Lithoz: How lithography-based ceramic AM is expanding the opportunities for technical ceramics

The impact of Additive Manufacturing is today being felt far beyond the metal and plastics industry. This is particularly true in the world of technical ceramics, where processes such as Lithography-based Ceramic Manufacturing are opening up new markets for new applications but also supporting technologies such as Ceramic Injection Moulding through the delivery of functional prototypes. In the following report Isabel Potestio, from Austria's Lithoz GmbH, reviews the process, its parallels with CIM, and the opportunities that it presents to the ceramics industry.

The excellent properties of ceramics make them useful as components for a variety of applications, from industrial to medical. However, the ability to produce ceramic components with complex geometries and fine details can often be limited in Ceramic Injection Moulding because of the need for complex moulds. This in particular makes the production of parts in small series highly expensive. In addition, prototyping can be time consuming and customisation is impossible.

As a result, Additive Manufacturing is seeing increasing use in several areas as a solution which meets the increasing challenges faced by the ceramics sector. It enables the technological limitations of established ceramic processes such as CIM to be overcome and offers newfound design freedom as complex three-dimensional objects are produced layer-by-layer. AM therefore has the potential to transform the entire ceramic manufacturing value chain, as the optimal tool for adding value to products, operations, logistics and service, marketing and sales [1].

Early AM adopters, such as companies in the medical and aerospace sectors, are accelerating prototyping, exploring new designs that improve the function of products, and developing innovative and customised applications. In addition, companies are benefitting from a lean manufacturing chain with fewer production steps and shortened assembly time. The time required for conventional production is thus reduced, as complex components can be produced all in one piece. The digital storage of additively manufactured parts also offers some innovative solutions in terms of stock management and delays in logistics.

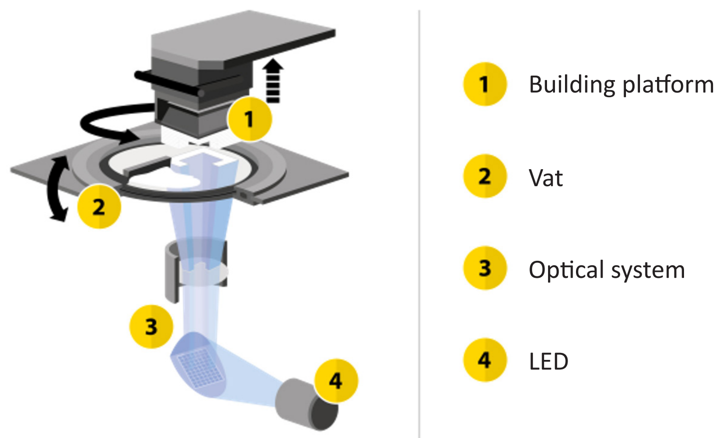

Fig. 1 Schematic illustration of the operating principle of CeraFab LCM systems. The arrows indicate the moving directions of the building platform and the vat

Fig. 2 The process chain for ceramic AM by means of LCM. The double-step approach of forming and thermal post-processing enables the production of high-performance ceramic parts that have similar properties to CIM

Whilst there is a wide variety of techniques for the AM of ceramics, success will always depend on identifying the right application in combination with the right technology. One of the most widely adopted methods for additively manufacturing high-strength, dense and accurate ceramics is Lithography-based Ceramic Manufacturing (LCM). This technology is well suited to ceramic applications where high precision and accuracy are required in combination with density and mechanical performance, similar to Ceramic Injection Moulded parts.

This article describes the LCM process developed by Lithoz and compares it to both Ceramic Injection Moulding and machining. In addition, the article highlights industries which have recognised these advantages early on, such as the casting and medical sectors, and how pioneers have employed lithography-based technology to develop functional applications.

What is Lithography-based Ceramic Manufacturing technology?

Lithography-based Ceramic Manufacturing is a vat photopolymerisation technology in combination with Digital Light Processing (DLP) for forming three-dimensional objects layer-by-layer by the selective photopolymerisation of a ceramic-loaded liquid formulation.

As in all Additive Manufacturing technologies, the first step is the creation of a CAD model of the part, which is used to prepare the build job. The job information is digitally transferred to the AM system direct from a computer. CeraFab machines, developed by Lithoz, allow for photocurable ceramic slurry to be automatically dosed and subsequently coated on top of a transparent vat. The movable building platform descends into the slurry, which is selectively exposed to visible light from below the vat. The layer image is generated via a Digital Micromirror Device (DMD) coupled to a projection system. By repetition, a three-dimensional green part can thus be generated layer-by-layer. A schematic illustration of a CeraFab system is shown in Fig. 1.

