RESEARCH ON LAYER MANUFACTURING TECHNIQUES AT FRAUNHOFER

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Abstract

Within the German Fraunhofer-Gesellschaft, the Fraunhofer Alliance Rapid Prototyping unites the competences of 12 institutes in the field of solid freeform fabrication. Covered competences are virtual and computer-aided product planning methods and techniques, the development and integration of materials and processes for different industrial sectors. This paper presents actual research results on layer manufacturing within the Fraunhofer-Gesellschaft based on examples from **Fraunhofer ILT** »Laser Melting - Direct manufacturing of metal parts with unique properties«, **Fraunhofer IFAM** »ecoMold - A novel concept to produce molds for plastic injection molding and pressure die casting« and **Fraunhofer IPT** »Quick manufacture, repair and modification of steel molds using Controlled Metal Build Up (CMB)«.

Introduction to Fraunhofer

The Fraunhofer-Gesellschaft undertakes applied research of direct benefit to private and public enterprise and of wide benefit to society. Its services are solicited by customers and contractual partners in industry, the service sector and public administration. The organization also accepts commissions and funding from German federal and state ministries and government departments to participate in future-oriented research projects with the aim of finding innovative solutions to issues concerning the industrial economy and society in general.

The Fraunhofer-Gesellschaft was founded in 1949 and is a recognized non-profit organization. Its members include well-known companies and private patrons who help to shape the Fraunhofer-Gesellschaft's research policy and strategic development.

At present, the Fraunhofer-Gesellschaft maintains roughly 80 research units, including 58 Fraunhofer Institutes, at over 40 different locations in Germany. A staff of some 12.700, predominantly qualified scientists and engineers, work with an annual research budget of over 1 billion euros. Affiliated research centers and representative offices in Europe, the USA and Asia provide contact with the regions of greatest importance to future scientific progress and economic development.

The organization takes its name from Joseph von Fraunhofer (1787-1826), the illustrious Munich researcher, inventor and entrepreneur.

Laser Melting - Direct manufacturing of metal parts with unique properties

Within the broad variety of generative manufacturing processes for metals, the powder bed-based processes are limited by the use of a specific material or material composition that results in insufficient mechanical properties. In order to overcome this limitation, Fraunhofer ILT has developed the Laser Melting process in recent years.

In comparison to other powder bed-based generative metal processes, two major differences arise. On the one hand, the material used is a single component metal powder like heat-treatable steel 42CrMo4, tool steel X38CrMoV5-1, Titanium GdII or Titanium TiAl6V4. On the other hand, the physical process is a complete melting of the powder layer with a metallurgical bonding between the layers, thereby yielding densities of approx. 100 % in one step. These characteristics enlarge the field of application for this technology from Rapid Prototyping to Rapid Manufacturing of parts [5].

The starting point, as for all layer manufacturing processes [1], is a 3D-CAD model, which is subdivided into layers of a definite thickness. The actual part is generated by a repeating process of applying new material layers and transferring the area and contour information of each layer into the material using a laser beam. The transfer of the area and contour information of each layer is carried out by subsequently scanning the area and the contour with the laser beam in overlapping tracks. Through the proper adaptation of the process parameters, a density of approx. 100 % can be achieved using different materials, **Fig. 1** [2-4]. The typical layer thickness is in the range of 30 µm to 100 µm.

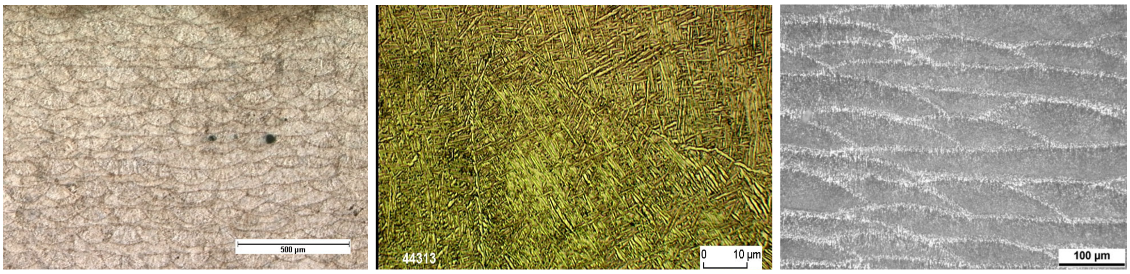


Fig. 1: Cross sections of Laser Melting parts, Tool Steel H13 (left), TiAl6V4 (middle), AlSi10Mg (right)

Due to the high density resulting from the Laser Melting process, the samples exhibit good mechanical characteristics, **Fig. 2**.

