Additive Manufacturing — an Update

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Writing about additive manufacturing (AM) and the 3-D printing of gears is somewhat akin to publishing an updated dictionary. A new edition dictionary is literally already out of date before it hits Amazon's or your local bookseller's shelves. New words are coined and definitions are updated constantly. So it is with AM — the technology is evolving so quickly that technical papers and other sources of AM information require constant revision.

That said, the benefits, rewards and promise of AM have remained pretty much the same. They include:

- The manufacture of complex geometries such as internal cooling or lubrication channels
- Reduce gear system inertia through the use of advanced designs that are difficult to manufacture conventionally
- Improvement of durability by the use of multiple, optimized materials in a single part
- Changing the cost of manufacturing by only placing material where it is needed
- Reducing product development time and time to market
- Improve safety and repeatability, and assist humans with aids and tools

And by the way, just what *is* additive manufacturing? It is the term used to describe the technologies that build 3D objects by adding layer upon layer of material such as plastic and, ideally for the 3D printing of gears — metal. After collaborating for a year, in January, 2020 the AGMA 3D Printing committee merged with the New Materials committee. The goal of the 3D Printing committee for 2020 was to dive deeper into binder jet for small MIM-type gears, L-PBF for high-end applications and DED for large gear repair. They have also been tracking new technology and materials development in this area closely.

Understand—3D printing for mass productions of gears is still just a goal not an achievement — yet. The committee has been following with great interest the development in the materials development space with the intention of learning more. So they developed a series of specific questions related to new materials and identified seven companies to answer them. The fruits of the committee's labor are reflected by the responses provided by the three responding companies featured in this article.

Therefore the following Q&A provides the latest information available according to experts in the AM materials industry. They include Jeff Grabowski, manager of business development for QuesTek; Dr. Anthony Manerbino, technical sales engineering, Ph.D. materials science, Elementum 3D; Manfred Reiter, business development manager additive manufacturing powder, voestalpine BÖHLER Edelstahl GmbH & Co KG, and Denis Oshchepkov, product manager, additive manufacturing powders for Höganäs AB.

One might consider the following an update to the 2019 white paper report — "Additive Manufacturing Technologies for Gears" — prepared by The Barnes Group Advisors, written primarily by Dr. Kirk Rogers under the auspices of the American Gear Manufacturers Association (AGMA).

Is your company currently producing any powder metallurgy alloys specifically for use in 3D printing applications? Do you know if any of your standard PM alloys are being purchased for use in these types of applications?

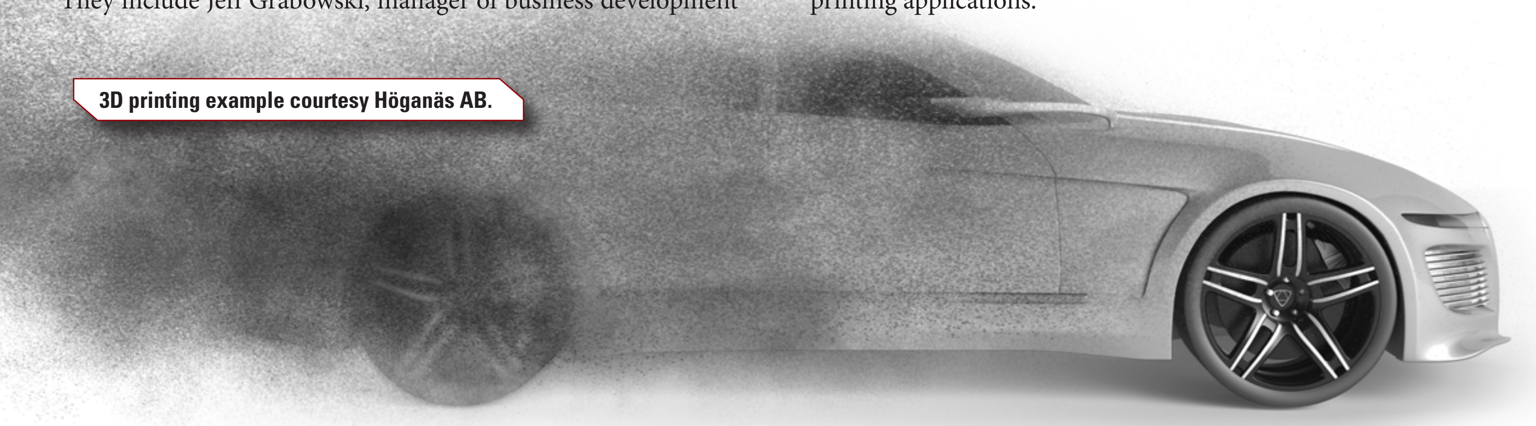
QuesTek. QuesTek does not manufacture powder, but we have worked on more than 50 projects in metallic additive manufacturing to resolve technical and matalallurgical issues that are known in industry. The major issues are cracking of commodity alloys upon rapid cooling, as well as the modeling and fine-tuning of unique microstructures (both beneficial and detrimental phases) that subsequently form.

