Fast Production of Technical Prototypes Using Direct Laser Sintering of Metals and Foundry Sand

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1. Introduction

Currently most RP-Parts are used for visualisation, assembly checks and some functional testing. The next stage between these functional prototypes and the pre-series is technical prototypes, which are used for final functional testing and optimisation of the production process. These must not only have the same material as the series parts, but must also be manufactured with the same production process. Due to the second of these requirements layer manufacturing processes cannot be used to build these prototypes directly, but they can be used to make the negative moulds or tools.

Two new RP-processes based on laser sintering now have the capability to produce the moulds and tools via very short and fast process chains. Both have already been in commercial use in Europe for about one year.

The first process manufactures tools for injection moulding of plastic parts by Direct Metal Laser Sintering (DMLS). The second process, called the Direct Croning Process (DCP), is used to build sand moulds and cores for sand casting of metal parts directly from Croning-Sand without any tools. These technologies have been developed by EOS GmbH, Munich, and are marketed under the names EOSINT M and EOSINT S respectively.

2. Direct Metal Laser Sintering (DMLS)

The most important application for laser sintering of metals is the production of tooling and moulds for injection moulded parts. Two fundamental approaches are possible:

- Indirect laser sintering with organic binder followed by solid state sintering in a furnace /1/
- Direct liquid phase sintering (DMLS).

EOS has concentrated on DMLS, because the indirect process chain makes it very difficult to achieve the narrow tolerances required in toolmaking without repeated iterations. With DMLS it is possible to get very close to the final geometrical and material properties already in the direct sintering process, thereby avoiding the loss of time and accuracy associated with secondary sintering processes.

2.1. Material and process

The basic composition of the DMLS material was developed and patented in the late 1980s by Electrolux Rapid Development, Finland for tooling production by pressureless furnace sintering. EOS now owns the exclusive worldwide licence to these patents. The composition of the bronze-nickel based powder was described at the last two SFF symposia in Austin /2/, /3/.
By using the right parameters the typical shrinkage due to the liquid phase sintering can be completely compensated by an expansion of the material caused by diffusion of the

components so that this material has no net volume change during the laser sintering process. This eliminates the need for a high temperature environment, which is otherwise required to reduce the internal stresses induced during laser sintering of other metal powders. The DMLS-process works at ambient temperature.

Due to the small laser focus of 350 μm and the comparatively high scanning speed of 300-800 mm/s the duration of heating is short enough to avoid oxidation even without inert gas atmosphere. The phosphor content of the third material component inhibits oxidation of the powder mixture and also improves the wetting of the solid particles in the molten phase.

This short reaction time of few milliseconds was the reason for the relatively poor mechanical properties of the first laser sintered samples of the initial powder mixture, which had been optimised for furnace sintering. The wetting and the diffusion reaction were not completely finished because the available time was simply to short.

During the last nine months the mechanical properties and the reliability of the process have been significantly improved by adapting the material composition to the specific requirements of the laser sintering process.The most important variations are an icreased content of the liquid phase, an enlarged surface area for the diffusion and an optimisation of the laser and scanning parameters.

The tensile strength of the green part has been improved from 81 N/mm² last year to currently 150 N/mm² and the bending strength from 150 to 300 N/mm².

The resulting porosity of these parts when sintered without shrinkage to obtain the highest accuracy is approximately 25%.

The green parts can be machined just like an aluminium part by milling, grinding, drilling etc. and the strength is already sufficient for special applications like blow-moulding or vulcanisation moulds.

These figures can be improved by an infiltration process that fills the pores. The preferred infiltration fluid is a high temperature epoxy resin, because this secondary process has no influence on the accuracy due to the relatively low heat impact to the metal. The result of the infiltration is an improvement of the bending strength to approx. 400 N/mm² and a smoothing of the surface.The hardness after the infiltration is 108 HB.

