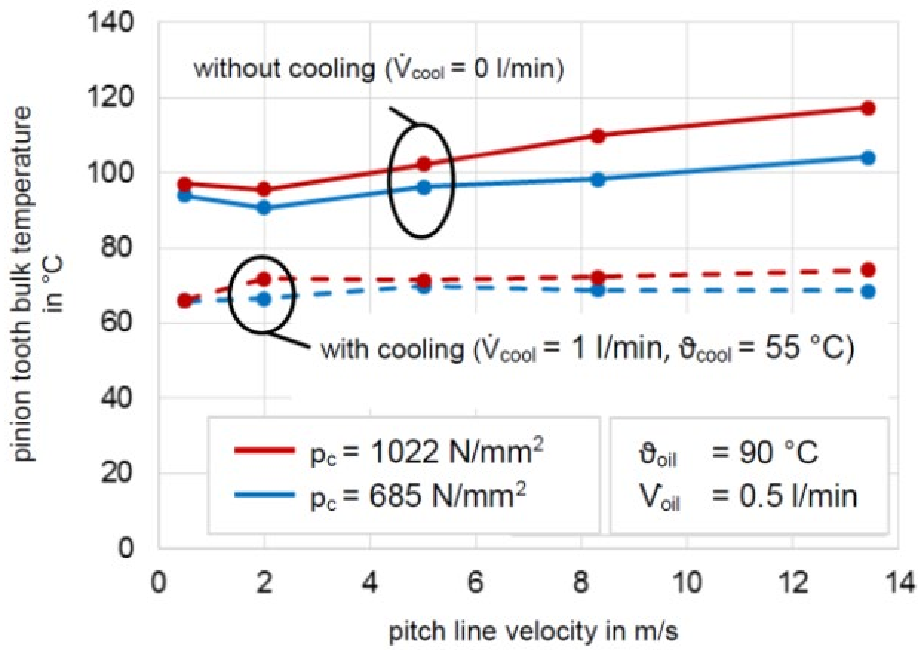


Figure 13. Tooth bulk temperature of gears with and without internal cooling channels.[32]

Internal gear cooling channels have also been researched for their potential to increase the safety factor against scuffing. Dennig et al. researched a quenched and tempered 30CrNiMo8 steel gear with internal cooling channels.[33] 30CrNiMo8 was chosen over common AM gear steel 16MnCr5 because of its high strength and toughness, and to demonstrate feasibility of AM using a difficult-to-process steel that had not been studied extensively. The gear design was similar to the standard FZG Type-A 91.5-mm center distance geometry, except that the tooth width was reduced from 20 mm to 10 mm on the pinion to achieve scuffing on the given test rig. The internal cooling channels were designed with a serial flow and a 2-mm circular cross section. The flow design is shown as a 3D model in Figure 14a, and the CT scan in Figure 14b was used to verify the cross section of the internal channels.

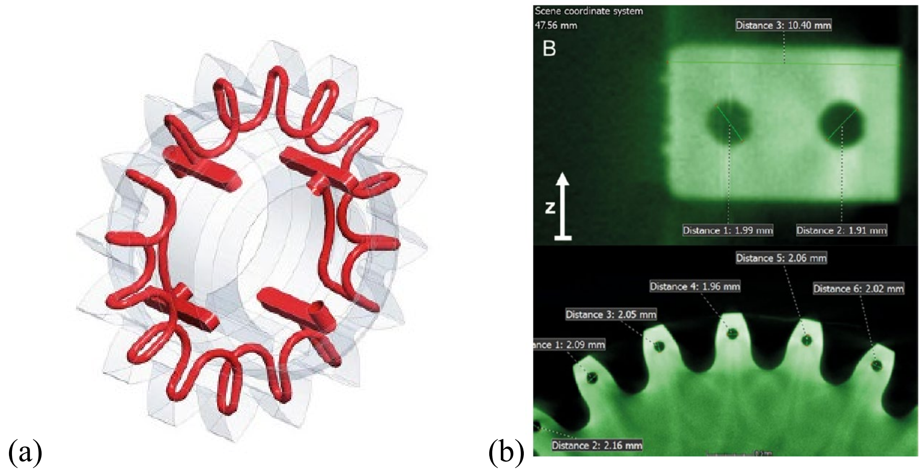


Figure 14. Gear with serial flow internal cooling channels: (a) illustration of the channel path and (b) CT scan of gear tooth cross section.[33]

