Machining of DMLS printed parts

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Abstract

This article deals with technological possibilities of production of functional parts by means of additive technologies combined with chip cutting machining. DMLS technology (Direct Metal Laser Sintering) allows the production of components from different construction materials such as steel, stainless steel, aluminum, titanium and many others. This components offer full mechanical properties after thermal treatment and therefore can be used as functional parts. However, in the case of precision mechanical parts, this technology does not allow production with sufficient dimensional accuracy and surface quality. For these reasons, additional machining may be necessary. However, from a productivity and economy point of view, it is advisable to limit machining to the minimum amount of material taken and, above all, to the minimum machining time. For this purpose, the part should be designed from the beginning with regard to further processing.

Keywords: Machining of Shaped Surfaces, DMLS Workpiece, Precise Machining, DMLS Post processing, Hybrid technology

1 Introduction

Metal 3D Printing with method Direct Metal Laser Sintering (DMLS) enables the construction of material components with unprecedented shape freedom by sintering the metallic powder. Thanks to additive technology, we can create a product with complex shapes which would be difficult to produce by other methods, in a relatively short time with a minimal increase in production costs. The key advantages are, for example, the hollow object printing or the printing of internal structures.

However, the metal 3D printing carries a number of disadvantages, such as production accuracy, surface roughness, limited working space, integration into serial production due to the long production times and the need for post processing of prints. The quality of a printed surface depends primarily on correctly set parameters of the printing process and machine calibration. The combination of material selection, print settings, protective atmosphere and subsequent post processing provides options to achieve better product quality. The surface of the laser-sintered parts, however, currently fails to achieve the required roughness and accuracy of functional surfaces, which can be achieved for example by chip machining. This article, therefore, discusses the realm of achieving the required accuracy and roughness on functional shape surfaces for 3D printed products by hybrid technology: a combination of 3D printing and chip cutting machining.

Most of the published works, dealing with post processing of metal parts made by DMLS technology, address the improvement of surface quality. These researches mainly deal with other technologies for improvement of the surface properties of printed surfaces rather than chip cutting machining and only solve the quality of printed surfaces.

One option is Surface modification by ultrasonic cavitation abrasive finishing (UCAF). UCAF improves Ra of DMLS objects specimens by up to 45% [2]. Other options include wetblasting combined with polishing [3]. Improvement of the surface can be achieved by adding material using the plating technology. The surface finish has been improved from 17–19 to 2–3 μm by EN plating without losing any sort of dimensional accuracy [4].

2 The accuracy limits of current DMLS technology

Due to the large amount of external influences which have a direct impact on the printout accuracy, careful focus on print preparation is needed. Correct machine calibration is not the only factor determining the accuracy of the printout.

First of all, it should be noted that the printout accuracy is already specified by the metal powder layer itself. The thickness of the average layer usually ranges from 20-40 μm.

In terms of heat dissipation from the sintered region and deformation printout during the construction process, it is necessary to properly design the support. Supports are printed from the same powder as the product and the subsequent heat treatment are removed from the printout. Proper choice of support is key to the correct product printing and its ultimate accuracy. The limit angle for the construction of inclined surfaces without supports is about 45° to the printing platform. However, the location of the support depends on the printed material, the amount of heat input and the overall design of the component.

Other possible problems caused by 3D printing might for example result in the formation of sharp edges. Deformations and inaccuracies can occur more easily in these places, and therefore a rounded printing of at least R 0.5 mm is recommended. If we are talking about the possibility of printing hollow bodies, it is always necessary to print into a closed, hollow profile an opening in order to pour out the powder.

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The final quality is also influenced by the orientation of the printed component on the platform. The straight edge of the workpiece should not be parallel to the edge of the printing platform, as it may interfere with the movement of the recouter and the subsequent deformation of the leading edge. If the object is located at the edge of the printing platform, it exhibits less accuracy due to an angled laser beam.

A significant influence on the precision has the laser itself whether it is its parameters or settings. Furthermore, the width of the melted area should be taken into account. The beam melts an area of about 0.15 mm in diameter, which does not have an exact boundary between the melted and not melted areas. The accuracy and roughness of the surface are also different depending on the orientation of the area relative to the printing platform. This is particularly noticeable on overhanging surfaces (bottom skin) because the laser beam partially melts 3 to 5 layers under the currently sintered layer. [5]

As part of the research in the possibilities of DMLS technology, a number of test samples of stainless steel 17-4 PH were printed, which were then thermo treated in accordance with the manufacturer's recommendations. The processing corresponds with H900 according to ASTM A564. It is a low-temperature curing with the highest strength properties and the lowest plasticity. Samples were printed on a metal 3D printer Concept laser M2 Cusing. Several identical samples were printed with different orientation and position on the printing platform.