The infiltration is driven by the capillary forces, only the rear side of the mould must be dipped into the resin. This procedure needs about half an hour, the post curing in a simple oven at 160°C needs about two hours. Preheating of mould and resin to 60°C accelerates this process and reduces the residual porosity.

Silver-based infiltrants are currently in the evaluation phase. Although the mechanical properties can be improved, the cost of the necessary equipment and the loss of accuracy due to a shrinkage of more than 2% are a major disadvantage /3/.

The negligible shrinkage of the DMLS process enables an accuracy of epoxy infiltrated parts of 0.05 to 0.1% in the first trial, which is even comparable to stereolithography. The limit for the accuracy is the mean particle size of 35-40 μm. Typical layer thicknesses of 80-100 μm are used to obtain a comparable resolution in the z-direction.

The roughness of the infiltrated part is about Ra = 3..5 μm, which is comparable to a rough EDM surface. With standard manual polishing, a roughness of Ra < 1 μm is possible.

The heat conductivity of the sintered tools of 110 W/mK is slightly lower than the value of aluminium.

2.2. System

All EOS laser sintering machines are designed according to the specific requirements of the used material and optimized for the intended application.

The main difference between the sintering systems for metal and for polymers is the design of the optics and the laser, because the much higher sintering temperature of approximately 900 °C requires a higher power density. Therefore the focus diameter was reduced to 350 µm and the laser power was increased to 250 Watts. The power density thereby was increased from 25 W/mm^2 for plastic powders to 700 W/mm^2 for metal. More powerful lasers are still in the test phase.

Since no preheating of the powder is needed, the design of the process chamber is less complicated.

The working area of the EOSINT M 250 machine is 250 mm square, the maximum part height is 150 mm. With a density of the sintered material of 6,1 g/cm^3 the maximum weight of the part is more than 50 kg.

2.3. Applications

The most important application of DMLS is the production of prototype tooling for injection moulding. The process is especially useful for complex moulds.

If the geometry of the tool is simple enough to be manufactured just by milling, the rapid tooling processes generally cannot compete against high speed milling machines.

However if EDM is required for some details in the tools, the DMLS process is usually faster and often less expensive than the conventional methods.

Sintering and infiltration of the mould inserts needs only 1-2 days, depending on the size. The time needed for CAD design of the tool and for finishing and mould assembly is the same as in the conventional process for aluminium tools. The building accuracy of the split planes is sufficient that only manual finishing is needed, thereby eliminating the need for the expensive and time consuming design of an offset on these planes and an additional machining step.

Using DMLS several service bureaux have made many projects in a total processing time of only one week, including tool concept, CAD design of the tool, DMLS, infiltration, finishing, mould assembly and injection moulding.