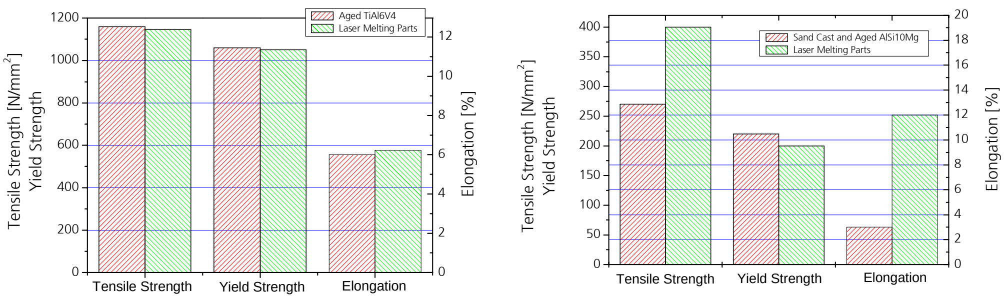


Fig. 2: Mechanical properties of TiAl6V4 (left) [3] and AlSi10Mg (right) [4] parts

For TiAl6V4 tensile strength, yield strength and breaking elongation proved to be comparable to the values for cast specimen, which exhibit a similar microstructure [3]. In the case of AlSi10Mg, the Laser Melting samples exhibit an even higher tensile strength and breaking elongation in comparison to sand cast and aged samples [4].

Injection Molding Tools

The almost unlimited geometric freedom due to the layer by layer manufacturing enables new options in the design of cooling channels, a decisive factor for cost effective production. The designer of the mold cooling no longer has to comply with the manufacturability by conventional technologies like drilling. Cooling channels can be designed for example in equal distances to the cavity, adapted to the cavity's shape (conformal) and provided in areas inaccessible by conventional manufacturing, **Fig. 3**.

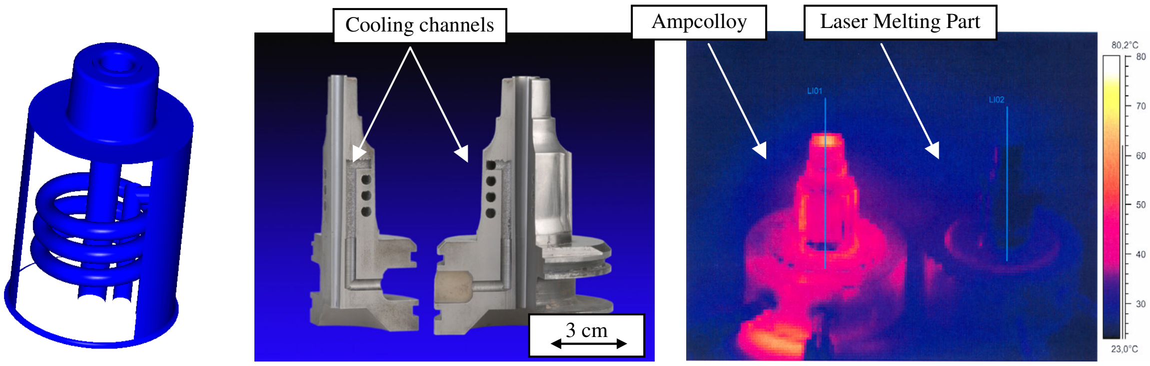


Fig. 3: CAD model (left), manufactured Laser Melting part (tool steel H13, manufacturing time 18 hours, middle) and thermographic image of Ampcolloy and Laser Melting part (right) (in cooperation with Braun GmbH)

Conformal cooling has a direct effect on injection cycle time and the quality of the parts by influencing shrinkage. A comparison to an insert out of a copper based alloy (Ampcolloy) using thermographic imaging showed that despite a much higher thermal conductivity of the copper insert, the Laser Melting part yielded a significantly higher cooling rate. The reduction of injection cycle time scales with the number of parts produced, therefore the design of special cooling channels is ideally applicable for serial mold inserts. As opposed to other metal prototyping technologies the Laser Melting process makes it possible to manufacture these inserts out of serial materials, thus making it a Rapid Manufacturing process.