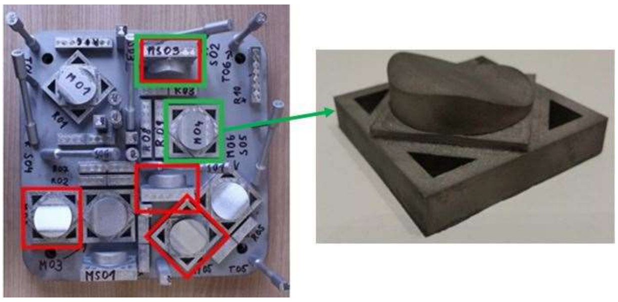

Fig. 1. *Printed samples.*

2.1 The measurement of the shape accuracy of the printout

After the thermal treatment, two artifacts (one vertically and one horizontally printed) were measured. The influence of the different cooling rate of the printout which is given by the distribution of its mass, was significantly affected. For this reason, the deflection of the flat surfaces into the center of the part can be observed. The deviation of planeness was about 0.1 mm on longer surfaces.

The measurement of the shape surfaces showed a significant difference between artifacts with different print positions. Samples printed horizontally indicate that the shape surface is more sinking and the height of the artifact is below the required values. On the other hand, the samples printed in the vertical position show significantly larger dimensions on the overhangs, up to a maximum of 0.5 mm.

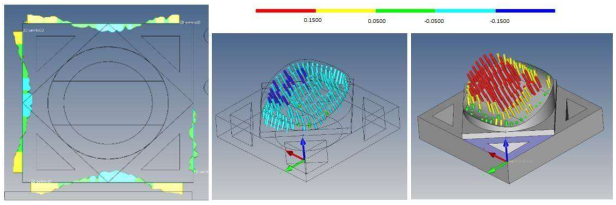

Fig. 2. *Deflection of planar surfaces and deviation in shaped surface in a horizontally printed artifact (left and in the middle), vertically printed artifact (right).*

Tab. 1. *Dimensional deviations after thermal treatment.*

Deviations [mm]	horizontal	vertical
Base planes for clamping	0,174	0,094
Wave shape surface	0,329	0,559

3 Machining of 3D printed components

Despite all the effort, at this stage it is not possible to provide such an accuracy and quality of surfaces while using additive technology as it is in the case of machining. The accuracy of proportions and roughness are important when it comes to the functional components that are supposed to guarantee a mutual position in prescribed tolerances, work as support or guiding surfaces of other components and ensure the tightness of connection in joint areas. Hybrid technology offers a combination of additive technology and machining in the sense that most of the areas are obtaining their final shape through 3D printing and only precise functional surfaces are henceforth being machined.

3.1 Cutting conditions

In order to achieve the best possible results in precise machining, it is imperative to ensure the highest stability during the cutting process. The stability is influenced by the toughness of the machine, unloading and toughness of the tool, clamping of the workpiece, toughness of the workpiece and cutting conditions. To optimize cutting conditions, it is suitable to minimize cutting forces and most importantly, to achieve continuity of the cutting process while keeping the constant parameters and therefore, to minimize any changes in the cutting forces. For this reason, ideal conditions represent a constant thickness of the working allowance and pursuit of a constant angle of the tool bending. [6]

On the already mentioned printed artifacts from the steel 17-4 PH, an experiment of milling the shaped surfaces was performed. Firstly, the cylindrical surface around shaped wave was machined and at the same time, the machining of adjoining frontal surface was achieved. Thanks to this, the accurate base for the following measurement on a coordinate measuring machine was created. Machining was performed by a cylindrical milling cutter with the diameter of 15,6 mm. The shaped surface with the characteristic of the wave was machined by a ball nose milling cutter. In order to achieve the most precise shape of the finished surface, the strategy of the longitudinal lineage strategy was chosen. As soon as the cutting movement in the particular line started, axis Z and axis X were locked and the workpiece was moving only on the axis Y in relation with the machine. This led to a decrease in the machine´s inaccuracy on the variability of the process. The lineage was leaded based on the contour lines of the wave so the angle of the tool bending was not changed during the individual cuts.

As the tool, the ball nose milling cutter with the diameter of 10 mm and replaceable insert Gühring 2520 – 10 DK 460 UF was used. This tool is recommended for very precise finishing of the shaped surfaces.

Fig. 3. *Ball nose milling cutter*

Cutting conditions were chosen very conservatively in order to achieve the most accurate surface. Cutting speed v_c = 52 m/min, feed per tooth f_z = 0,012 mm/tooth, depth of cut a_p = 0,2 mm. Width of cut was variable, depend on the residual height of material. Scallop parameter was setup on 0,002 mm.