After building, the parts produced consist of ceramic particles embedded in an organic photopolymer network. Any excessive slurry must be removed from the surfaces and channels by cleaning the parts using compressed air and appropriate solvents, which are capable of dissolving the slurry without damaging the cured structure [2].

Subsequently, green parts have to be debound and sintered according to the requirements of the material used. From this perspective, LCM is very similar to any binder-rich ceramic forming technology and is similar to CIM or ceramic tape multilayer fabrication. Thus, following the conventional thermal treatment of the additively manufactured green bodies, theoretical densities above 99.8% are achieved and a homogeneous microstructure is developed [2]. Fig. 2 shows the steps involved in the AM of ceramics by LCM.

A smart technology for fully-dense and high-performance ceramics

LCM meets the challenge of delivering fully-dense ceramic components with very good mechanical properties and surface finish in a highly precise and reproducible manner. The layer formation method, typical for LCM, has a number of significant advantages. Unlike other vat photopolymerisation methods, the parts are not submerged in the slurry, thus reducing the required amount of material needed to a minimum and avoiding the introduction of defects connected to interactions between the green parts being built and the mechanical coater.

Furthermore, this process reduces the operation of clearing the uncured suspension between submerged parts, as well as eliminating material recovery operations. Compared to laser-based build processes, where the point-by-point scanning of each layer's cross section is time consuming, the DLP device in the LCM system exposes the entire layer simultaneously, which decreases manufacturing times irrespective of shape, complexity or exposure area.

Besides a high-quality process and industry-oriented equipment, high-quality raw materials are needed to achieve properties comparable to Ceramic Injection Moulding. A broad range of ceramic slurries are available for LCM as standard materials: alumina, zirconia, silicon nitride, biodegradeable ß-tricalcium phosphate and hydroxyapatite (and mixtures of the two), as well as

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Fig. 3 Investment casting cores manufactured from silica-based LithaCore 450 after printing and sintering, along with a cast metal part. The cores were produced on a CeraFab 8500 printer (Photo Manfred Spitzbart)

silica-based materials. For instance, the 4-point bending strengths for alumina and zirconia tested according to DIN EN 843-1 are 430 MPa and 930 MPa, respectively, whereas the 3-point bending strength for silicon nitride is 940 MPa.

In addition, alumina-toughened zirconia and zirconia-toughened alumina, together with cordierite, magnesia, glass ceramics, piezo- and transparent ceramics have successfully been processed using LCM.

Key drivers, early adopters and cutting-edge innovations

There are several key drivers for the increasing adoption of ceramic AM technologies. The freedom of design allows engineers to develop value-driven applications, which increase efficiency and provide additional functionality of products. The supply chain can benefit from increased flexibility as designs can be quickly changed, prototypes can be rapidly tested and re-adapted, tools can be digitally stored and complex part assemblies can be manufactured in one piece, avoiding assembly steps and reducing overall production costs and time.

The following examples highlight the diverse industry sectors which have recognised these advantages early on, and show how pioneers employ LCM to develop innovative functional applications and produce a broad range of different geometries, ranging from parts with fine and delicate features to relatively large and bulky parts.

Ceramic casting cores

In the aeronautical and industrial gas turbine market, typical applications of AM casting cores include cores for turbine blades made from nickel-alloys in single crystals (SX) and directionally solidified (DS) and equiax-cast (EX) materials. In this context, LCM offers a solution for different needs. Of utmost importance, LCM is effectively used for the production of the most recent casting core designs. These have multiple layers of cooling channels, which can no longer be produced by Ceramic Injection Moulding. Ceramic casting cores, with complex branching structures and trailing edges with thicknesses smaller than 200 µm, can now be produced with outstanding dimensional reproducibility and accuracy.

Furthermore, LCM is a tool-less manufacturing process and thus offers a fast and low-cost production method for prototypes and small-scale series. It bypasses the costly and laborious fabrication of moulds required in Ceramic Injection Moulding, ultimately delivering a significantly faster time-to-market in combination with a shorter product life cycle. Ceramic Injection Moulding requires a mould for each product variant and, in the case of casting cores, this typically involves investments in the order of tens of thousands dollars and lead times of several months [3].