We have used physics-based models and Integrated Computational Materials Engineering (ICME) technologies to optimize the composition and thermomechanical processing steps to design entirely new alloys across the metallic alloy spectrum including high strength steel, stainless steel, aluminum, titanium, nickel, copper, magnesium, and tungsten. These efforts aim to combine alloy printability with performance.

To date, we have focused on additively manufacturing prototype components of our new Al and steel designs.

Elementum 3D. (We) manufacture a family of Aluminum alloys (1000, 6061, 2024, 7050) refractories, nickel super alloys, and copper powders and Copper powders specifically designed for 3D printing for use in space, aerospace, and automotive applications.

Höganäs AB. We produce a wide range of materials for 3D printing applications.



3D printing example courtesy Höganäs AB.

Are the PM grades that you are manufacturing for 3D printing applications limited to austenitic alloys? Or are you producing martensitic alloys as well? What martensitic grades do you currently offer, and what do you have under development that you can share?

QuesTek. The following are four martensitic steels that QuesTek has designed, patented and demonstrated in AM processes:

- Ferrium C64 steel for gear, tool and die applications.
- QuesTek 17-4 PLUS. QuesTek is near completion of a project focused on designing a best-in-class martensitic stainless steel. QuesTek has demonstrated the ability to achieve higher performance, less variability and less sensitivity to manufacturing (fully heat treated and as-printed conditions) than traditional PH 17-4.
- Ferrium M54, demonstrated in wire AM as a performance upgrade from 4340 and 300M.
- Ferrium PH48S, a high strength, high toughness martensitic stainless steel.

Elementum 3D. We do not manufacture steel powders in house, but have partnered with voestalpine BÖHLER Edelstahl who currently produce powder for 3D printing applications in nickel-based alloys, tool steel, stainless steel, and low alloy steel. Several of these are martensitic grades. Two martensitic grades — BÖHLER M789 AMPO and BÖHLER E185 AMPO — were developed specifically for 3D printing to address the unique challenges of printing martensitic grades.

Höganäs. We produce a range of alloys on Ni, Co and Fe base. Fe alloys include austenitic, ferritic and martensitic grades. Martensitic grades in standard portfolio are following:

- Low alloyed: 4130, 4140,
- Martensitic stainless steel 420
- Maraging steel 1.2709 (18Ni30)
- Martensitic tool steels H13, H11

Additively manufactured piston by laser powder bed fusion (l-pbf) printed at the DMRC Paderborn from BÖHLER E185 AMPO.

What grades of case carburizing steel alloys are currently being produced (if any are) by your company for use in metal 3D printing applications? Are you planning to develop any PM grades of case carburizing alloys such as AISI 8620, 9310, 4320, 3310, etc. that could be used for 3D printing metal gears? Do you offer any other case carburizing alloys that have been used in traditional gear manufacturing that are also available in PM form for 3D printing?

QuesTek. Carpenter Technology is producing QuesTek's Ferrium C64 steel under a license agreement.

One of QuesTek's most advanced alloys in Additive Manufacturing is Ferrium C64 steel. As a wrought / forged product it is one of the highest performance gear steels available due to a unique combination of strength, toughness, fatigue life and temperature resistance. This alloy is beginning to replace common gear steels such as 9310 and Alloy 53, allowing for light-weighting, increased power density and improved thermal stability.