Medical Implants

Another challenging field for Laser Melting parts is the manufacturing of medical implants. In recent years the use of rapid prototyping technologies has become common practice in this area. Using special software 3D-CAD models can be generated from CT data, providing the basis to achieve master models with the help of prototyping technologies such as stereolithography.

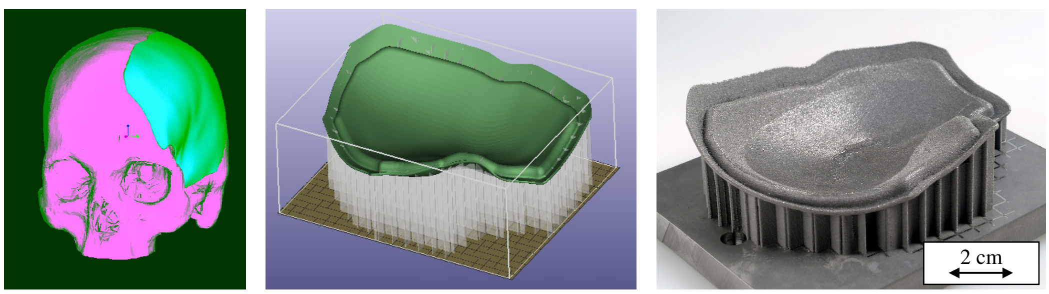


Fig. 4: CAD construction using CT-data (left), data preparation for Laser Melting (middle) and actual Laser Melting part out of Titanium GdII (right)

Through the use of Laser Melting, new process chains for medical implants will be created directly from the CT-data of patients to the manufacturing of individual implants without intermediate steps like casting, **Fig. 4**. At the end of this process chain, a fully automated production system like a Laser Melting machine could generate individual parts or parts in small lot series out of different materials. For the implant shown in Fig. 4 the manufacturing time including post-processing like removal of the support structures could be reduced from four weeks to 14 hours. In addition, the thickness was varied throughout the cross section of the implant in order to meet the specific requirements of the patient.

Complex Internal Structures

Due to the layer by layer manufacturing Laser Melting enables a high degree in design freedom and does not comply the user to geometric limitations given by conventional manufacturing methods. Design features like internal hollow structures, which cannot be manufactured by conventional methods, can be realized, **Fig. 5**.

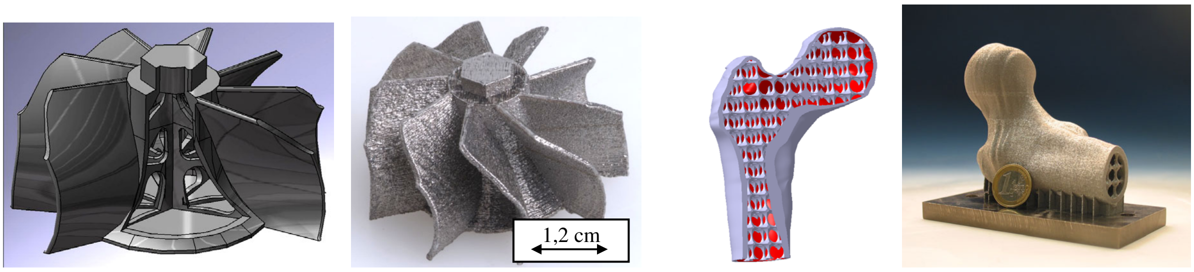


Fig. 5: CAD model and Laser Melting part out of Inconel 718 (left), CAD model and implant with internal structure (right)

The light weight design also has advantages for dynamically loaded parts. Through the use of a Nickel-based alloy, the superior material properties for high temperature applications could be combined with a weight-optimized structure. This advantage can also be used for parts with load-optimized internal structures like the implant shown in Figure 5. In combination with a light weight material such as Titanium even ultra light structures for, example for aerospace applications, can be produced.

