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A Quarter Century of Change in 3D Printing Molds and Cores: An Evolution from The Direct Shell Production Casting Process

K.J. Kerns
HA International, LLC, Westmont, Illinois, USA

ABSTRACT

Additive manufacturing technologies emerged over 25 years ago with a technology known as Direct Shell Production Casting (DSPC). This viable process produces molds with in-situ cores to pour castings directly into near-net shape parts. The evolution of innovation has taken a fast track in the 3D printing of cores and molds. This paper will review the generational developments in process technology, applications, materials, and rapid adoption of 3D printing in the metalcasting industry.

Keywords: additive, DSPC, rapid prototyping, jetting, 3D, sand, printing, metalcasting, near-net, foundry

INTRODUCTION

Additive Manufacturing (AM), also known as 3D Sand Printing (3DSP), Rapid Prototyping, and Direct Digital Manufacturing (DDM), is a manufacturing process that constructs sand cores, molds, or molds with core geometry in-situ using a 3D printer. The AM concept has revolutionized traditional sand casting techniques. It continues to evolve quickly due to industry demands and investments by Original Equipment Manufacturers (OEMs) and their partners to expand the size, dimensional capability, speed, process capability, material advancements, and cost of use.

Professor Ely Sachs, Ph.D., a true visionary and pioneer in the field of 3D printing, was known as the inventor of binder jet printing technology. Sachs joined the faculty of Massachusetts Institute of Technology (MIT) in 1986 and quickly became a leader in the field of rapid prototyping, revolutionizing the concept of 3D printing, and is credited with coining the term "3D printing." While early 3D printing was primarily used for creating models and patterns for prototyping and testing, Sachs envisioned a future where 3D printers could produce functional parts directly. This vision became a reality, and today, 3D printing technology is used in a wide variety of applications, from creating medical implants to manufacturing aerospace components.

Binder jet printing, invented by Sachs, is a unique 3D printing technology that uses a liquid binding agent to selectively bind powder particles together, layer by layer, to create a 3D object. This technology offers several advantages over other 3D printing methods, including:

- High speed—binder jet printing is one of the fastest 3D printing technologies available, making it ideal for mass production.
- Versatility—binder jet printing can be used with a wide variety of materials, including metals, ceramics, and polymers
- Cost-effectiveness—binder jet printing is a relatively inexpensive 3D printing technology, making it accessible to a wider range of users.

3D INKJET PRINTING FIRST EMERGES AS DSPC

First developed in the early 1990s by Ely Sachs, Ph.D., and fellow researchers at MIT, binder jetting emerged as a versatile manufacturing method compatible with various materials, including metals, ceramics, and sand. In the early 1990s, Soligen Technology, Inc. licensed the technology and developed the Direct Shell Production Casting (DSPC) process using a single jetting printhead in their Alpha. A group of users, including aerospace, biomechanical, foundry, universities and material development partners created a consortium that developed a Beta version of the DSPC process before the company closed in the late 1990s. Those familiar with the technology revered the DSPC process as being ahead of its time, but it was slow to be adopted by the market, and it became difficult to sustain its development.

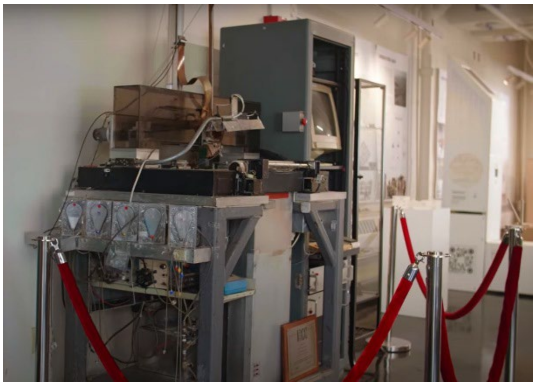

Figure 1. The "Alpha machine," the first "real machine," was developed at MIT for 3D jet printing.

Direct Shell Production Casting (DSPC) was a process that used Stereolithography or STL geometric files to generate molds to replace tooling and indirect short-run metal parts. Molten metal was poured directly into a ceramic casting shell, which included the gating systems. DSPC could create cores, molds, and molds with in-situ cores, meaning that the cores were made integral. within the mold. This saved time and improved the accuracy of the produced parts.