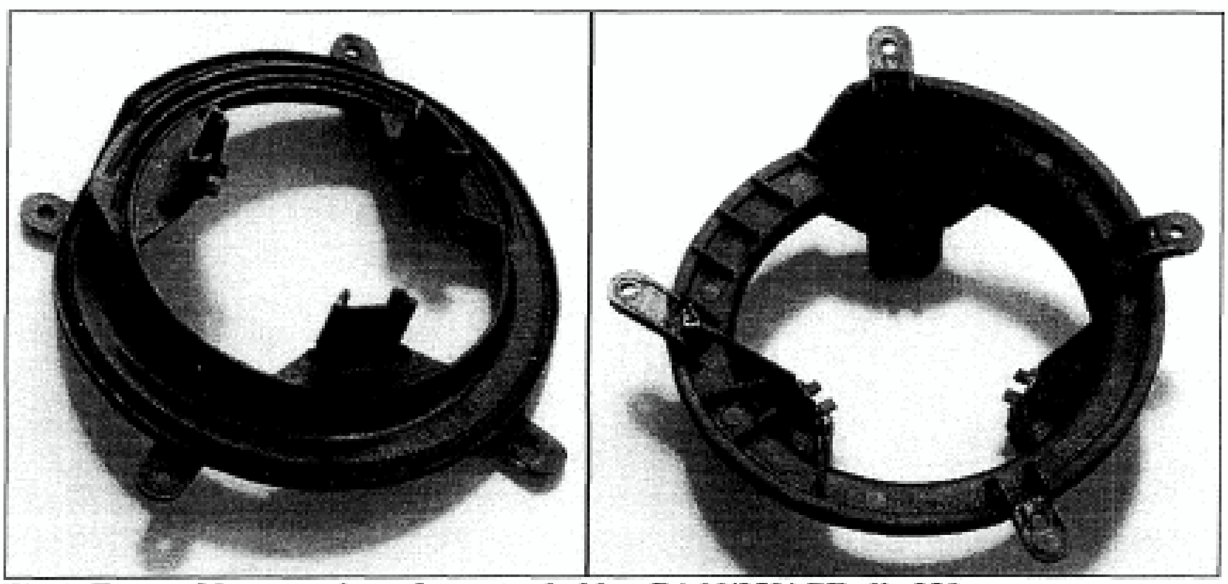

Fig 1: Top and bottom view of a motor holder, PA66/35%GF, dia 230mm

ambient temperature this coating is dry and hard. The total resin content of the mixture is about 5 %, which is comparable to standard foundry sands. The use of this material for building moulds and cores by laser-sintering has been patented by EOS.
At a temperature of 150 - 200 °C the polymerisation reaction starts and leads to an irreversible thermoset bonding between the sand particles. In the conventional foundry process the Croning sand is poured over hot steel tools having the positive part geometry, in the Direct Croning Process the energy input is completely provided by a CO_2 laser. No additional preheating of the process chamber or the sand is necessary. The process also does not require an inert gas atmosphere.
The sand costs are about 1% of typical stereolithography resins and unsintered sand can be reused several times.
Due to the low binder content the shrinkage of the material is neglegible (< 0.1%). The accuracy of the sintered moulds is therefore only limited by the positioning accuracy of the scanners and the particle size (for fine details).

The surface quality of the cast parts is comparable to the typical figures for conventional sand casting. If a smoother surface is required, these specific regions can be coated with the commonly used ceramic blackwash.

DCP without blackwash	50 - 80 µm
DCP with blackwash	25 - 30 µm
Green sand	50 - 70 µm
Croning shell	20 - 40 µm

Table 1: Roughness R_a of aluminium castings depending on the mold material

Generally every alloy that can be used for sand casting can also be used with DCP moulds. So far various alloys of aluminium, magnesium, iron and steel have been cast sucessfully.

3.2. System

The EOSINT S700 sand laser-sintering machine is the first RP system to use a twin-laser setup. Each laser has its own scanner and they operate simultaneously and in parallel to effectively double the building speed. Each of these scanner heads has a working area of 380mm square, which allowing for a small overlap in the middle gives a total building area of 720 mm by 380 mm. The maximum part height is also 380 mm.
The sintered parts are removed from the machine in a container and separated from the loose sand in an external recycling station. The machine can immediately start the next job. The high maximum part weight of more than 200 kg requires a special handling system for the part containers, which is supplied with the machine.
A pneumatic handling system is also included in the machine for automatically refilling with sand without interrupting the building process.

The twin head design and the high scanning speed of 2000 mm/s enable a very high process productivity. Depending on the complexity of the geometry the typical rate is 0,8 - 1.5 kg part weight per hour.

3.3. Applications

Like laser sintering of thermoplastic materials, DCP has very few limitations on the part complexity. Almost every geometry which can be cast can also be built with this process. The limits of sand casting (e.g. a minimum wall thickness of 1.5-2 mm) can be achieved without problem.