Conclusion

The presented examples demonstrate the potential of the Laser Melting process. In particular the use of serial materials offers new possibilities in the direct manufacturing of parts. The realization of new geometric features represents a supplementation of conventional manufacturing in various different fields of application like manufacturing of medical implants, aerospace applications, mechanical engineering and tooling.

ecoMold - A novel concept to produce molds for plastic injection molding and pressure die casting

Rapid prototyping (RP) technologies are established in the early stage of the development process to verify the design, to improve the communication within the company and to accelerate the development. The properties of the parts which are produced by common RP technologies differ in particular in the mechanical behavior from the serial parts. Thus they cannot be used to be tested under realistic conditions. The properties of plastic injection molded or pressure die-cast parts depend strongly on the process parameters of the production process. Therefore it is necessary to produce molds, which are used in the serial production process, to manufacture these technical prototypes. The production of the molds by conventional technologies is very time- and cost-intensive [6]. To overcome this bottleneck RP processes, e.g. Selective Laser Sintering (SLS) of metal powder, to produce molds faster have been investigated. A significant drawback of these processes is the low building rate of the currently available systems. It is not possible to economically produce large parts with a high volume. The range of reasonable applications is limited to small parts with a complex shape [7].

Idea of the ecoMold project

Actual laser sintering systems have low building rates. Hence large parts with high volume cannot be produced economically. The basic idea is to use several pre-manufactured standard modules with laser sintered shape geometries to build up larger molds. **Fig. 6** shows the basic idea of the ecoMold project.

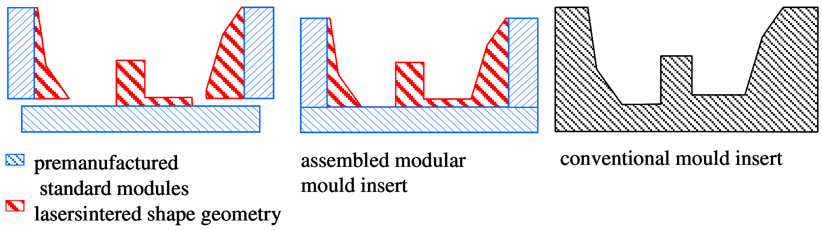


Fig. 6: Basic idea of the ecoMold project

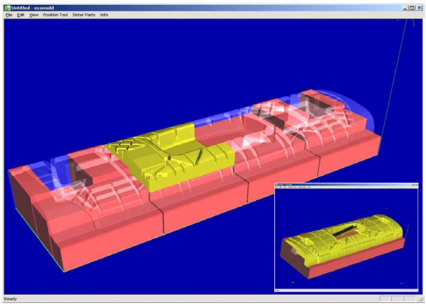
The mold is divided into different modules that are built separately. Each module consists of a base geometry and a shape geometry. The base geometries are pre-manufactured milled standard elements which are fitted into the geometry of the mold. The shape geometry is generated via laser sintering onto the standard elements. After finishing the different modules, they are assembled into the complete mold insert. The next chapters describe the developed eco-Mold software tool, the positioning system and the manufacturing of the reference tool.

The ecoMold software tool

The developed software tool can be used to fit a rectangular geometry into a given tool geometry under building restrictions. The geometry format is STL as is standard for Rapid Prototyping. The first step after loading the STL data of the complete mold insert into the software is the definition of a building plane on which the positioning of the standard elements will take place. The implemented function allows the manual definition by entering the dimensions and the position of the front left corner of the building plane. The automatic calculation will define a building plane with maximum possible extension directly beneath the model. When the building plane is defined a database of standard elements can be loaded or new elements can be defined by specification of their dimension and orientation. All defined standard elements can be placed manually on the building plane by defining their front left corner relative to the building plane. Collision checks with other elements or the surface of the model aid in correct placement.

Another possibility is the automatic placement of standard elements which will result in a complete covering of the building plane after the specification of suitable calculation parameters. All placed elements can be deleted or changed in their position manually afterwards and the whole database of standard elements can be stored. For better visual inspection it is possible to draw gaps between all elements.