Starting in 2016 under US Army funding, QuesTek began to evaluate and demonstrate Ferrium C64 in Additive processing. It has been atomized several times in >500 lb batches. QuesTek has repeatedly printed on EOS machines test pieces for mechanical testing and microstructural evaluation. The strength and elongation has been found to be nearly the same as C64 forged bar. There is a slight debit in fracture toughness. Initial axial and single tooth bending fatigue results are comparable with that of Ferrium C64 forged bar. The following properties have been achieved on printed C64 that was heat treated: 200 ksi yield strength, 230 ksi ultimate tensile strength, 18% elongation, 85 ksi-in fracture toughness and a surface hardness of 64 HRC. The additive performance of Ferrium C64 so far has outperformed that of wrought AISI 9310.

QuesTek has also printed gear components for testing and has printed gear prototypes for a major aerospace corporation with plans for rig / system testing.

Ferrium C64 powder is commercially available from Carpenter Technology / Carpenter Additive.

Höganäs. Currently in production are case hardenable grade 16MnCr5 and several customer specific grades. We are open for development of other case hardenable grades based on clear business case in the meantime we believe that standardization is very important prerequisite for automotive industry to keep cost down.

Elementum 3D. The BÖHLER E185 AMPO is a low-carbon, low alloy steel designed specifically for case hardening applications, including carburizing, nitriding, and carbonitriding. voestalpine BÖHLER Edelstahl's development partner of this grade specifically targeted gearing applications. However, it does not require these heat treatments to achieve high strength, toughness, and good ductility; a development goal of BÖHLER E185 AMPO was also to achieve these important properties in the as-printed state, without any heat treatment, so it could also be used for rapid prototyping. But when heat treated you can even further improve the mechanical strength properties.

The issue of porosity in the 3D printing of metals is an important factor in determining their suitability for heavy or critical loading applications. A number of different issues can impact this. The lack of consistency of the powder particle geometry (spherical particles are preferred), size range in particle diameters for a given load of material, and oxidation on the surfaces of the powder particles can all potentially aggravate porosity issues. What tolerances on these parameters is your manufacturing process capable of holding today? Do you have the ability in your production process to alter the manufacturing steps and procedures that are available for narrowing the range(s)

Additively manufactured C64 single tooth bending fatigue gear samples. (Courtesy QuesTek.)

on any of these specific parameters?

Elementum 3D. The BÖHLER AMPO powders that voestalpine BÖHLER Edelstahl produces are all done with state-of-the-art VIGA units. Vacuum induction melting insures low gas contents. Argon atomization produces excellent sphericity. Oxidation is controlled with the use of Argon throughout atomization, sieving, and handling. These steps are used with all powder production; therefore, it is not intended to tweak manufacturing steps in order to alter the printing characteristics. With powders produced with state-of-the-art technology, Elementum 3D also refines 3D printer machine parameters to optimize part specific manufacturing.

Höganäs. We possess different atomization processes for production of powders for 3D printing actual tolerances depend on specific process, particle size distribution and alloy. The actual tolerances are also dependent on the produced volume and variations of the alloys therefore Höganäs seeks standardization of the steel alloys.

QuesTek. We are not a producer of Ferrium C64 steel, and the parameters in question are controlled by the alloy producer. Ferrium C64 has been atomized several times and printed with porosity levels ~0.1%.

What interest in hardenable steels is there in the AM community?

QuesTek. For applications in gears, hand tools, tool and dies and fast replacement of old gears where the supply chain no longer exists.

There is currently a void in industry where materials such as stainless, maraging and tool steels which are widely available in powder for AM are not ideal for gears because they are lacking one or more of the following: strength, toughness, ductility, ability to surface harden / low surface hardness.

Höganäs. The automotive and general industry show high interest in such material.

Elementum 3D. We, along with partner voestalpine BÖHLER Edelstahl, have established this relationship because we do believe there is strong interest in hardenable steels for Additive Manufacturing. This is why nearly all of BÖHLER AMPO powders for these applications can be heat treated, whether through quenching and tempering, maraging, or precipitation hardening.

Which gear steels have you produced in powder form for AM or other use?

Elementum 3D. BÖHLER E185 AMPO is designed specifically for gear applications, using 3D printing.

Höganäs. 16MnCr5.