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Fig. 4 (a) A patient-specific hydroxyapatite implant for treating bone defects in the mandibulum (lower jaw) (Design courtesy Michael Bergler, University of Pennsylvania, USA) (b) Patient-specific bioceramic implants and scaffold for applications in cranio-maxillofacial surgery can be produced out of medical grade bioceramics (alumina, zirconia, hydroxyapatite, ß-tricalcium phosphate and mixtures) by means of LCM (Photo Sebastian Geier)

LithaCore 450 is a silica-based material used for the production of casting cores by LCM. The material was specifically developed for the AM of ceramic cores with fine details and high accuracy. Sintered ceramic cores made from LithaCore 450 have very low thermal expansion, a high porosity and outstanding surface quality (Ra < 3 µm), ensuring that internal channels in the final cast alloy have a smooth finish and good leachability. In addition, results from dimensional inspections performed on cores printed by LCM reveal maximum deviations < 0.1 mm from the CAD model, which is within the expected dimensional compliance for casting core application. Fig. 3 shows printed and sintered cores formed using LCM.

Fig. 5 In dentistry, LCM allows for the production of full ceramic crown, ultra-thin occlusal veneers for minimal invasive reconstruction and endosseous screw-type dental implants. Fine edges down to 100 µm can be achieved

Medical and dental

Whilst CIM has made progress in recent years in the development of implant applications, because of the nature of the process these are restricted to standard sizes. Medical data generated from patients are, however, unique for every individual; the geometrical flexibility that AM provides makes it an obvious route for generating patient-specific products from patient data. Thus, the dental and medical industries have been amongst the earliest adopters of ceramic AM. As early as 2017, ten successful cranio-maxillofacial surgical procedures were performed using bioresorbable ceramic implants produced using LCM.

In dentistry and cranio-maxillofacial reconstruction, various ceramic materials are used for different clinical situations and ceramic AM is contributing significantly to various fields such as prosthetics, implants and surgical instruments. In bone-tissue engineering, AM allows for the production of interconnected porous scaffolds with defined geometries and sizes, which facilitate the ingrowth of bone from adjacent tissues, as can be seen in Fig. 4(a) and (b) and Fig. 5 [5].

A range of medical grade materials is available, from the inert to the bioresorbable. Each material has been developed specifically for LCM. Inert ceramics such as alumina and zirconia offer a mechanically stable metal-free solution for dental implants, crowns and load-bearing bone defects. These materials do not release their components into the human body nor generate an antibody response and thus the success rate is expected to be higher than for metal implants.

Bioresorbable ceramics, such as ß-tricalcium phosphate and hydroxyapatite/ß-trcalcium phosphate mixtures, in the form of 3D interconnected structures, are a smart solution for the regeneration of bone defects. These materials exhibit the added value of stimulating bone ingrowth and are gradually degraded while being replaced by the natural bone tissue.

Industrial and machinery

One of the major advantages of ceramic Additive Manufacturing is that it enables the production of designs that cannot be moulded or otherwise fabricated. This has offered several companies the opportunity of exploring new designs for improving the function of products and, thus, the development of value-driven applications.

Alumina Systems GmbH produces customised ceramic and metal-to-ceramic components for the semiconductor and medical industries. Besides conventional technologies, the company uses LCM to develop products with high added value for its customers. By using LCM, Alumina Systems GmbH, together with its project partner plasway-Technologies GmbH, developed a ceramic distributor ring for etching and coating of silicon wafers for semiconductor components for higher process productivity (Fig. 6).