The next step is the cut of the original model along the borders of the standard elements to get the sinter elements. This operation is also done automatically by several geometric calculations. The results of this operation are geometry data for each sinter element which is to be sintered by the RP device, **Fig. 7**. This geometric data can be visually inspected all together or separately. They can be saved to disc as a STL-file together with all other relevant data by saving the whole project data. Separate file names for each sinter element are generated automatically.



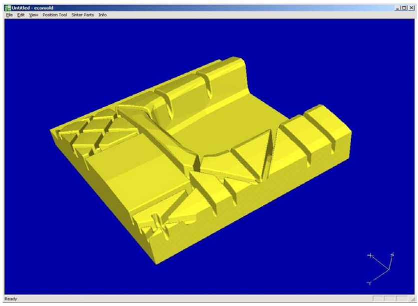
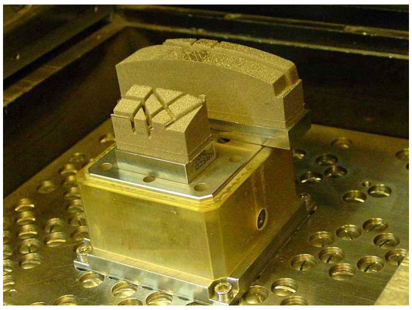


Fig. 7: Automatic calculation of sinter geometry and STL-data of the mold insert

The ecoMold positioning system

For the manufacturing of combined laser sintering and milling parts, it is necessary to use a method which allows an exact positioning of the parts within the building room of the laser sintering machine and on the working plane of the milling system. The positioning must be done with zero tolerance. Within this project such a positioning and fixing system was developed. The system is very easy to use and fulfills these demands. The system must be used for the laser sintering of the modules and for the die spotting of the laser sintered modules on the milling machine.

The positioning system assembled in the laser sintering machine EOSINT M250 X^{tended} is shown in **Fig. 8, left**. The positioning system assembled on the working plane of the milling system is shown in **Fig. 8, right**.



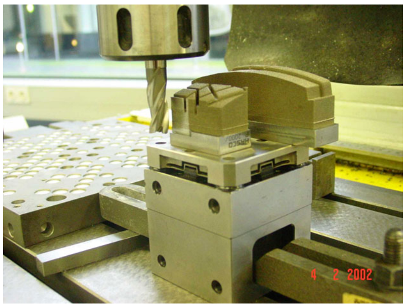


Fig. 8: Positioning system for laser sintering (left), milling and die spotting (right)

The ecoMold process chain

Within the project a reference tool was developed to test the ecoMold process chain. The test part was a glove-box-cover (size 420 x 140 x 75 mm^3). The data for the reference tool were prepared with the ecoMold software tool (Fig. 2 - 5). Based on this data preparation, 14 laser sinter modules and 10 standard modules were used to build up the mold insert. A laser sintered module is shown in **Fig. 9, left**. All used laser sinter and standard modules are shown in **Fig. 9, right**.

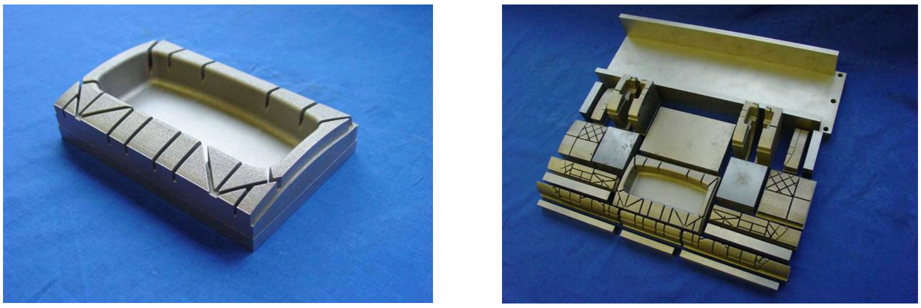


Fig. 9: Laser sintered module (left) and modules of reference tool (right)

After surface polishing and assembling the mold inserts in the mold frame, test parts were injected by using different plastic materials. The reference part is shown in **Fig. 10**.

