Direct Manufacturing of Metal Prototypes and Prototype Tools

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Abstract

Due to the limited mechanical characteristics of the materials which can currently be processed using industrially available Rapid Prototyping machines, a lot of research is focused on the development of techniques which allow a direct manufacturing of metallic parts. These include Selective Laser Sintering and Controlled Metal Build Up. Both methods produce the workpiece not by removal of material but by a layerwise deposition and local melting or sintering of a powder material without part-specific tooling.

Controlled Metal Build Up is a new Rapid Prototyping technique similar to Fused Deposition Modeling combining laser generating/welding with conventional 2½ dimensional milling. Due to the excellent surface quality and high dimensional and form accuracy achievable with Controlled Metal Build Up, this technology offers an interesting alternative to the conventional time consuming processes for the manufacture of prototype tools required for limited production runs.

With respect to Selective Laser Sintering, a test facility was developed for experimental investigations into the direct sintering of low and high melting metallic powders without the use of a polymer binder as well as ceramic powders. Great potential is expected from Selective Laser Sintering concerning the prototyping of molds and dies.

This paper will discuss current developments for these two techniques as well as point out possible applications and future developments.

Introduction

Recent developments in Rapid Prototyping have to a large extent been focused on the manufacture of prototypes with characteristics closely corresponding to the characteristics of the serial part being developed, allowing functional testing [1, 2, 3, 4]. The production of a prototype suitable for functional testing requires the prototype to be identical to the serial part in shape, material and production process. While the first requirement is being thoroughly adressed through e.g. constant improvement of machine accuracy, the second requirement has only sufficiently been met for a small number of plastics [1, 3, 4]. During 1995, two commercial Rapid Prototyping systems for the manufacture of metal parts (DTM RapidTool, EOS EOSINT M) were released [5, 6]. The fast generation of metallic tools e.g. for injection molding enables the production of prototypes in large quantities that exactly match the characteristics of the serial part.

However, these two new Rapid Prototyping systems have some drawbacks. The RapidTool process brought into the market by DTM, utilizing a polymer-coated steel powder for Selective Laser Sintering, is characterized by several time consuming infiltrations and part shrinkage during burn-out of the binder [5]. EOS selectively sinters a bronze-nickel powder and parts also need to be infiltrated to achieve full density [6]. Both processes require extensive part finishing [5, 6].

To overcome the problems associated with part density and accuracy, the IPT has developed a new process called Controlled Metal Build Up (CMB) in close cooperation with Albrecht Röders GmbH & Co. KG, Soltau, Germany, which combines laser generating with high speed milling.

Research being conducted in the field of Selective Laser Sintering is focused on the machinability of conventional tool steel to high densities as well as light metals and ceramics.

Controlled Metal Build Up

Controlled Metal Build Up is based on laser generating, a technique pioneered at the Fraunhofer Institute of Production Technology IPT [7, 8, 9, 10]. A metal powder is blown into a focused laser beam and completely melted inside a nozzle, Figure 1. A fine bead of material is deposited beyond the nozzle onto the surface of the workpiece while the equipment is moved to scan the inner regions and the outline of the part.

