DIRECT LASER SINTERING OF CERAMICS

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Abstract

For more than one decade layer manufacturing technologies assist the development of new products. Due to a layer-wise build-up of a three-dimensional geometry, nearly every complex design is producible in a short period of time. Selective Laser Sintering is a powder-based technique to produce plastic prototypes (Rapid Prototyping) or metal mould inserts (Rapid Tooling). The laser sintering of ceramic powder is not yet commercialized but applications could be both Rapid Prototyping and Rapid Tooling. The former involves the laser sintering of investment casting shells and cores to cast metal prototypes and the latter the laser sintering of ceramic master patterns for metal spray forming of steel mould inserts. The advantage compared to actual processes are a faster availability of the final product. To facilitate these applications, special ceramic powders as well as new process parameter combinations were investigated. This paper will present achieved results within the above-described applications.

Introduction

Steadily decreasing product life cycles make it ever more important to reduce the development time for new products. Time-to-market instead of development costs has become the key factor for a products success. New methods from the organizational (Simultaneous Engineering) and the operative point of view have been developed [1].

At the end of a product development, technical prototypes which closely resemble the final product are demanded. Viable solutions for plastic components have been around for years, but the prototyping of metal components has often thought to be too time-consuming, and has been unable to meet comparable specifications. The fast production of metal prototypes still remains a central concern in the area of layer manufacturing technologies [2].

Within the sphere of **direct manufacture of metal prototypes**, a few technologies such as 3D Printing or laser sintering are already commercialized. Since laser sintered or 3D printed metal prototypes contain low melting alloys, the mechanical properties are limited.

The **indirect manufacture of metal prototypes** provides two different approaches either the direct Rapid Tooling where mould inserts instead of prototypes are layer-manufactured or the combination of Rapid Prototyping techniques and casting processes (indirect Rapid Tooling). The direct Rapid Tooling is utilized if higher quantities of prototypes are necessary. To date, this application achieves good results for plastic injection molding. Examinations and case studies of Magnesium and Aluminum die casting or thixo casting are carried out at several research institutes [2, 3, 4].

If smaller amounts of metallic prototypes are required the combination of rapid techniques and casting processes such as investment casting is used. Virtually, all metals may be cast and thin walls or small details are readily reproduced because the metal is poured into a closed hot shell. With actual Rapid Prototyping techniques the manufacturing time for the necessary master pattern is minimized but the time-consuming slurrying, sanding and drying of the samples is not eliminated.

Ceramic Laser Sintering

The laser sintering of ceramic materials is comparable to plastic or metal laser sintering whereas ceramic laser sintering is a transient liquid-phase sintering. With regard to the process, the combination of layer thickness, laser power, scan velocity, hatch spacing and scanning vector length has to be adjusted to the ceramic powder, **Fig. 1**.

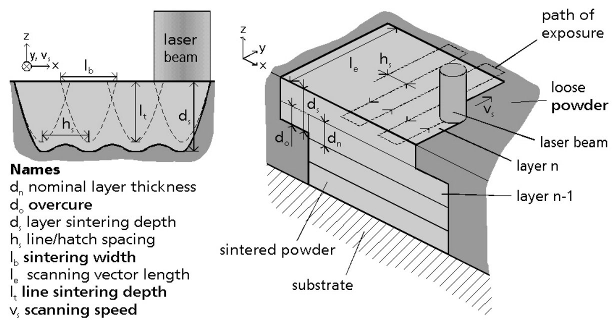

Fig. 1: Process parameters of ceramic laser sintering

The investigations on ceramic laser sintering at Fraunhofer IPT started on a laser sintering system with up to 100 W of laser power (CO_2). From initial tests with different ceramic powders such as aluminum oxide, aluminum silicate or zirconium silicate, the zirconium silicate powder ($ZrSiO_4$) was found the most suitable to process [5]. Today, a 200 W laser sintering system is used.