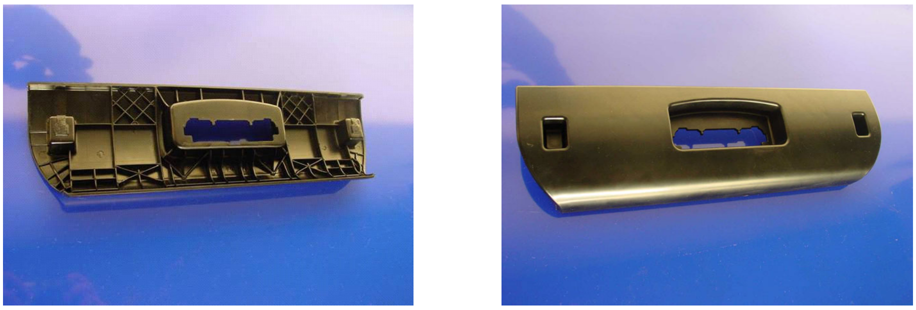


Fig. 10: Rear side (left) and front side (right) of reference part

Conclusion

A novel concept to produce molds for plastic injection molding and pressure die casting was developed. Within this research project the field of applications of the laser sintering was enhanced to medium sized molds. The basic idea was to divide a mold into different modules and use several pre-manufactured standard modules with laser sintered shape geometries to build up larger molds.

With the system described, a new manufacturing concept is available, which, by combining laser sintering and milling processes, also enables the use of direct metal laser sintering for Rapid Tooling applications of larger parts. Initial experiences and calculations have yielded that, in comparison with conventionally manufactured mold inserts, the costs can be reduced by approximately 35 % and associated development time by approximately 30 %.

Quick manufacture, repair and modification of steel molds using Controlled Metal Build Up (CMB)

A number of approaches that combine the advantages of automated generative build up with the benefits of material deposition in a welding operation are currently being pursued in the market place and in various projects conducted by research facilities. The most common of these is powder-based deposition welding, in which metal powder is blown into the focus of a laser which is guided over the workpiece by a nozzle-type device. The LENS™, 3-D welding and DMD™ techniques are among the technologies which have already been commercialized [8-13]. These methods can also be used for repairs. In conjunction with a robot, these techniques permit flexible deposition of material on large work pieces [14]. Methods which use an automated wire feeder instead of a powder nozzle are not in widespread use.

Controlled Metal Build Up (CMB)

However, none of the above mentioned approaches is capable of providing the required level of surface quality and dimensional integrity without a finishing operation. Any finishing operation conducted, for example by milling, can only be carried out retrospectively and therefore compromises the benefits gained by generative build up.

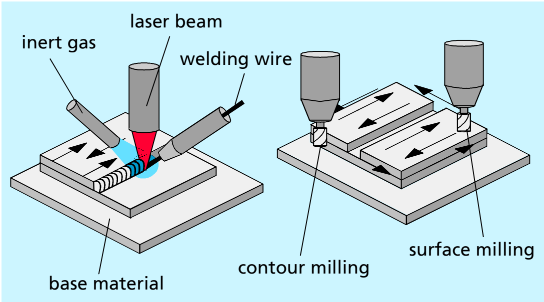


Fig. 11: Process principle of CMB

The Controlled Metal Build Up (CMB) technique originating from an idea at the Fraunhofer IPT integrates laser deposition welding within a milling machine tool [15-17]. It performs a layer-by-layer combination of welding and milling, thus permitting even deep slits to be contoured using small tools, **Fig. 11**. The use of an HSC-milling machine tool guarantees high-precision machining and also the removal of damaged areas, build up and finish machining in one clamping position.

The welding device consists of a material feeder and a laser source mounted besides the spindle of the 3-axis portal-type milling machine tool. When milling, the welding device is moved upwards by a pneumatic mechanism to prevent it from damage and avoid collisions with the workpiece.

Generally, there are two variants of CMB: A powder based one using an externally mounted fibre coupled 300 W Nd:YAG-Laser and a wire-based variant using a 1.200 W High Power Diode Laser (HDL) mounted inside the machine tool workspace, **Fig. 12**. The wire based option has been used for the work described in this paper. The focus provided by the HDL is nearly square-shaped and has a size of approx. 0.8 x 0.8 mm². The laser power as well as the wire feeding drive is set by NC-commands.