DCP often allows the design of the mould to be significantly simplified, for example no draft angles are needed, undercuts are easily possible and the number of the necessary core-pieces can often be reduced. **(see Fig 3)**

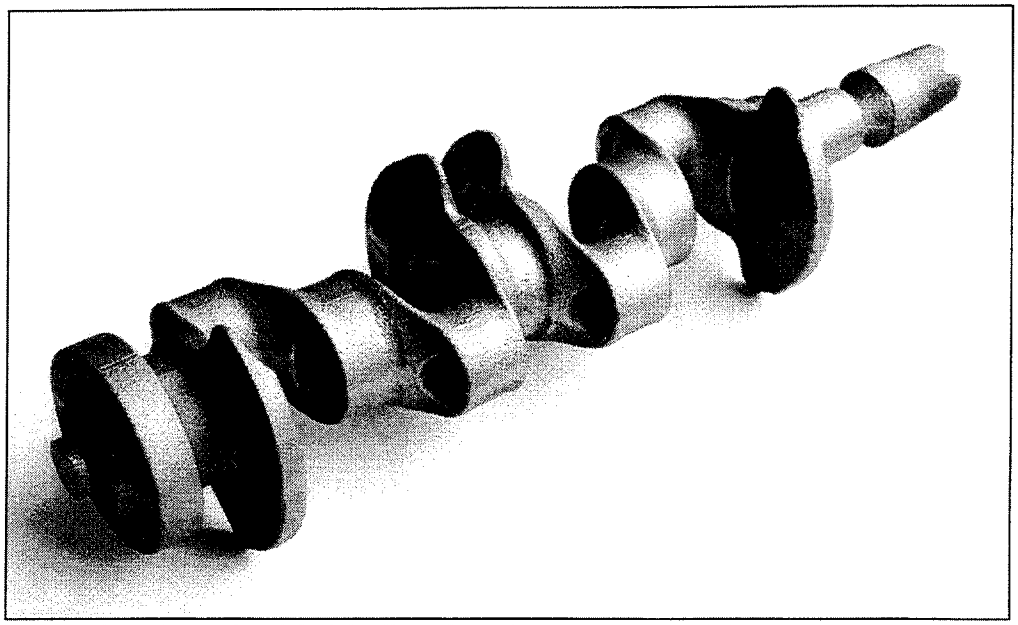

Fig 3: Crankshaft with 9 hollow bearingseats, casted in a two-part mould

Although DCP has many applications including hydraulic parts, pump components etc., the most important one is the production of prototype parts for engine development.

The potential of this process is impressively demonstrated by the example of cylinder head development. Due to the extremely complex geometry of this component with internal water cooling channels, valves and many inlet/outlet channels, prototype tooling is very complicated and difficult to manufacture. The time required between CAD design and the first casting using conventional methods is 15-20 weeks. Because the design of the cylinder head has a very significant influence on the engine performance, many iterations and optimisations are necessary for this component. Therefore this part is usually the most time-critical component which determines the duration of the engine development.

The build time for a 1-cylinder head using DCP is only 2 days, for a 4 cylinder head about one week. Together with the additional design of the mould and the runner/gating system which is needed anyway, the total processing time of a new head can be reduced to 2 - 3 weeks, which means a time saving of 80%! The DCP-produced cylinder heads are virtually identical to series parts and can run in test engines.

These figures are based on the experiences of the beta customer BMW, who was involved in the development of the system and the process from the start. With the two units that were installed in their foundry 6 and 12 months ago they have already cast almost 100 different engine designs. The other partners of the beta test programme are Mercedes Benz and several service bureaux that work for the automotive industry.