The gears were tested at a speed of 2350 rpm under increasing load stages between 24 and 78 Nm, and an oil without additives was used to induce scuffing. To evaluate the gears, the contact pattern was examined between stages to determine the scuffing area. The data is shown in Figure 15. Gears without cooling channels started scuffing at 34 Nm, while gears with cooling channels started scuffing at 55 Nm. The plot of the standard deviations shows repeatability among the data, and a notable difference in scuffing at all load stages between the gears with and without cooling channels. It was concluded that the cooled teeth are expected to increase scuffing resistance by approximately 30%.[33]

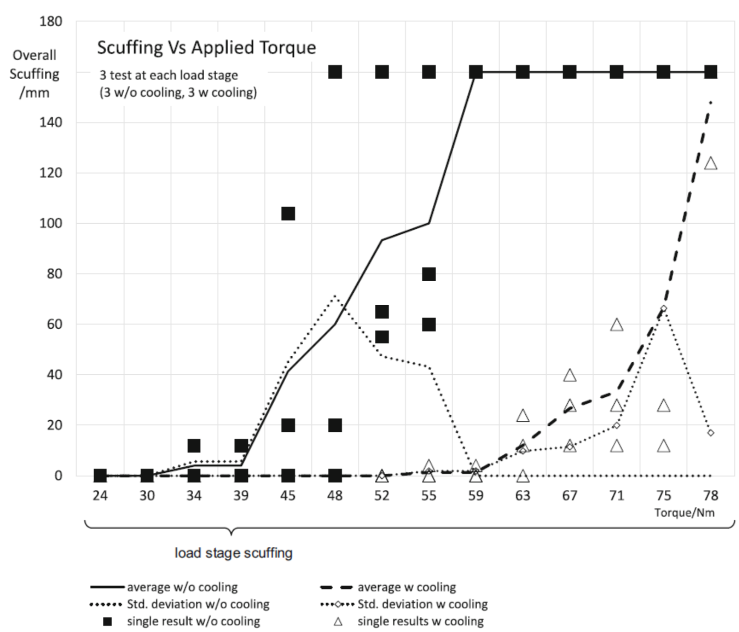


Figure 15. Scuffing vs. applied torque of gears with and without internal cooling channels.[33]

7. Additive Manufacturing Defects

Numerous studies have encountered difficulties due to defects in AM components related to the production process. More research needs to be conducted to reduce these defects and reliably manufacture parts that would pass current quality-control requirements.

During Boeing's research effort to produce an AH-64 nose gearbox capable of withstanding flight loads, all four of the test builds encountered planned or unplanned events that negatively affected the part quality enough that it is likely they all would have been rejected in a production environment.[7] Some of these events included part separation from the build plate, fractured build supports, build misalignment, porosity, and cracking. The misalignments occurred during a pause in the build, either due to scheduled maintenance such as refilling the powder or unplanned faults of the build machine.[7]

Examples of part separation, fractures, and cracks are shown in Figure 16. They are believed to be a result of thermal stresses encountered during the build process. Examples of porosity and non-fused areas that were also discovered in the build specimens are shown in Figures 16b and 16c. These defects were caused by uneven powder distribution of each layer and insufficient powder present for fusion.[7]

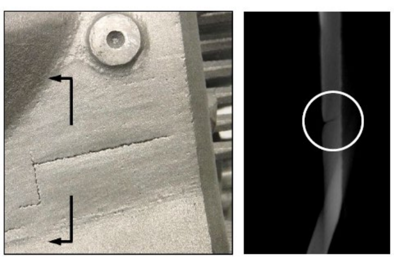
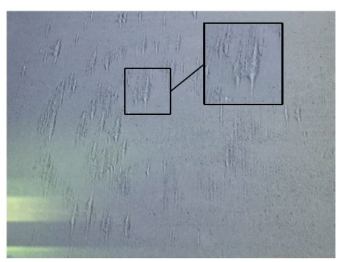
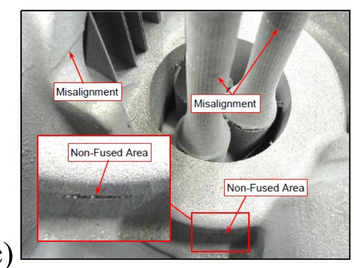
(a) 
(b) 
(c) 