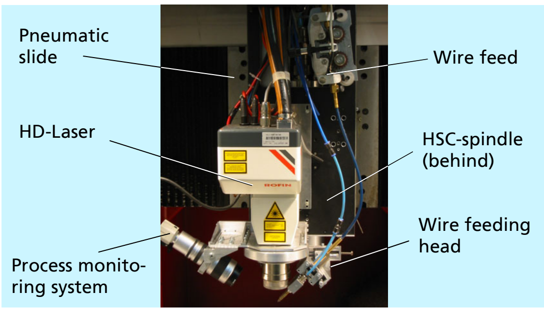


Fig. 12: CMB machine tool: High Power Diode Laser and wire feeding system

Data generation

One of the major goals of the actual work is the automatic generation of ready-to-use NC programs. Each layer requires individual programs for welding and subsequent plan machining which need to be put into the right order for machining. When a repair is made, the data generation has to be done with respect to the existing part geometry. An additional problem arises from the fact that each layer contains contour and fill welding paths with different process parameters. Within the project, a solution has been developed which is based on a commercially available 3D-CAD/CAM-system (Delcam PowerMILL/PowerSHAPE). The graphical user interface allows a comfortable selection of base and weld up geometry from the common CAD-views, **Fig. 13**.

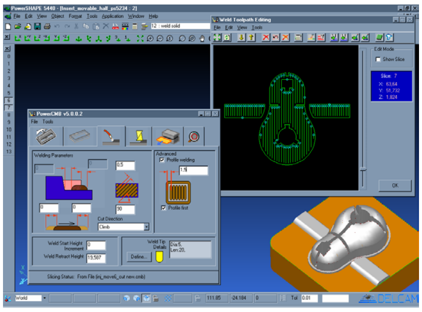


Fig. 13: Software tool for CMB data generation

After setting process parameters for welding and plan machining, the data is divided into slices and all weld and plan milling tool paths are generated. After that, there are many options for easy editing or adapting certain elements like slices or tool paths. A second step of improvement will soon also cover automated routines for contour cutting procedures. The development of such a software tool has given major improvements to the data preparation for CMB, which has until now been a critical bottleneck in the process chain. Creating ready-to-use welding and plan milling programs is now a matter of minutes instead of hours or days as before. As a supplementary feature a post processor was also developed which allows a quick and easy welding data generation including all laser and wire commands directly from any tool path available in the CAM-system. This becomes interesting in cases where just a few layers containing 3D welding lines shall be generated that are not allocated in parallel planes.

Generation of mold inserts

Within the project a special test geometry has been designed which contains several features also occurring in industrial molds for die casting and injection molding. This has allowed a continuous test of CAD/CAM-functionality, laser welding parameters and applicableness of the produced mold inserts. The test geometry which was to be molded later on contains two shells that can be snapped together. There is one to be made by die casting and another one to be made by plastic injection molding. In total, there have been three mold making steps using CMB for these inserts: the making of new molds, repair and modification. Each of them measures 60 x 60 mm² in xy-direction and approx. 35 mm in z-direction, **Fig. 14**.

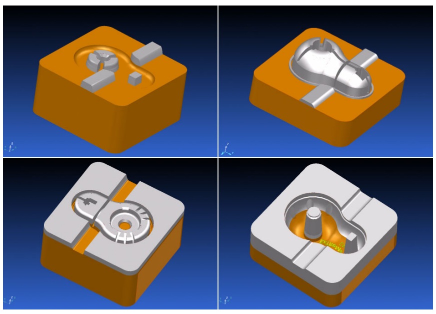


Fig. 14: Die casting (left) and injection molding (right) inserts

Before a CMB process starts, the data has to be prepared and a decision for the building strategy has to be made. The inserts have therefore been divided into parts which were pre-machined just by HSC alone and parts to be build up. Areas that contain corners and grooves with high aspect ratios and that would require a EDM operation are defined as »welding geometry«, the others are pre-machined using HSC and act as a base for the welding. Building up instead of cutting from a full piece is also recommended in cases where a relatively small portion of material extrudes from a plane. The decisions to build up or cut down have to be made individually. Figure 14 shows the welding and pre-machining sections grey resp. brown.