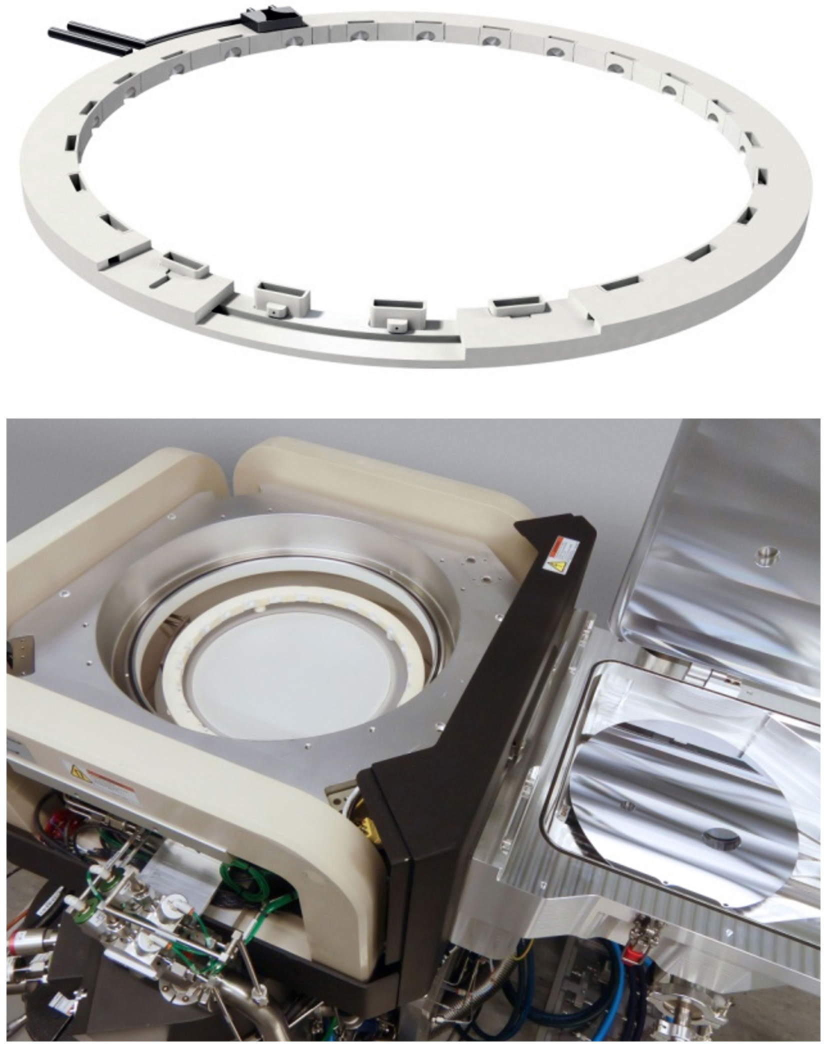

Fig. 6 Distribution ring with integrated ceramic AM nozzles (above). The distribution ring assembled in the Atomic Layer Deposition equipment (below) allows for 200% higher coating rate (Courtesy Alumina Systems GmbH and plasway-Technologies GmbH)

LCM enabled the production of engineered nozzles with an optimised flow-path for gases. Such a component could not be produced using conventional manufacturing processes. The nozzles are integrated by means of soldering in a slip cast ring. This engineered solution allows for a significantly higher productivity rate (around 200% higher coating rate) with significant manufacturing cost reductions for the final user. This shows the major impact which AM can have when a value-orientated design approach is followed. When the added value is so significant, the cost of the product becomes far less important.

Miniaturisation

The production of highly complex and precise ceramic components in the millimetre and sub-millimetre range requires a technology which can meet the demand for high degrees of both accuracy and repeatability. Established technologies such as Ceramic Injection Moulding, milling, drilling and grinding have limitations when it comes to very small or thin objects.

In the CIM process, one challenge is to achieve precise dimensional control over very small parts or features. The main obstacle is binder-powder separation, which can occur in the ceramic feedstock

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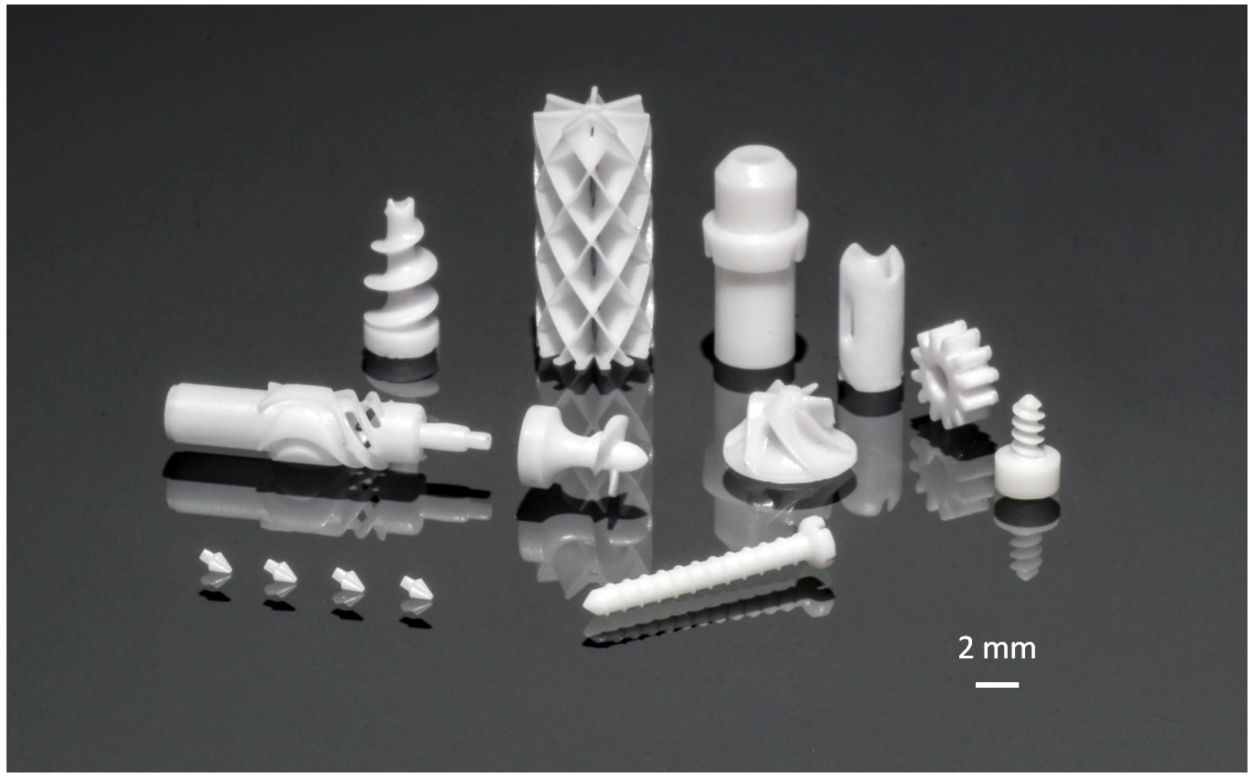