Figure 16. AH-64 AM housing defects: a) visible cracks, b) uneven distribution of powder across build area, and c) non-fused areas.[7]

AM gears have exhibited problems during research that led to accelerated pitting damage on the tooth surface, which is thought to be caused by defects introduced during the build process, including cracking and porosity. Texel et al. investigated failure modes of AM 420 steel spur gears by comparing AM gears, AM and surface-polished gears, and conventionally manufactured gears.[34] The gears were operated at speeds of 250, 500, and 1000 rpm and low torques of 0.25 and 0.5 Nm for 10^5 cycles. The AM parts exhibited similar density and hardness to those manufactured by conventional methods. However, the wear on gear teeth produced by DMLS was significantly greater than wear of the gear teeth produced by a conventional hobbing machine, which can be seen in Figures 17a and 17b. The wear on the AM gears was investigated and determined to be mostly caused by non-sintered powders. The surface polishing after AM did have a preventive effect on gear wear and damage, as shown in Figures 17a and 17b, as the AM-polished gear exhibited less wear than the unpolished at almost all experimental conditions.[34] It was therefore concluded that postprocessing methods including surface polishing are beneficial in preventing wear and damage of AM gears.[34]

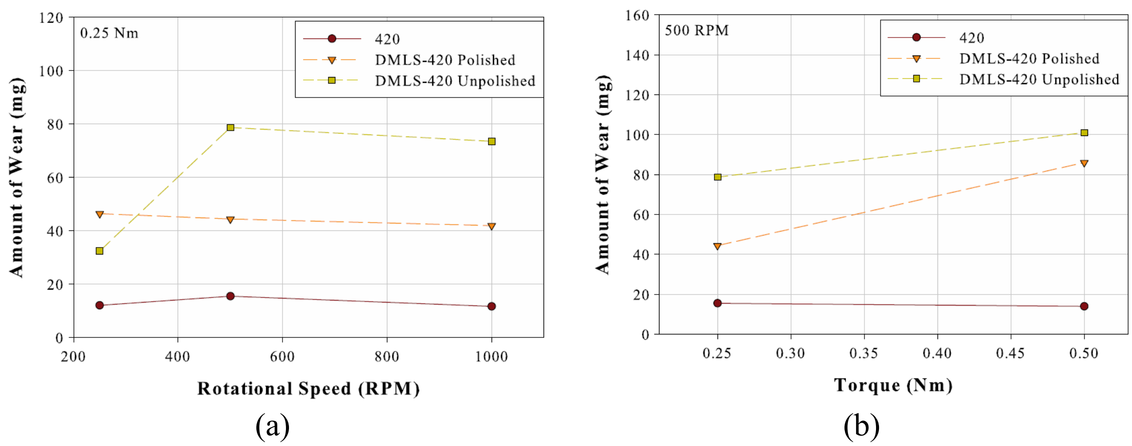


Figure 17. Wear of 420 steel gear teeth (a) depending on rotational speed at 0.25 Nm and (b) depending on torque at 500 rpm.[34]

8. Conclusion

AM has the potential to facilitate significant improvements to the aerospace drivetrain industry. 3D printing has been used for rapid prototyping, but a recent shift has seen AM adapted to produce high-performance parts with complex geometries that would be impossible to fabricate using traditional methods.

Gearbox housings that are traditionally made of sand-casted magnesium alloys have been researched as components that can benefit from AM. Boeing has shown that an AH-64 NGB can be successfully fabricated with AM methods and withstand flightworthy fatigue loads. AM allowed for design improvements that reduced weight, added cooling channels, and increased thermal cooling efficiency.[7] More recently, Boeing completed a successful flight test with an AM gearbox in a Chinook.[16]

The research community has also investigated the advantages of AM gears. Advancements such as gear body lattice structures to reduce weight and vibration, integrated sensors to facilitate condition monitoring, and cooling channels to reduce gear mesh temperatures have shown promising results.

One of the main factors limiting AM implementation at a production level for rotorcraft transmissions has been the available materials. While magnesium alloys and gear steels have historically been restricted due to the inability to be atomized into a powder for AM, recent developments and new materials are paving the way for AM to expand. Ferrium C64 has been selected as one of the primary gear materials of choice for next-generation aircraft, and its ability to be fabricated via AM and exhibit material properties exceeding wrought is being researched extensively.