4 Construction of a 3D printed part with emphasize on precision machining

It is necessary to adjust the design in order to achieve a precise surface on a printed part during the following chip-forming cutting proces at the blueprint stage by such a way that enables a workpiece to be properly clamped, aligned and machined during a stable, cutting process.

4.1 Optimal allowance for exact machining

From both the economic and technological standpoint it is desirable to choose the smallest possible working allowance for machining. However, the minimal size of such allowance has its limitations that are specified by several conditions.

The minimal thickness of a cut off layer, which has to be maintained, can be defined in general as a double radius of the main cutting edge. Therefore, it is the matter of material and geometry of the tool, as well as the thickness of coating levels on the tool. Otherwise, the result would be shaping of a workpiece instead of cutting. This parameter is mostly limited by the size of a feed instead of cutting depth.

Firstly, we have to take into consideration the total amount of possible deviations that might occur in order to always have sufficient material on the entire shaped surface for cutting off without a threat of staying on the functional surface caused by inaccuracies and deformities of the machined area.

The artifact used for our experiment was modeled with a consistent working allowance of 0.2 mm on the tested wave shape surface.

4.2 Clamping of the workpiece onto a machine

The first objective is to correctly design a particular part in order to be able to clamp it onto a machine. If the construction of a part does not allow a creation of a surface, which is convenient for clamping by using a standard procedure such as vice, chucks, clamps, magnet usage or between jaws, it is imperative to find another way of clamping during the designing stage. One of the solution could be a direct printout of a special preparation with a negative shape of a workpiece surface.

Since this is considered to be exact machining, it is important to eliminate any chance for occurrence of vibrations and possible shifting of a workpiece in relationship with the machine's system of coordinates. For this particular reason, the clamping should be as rigid as possible and should be administered as close to the machined area as possible. It is imperative to have the surfaces for clamping proportioned in such a way that the clamping strength, which is necessary for stabilization of a workpiece, would not result in a deformation due to a clamping pressure.

A problem might occur as early as during the actual clamping of a part. The tested artifact was designed for the clamping onto the vice utilizing a relatively bulky base. The walls of the base were - according to the measurement – concave deflected. Therefore, there is a possible complication with the perpendicularity of the opposing walls and particularly with the surface contact between the workpiece and the jaws of the vice. The impressions are often separated from the platform by a wire-cut, which was the technique applied in case of the tested artifact. The deviations in the planeness of such cut-off surfaces can, according to our experiment, reach levels of up to tenths of one millimeter.

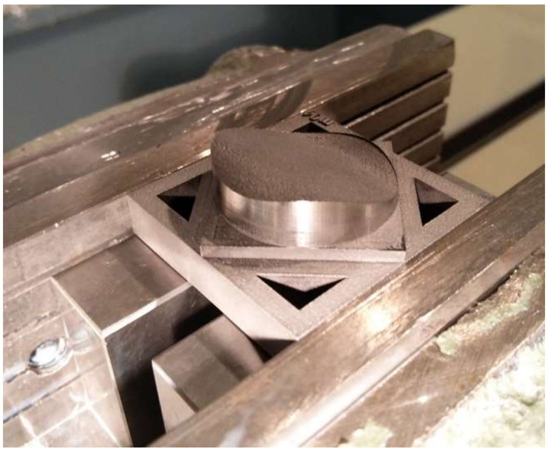

Fig. 4. *Clamping of artifact.*

Based on these findings, it is important to adjust the clamped surfaces by machining prior to clamping or to pay a special attention towards the alignment of individual parts during the clamping procedure.

4.3 Alignment of the part on a machining-tool

In addition to the clamping surfaces of a printed workpiece, it is necessary to specify in advance technological bases, based on which it would be possible to align the workpiece and therefore, to define a system of coordinates for a particular workpiece. Due to possible deformations of the printed part, it is important to consider a placement of geometrical bases as close as possible to the elements with respect to positionally defined machined surfaces.

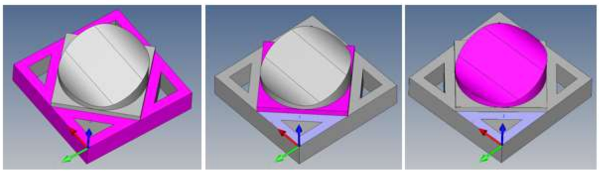

Fig. 5. *The base for clamping (left), control platform (in the middle), machined area (right).*

In case of the tested artifact, the control platform (horizontal surface of this base) was machined in one operation directly with the sizing of the exact cylinder surface. For the purpose of control, an exact base with an exactly defined position in regards to the shaped surface was created. However, during the initial clamping onto the machine, an alignment of the unmachined clamping base in relation to the system of coordinates was performed as depicted in figure 4.