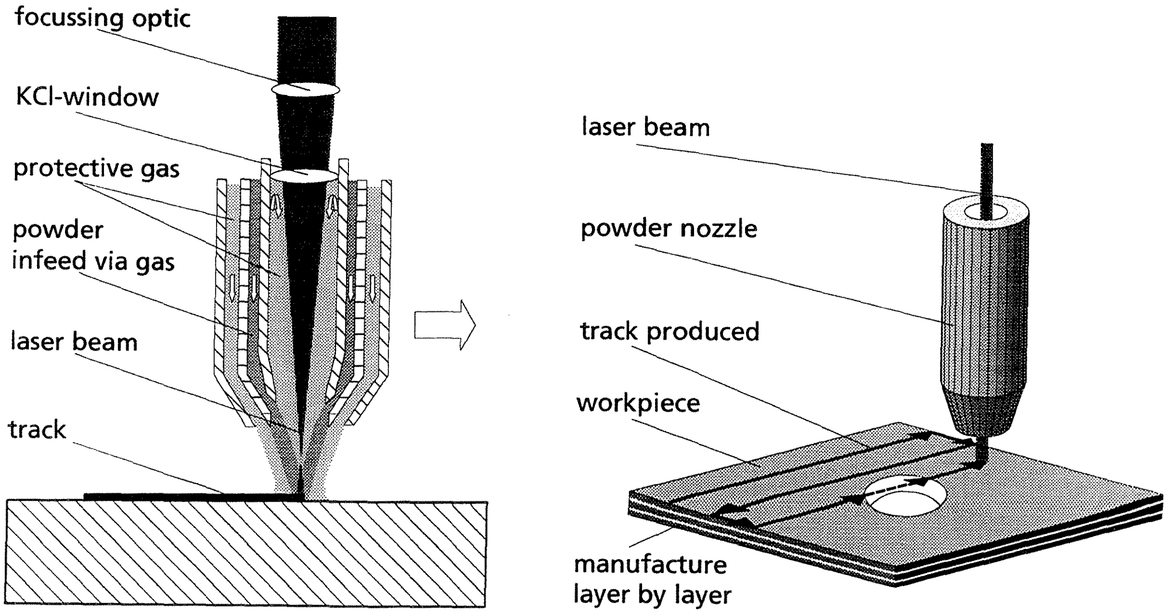

Figure 1: Powder nozzle used for CMB and principle of operation

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.

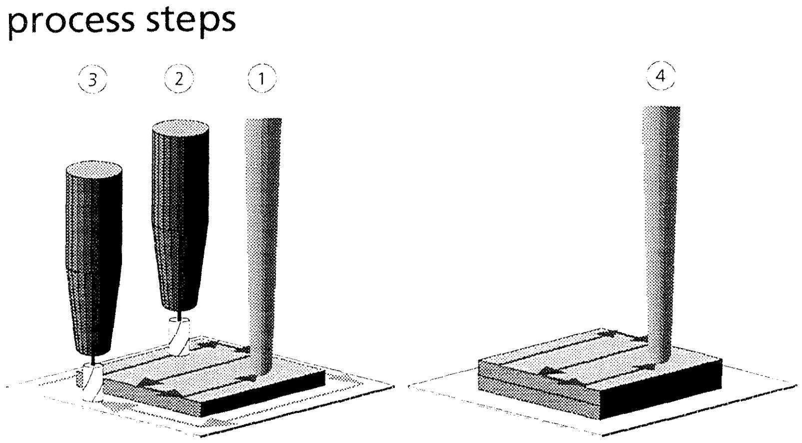

Figure 2: Process steps of CMB

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 powders is shrinkage and the induction of thermal stresses resulting in distorted and curled parts. The development of materials with virtually no shrinkage (EOS) has to some extent eliminated this problem, however neglecting the desire to be able to produce parts out of the material used in series production.