DSPC used an inorganic colloidal binder and a fine ceramic powder. The binder used green strength to bond the ceramic powder together, followed by the printed bed of powder being placed in a kiln to calcine and transition the colloidal silica to an irreversible bond to set the printed geometry. DSPC molds were dimensionally stable, meaning that they retained their shape and size after firing and during casting. The unprinted material was removed and recycled to reduce waste. DSPC castings were a near-net shape, meaning that they required little machining after casting. Overall, the DSPC process supplied what could be considered the first versatile way to produce short-run metal parts indirectly without tooling.

Figure 2. DSPC, Soligen Technologies Inc.'s Beta generation machine, and CEO and creative Yehoram Uziel.

NEED FOR 3D SAND PRINTING TECHNOLOGY IN MANUFACTURING A QUARTER CENTURY AGO

Within a generation, rapid prototyping technologies have become widely accepted and used. The three types of rapid prototyping technologies are subtractive, additive, and hybrid. These technologies present a valuable resource for making well-informed decisions in the planning, design, testing, and production of castings.

One of the key benefits of rapid prototyping is its use in advanced engineering technologies and concurrent design methodology. This allows for the effective execution of product solutions.

Looking back to the early days of rapid prototyping, managers and engineers had a vision of success but lacked the technology to achieve it. Successfully launching a new product depended on quick and efficient product development methods and flexible manufacturing processes.

Timing was essential, and even relatively short delays could result in a loss of market share. In 1994, Dr. David Cole, at the University of Michigan's Transportation Institute, estimated that the average lead time for US automakers to introduce a concept car was 52 weeks, compared with the competition's 40 weeks. Dr. Cole predicted that, by 2003, the U.S. automaker's lead time was expected to be 38 weeks and 34 weeks, respectively, narrowing the gap. He further said that to regain the competitive advantage, the industry must reduce lead time, improve sales and service to the customer, and increase the awareness of technological change and its implementation of this technology in the industrial climate.

Paul Mikkola, who at the time of this original paper was already using rapid prototyping to produce experimental prototypes at GM's Powertrain Division, said, "In order for foundrymen to be competitive, it is necessary to become aggressive and produce near-net shape castings that reduce or eliminate machining. Rapid prototyping has proven that it has the potential for accomplishing this goal for the automotive metalcasting industry."[1]

Don Sabin, a design engineer for John Deere's Product Engineering Center, Waterloo, Iowa, noted during this period, "Currently, the time required to introduce a new tractor to the market is almost five years. We would like to see this time reduced to less than three years and find out what rapid prototyping can do to reduce the 'conceptualization-to-market introduction' time span. There is a definite need for a fast way to produce functional prototypes that can be used for verification or as a pattern to produce a metal casting."[2,3]

FAST FORWARD 3DSP FOR FORD ECOBOOST

Manufacturing cylinder heads is challenging, requiring 12 to 20 cores and mold components to be sand-cast. Traditionally, the process involved making patterns by machining them from tooling boards and packing foundry sand in the mold. However, 3D sand printing has revolutionized the production of sand molds for metal castings, offering significant speed, flexibility, and cost advantages.

At Ford, Paul Susalla, Section Supervisor of Rapid Manufacturing at the Dearborn, Michigan facility, says, “Creating all the tooling would take months and a lot of money. Plus, some of these cores are extremely tough to make. Now, when using 3D printing, it is just a matter of getting a file, putting it through the machine, and coming out with the same cores,” he says. “There is no tooling, no time involved.” [4]

The most significant benefit of 3D sand printing is its speed. “In a nutshell, if you look at the traditional way of making a casting, you are months out before you get your first casting, and with 3D sand printing, you can have a casting in a matter of days to a couple of weeks,” Susalla says. He explains that if you are using tooling, it might be four months before you get your first part and realize that it is not what you want, then the tooling must be changed. “If you look at the product development cycle, Ford, GM, and Chrysler only give you x number of months to years to put it on paper and then get it on the street,” he says. “As an engineer, you only have a certain amount of time to get your part right. The traditional method might give you only three shots at getting the part right, but 3D sand printing allows you to create multiple iterations simultaneously because you are not committed to tooling.”

