Additive Manufacturing of metal parts by Selective Laser Melting has become a powerful tool for the direct manufacturing of complex parts mainly for the aerospace and medical industry. With the introduction of its desktop machine, Realizer targeted the dental market. The contribution describes the special features of the machine, discusses details of the process and shows manufacturing results focused on metal dental devices.

Keywords: Additive Manufacturing; Selective Laser Melting (SLM); Cobal Chrome; Dental bridges; Scan Strategy

1. Introduction

Within the last years, the direct digital manufacturing process called Selective Laser Melting has developed to be the most effective powder based Additive Manufacturing method for metal parts. It is used for making non-machinable complex parts for direct use preferably in the aerospace and aeronautic and the medical industry. Based on its mostly dense the parts show very good mechanical properties. The process requires just the removal of the supports and a surface finishing. If necessary, the parts can be machined and surface treated using any kind of traditional methods.

But the success of SLM was mainly based on quite voluminous and consequently expensive machines that additionally had to be run by well-trained staff - all of them reasons to keep small companies and especially crafts enterprises well away.

In late 2009 the first desktop SLM machine was introduced to the market. It was adapted to the needs of small business companies that need small but individually shaped parts. Consequently mainly crafts enterprises like dental laboratories were targeted.
To provide a support for the prospective applicators the paper deals with the capabilities of the machine, the specialties of the build process and show the state of the art.

2. The SLM process

The Additive Manufacturing process of Selective Laser Melting (SLM) is a Laser Sintering process, specially developed to process fully dense parts by creating a fluid phase, the so-called melt pool. The basics can be studied in the literature, e.g. [1], and will not be discussed further.

SLM basically is a laser welding process and all welding related problems as shrinkage, distortion, cracks, residual stress and surface hardening are to be expected. To control this complex set of parameters, the process runs under shielding gas, fine grained powders are applied and sophisticated scan strategies are used to govern the exposure by the laser beam. To achieve fine details and a minimum of stair stepping, a small layer thickness and a small laser beam diameter are necessary. Today fiber lasers in the 100W range with beam diameters in the range of 0,2 μm to 0,4 μm are used. The layer thickness is in the range of 30 μm.

As materials, commercially available powders can be used. The grain size is in the range of 20 μm to 50 μm.

2.1. The Realizer Desktop

The Realizer 50 is the first Desktop downsized SLM machine. It is designed for making small but macro size parts. It does not only show a small footprint of 800 x 700mm but a height of 500 mm and a weight of approx. 80 kg. Requiring bottles of argon gas and a plug (22V, 16A, approx. 1kW) it can even be transported and installed at various places.

The machine consists of a sealed build chamber containing the powder feed and handling system, the round process chamber with the movable build platform, the leveling system, the laser window and a microscope for visual inspection during the build (see fig. 1).

In summary the machine is designed for small companies that continuously make different but small parts.

Fig. 1. The Realizer 50 Desktop SLM Machine. (a) Overall view; (b) Cross section of the Build Chamber, Sheme. Source: Realizer GmbH
The build space shows a diameter of 70mm and a height of 40mm. As a distance to the wall of the process chamber of approx. 10mm is necessary and the elevator that moves the build platform travels maximum 29mm, the usable build space is 60mm (diameter) and up to 27mm (height).

Conditioned and sifted powder comes in special containers that are mounted upside down on top of the build chamber and drops the required amount of powder onto the build area directly into the process chamber.

A double bladed level bar takes a defined amount of powder, spreads it over the build area and provides the required layer thickness in the process chamber. After the laser beam has exposed the actual layer contour, the build platform is lowered by the amount of one layer thickness and the procedure starts a new until the part is completed. As it is cold, it directly can be removed from the machine with the whole platform.

The post processing requires the manual removal of the part from the platform, of the supports from the part and of the support’s footprint from parts down facing layers.

3. Dental Crafts Enterprises

In Germany like in many countries of the world, dental crafts enterprises work as service bureaus for the dentists. The majority has less than 10 employees, the big ones seldom more than 50. In the recent years most of them had to face a lot of problems. Competitors abroad offered low-priced alternatives due to low wages while others tried to commercialize the business in an industrial scale.

The upcoming digitalization of the traditionally fully manual process first was regarded as another harassment. But more than 100 participants at the (first 2009 and second 2010) Conference on digital dental technology at the German Additive Manufacturing Conference and Fair, RapidTech, impressively showed that the leading enterprises are willing to accept this challenge.

Among the various services provided by dental crafts enterprises the making of crowns or bridges takes a prominent place. A digital process chain is achieved by a successive replacement of manual steps:

- The dental model is obtained as a digital data set by scanning the dental impression (labside) or directly intraoral (chairside) from the patient. Different Systems are worldwide available; e.g. CEREC AC with Bluecam (Sirona, Germany), LAVA Chairside Oral Scanner C.O.S.(3M, ESPE), iTero (Cadent, USA), E4D (D4D Technologies, USA), directScan (Hint-ELs, Germany).
- The formerly manual process of preparing the bridge is completely done virtually using dental design software, e.g. Dental Designer / CAM bridge (3shape, Denmark) or the CEREC 3D (Sirona Dental, Germany).
- The manufacturing must not only be based on casting but can be done directly by CNC milling or by Additive Manufacturing supported by special CAD/CAM software interfaces.