For injection molding, the base of the inserts has been pre-milled from 1.2767. For welding a Cronitex 170ST has been chosen which is comparable to an 1.2767. The pre-machining of the die casting inserts was done in 1.2343, the welding with Cronitex RC44, comparable to 1.2344. The total process took between 2 and 5 working days for each insert. These values include all data preparation, all CAD/NC-programming, all pre-machining and all CMB processing times. The time consumption is increasing with the complexity of the part as well as with the amount of intermittent milling steps with very small tools, which are required for the deep narrow grooves.

All inserts have a surface quality which is comparable to conventional milling and are almost 100 % dense. In some cases there were slight blowholes appearing at the surfaces after final cutting. This is due to an unfavorable layout of fill weld paths which hit the contour path in a way that the process gets unstable. Improved editing options during programming can now help to avoid these errors. Values for surface roughness R_a vary from 0.4 to 3 µm according to cutting parameters. At vertical walls there was a stepping effect reported in some cases containing undercuts with a depth of up to 100 µm in the areas where a new welding layer was laid onto a previously already machined one. These faults are related to the intermittent contour cutting and the follow-on welding cycles which can damage the underlaying surfaces. The investigations into that are still running, and the solution will most likely be found in the welding parameters.

Measurements taken to analyze the overall accuracy have given values around ±0.03 mm. According to the mold makers the fit-together of the inserts was excellent. **Figure 15** shows the inserts and molded parts.

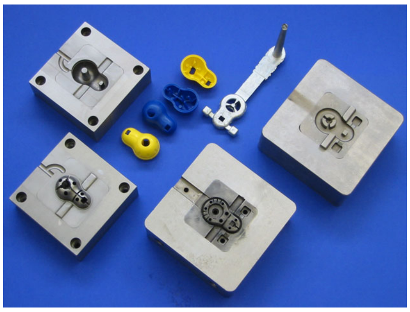


Fig. 15: CMB-made injection molding (left) and die casting (right) inserts together with molded parts

The molding experiments have shown a good stability and wear-resistance of the inserts. For plastic injection molding, a lifetime of several 100.000 shots can be seen as realistic. For die casting, the first results do also look promising in terms of tool lifetime. There have been, however, some difficulties while ejecting the parts due to the mentioned undercuts at walls with very steep drawing angles.

Hardness measurements taken for various welding materials show high values up to nearly 60 HRC at the uppermost layers and decreasing ones for the layers beyond. This is due to their thermal treatment by the succeeding welding steps. The measurements have been taken from sample parts which have been cut down from originally three mm height in several steps to obtain hardness data from inside.

Tool repair

For tool repair, conventionally pre-manufactured inserts like described above have been chosen and repairs were simulated. The areas which were defined as »damaged« have been cut away and built up again. The data were generated using the developed software tool. The total amount of time used for the repair of one injection molding and one die casting insert was approx. 3 h each including all CAD and NC-programming, welding/CMB time and the final finishing milling. The CMB process alone (welding and plan milling) took approx. 30 min each. The integrated approach also allows an semi-automated repair for cases where the errors can be detected based on a comparison of a point-cloud (laser)scan and the original CAD-data of the parts.

For plastic pinching, a tool insert containing a pinch rib has been repaired. The data was generated using a direct approach with the help of the special post processor which can write out NC data for welding based on any available tool path data of the CAM-system. In this case, a deposition of 3 lines onto the top of the rib was sufficient, which leads to a deposition of approx. 1 mm before final cutting. The insert has a dimension of 265 x 145 x 70 mm^3.

Conclusion

CMB features the generative manufacture of steel parts using a combination of laser deposition welding and high speed milling whereas each welded layer is machined in the planar surface and optionally also in contour. The layer-by-layer based approach enables deep slots to be manufactured without the need for EDM because the milling tools lengths can be kept short. The technology was originally developed in the background of Rapid Tooling, but the results have proven its capability to serve for serial mold making and tool repair/modification as well. Improvements include a cleaner process, by feeding wire instead of powder and a graphical user interface based on commercial CAD/CAM-systems. Integrating HSC offers benefits in terms of surface quality and dimensional accuracy compared to conventional layer-based approaches as well as the realization of process chains for repair and modification of existing tools and molds. Future work will be aiming at process optimization, the integration of scanning systems as well as on further implementation in industrial practice.

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