According to Susalla, instead of one design, you are looking at five to six designs right off the bat. Then, within a matter of weeks, you can have already evaluated those five or six designs, made some engineering decisions, and produced alterations or even innovative designs to evaluate. So, with 3D sand printing, he says you have plenty of opportunities to optimize the design for quality, cost, time, fuel economy, performance, and safety.

Another known benefit of 3D sand printing is that it eliminates traditional design limitations. “You can make something the way it wants to be designed versus how it can be manufactured,” Susalla says.

He notes, however, that when Ford makes a cylinder head, the mold is shaped the same as it will be in production—with draft angles and parting lines—so that the test part represents what will be coming out of the production process.

There are many advantages to producing CAD-based prototypes over conventional computer numeric control (CNC) prototypes. These advantages can reduce engineering part design time and minimize costs due to unnecessary changes to the production tooling.
Design and manufacturing engineers have always faced tough questions about whether to build a prototype to ensure understanding or go directly to tooling based on a solid model or simulation alone, expecting to save time and cost. Rapid prototyping tools can provide key technical observations and peace of mind. Whether a printed prototype or a casting produced using a 3D printed sand mold with in-situ cores, rapid prototyping intends to obtain greater knowledge to evaluate product form, fit, and functional performance earlier in the development cycle.

PATTERN SHOP PERSPECTIVE

Many pattern shops are still content with traditional patternmaking methods, but these methods are increasingly problematic. An article on changes in the patternmaking industry identified the following critical problems:

- Elevated levels of handwork—finishing operations constitute a significant bottleneck for high-volume production of precision patterns and molds. Too much time is spent finishing critical features.
- Disappearing skills—the average age of patternmakers in the US is fifty-eight. The long apprenticeship needed to train new patternmakers means that the industry lacks the skills and experience to meet the stringent requirements of today's competitive foundries.
- Tighter tolerances and greater accuracy—foundries are moving toward near-net shape casting, which requires tighter tolerances than those expected in machining. While 0.060 inches was once good enough, 0.005 inches is now the standard tolerance, and some customers demand 0.002 inches or better.

The identified challenges are all interrelated. For example, the elevated levels of handwork and disappearing skills make it difficult for pattern shops to meet the tighter tolerances and greater accuracy demanded by foundries. Traditional prototyping and subsequent patternmaking methods have become increasingly inadequate to meet the demands of modern manufacturing. Pattern shops and foundries wanting to remain competitive must embrace modern AM technologies and develop new skills to utilize them effectively.

EVOLUTION FROM DSPC PROCESS

Binder jetting is a versatile additive manufacturing technology that MIT researchers developed in the early 1990s. In 1996, Extrude Hone obtained an exclusive license to commercially develop inkjet 3D printing processes invented at MIT for use with metal, ceramic, and sand materials. ExOne, a leading provider of binder jet 3D printers, was founded in 1995 as the "ProMetal" division of Extrude Hone with the mission of developing metal 3D printers. The name ExOne was derived from the Extrude Hone Company. The process is sometimes called "indirect" 3D printing, printed tooling, and mold printing because the printed objects are used to create the final manufactured object.

Figure 3. The ExOne S-Max sand printer.

Also, on the 3DSP front, "voxeljet" was born as a start-up from the Technical University of Munich in 1995. In 1998, they gained their first patents, entering the 3DSP market of the same year. They shipped their first sand printer in 2002 to BMW.

In the following years, both companies pioneered significant contributions to the market in printer materials, speed, accuracy, and build envelope size. Both companies have crossed the threshold to continuously operating 3D printing technology that allows cost-effective building and unpacking process steps to run in parallel without interrupting the entire system's operation.

Figure 4. A voxeljet VX 2000 3D sand printer.

Advancements in binder jetting equipment and process control have revolutionized this additive manufacturing technology, enabling the production of higher-quality parts, increasing production efficiency, and expanding material options.

