Ceramics Additive Manufacturing, a Mature Technology Adapted to Industrial Production

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3D printing is the iconic technology of the fourth industrial revolution, characterized by a merger of diverse technologies that is blurring the boundaries between physics, digital technology and biology. Previously associated with prototyping only, additive manufacturing has won acclaim by adapting to a wide variety of materials and industrializing its processes. But what about the most technically challenging materials such as ceramics? Technical ceramics take benefit of this new technology also: 3D printing enables new innovative development in various market field, the production of Solid Oxide Fuel Cells (SOFC) being the most meaningful use case.

1. Introduction

Technical ceramics is no stranger to the fourth industrial revolution. There is a clear demand for the production of complex parts, for new designs or new applications, that involve short lead times and limited investment. Many users of technical ceramics are counting on 3D printing to make ceramics more accessible, by cutting development times and simplifying the production process. Yet, aside from 3D printing technology itself, the complexity involved in working with ceramics puts off many 3D printer manufacturers and pioneers of additive manufacturing of ceramic parts, such as 3DCeram-Sinto, were compelled to design their own tool to meet their needs. Among other initiatives, the French company developed its 3D printer (Ceramaker) based on laser stereolithography (SLA) in 2010 to satisfy orders for prototypes. The high quality of the parts produced, with the same properties as those made using conventional processes (pressing, injection, etc.), has gradually opened doors to other applications (biomedical implants, luxury goods and more), thanks to small production runs of very high-quality parts.

2. Shift Toward Automated 3D Production Lines

Demand has naturally evolved and now concerns the more wide-scale production of functional parts, leading manufacturers to further enhance the capacity of their printers. The Ceramaker printer, for example, now offers work trays of up to 600 x 600 mm, thereby earning the status of genuine production tool. However, certain operations involved in the manufacturing process, in particular post-printing operations, still require human actions that are unsuitable for industrial production. In order to meet the growing need for automated production of ceramic parts and attempt to conquer new markets, 3D printers need to be integrated into a fully automated line, from printing to sintering.

In this configuration, the printer is fitted with an automatic loading and refill system that allows it to print continuously on a tray inserted by a robotic arm. Once the parts have been printed in 3D, the tray is then transferred to the suction unit for removal of any non-cured paste and to the automatic cleaning booth. An operator checks the part and performs any final cleaning operations if required before sending the parts to a double-chamber reversible oven - capable of producing the best results - for debinding and sintering without the need to cool the product between the two stages. This latest-generation oven has reduced heat treatment operations to just 34 hours compared with 120 hours for conventional ovens. This line makes for a shorter printing time, reducing the overall process time and the amount of waste, without compromising a high production rate. It is scalable and can be adapted for two printers and/or two ovens and - the ultimate simplification of the additive manufacturing process - it incorporates a multi-material printing option which opens doors to even more new markets. In this configuration, the 3D printer can for example be fitted also with a hybrid printing module combining several 3D printing technologies and several materials. This option enables the production of parts made up of different types of ceramics or a combination of ceramics.

3. More and More Ceramics Available for 3D Printing

The materials traditionally used for 3D printing of ceramic parts are alumina, zirconia, calcium phosphates, etc. They have recently been joined by silicon nitride (Si$_3$N$_4$), zirconia 8Y, silica (SiO$_2$) and ATZ, thereby boosting the range of ceramics available. These pastes contain ceramic powder and resin in varying proportions - usually around 80% for the former and 20% for the latter.

4. An Ever-increasing Range of Applications

The latest technological developments guarantee that the specifications for industrial applications are met. Read on for a brief description of some of the productions that have now reached maturity.

For the historical biomedical market, 3D printing is able to
produce bone substitutes, customized ceramic implants and surgical instruments. The bioceramics produced using additive manufacturing have an excellent level of biocompatibility, an extremely regular porous structure and outstanding mechanical resistance. In the aeronautics industry, for example, the production of casting cores was a relatively closed market not prone to innovation until a few years ago. The use of 3D printing technology optimizes production, since the 3D printing process makes it easier to produce complex cores. In the aerospace field, for the past ten years or so, optical instruments for unmanned aerial vehicles (UAVs) have been optimized in order to reduce the equipment’s weight and volume. It was therefore essential to develop new innovative systems integrating new manufacturing methods to accompany these developments. Additive manufacturing has become a key component when it comes to the design and production of optimized optical instruments, and more specifically plane mirrors for frontal laser engines (galvo mirrors for high-energy laser applications). The development of a multi-material / multi-technology hybrid 3D printer paves the way for even more potential applications. To cite just one example, this new type of printer meets the specifications for the production of Solid Oxide Fuel Cells (SOFC), highly promising technology that is set to transform energy production. SOFCs have a host of advantages [2], including very high efficiency, low emissions, extremely low noise levels and net water production, but they are not yet widely used, largely due to the fact that their production requires considerable investment while their performance can still be improved.

Fuel cells are made up of several ceramic layers, resulting in a long and costly production process involving several stages, such as tape casting, screen-printing, thermoforming, heating and several high-temperature heat treatments. The cells produced are then assembled manually and sealed to become fuel cells that still need to be made more robust. This manufacturing process involves over 100 stages and is limited by conventional manufacturing processes for ceramic parts, which means it is extremely expensive to produce complex parts. The SOFC cells and stacks manufactured at present are therefore costly, difficult to upgrade, and slow to place on the market. The goal of the European Cell3Ditor [1, 4] project is to develop 3D printing technology for mass manufacturing of SOFC stacks by bringing together European universities, research institutes and private companies. This project represents a major step forward since it is based on the use of a hybrid Ceramaker printer (multi-material and multi-technology). With this hybrid production technique, preliminary analysis of the investment required to manufacture SOFCs suggests the capital cost will be reduced by 72%.

The hybrid printer combines a variety of printing techniques (SLA, robocasting, inkjet printing). This hybrid technology boosts the production capacity by eliminating all the assembly stages, reducing the shaping process to a single stage and automating other stages of the process. Over 100 manufacturing stages can be eliminated in total, and there is no longer any need for manual assembly of parts. The combination of this new technology and a new single-stage co-sintering technique cuts manufacturing costs by an estimated 59% compared with current technology (estimate based on annual production of 1000 5 kW-fuel cell units) [3].

The SOFC stacks produced using this innovative technology in just two production stages (printing and sintering) have unrivaled properties: an extremely robust monolithic architecture, a significantly lower number of interfaces and fewer sealing problems, improved energy transfer by evaporation and a notably enhanced overall performance. This simplification of the manufacturing process reduces costs and the initial investment required and increases the design flexibility and manufacturing reliability of SOFCs.

After a decade of development and production often frustratingly limited to prototyping, 3D printing applied to technical ceramics is now being extended to new applications and is revolutionizing production usages. It leads to a fresh approach to parts creation and design, thereby shaking up traditional design office methods. A host of applications remain to be explored, and the extraordinary potential of technical ceramics has many surprises in store for us.

References