As a result, the crafts enterprise can deliver high-class crowns and bridges and stay in close contact with its customers.

4. Making dental crowns and bridges by Selective Laser Melting

Selective Laser Melting is a new manufacturing method for dental crowns and bridges but it has to face strong competitors. Casting is a proven process and CNC milling shows high accuracy and is based on the same digital data as SLM.

To get a good idea of the characteristics of SLM, the process is monitored according to some key issues. As selective laser melting basically is a laser welding process, all concomitant phenomena, such as pores, cracks, distortion and warping and residual stress must be taken into consideration. To avoid this, or at least to reduce it to a minimum the basic machine parameters as the laser diameter have to be assured and the scan strategy has to be optimized.

An optimization has to be carried out for every material and according to the geometry of the part and of the supports. The resulting data set is called material data set.
5. Scan Strategies

Each layer is defined by its outer and inner contours (boundaries) as obtained from the dental design program. To make it a physical area, the contours have to be linked by hatches (also called fills). Boundaries and hatches are the paths the laser beam travels over the build area thus locally melting the metal powder and leaving a solid layer after resolidification.

Fig. 2 shows a simplified slice based wire model of a dental bridge by its inner and outer contours. The outer contour defines the boundary of the layer and the part respectively (b). The laser path has to be retracted by the amount of the half of the beam diameter (beam width compensation). Recursive paths in circumferential direction followed by hatches in radial direction form the layer’s area (c, d).

Fig. 3 shows the top view of a structured layer.

Fig. 2. (a) Simplified layer model of a dental bridge; (b) Layer taken from (a), (c,d) scan lines: borders and hatches

Fig. 3. Top view of a layer showing the laser path grid due to the scan strategy. The distances 1 to 5 equal approx. 100 μm each.
Depending on the material, the part geometry and the support geometry, each area can be made by boundaries, hatches or a favorable combination of both.

6. Phenomena

One of the most important properties (not only) of dental parts is density. Blowholes and micro pores have to be avoided. Fig. 4 shows a cross section of the dental bridge (Fig. 2. (a)) with a micro pore of approx. 30 μm diameter. On Fig.4 there also can be seen some cross-sections of supports (b) before they join the part some layers later.

Fig. 4. (a) Micropores. (b) Supports (cross sections)

In the very near of the surface (outer boundary) particles may be partly molten and tend to adhere thus leaving a so called “fur” that causes an uneven surface of the part and maybe inaccuracies (Fig. 5).

Fig. 5. Adherent semi molten particles at the outer contour. Especially volcano shaped details tend to set within the boundaries which very much influences on the details of the tooth geometry as can bee seen on Fig. 5. This phenomenon can also be influenced by the scanning strategy.
7. Results

As investigated on behalf of a specially designed three-piece demonstrator bridge, SLM delivers dense parts.

To verify its accuracy, unlike in nature, the bridge was designed with two conical snags showing a defined release angle. The bridge was built upside down, to achieve a quality edge of the conical part. Consequently the fissure in the tooth surface interferes with the supports which causes some manual finishing effort. The accuracy was proved to be sufficient by means of a gauge that can be seen on Fig. 7.

After manual work out, the part showed a good surface quality. The density and the absence of pores was verified by microscopic inspection (Fig. 8)
8. Materials

SLM can process any commercial metal powder and even powder blends. For a variety of materials material data sheets are already available and are tested by the machine manufacturer who usually does the logistics as well.

If proprietary powders are desired, the elaboration of the material data set as well as the certification of the material lies in the responsibility of the user who needs either own qualified personal or tasks the manufacturer or a university to do it.

For technical applications there are available: tool steel (H 13), titanium, titanium V4, aluminum, stainless steel 316 L, nickel and cobalt base alloys like cobalt chrome (CoCr) and Inconel 718, Gold.

For dental applications certified (DIN EN ISO 22674) non noble metals like CoCr and noble materials like gold based dental metal-ceramic alloys are available.

As the alloying of powders is almost unlimited, a great variety of new materials are expected in near future.

9. Conclusions

Selective Laser Melting is a suitable manufacturing technology for making dental parts. To obtain optimal results the material database has to be worked out separately for every material and preferably for geometric similar parts and support structures as well. Additionally an optimized support structure and scan strategy has to be implemented. This preparatory task requires well-trained personal.

Based on this work the staff of a dental crafts laboratory will be able to run the system after a special training. Regarding the break-through of the SLM technology in the dental field two aspects have to be taken into consideration.

First, as mentioned above, SLM is not the only promising technology. Based on digital data acquisition from the imprint or intraoral, both, casting and milling are high competitive manufacturing processes. Casting has improved tremendously by integrating plastic rapid prototyping processes for making lost masters. Milling is a completely digital process like SLM. Milling machines became better and cheaper. Certified dental material is available for both processes. If material costs gain more economical weight, which is true for gold based alloys, SLM will become advantageous because of almost zero chipping compared to milling and very little waste compared to casting.

Second, crowns and small bridges are comparably simple parts. Complex parts like multi-parts bridges or even partials are much more challenging. They require filigree cross sections must assure a defined flexibility over its whole lifetime. This is a big challenge for casting and milling too.

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