5 Machining of the shaped surface on a printed artifact

Two artifacts were chosen for this experiment. The first artifact was printed in a horizontal position and second artifact was printed in a vertical position.

According to the measurements carried out before the machining process but already after the thermal treatment of both artifacts, significant deformations both in plane and shape surfaces became highly visible (see table 1).

In case of horizontally printed artifact, due to the extreme deviation in planeness of the upper surface base, it is of the utmost importance to decide from which point the axis Z is measured. The most of the deviations in contoured surfaces (waves) were pointing towards negative values. However, in this particular experiment the axis Z was specified at one of the lowest measured points. Therefore, thanks to this occurrence, with the theoretical cutting depth of 0.2 mm, the entire wave surface was machined.

In case of vertically printed artifact, after the thermal treatment, a deviation variance of more than 0.5 mm from the ideal shape generated in CAD was measured on the wave surface. The majority of these deviations were pointing towards positive values. Therefore, the axis Z was measured from the higher points of the upper surface base. After the completion of machining with the theoretical machining allowance of 0.2 mm, a significant area of the contoured surface remained not machined. The machining process was curried out one more time with the lowering of level Z by 0.1 mm and after that, the same procedure was repeated again with another lowering of level Z by 0.1 mm. Only after the theoretical allowance was raised to 0.4 mm, the machining of the entire wave surface was accomplished. Despite the fact that most of this surface showed larger measurements in axis Z, particularly in the lowest point of the wave, there were occurrences of these deviations being in negative territory. That was the reason why specifically in this region not the entire surface was machined during the first two attempts.

In case of actual functional surface is the 0.2 mm shift absolutely critical and the product becomes rejected. It has to be either printed with a higher allowance or it is necessary to solve the suitability of the technological base from which it would be aligned. Simultaneously, it is convenient for the sake of alignment to define not only surfaces, but also concrete points on the surface from which the system of coordinates will be measured.

With the exclusion of these findings, there were no anomalies reported during the machining of the sintered materials. Considering the very defensive cutting conditions that were chosen, it would be highly unrealistic to expect any negative occurrences. The measurement for any shape deviation in machined surface was undertaken in case of horizontally printed artifact, and the maximum deviation from nominal contoured surface was 0.139 mm.

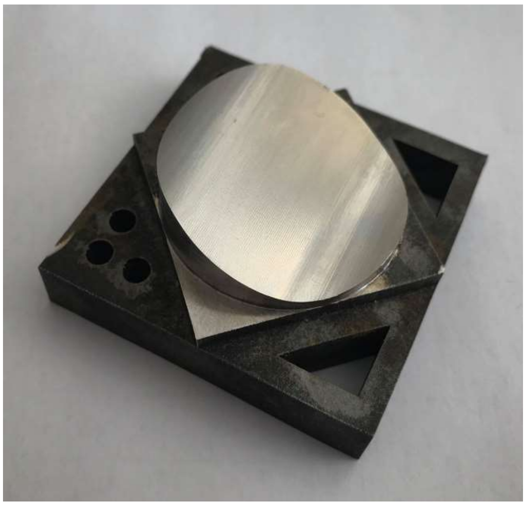

Fig. 6. *Machined artifact.*

6 Conclusion

The main purpose of this experiment was the creation of functional shaped surfaces on 3D printed parts utilizing the DMLS method. Based on the limitations in regards to dimensional accuracy and surface quality of the sintered parts, a hybrid technology, combining a 3D print and precise machining, was chosen.

For the purpose of subsequent machining, it is necessary to resolve the clamping issues already during the designing process. The printed component is most of the time loaded by significant deformations and although there are geometrical elements for specific clamping suggested in the design, such a clamping does not necessarily represent either an exact, or a sufficiently rigid solution.

It is particularly a deformation of a printed and thermally treated workpiece which has a significant role in the matters related to alignment of components on a machine-tool. If the system of coordinates is aligned for instance with respect to planer or cylindrical surfaces, then the specific positioning of such system of coordinates does not necessarily has to be explicit. Its position will depend on the points from which the technological base is measured.

The minimal allowance for machining depends on several factors. Firstly, it is the size of the shape deviation from nominal shape of the machined surface. In case of the tested artifact with minimal dimensions of 50x50x23 mm, a shaped surface deviation of 0.56 mm in vertically printed sample was measured! Just by changing the orientation of the printing, it is possible to significantly lower this deviation, as shown on the horizontally printed artifact where the shape deviation was only 0.33 mm. The resulting measurement of an actually machining allowance depends also on already mentioned alignment of components and introduction of a system of coordinates in the working area of a machine-tool.

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