Binder jetting machines have advanced significantly in recent years, with print heads that can deposit binder droplets with precise control and high resolution. This adaptability to various binder formulations has produced parts with superior surface finish, resolution, and mechanical properties.

Advanced powder handling and recoating systems create uniform and consistent powder layers, which improve part quality and dimensional accuracy. These systems minimize powder agglomeration, clogging, and uneven spreading, ensuring each layer is deposited with the desired thickness and uniformity.
Binder jetting equipment now includes advanced sensors, cameras, and software enabling real-time printing monitoring and control. This allows for detecting and correcting potential issues, such as powder bed irregularities, binder saturation levels, and temperature fluctuations. This ensures that the process remains stable and consistent throughout the build, resulting in parts with improved dimensional accuracy, surface finish, and mechanical properties.

EVOLUTION OF BINDER TECHNOLOGIES

While the DSPC process utilized a colloidal inorganic binder and fine powder ceramic, the success of modern 3DSP systems have also benefited from several developments in materials.

Research conducted with the University of Northern Iowa utilized acquired technology, including the ExOne S-Max, voxeljet VX1000, and Tinker-Omega alpha and beta sand printers, to provide valuable feedback to the suppliers for resin, activators, cleaners, refractory coatings, sand modifiers, and print bed material. The ongoing collaborative research has yielded new materials for the binder jetting process that produces high-quality parts with minimal post-processing and fast part extraction and over twenty-five domestic sources of silica and zircon, ceramic, and chromite specialty sand in collaboration with the market supply chain for the 3D sand printing process. The research was part of an America Makes project call to increase the adoption of 3D sand printing in the foundry industry.

Binder jetting is a type of additive manufacturing that is increasingly used to create sand cores and molds. It does this by depositing a reactive resin, typically a furfuryl alcohol- based (FA) binder, onto a substrate, such as silica sand, pretreated with an acid catalyst. Other aggregates used in metal casting, such as zircon, chromite, and synthetic ceramics, can also be used as the substrate.

Binder jetting uses a furfuryl alcohol-based (FA) binder like the more common furan nobake binder. The FA binder cures when it comes into contact with a sulfonic acid catalyst, such as toluene sulfonic acid in water.

Figure 5. Printhead jetting furfural alcohol-based binder.

The binder jetting process begins with a layer of pre-treated substrate, such as silica sand, spread evenly across a build box. Build boxes can range in size from 300 x 200 x 150 mm to 4000 x 2000 x 1000 mm. The thickness of the pre-treated substrate is typically around 0.3 mm.

A print head then jets the reactive binder onto the sand layer. The print head uses technology similar to standard inkjet printers but deposits the binder in a specific pattern to create the desired part geometry. This process is repeated until the entire part is built.

The build box contains both bonded and unbonded sand. After the printing process is complete, removing the core shapes from the build space can be time-consuming and difficult. The cured shapes must be handled carefully, and the unbonded sand must be carefully brushed or vacuumed away from the part. It should be noted the reactive furan binder can migrate away from the desired geometry and also cure, creating "sticky" sand that can be more difficult to remove from the part, especially compared to fully uncured sand.

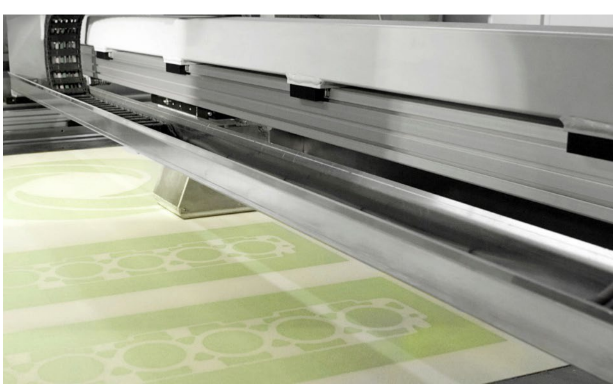

Figure 6. Printed bed with cured furfuryl-alcohol printed cores and activator-coated but unprinted sand.

While the furfuryl alcohol-based binder/acid systems are the most used phenolic type binders, 2-part cold curing and 1-part heat curing systems are gaining popularity due to their hot strength and post-processing desandability. Inorganic systems are also becoming viable.