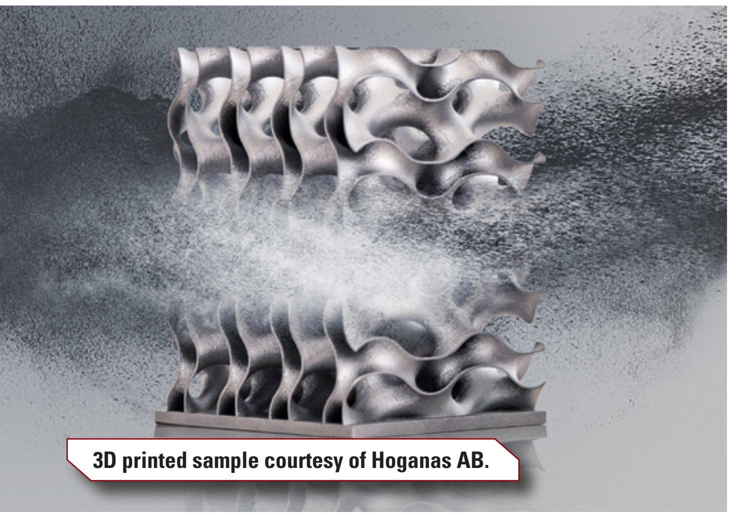
QuesTek. We do not produce powder.

Are you aware of any developments in AM-specific hardenable steels for uses such as gears?

QuesTek. I am not aware of any steels that were "designed" specifically for Additive Manufacturing (in that the material did not exist prior to AM being so popular).

Based on QuesTek's knowledge of the metal AM marketplace, we feel Ferrium C64 steel appears to be one of the most technically advanced high-performance gear steels being demonstrated in AM, though I am aware of others such as a product from GKN. Ferrium C64 was highlighted as such in the 2019 AGMA white paper on AM opportunities for the gear industry.

Elementum 3D. BÖHLER E185 AMPO was specifically developed as an AM-specific, hardenable steel for use in gears.



3D printed sample courtesy of Hoganas AB.

Have you done any comparative studies on your AM alloys compared to their traditionally manufactured counterparts? What did the studies reveal?

Elementum 3D. The development of **BÖHLER** E185 AMPO included comparative tests against the European standard grade for carburizing, DIN 1.71731 (16MnCr5). Tests included plasma nitriding, which showed BÖHLER E185 AMPO produced slightly harder, deeper case hardening when treated alongside 16MnCr5. Tests in the heat-treated condition showed also slightly better mechanical properties with a 3 times higher toughness than 16MnCr5.

Höganäs. We are constantly working on property verification and process development for 3Dprinted steels, including benchmark with traditional steels.

QuesTek. So far it is fairly similar, with no clear debit on mechanical tests. Fracture toughness was slightly lower and fatigue is still under evaluation. Component level testing will be conducted in later 2020.

What size parts have been produced out of your ferrous alloys? What quality expectations have there been for these parts?

QuesTek. Up to about 5" in length and 3" in diameter. Components printed well without cracking, and are nearing component level testing.

Elementum 3D. Size ranges are only limited by the build volume of the 3D printer. For laser bed powder fusion

(LBPF), Elementum 3D utilized EOS M290 and M400 3D printers with build volumes of 10" × 10" × 12" and 15" × 15" × 15" respectively. In most of the cases the expectation for the 3D printed parts is to provide equal life to the conventional parts, while enabling improvements in design and weight reduction that 3D printing is known for.

Höganäs. As we are aware, there are components up to 200 × 200 × 200 mm (being) produced, but in many cases customers are not sharing their application.

Have any of your AM alloys been used in a gearing application? If so, do you have any field performance feedback?

Höganäs. We have run internal investigation for 3D printing of gears.

Elementum 3D. BÖHLER E185 AMPO was developed with a partner for these specific applications and is currently being evaluated for long-term field performance of gears.

QuesTek. There has been no application of Ferrium C64 steel to date into real world applications. However, QuesTek has found significant interest from major aerospace OEMs, gear manufacturers and other companies that have to maintain large inventories of part numbers of gears and see AM as a solution. As the initial round of DoD funding is winding down, QuesTek is expecting 1-2 new contracts focused specifically on further advancement to raise the Technology Readiness Level of Ferrium C64 in AM.

The potential exists to achieve similar to improved gear performance by using an AM process versus traditional manufacturing and there are many potential benefits such as shorter lead times on small quantity orders and ability to use AM to further light weight a component. However, at the moment it is likely a more costly manufacturing method and thus the business case must be made.

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