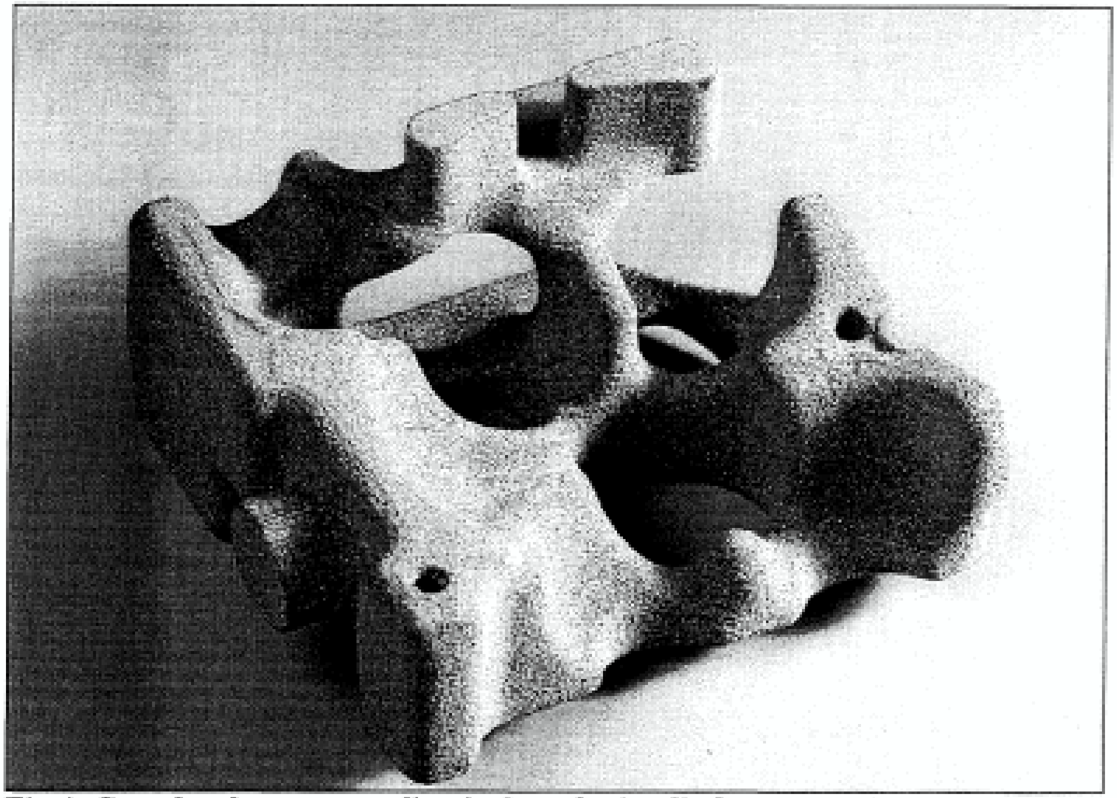

Fig 4: Core for the water cooling jacket of a 1-cylinder test engine

The high build speed makes it possible to produce not only single prototypes but also small series. The biggest order so far for one of the service bureaux was the production of 1000 complicated cores (120 x 120 x 80 mm) for a water jet system.

4. Conclusions

The production of technical prototypes (i.e. in series materials and with series production techniques) by Rapid Prototyping was until recently only possible via Rapid Tooling process chains involving at least one conversion process, due to the limitations of the available RP materials. The recent introduction of Direct Metal Laser Sintering (DMLS) and the Direct Croning Process (DCP) has for the first time enabled the direct production of tooling and moulds for injection moulding and sand casting respectively, and thereby the fast and efficient production of technical prototypes in both plastics and metals. This marks a very significant advance in Rapid Prototyping and Tooling technology. The ability of DCP to directly manufacture one-off and small-series parts with identical quality to conventional sand-cast series parts has also for the first time made the breakthrough into true Rapid Manufacturing.

Since neither the sharpness of the edges nor the levels of form and dimensional accuracy achieved meet the requirements of a pre-series tool, the contour of the part is milled. The upper surfaces also undergo a milling operation to keep the distance between the upper edge of the last deposited layer and the lower edge of the powder nozzle constant, Figure 2. Similar to the other Rapid Prototyping techniques, the workpiece is created layer by layer.