The basic research with **zirconium silicate** was carried out with ground powder. Several grain size distributions like 125 mesh, DIN 70 and 325 mesh and mixtures of these powders were tested. The result was that a high portion of small grains not only improves the surface quality but also improves the sintering itself since smaller particles need less energy to melt than larger particles. In contrast, an increased amount of small grains increases agglomeration so that an automatic recoating with a uniform surface was not possible. Dedusting and fractionating of the powder solved these problems. Today, the use of granular powder is preferred: due to the spherical surfaces a recoating with small granules is possible.

To determine the influence of process parameters on laser sintering each parameter has to be varied on its own. An increase in **laser power P_L** leads to an increase in the density of the specimen, since more energy is delivered into the powder and larger melt pools fill up the porous structures of previous layers. However, surface roughness also increases because the molten particles tend to form larger spherical structures due to their effort to reduce the free enthalpy by optimizing the ratio between the area of free surfaces and the related volume.

Increasing the **scan speed v_S** has the opposite effect: due to higher velocity of the laser focus, less energy is delivered into the powder bed and less material is sintered. The result is that the density decreases but the surface finish improves.

A variation of **hatch spacing h_S** leads to different effects: if hatch spacings are too small, the molten powder particles form larger beads of high density leading to an overall high density of the part, yet the surface roughness also increases. For a hatch spacing larger than the focal diameter, the molten beads of material from line to line are not connected to each other and the gaps are filled with unsintered powder, resulting in a rough surface and low density respectively low strength.

A reduction of **layer thickness d_n** allows a faster scan velocity because the necessary sintering depth to ensure a fusion to the previous layer is reduced. Additionally, a smaller layer thickness increases the dimensional accuracy of the laser sintered part since the step effect is minimized. The thickness is limited by the grain size of the powder. Actually, the smallest layer is 50 µm.

Of all the parameter combinations that lead to a stable sintering process, the maximum density achieved was approx. 50 % of theoretical density so that two direct applications arise: the laser sintering of casting components and the laser sintering of master patterns for metal spraying.

Investment Casting Application

The conventional investment casting process begins with the fabrication of wax patterns with the same basic geometrical shape as the finished cast part. These master patterns are normally made by injection molding. Once a wax pattern is produced, it is assembled with other wax components to form a metal delivery system, called the gate and runner system. The entire wax assembly is then dipped in a ceramic slurry, covered with sand and allowed to dry. The dipping, sanding and drying process is repeated until a shell of approx. 6 mm to 8 mm is applied. These process steps generally require several days. Once the ceramic shell is finished, the entire assembly is placed in a steam autoclave to remove the wax. Finally, the mould is preheated to a specific temperature and filled with molten metal, creating the metal casting [6].

The major impact Rapid Prototyping processes have had on investment casting is their ability to make master patterns without the cost and lead times associated with fabricating injection molds, **Fig. 2**.

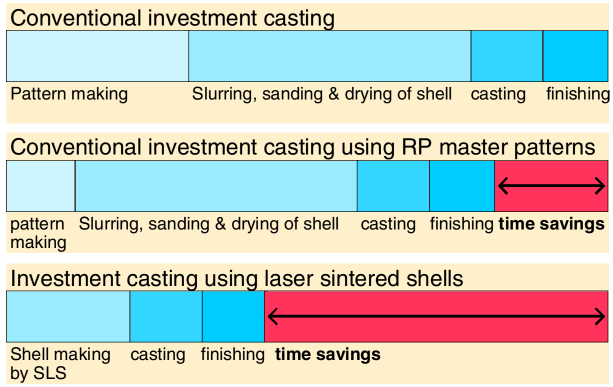

Fig. 2: Comparison of investment casting processes

A direct generation of casting shells without the need of master patterns could have the highest time savings because the iterative process steps of slurrying, sanding and drying of master patterns are eliminated. But since complete shells are generated the running systems and risers have to be designed and incorporated within the part geometry. A cavity is generated within the complete system with an external off-set of 6 mm to 8 mm (corresponding to the wall thickness of the shell).