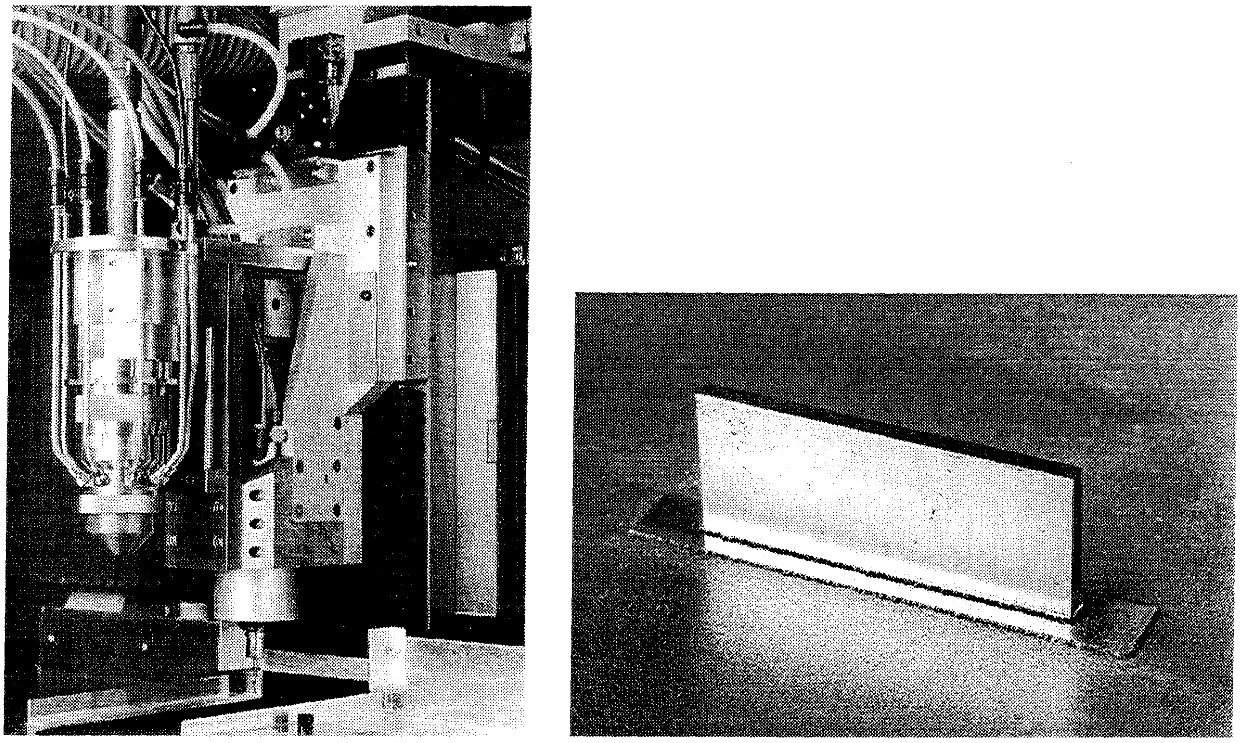

Figure 3: CMB test facility at the IPT and simple generated geometry

A test facility was developed at the IPT for direct sintering of powder materials. The process chamber of the test facility may be flooded with inert gas to avoid oxidization during sintering. The powder is supplied by a powder cylinder and spread across the part cylinder with an aluminum wiper. The test facility is equipped with a Nd:YAG-Laser with a maximum output power of 300 W.

Research conducted at the Fraunhofer Institute of Production Technology is focused on the direct sintering of metallic parts. Emphasis is put on achieving high densities during the SLS process by a careful adjustment of the process parameters, while maintaining a good surface quality. This way it is hoped that infiltration can be dispensed with without increasing the effort necessary for finishing.

Figure 4 demonstrates the influence of laser power P_L, scan velocity v_s and hatch spacing h_s on typical workpiece quality parameters. Here, a single layer of bronze was sintered using 3 different energy densities by varying the above mentioned parameters according to

$$E = \frac{P_L}{h_s \cdot v_s}$$

and measuring the resulting sintering depth, density and surface roughness.