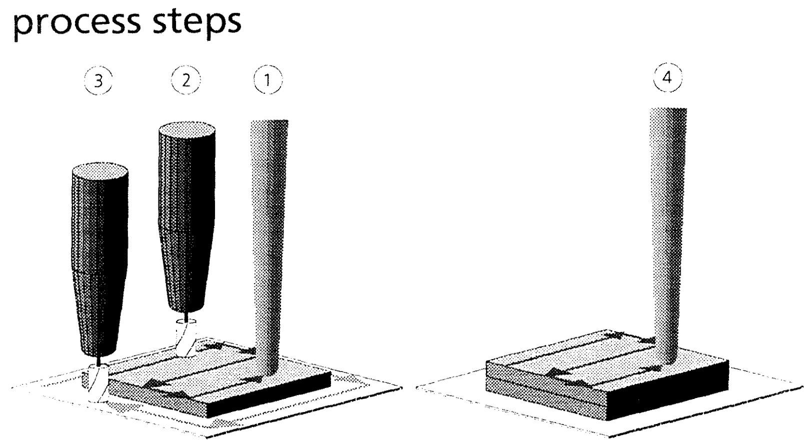

Figure 2: Process steps of CMB

CMB allows processing of numerous metallic materials ranging from bronze through steel to hard alloys which are frequently used to protect against wear. Since CMB is, in contrast to conventional cutting operations, a generative process, narrow, deep grooves may easily be produced using a constant, low engagement depth of the milling tool. The suitability of this method for automation in comparison to e.g. conventional 5-axis milling is a powerful advantage. By virtue of the layer-by-layer nature of this technique, the CAD data may be processed quickly and with considerably less effort.

The test facility at the Fraunhofer IPT is essentially a high speed milling machine supplied by the Albrecht Röders company on which a laser generating head has been mounted, Figure 3. To date, simple geometries have been built using different materials in order to investigate the principle underlying the CMB process (Figure 3).

Selective Laser Sintering

Current approaches to sinter metallic powders are concentrated on the direct or indirect sintering of the chosen material. Indirect sintering, deploying a binder phase (e.g. a polymer), has the advantage that only the binder material needs to be melted, most of the time at a low temperature allowing manufacturing of metallic parts using conventional plastic sintering machines. However, the workpiece must be debindered and infiltrated, causing loss of accuracy and prolonging the time needed for manufacture. Direct sintering is aimed at melting the chosen material during the SLS process directly, eliminating the need for debindering. However, since processes currently industrially available leave the parts with a porosity of about 70%, infiltration is still necessary to achieve full density. Another problem related to direct sintering of metallic

These technologies have also introduced new technical innovations which are pushing RP technology forwards. EOSINT M 250 is the first commercial system to build parts directly in metal, while EOSINT S 700 is the first RP system worldwide to use two laser-scanner systems in parallel for increased productivity.

Due to the considerable time-saving benefits of these new technologies they have established themselves very rapidly in Europe. EOSINT M and EOSINT S systems have been in use at service bureaux and industrial end-users since the summer of 1995, including such reference names as BMW, Mercedes and Electrolux. These companies are already experiencing the technical and commercial advantages of true Rapid Tooling, and the growing user-experience being generated by the rapidly expanding customer base is indicating a number of exciting new applications which will be reported in future.

References

/1/ Badrinarayan B. and Barlow, J. W.,"Metal Parts from Selective Laser Sintering of Metal-Polymer Powders", Solid Freeform Fabrication Symposium, Austin 1992, 141-146

/2/ M. Sindel, T. Pintat, M. Greul, O. Nyrhilä, C. Wilkening,"Direct Laser Sintering of Metals and Metal Melt Infiltration for Near Net Shape Fabrication of Components", Solid Freeform Fabrication Symposium, Austin 1994, 94-101

/3/ T. Pintat, M. Greul, M. Greulich, C. Wilkening,"Accuracy and Mechanical Behavior of Metal Parts Produced by Laser Sintering", Solid Freeform Fabrication Symposium, Austin 1995, 72-78