The primary binders developed are specialized furan binders for binder jetting. These binders must have specific physical and chemical properties, such as dynamic viscosity and surface tension, to work successfully in the jetting process. Binder jetting requires a binder that has a low dynamic viscosity so that it can be easily jetted through the print head. The binder must also have a low surface tension to spread evenly on the sand layer. Specialized furan binders for binder jetting have been carefully formulated to meet these requirements. This ensures that the binders can be jetted accurately, optimize the life of the printhead, and produce high-quality cores and molds.

The economic viability of 3D sand printing depends on both productivity and the speed of part extraction. In other words, it is essential to print cores and molds quickly, but removing them from the build box is also important so that the next print can begin. Researchers and engineers are working to improve the binder jetting process in several ways, including:

- Reducing resin migration—this will help improve the printed parts' quality and reduce the amount of post-processing needed.
- Improving part clarity—this will make it easier to inspect the printed parts and identify any defects.
- Speeding par
- Extraction—this will increase the productivity of the binder jetting process and make it more cost-effective.
- Reduced environmental impact—environmentally friendly, biodegradable binders can help to reduce the environmental impact of binder jetting processes.
- Stronger parts with fewer defects—improved binders can lead to more vital parts with fewer defects, which is critical for many applications.

ADDITIVE MANUFACTURING: THE NEXT FRONTIER OF COMPETITIVE ADVANTAGE

It may have taken a quarter century to reach the point that pattern shops and foundries fully engage in additive 3D printing of sand. However, many people think of additive (3D) manufacturing as a modern innovation of technology, and in this context, it is inevitable. It has been used primarily for printing plastics and metals but has become more prevalent in the metalcasting industry for printing sand cores and molds.

The move into sand 3D printing and the adoption of indirect sand 3D printing has moved faster than other 3D printing markets, i.e., metal printing, likely because the final metal casting process and casting properties are already familiar and acceptable to most engineers or metal casters.

The move into sand 3D printing and the adoption of indirect sand 3D printing has moved faster than other 3D printing markets, i.e., metal printing, likely because the final metal casting process and casting properties are already familiar and acceptable to most engineers or metal casters. Utilizing 3DSP printing to produce finished castings is growing, especially for highly specialized and low-volume parts.

In 1996, Extrude Hone obtained a license from MIT to commercially develop 3D inkjet printing for use with metal, ceramic, and sand. In 2002, the company introduced its first printer to the market, producing sand molds and metal casting cores. In the several years that followed, companies and the 3D sand printing process evolved rapidly, with the technology gaining functional capability and user confidence.

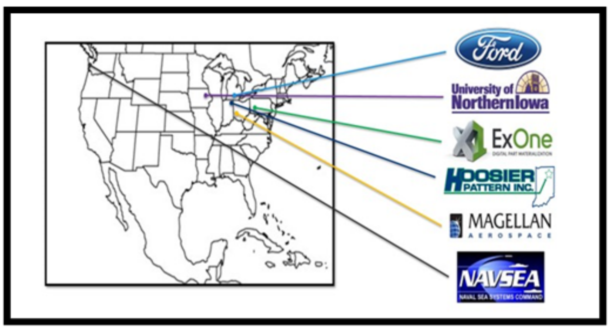

Figure 7. Early adopters of 3D sand printers installed in 2014. (Courtesy of America Makes, Lamoncha.)

In 2014, the metalcasting market matured through early adopters who were crucial in refining the technology and materials for optimal performance and cost-effectiveness. With the introduction of these advanced platforms, foundries could now leverage the technology firsthand, either by investing in their equipment or by sourcing sand molds and cores from specialized service providers.

The North American metalcasting industry is experiencing a revolution driven by the rapid adoption of 3D sand printing technology. In the past 8 years, the user base has exploded, with over 100 machines installed across North America.

This surge is fueled by a combination of factors:

- Emerging Technologies—advancements in 3D sand printing hardware and materials have made the process faster, more efficient, and more cost-effective, opening doors for broader adoption.
- Increased Awareness—as the benefits of 3D sand printing become more apparent, foundries, pattern shops, and core shops recognize its potential to streamline workflows, reduce waste, and enhance design flexibility.
- Domestic Market Champions—several US-based companies are leading the charge, providing innovative 3D sand printing solutions and comprehensive support, fostering confidence in the technology within the domestic market.