Another historical disadvantage of AM components has been a lack of repeatable build quality. The thermal stresses encountered during the build process result in cracking or high-stress zones that can lead to premature part failure. The incorporation of postprocessing methods such as heat treatment and surface treatments have shown to resolve some of these issues, although more research is needed to reliably produce aircraft drivetrain-worthy components at a production level. Adoption of AM gears in particular will require significant additional research to determine their ability to withstand high-contact stresses and demonstrate adequate fatigue life for aircraft drivetrains.

Weight reduction, higher efficiency, and increased performance are all demands of future aerospace drivetrain components. AM housings have shown significant viability to flight applications, although the design advantages have only begun to be explored. AM gear research has demonstrated the use of LPBF and DED to produce high-quality metal coupon specimens that meet or exceed wrought equivalents. However, application of AM gears to the component and system level that can withstand flight speeds and loads with adequate fatigue life needs to be investigated further. Novel AM gear designs have been explored and have demonstrated proof of concept of topics such as integrated cooling channels, lattice structures, and multimaterial specimens, but more developments are needed to transition these designs and technologies to production-level components. AM has the potential to revolutionize rotorcraft drivetrain technology. The new design freedoms and flexibility it offers have only begun to be explored.

9. References

1. ASTM ISO/ASTM52900-15. Standard terminology for additive manufacturing - general principles – terminology. ASTM International; 2022.
2. American Gear Manufacturers Association. Additive manufacturing technologies for gears. The Barnes Group Advisors, LLC; 2019.
3. Thompson MK et al. Design for additive manufacturing: trends, opportunities, considerations, and constraints. CIRP Annals - Manufacturing Technology. 2016;65:737–760.
4. Christensen A, Kircher R, Lippincott A. Qualification of electron beam melted (EMB) Ti6Al4V-ELI for orthopaedic applications. Medical Device Materials IV: Proceedings of the Materials and Processes for Medical Devices Conference 2007. p. 48–53.
5. Pragana JPM, Sampaio RFV, Braganca IMF, Silva CMA, Martins PAF. Hybrid metal additive manufacturing: a state-of-the-art review. Advances in Industrial and Manufacturing Engineering. 2021;2:85–94.
6. Narra SP. Powder bed fusion - metals. In: Caballero FG, editor. Elsevier; 2022. (Encyclopedia of materials: metals and alloys; vol. 3.)
7. Cross GM, Filler RR. Boeing Research & Technology. Additive manufacturing (AM) of a rotorcraft gearbox housing independent research & development (IRAD) project. Vertical Flight Society Forum. 2019;75.
8. Svetlizky D et al. Directed energy deposition (DED) additive manufacturing: Physical characteristics, defects, challenges and applications. Materials Today. 2021;49:271–295. ISSN 1369-7021.
9. Shishkovsky I, Missemer F, Smurov I. Metal matrix composites with ternary intermetallic inclusions fabricated by laser direct energy deposition. Composite Structures. 2018;183:663–670. ISSN 0263-8223.
10. Yue W, Zhang Y, Zheng Z, Lai Y. Hybrid laser additive manufacturing of metals: a review. Shantou University; 2024.
11. Mostafaei A et al. Binder jet 3D printing—process parameters, materials, properties, modeling, and challenges. Progress in Materials Science. 2021;119. ISSN 0079-6425.
12. Gibson I, Rosen D, Stucker B, Sheet lamination processes. Additive Manufacturing Technologies. Springer; 2010.

13. Weden GJ, Coy JJ. Summary of drive-train component technologies in helicopters; National Aeronautics and Space Administration; 1984. NASA Technical Memorandum 83726; USAAVSCOM Technical Report 84-C-10.

14. Luo AA. Magnesium casting technology for structural applications. Journal of Magnesium and Alloys. 2013;1(1):2–22

15. Woodworth H. Digital transformation of a 6000-year-old process. Vertical Flight Society 78th Annual Forum and Technology Display; 2022; Fort Worth, TX.