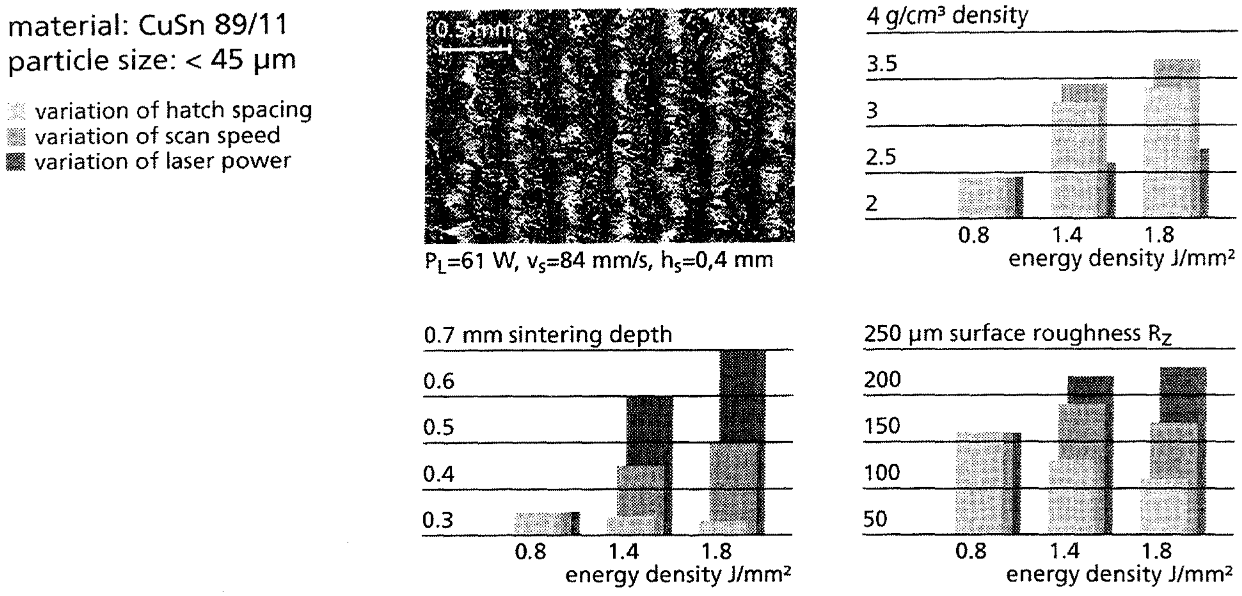

Figure 4: Influence of energy density on layer sintering

Increasing the energy density by increasing laser power or decreasing scan velocity leads to higher sintering depths, while decreasing hatch spacing has almost no influence on the thickness of a layer. A possible explanation is that for small hatch spacings, most of the light of the laser beam is reflected or absorbed from the previously drawn, solid line which has a coefficient of absorption significantly less than the one of the powder. The amount of energy absorbed by the line melts the material again without adding further to the sintering depth. The amount of energy absorbed by the powder itself is small for small hatch spacings, thus not increasing the sintering depth any further.

The density of the single layer increases with increasing energy density. A variation of hatch spacing or scan velocity has a greater effect on density than a variation of laser power, since the melted agglomerates of material are positioned closer together for slower scan speeds and smaller hatch spacings. Thus, an increase in scan velocity may not be compensated by an increase in laser power.

The surface roughness increases with increasing laser power. Higher laser powers lead to the formation of large, segregated agglomerates, being the reason for a poor surface quality. Decreasing the scan velocity also causes an aggregation of solidified material, increasing surface roughness until the velocity is so low that it allows formation of continuous solid lines. Once continuous solid lines may form, the surface quality is enhanced. Decreasing hatch spacing improves surface quality due to a continuous melting of small amounts of powder that attach to the previously solidified material.

The Fraunhofer Institute of Production Technology is working in collaboration with the Fraunhofer Institute of Laser Technology on the development of SLS of steels, light alloys and ceramics. By a careful adjustment of process parameters, especially scan vector length, the

Fraunhofer Institute of Laser Technology was able to produce SLS test parts made of stainless steel with a density greater than 95% and an acceptable surface quality. Figure 5 shows the test parts (the surface was milled to visualize the full density of the workpieces) and a cross-sectional view, displaying the low porosity. A tool was sintered for verification of the suitability of this process for injection molding, Figure 6.

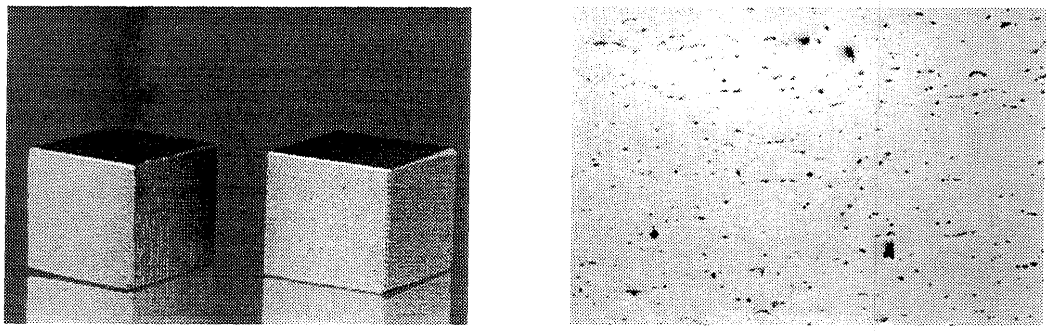

Figure 5: Stainless steel test parts (10 x 10 x 10 mm^3) and cross-sectional view

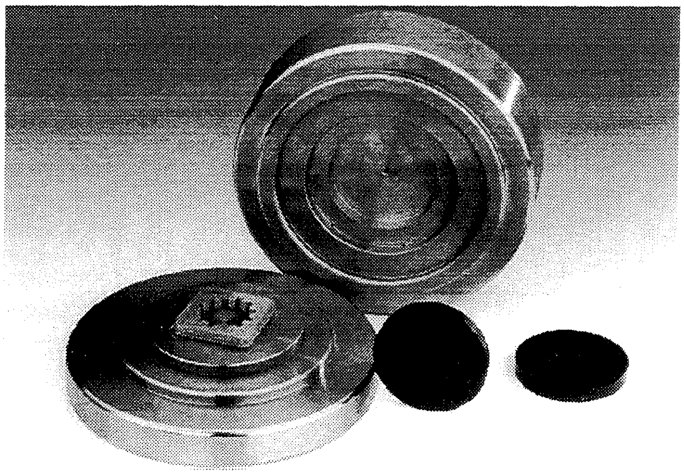

Figure 6: Stainless steel tool for injection molding of rubber parts

The ILT and IPT were also able to sinter silicon carbide (SiC) directly without utilizing a binder material, Figure 7. The resulting green part may be infiltrated with silicium and reaction sintered to a fully dense ceramic part.