Fig. 7 Sintered ceramic parts manufactured on a CeraFab 7500. The range of applications demanding high precision for small complex features includes industrial applications such as micro-nozzles and valves with flow-optimised paths, miniature rotors and micro-milling tools; electronic applications such as complex and precise substrates, sensors and instrumentation; and medical applications such as minimally invasive instruments and surgical tools (Photo Manfred Spitzbart)

Fig. 8 LCM for industrial serial production of AM ceramics: the CeraFab System. (Courtesy Lithoz GmbH)

due to high shear forces while flowing inside the mould. Generally, this results in non-uniform shrinkage and warpage of parts. In machining, it is extremely difficult to produce filigree parts, as edges and small details easily break off.

As LCM does not require a mould, there are no shear forces associated with flow into mould cavities, and a high level of dimensional control can therefore be guaranteed. Furthermore, since LCM employs a layer-by-layer building method, no cracks, fractures or edge chipping due to machining will occur.

In terms of applications requiring very small feature sizes, parts with walls and holes as small as 100 µm, which also have a high degree of complexity and excellent surface quality, can be produced.

Scaling up to serial production: process reliability and productivity

In recent years, the biggest development in ceramic AM has been the shift from prototyping to serial production. Today, the demand for value-driven applications is constantly increasing in sectors such as semiconductors, dental, medical and aerospace. This is resulting in multiple ceramic AM machines being delivered to customers, with production of more than a thousand parts per month now commonplace.

As industrial companies face permanent cost pressures, increasing the build speed and productivity of the AM process is a key factor in reducing production costs and accelerating the widespread use of AM ceramics on an industrial scale. With the AM of ceramics there is plenty of room for a significant reduction of manufacturing time and, consequently, costs. This can be achieved while still maintaining the desired level of product quality. Depending on the characteristics of the part, this is carried out by fine-tuning several settings.

In the case of high-volume production, a reliable technology is necessary. The reliability of AM of ceramics is dependent on a combination of factors – in particular, the system, software, material, printing process and the post-processing. All of these aspects need to be taken into consideration in order to guarantee consistency of customers' production and improve the output quality of their AM process.

The CeraFab System (Fig. 8) can incorporate up to four production units with an increased building speed compared to previous models, allowing for a significant increase in productivity. Furthermore, the CeraFab System fulfils the highest requirements regarding mechanical and dimensional accuracy and reproducibility of produced parts.

Conclusion

LCM is today a complementary technology to Ceramic Injection Moulding. A wide spectrum of industries is applying LCM to the production of a broad range of different applications, ranging from fine and delicate miniaturised components to large casting cores, bioceramics and bioresorbable medical and dental implants.

The diverse industries which have adopted the AM process at an early stage are now shifting from prototyping to serial production, demonstrating that the demand of value-driven applications is constantly increasing.

Whilst there are inevitably areas where ceramic AM will impact on CIM, LCM technology presents many more opportunities for CIM firms to successfully deliver a wider range of components that do not have the past restrictions of low production volumes or the restrictions of mouldable geometries.

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