Before casting, the loose powder in the shell has to be removed and the shell cleaned. As usual, the laser sintered shell is preheated in an oven directly before casting. **Fig. 3** and **Fig. 4** show some examples of metal prototypes cast in laser sintered shells:

Fig. 3: Impeller wheel cast in AlSi7

Fig. 4: Whirl chamber of a diesel engine cast in X15CrNiSi25 20

The processing time for three casting shells of the impeller wheel respectively four shells of the whirl chamber in parallel was only 10 hours, each. The dimensional accuracy of the cast prototypes is approx. +/- 0.6 % which is typical for investment casting. The surface roughness of cast prototypes is worse (R_a ~ 12 µm) compared to conventional investment casting (R_a < 6.3 µm) so that a mechanical finishing/polishing may be necessary.

Another problem of laser sintered shells is the lacking possibility to examine the quality of inner surfaces and contours before casting with the exception of Computer Tomography (CT) or endoscopy.

A comparable application of ceramic laser sintering is the use for investment casting cores. They are necessary for conventional investment casting if the metal part has complex inner geometries. Today, the core production is expensive and/or time-consuming since a metal pressing die or a mold for slip casting is needed. Thus, they are mostly used for mass production runs and not for prototyping. The production by laser sintering could be a fast and favorable way especially for prototypes, single part productions or small batches. A typical core geometry is shown in **Fig. 5**:

Fig. 5: Laser sintered water jacket core of a single cylinder ($ZrSiO_4$)

Since the laser sintering parameters are not changeable to ensure the tightness of cores, the surface quality is still bad. But a dipping of the laser sintered core into a ceramic slurry increases the surface quality (R_a ~ 4.0 µm) so that laser sintered cores are also usable for production runs, **Fig. 6**.

Fig. 6: Cast part split in two with an inner contour made by a laser sintered core

Spray Metal Tooling Application

Metal spraying belongs to the indirect Rapid Tooling where a master pattern is produced by Rapid Prototyping techniques. Afterwards, a metal alloy is sprayed onto the surface. Finally, the master pattern is destroyed, the mold insert is trimmed to the desired dimension and attached to the mother mold.

This process is well-known for low-melting alloys (e.g. Kirksite or Zamac) which are sprayed onto a plastic master pattern. Compared to conventional mould making, prototype moulds could be available in better time. In 1999, Ford Motor Company licensed this technology for carbon steel [3, 7].

Due to the high temperatures involved, ceramic master patterns are necessary in order to be able to spray steel. The requirements on ceramic materials for steel spraying are [7, 8]:

1. A low coefficient of thermal expansion,

2. A high thermal shock resistance,

3. A good compatibility to sprayed carbon steel and

4. A fast processing with laser sintering.

Ceramic powders like silicon oxide, silicon carbide, aluminum titanate and zirconium silicate are compatible with these four requirements, **Fig. 7**.

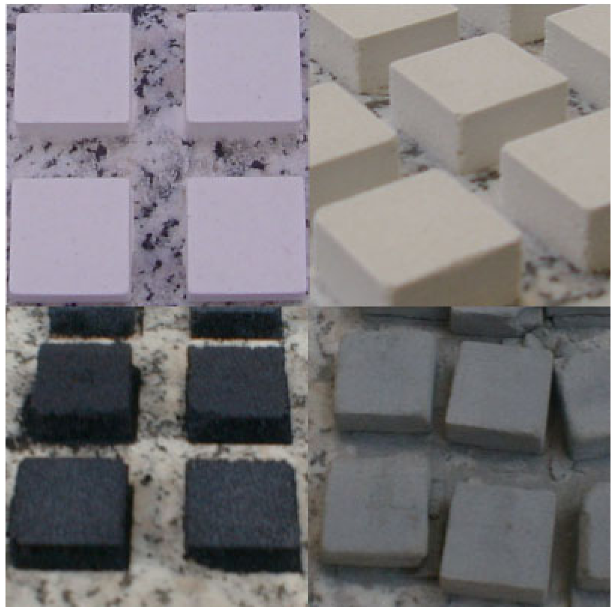

Fig. 7: Sample parts (from upper left to lower right: SiO_2, $ZrSiO_4$, Al_2TiO_5 and SiC)

While the laser sintering of silicon oxide led to an inaccuracy of the master pattern due to sporadic delamination the silicon carbide respectively aluminum titanate patterns were to fragile to handle. An infiltration with epoxy increased the strength but then the ceramic pattern were not removable by sand blasting so that zirconium silicate was used for practical tests [8].