16. Sertoglu K. Boeing takes to the sky with Chinook's first 3D printed flight-critical part. 3D Printing Industry; 2021 Aug 9 [accessed 2021 August 9]. https://3dprintingindustry.com/news/boeing-takes-to-the-sky-with-chinooks-first-3d-printed-flight-critical-part-194134/

17. Kremenetsky M. Hypercar maker czinger reveals "world's first" 3D printed gearbox case. 3DPrint.com; 2023 Mar 15 [accessed 2023 March 15]. https://3dprint.com/298677/hypercar-maker-czinger-reveals-worlds-first-3d-printed-gearbox-case/

18. Rodin cars uses 3D printing to produce titanium gearboxes for ultimate hypercar. 3D Systems; n.d. [accessed 2025 July 10]. https://www.3dsystems.com/customer-stories/rodin-cars-uses-3d-printing-produce-titanium-gearboxes-ultimate-hypercar

19. Coy JJ, Townsend DP, Zaretsky EV. Gearing. National Aeronautics and Space Administration; 1985. NASA Reference Publication 1152; AVSCOM Technical Report 84-C-15.

20. Radzevich SP. Dudley's gear handbook. CRC Press Taylor & Francis Group; 2012.

21. Zaretsky EV. Bearing and gear steels for aerospace applications. National Aeronautics and Space Administration (US); 1990. NASA Technical Memorandum 102529.

22. Concli F et al. Bending fatigue behavior of 17-4 PH gears produced by additive manufacturing. Appl Sci. 2021;11(7):3019.

23. Chavez A, Baker T, Fetty J. Future advanced rotorcraft drive system (FARDS) full scale gearbox demonstration. AHS International 73rd Annual Forum & Technoogy Display; 2017.

24. Kozmel T. Ferrium steels and additive manufacturing – QuesTek. Vertical Flight Society; 2023.

25. Grabowski J, Kozmel T. New high-performance materials tailored specifically for additive manufacturing processes. Proceedings of the AHS International 74th Annual Forum & Technology Display; 2018 May 14–17; Phoenix, AZ.

26. Kozmel T et al. Additive manufacturing of ferrium C64 for aerospace gear applications. Presented at Vertical Flight Society Forum 75; 2019 May.

27. Taskin K. Ferrium steels and other high performance materials for next generation rotorcraft transmissions and applications. Presented at 45th European Rotorcraft Forum; 2019 Sep 17–20; Warsaw, Poland.

28. Wei C, Li L. Recent progress and scientific challenges in multi-material additive manufacturing via laser-based powder bed fusion. Virtual and Physical Prototyping. 2021;16(3):347–371. https://doi.org/10.1080/17452759.2021.1928520

29. Coy JJ, Handschuh RF, Lewicki DG, Huff RG, Krejsa EA. Identification and proposed control of helicopter transmission noise at the source. NASA/Army Rotorcraft Technology Conference; 1987. USAAVSCOM-TR-87-C-2.

30. Ramadani R et al. Topology optimization and additive manufacturing in producing lightweight and low vibration gear body. International Journal of Advanced Manufacturing Technology. 2021;113:3389–3399.

31. Binder M et al. Additive manufacturing of a passive, sensor-monitored 16MnCr5 steel gear incorporating a wireless signal transmission system. 55th CIRP Conference on Manufacturing Systems; 2022.

32. Siglmueller F et al. Efficiency of additive manufactured gears with conformal cooling. In: 21st International Coloquium Tribology; 2018 Jan; Stuttgart, Ostfildern, Germany.

33. Dennig H-J, Zumofen L, Stlerll D, Klrchhelm A, Winterberg S. Increasing the safety against scuffing of additive manufactured gear wheels by internal cooling channels; 2021.

34. Tezel T, Topal ES, Kovan V. Failure analysis of 3D-printed steel gears. Engineering Failure Analysis. 2020 March;110:104411.

List of Symbols, Abbreviations, and Acronyms

3D	three-dimensional
AM	additive manufacturing
BJP	binder jet processing
CFD	computational fluid dynamics
CT	computed tomography
DED	directed energy deposition
DMLS	direct metal laser sintering
FARDS	Future Advanced Rotor Drive Systems
LDED	laser directed energy deposition
LOL	loss of lubrication
LPBF	laser powder bed fusion
ME	material extrusion
MRGB	main rotor gearbox
NGB	nose gearbox
PBF	powder bed fusion
PCB	printed circuit board
RFID	radio frequency identification
SBIR	Small Business Innovation Research
SLM	selective laser melting
VAR	vacuum-arc-remelt
VIM	vacuum-induction-melt

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