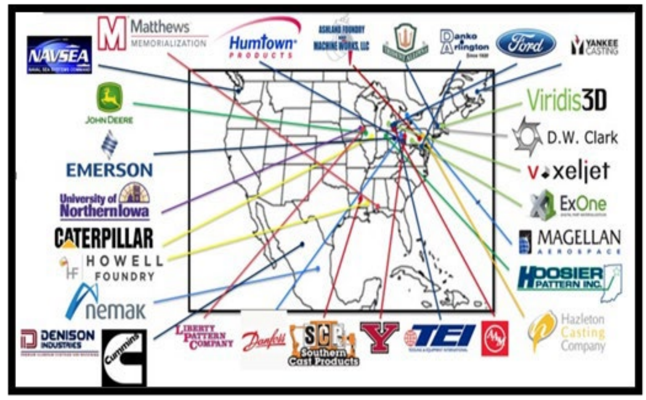

Figure 8. Significant growth of 3D sand printer installations in 2022. (Courtesy of America Makes, Lamoncha.)

Additive manufacturing is a rapidly growing technology with a wide range of applications. It is particularly well- suited for the metal castings industry, where it can be used to print sand cores, molds, and finished castings.

Pros of Additive 3D Sand Printing (3DSP) Manufacturing in casting production versus Conventional Methods include:

- Significant savings in development stages—3DSP will reduce development costs by cutting the need for traditional tooling and prototyping.
- Complex core making—3DSP can produce complex cores quickly and accurately, at competitive costs, and with a high degree of consistency.
- Zero or negative draft—3DSP can produce cores with zero or negative draft, which can be difficult or impossible to produce using traditional methods. This can lead to significant cost savings, improve the quality, and open the design consideration to improve the performance of the castings.
- Rapid design changes—3DSP allows for rapid design changes to molds, cores, or molds with in-situ cores, which can reduce lead times or allow for multiple designs at reduced costs.
- No tooling investment—3DSP does not require any tooling, which quickly cuts lead time and cost going directly to part production and allows for design changes with no additional costs.
- Compatibility with modeling software—3DSP is compatible with most modeling software on the market, making it easy to integrate into existing workflows.

APPLICATIONS OF 3D SAND PRINTING

Ford Motor Company uses 3D sand printing extensively for prototyping castings. In fact, every casting in a newer Ford vehicle was prototyped utilizing this technology.

Figure 9. A complex core 3D printed with inorganic binder and silica sand. (Artwork courtesy of ExOne.)

3D sand printing quickly generates molds and cores for prototype parts without making a pattern first. This allows for more design iterations, which can lead to improved vehicles.

For example, Ford Motor Company uses 3D sand printing to prototype every casting in a newer Ford vehicle. This allows Ford engineers to quickly and efficiently produce high-quality prototypes, which can lead to better vehicles.

Paul Susalla, Ford's section supervisor of rapid manufacturing at the Dearborn, Michigan facility, engages in much of this prototyping, using 3D printing with the ExOne S-15 sand printer. He emphasizes that "though we are speaking of prototypes, Ford's prototype volumes could surpass what many manufacturers consider full production. We use 3DSP for all our prototype castings in powertrain, suspension, and other components—cylinder heads, cylinder blocks, crankshafts, front covers, oil pans," Susalla says. "Basically, any castings you see in an engine or transmission, we are prototyping here using 3D sand printing."[4]

He says the prototypes for parts on Ford's EcoBoost engines were made this way, including "all of the original cylinder heads for the 2-liter EcoBoost that you can get on so many vehicles today." In fact, "the first 100 engines and their cylinder heads were cast using this technology."

Harold Sears, Direct of Additive Manufacturing at Ford, notes, however, that when Ford makes a cylinder head, the mold is shaped the same as it will be in production—with draft angles and parting lines—so that the test part is representative of what will be coming out of the production process.