The following picture shows four laser sintered master patterns of a sheet metal forming die, **Fig. 8**. The segments were produced on a laser sintering system with a maximum laser power of 200 W and a maximum work area of 250 mm by 250 mm (~ 9.8" by 9.8").

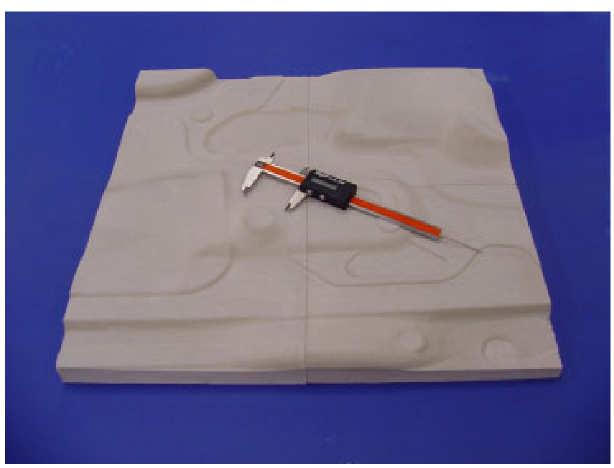

Fig. 8: Laser sintered ceramic master patterns

To prevent a relative movement of the segments during spraying, tongues and grooves were designed. The base of each segment was approx. 245 mm by 245 mm. The average manufacturing time for each segment was approx. 30 hours. Without tongues and grooves the manufacture would be reduced by 50 %. After laser sintering the segments were compared with the 3D-CAD data. The average dimensional accuracy was better than 0.2 mm, a very good result and acceptable for sheet metal forming.

Figure 9 illustrates the sprayed steel mold. The average surface roughness (R_a) was approx. 17 µm which is high compared to milled surfaces. In addition, cross lines due to the fitting of the four segments were visible so that a post-machining and polishing would be necessary.

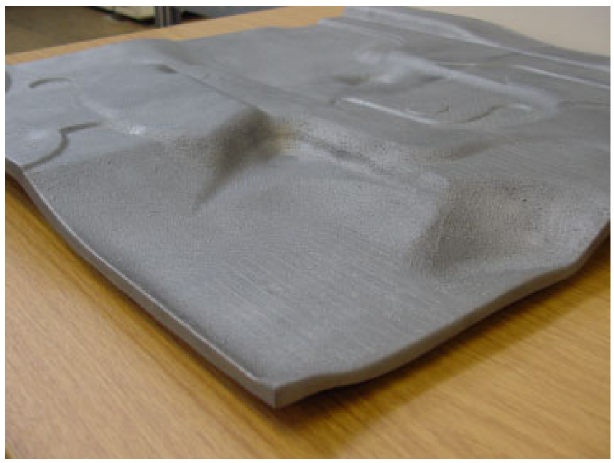

Fig.8: Sprayed carbon steel mold

The surface quality could be improved by painting the surface with a ceramic slurry similar to the one used to produce investment casting cores. The post processing would be minimized thereby. This could form the subject of the next investigation leading to a faster production of steel molds.

Conclusion and Outlook

It has been shown that ceramic laser sintering is a promising method of producing metal prototypes or moulds very rapidly. The examples shown illustrate that both ferrous and non-ferrous alloys can be successfully cast using laser sintered shells. The dimensional accuracy of the metal prototypes compare favorably with conventional cast parts.

The advantages of laser sintered investment casting cores are that they are usable for complex prototypes as well as for single part productions since a slurrying increases the surface quality. A quality analysis could be done directly after laser sintering and not after casting. Finally, laser sintered cores are easier to remove after casting than conventional cores.

The use for spray metal tooling of stamping dies or sheet metal forming moulds is only limited by the present work area of laser sintering systems. A segmentation of large moulds is possible but the dimensional accuracy could be affected.

Future research on laser sintering will focus on the investigation and assessment of further ceramic powders including aluminum oxide, zirconium oxide or silicon nitride with particular reference to medical and technical applications.

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