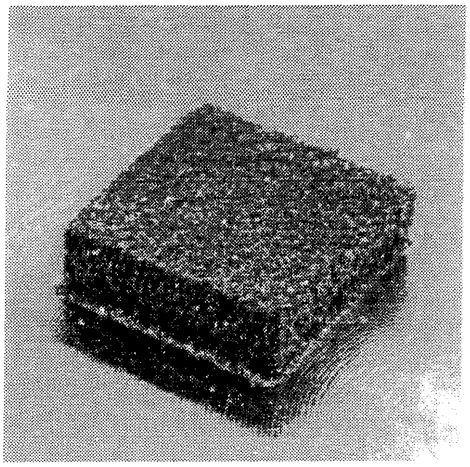

Figure 7: Test part (10 x 10 x 3 mm^3) sintered from SiC ceramic

Conclusion

Controlled Metal Build Up and Selective Laser Sintering are both promising methods for generating parts and tools out of powder materials. While two commercial SLS processes for the sintering of metal materials are commercially available, there are still many issues that need to be dealt with to make SLS of metals and ceramics applicable for widespread industrial use. Research at the Fraunhofer Institute of Production Technology is focused on the production of fully dense, accurate parts with a good surface quality through both of the above mentioned processes. The manufacture of various test parts have shown the feasibility of these methods for the rapid prototyping of parts and tools. Current developments in collaboration with the Fraunhofer Institute of Laser Technology are aimed at gaining a deeper understanding of the pricinples of SLS of metals, especially steel, and extending the machinable range of materials to ceramics.

References

[1] Venus, A. D.
Opportunities for Selective Laser Sintering (SLS) in Integrated Rapid Product Development
Proceedings of the 4th European Conference on Rapid Prototyping and Manufacturing, 13.-15.06.1995, Belgirate, Italy, pp. 55-67

[2] Haferkamp, H., Bach, F.-W., Gerken, J., Marquering, M.
Rapid Manufacturing - Direct Production of Metal Parts with Laser Radiation
Proceedings of the 4th European Conference on Rapid Prototyping and Manufacturing, 13.-15.06.1995, Belgirate, Italy, pp. 123-135

[3] Forderhase, P., Ganninger, M., McAlea, K.
Nylon and Nylon Composite SLS Prototypes
Proceedings of the 4th European Conference on Rapid Prototyping and Manufacturing, 13.-15.06.1995, Belgirate, Italy, pp. 185-195

[4] Gebhardt, A.
Rapid Prototyping - Werkzeug für die schnelle Produktentwicklung
Hanser-Verlag, München, Wien, 1996

[5] Process Enhancements - DTM's RapidTool
Rapid Prototyping Report, vol. 5, nr. 9, 1995, pp. 5-6

[6] New Equipment - EOS Introduces Sintering Machine for Metal Parts
Rapid Prototyping Report, vol. 5, nr. 12, 1995, p. 5

[7] Klocke, F., Clemens, U.
Rapid Tooling Combining Laser Generating and High Speed Milling
Proceedings of the 5th European Conference on Rapid Prototyping and Manufacturing, 04.-06.06.1996, Helsinki, Finland, pp. 211-221

[8] Klocke, F., Celiker, T., Song, Y.-A.
Rapid Metal Tooling
Proceedings of the 4th European Conference on Rapid Prototyping and Manufacturing, 13.-15.06.1995, Belgirate, Italy, pp. 225-246

[9] König, W., Celiker, T., Song, Y.-A.
Rapid Prototyping of Metallic Parts
Proceedings of the 3rd European Conference on Rapid Prototyping and Manufacturing, 06.-07.07.1994, Nottingham, UK, pp. 245-256

[10] König, W., Celiker, T., Herfurth, H.-J.
Approaches to Prototyping of Metallic Parts
Proceedings of the 2nd European Conference on Rapid Prototyping and Manufacturing, 15.-16.07.1993, Nottingham, UK, pp. 303-316