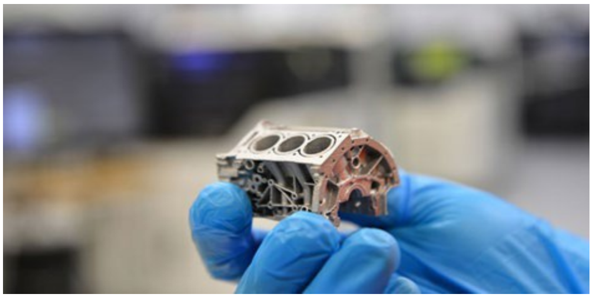

Figure 10. Binder jetting is used for automotive applications. (Artwork courtesy of ExOne/Ford.)

In the example at Ford, binder jetting can be used to manufacture complex engine components that integrate multiple parts, such as cooling channels, structural elements, and mounting features, into a single, cohesive design. This capitalizes on the advantage of 3DSP and its capability to produce parts that integrate multiple components into a single, monolithic structure. This can simplify assembly processes, reduce the number of individual components required, and improve the overall performance and reliability of the final product.

For the benefit of the metalcasting industry, one of the key advantages of binder jetting is its ability to produce parts with complex internal geometries. This includes lattice structures, honeycomb patterns, and conformal cooling channels. These features can enhance the performance of components by reducing weight, improving heat dissipation, or increasing strength-to-weight ratios. For example, binder jetting can produce lightweight aerospace components with lattice structures that help reduce fuel consumption and emissions. It can also produce tooling for die-casting tools with conformal cooling channels that improve cycle times and part quality.

THE LOOK AHEAD

Globally, companies are increasingly interested in the potential of 3D sand printing for the foundry industry. Three Chinese companies are exploring sales of their printers in North America, offering lower costs and faster printing speeds than the German printers currently available. North American manufacturers have been slowed by aggressive patent protection from German companies. However, one US manufacturer has developed a new 3D sand printer based on a single-part starch-based binder first developed in the 1980s.

VoxelJet, which currently produces a 3D sand printer with a working space of two meters by four meters, was recently awarded $14 million to develop and manufacture a new printer large enough to produce molds for the wind energy market with General Electric.

The new printer is expected to be over six square meters and will allow for the rapid production of exceptionally large castings, with the ability to revise designs as needed.

Additionally, on the consumables front, noteworthy progress has been made in binders, activators, cleaners, refractory coatings, sand modifiers, and use for specialty mold materials. The beginning emergence of inorganic binders in the market and their adoption is building. Efforts to produce sub-100 RMS finish through binder, coatings, and print file processing continue.

CLOSING REMARKS

Overall, binder jetting is a robust additive manufacturing process that offers several advantages over traditional manufacturing methods to produce complex parts. It is a versatile technology that can create various components for various industries.

As binder jetting technology matures, it is poised to play a vital role in the future of manufacturing, enabling the production of innovative, customized, and complex parts that were previously unattainable. With the ability to build complex parts with intricate geometries and internal features, 3DSP offers several advantages over traditional manufacturing methods when producing parts with challenging designs.

While challenges such as surface finish, resolution, and mechanical properties remain to be addressed, ongoing research and development are progressing considerably. Advancements in materials, binders, and multi-material printing are expected to drive the growth and adoption of binder jetting in a wide range of industries, including aerospace, automotive, medical, and consumer products.

The concept has come a long way in a quarter century from the technology first conceived at MIT and Soligen Technologies with the Direct Shell Production Casting process. This evolution in 3D binder jetting on the sand to make cores, molds, and molds with in-situ cores is a versatile additive manufacturing process particularly well-suited to produce today's complex prototype or low-production castings.

The next 25 years in 3D sand printing are poised to be transformative. As technology matures and evolves, we expect to see even more innovative and groundbreaking applications emerge. From faster and more efficient production of complex parts to developing new materials and manufacturing processes, the potential of 3D sand printing is limitless.

ACKNOWLEDGMENTS

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The author would also like to acknowledge the University of Northern Iowa's Industry and the Industry 4.0 Center for their invaluable contributions to working with equipment and consumable innovators to keep improving. Their interactions have helped better understand the supply chain's complex challenges and opportunities.

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