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Rapid Manufacturing with Direct Metal Laser Sintering

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ABSTRACT

The term Rapid Manufacturing is today very often used as a substitute for Rapid Prototyping, because the manufacturing processes and materials have developed so much that the parts produced with the machines can even be used as functional production parts. For Direct Metal Laser Sintering (DMLS) this was enabled by the introduction of the powders for 20 micron layer thickness; steel-based powder in 2001 and bronze-based powder in 2002. Successful rapid manufacturing with DMLS does not only mean the reduction of layer thickness, but it is a sum of many factors that had to be optimized in order to make the process work with the 20 micron layer thickness: the metal powder behavior in very thin layers is not the same as with thicker layers, the demands for the support structures are higher and the possibility of using multiples of the layer thickness gives additional freedom. By optimizing the process parameters the UTS values for the steel-based powder increased up to 600 MPa and for the bronze-based powder up to 400 MPa. At the same time the surface roughness (Ra) values after shot peening were 3 microns and 2 microns, respectively. Although using thinner layers also increases the building time the advantage is gained in drastically reduced finishing times due to increased surface quality and detail resolution. Typical geometries produced by DMLS are difficult-to-manufacture components and components typically produced by P/M or even by die-casting. The paper covers the development aspects in both material and process development and also presents some realized case studies.

INTRODUCTION

Rapid manufacturing (RM) can be briefly described as any manufacturing that is able to fabricate products in a time, which is short in a relative sense. The definition of short in time always refers to the present knowledge of available and established technologies and process chains. In addition, using a single additive technology may not always be the most effective way of fabricating parts. Instead, a combination of additive and conventional technologies exploiting their strengths is usually the fastest and most economical way of minimizing the project lead-time. Since the beginning of the Rapid Prototyping (RP) era in the beginning of the nineties the definition of a short lead-time has step by step changed from months to days. However, this change still can not be applied to every case and application, the larger and more complex the part is the longer is the fabrication time.

DMLS was first developed to be a Rapid Tooling (RT) method for injection molding tools. The development was done in cooperation by EOS Gmbh and Electrolux Rapid Development (now Rapid Product Innovations). The cooperation achieved success in 1995 when the first bronze-based powder for 100 μm layer thickness (DirectMetal 100) and a laser-sintering

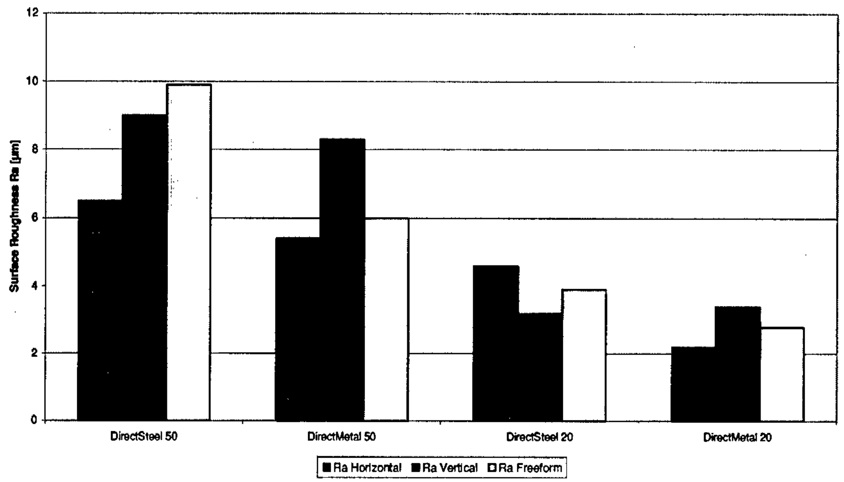

Figure 1. Surface roughness of the DMLS materials after shot peening.

machine for the powder were introduced [1]. Immediately after the introduction, the demand for more materials and better surface quality was evident. This led to further development of both the material and the process. The next step was the introduction of a bronze-based powder for 50 µm layer thickness (DirectMetal 50) in 1997 and a year later a new steel powder (DirectSteel 50) for the same layer thickness was also introduced [2]. At the same time an improved machine was also introduced with e.g. more accurate mechanics, more powerful laser and an atmosphere module for the generation of an inert atmosphere for laser-sintering of the steel-based powder. Although the surface properties of the bronze-based material were improved considerably, the use of 50 µm layers was not sufficient for the parts made of the steel-based powder. There was still need for too much post-processing. The latest solution to this problem was to develop a steel-based powder for 20 µm layer thickness (DirectSteel 20), which was introduced in 2001. In most cases the stair-stepping effect is not visible when using the 20 µm layer thickness. In fact, the surface quality of the parts produced of the powder was so good that in some injection molding cases no finishing was needed. After this the same development work was done for the bronze-based material and the result was introduced in early 2002 as the 20 µm bronze-based powder (DirectMetal 20), which in addition to the improved surface quality had also much improved mechanical properties. In fact, the tensile strength of the 20 µm bronze is almost the same as with the 50 µm steel. Figure 1 presents the surface roughness values of the current DMLS materials after shot peening [3]. Some of the properties of the DMLS materials can be seen in Table 1.

LASER-POWDER INTERACTION

The optimized metal powder mixes for DMLS are all based on the net-shape principle. Thus, the sintering and solidification shrinkages have to be compensated with volume expansion reactions [4,5]. The powder mixes contain only pure metals or metal alloys. With careful

Table 1. Properties of the DMLS materials.

	DirectMetal 100	DirectMetal 50	DirectMetal 20	DirectSteel 50	DirectSteel 20
Layer thickness	100 µm	50 µm	20 µm	50 µm	20 µm
Main constituent	Bronze	Bronze	Bronze	Steel	Steel
UTS	≤ 200 N/mm²	≤ 200 N/mm²	≤ 500 N/mm²	≤ 500 N/mm²	≤ 600 N/mm²
Brinell hardness	90-120 HB	90-120 HB	100-120 HB	150-220 HB	180-230 HB
Minimum porosity	20 %	20 %	7 %	5 %	2 %
Max operating temperature	600°C	400°C	400°C	850°C	850°C

selection of the powder elements the materials can be laser-sintered with negligible shrinkage. During the laser sintering process each scanned powder layer maintains its x-y dimensions and thus accurate metal parts can be generated. However, as the process is based on liquid phase sintering, the solidifying liquid phase always causes some stresses in the matrix during sintering. These stresses are mostly relaxed by the heat conducted from the consecutive layers.

During the DMLS process a high intensity laser beam scans the surface of the metal powder layer. The powder particles absorb the high intensity laser radiation and heat is generated instantaneously in the powder layer, which causes partial and very local melting of the powder. The formed liquid phase wets the remaining solid particles. In addition, the melting causes a rearrangement of the orientation and position of the remaining solid particles. Due to thermocapillary and gravitational forces the melt penetrates deeper into the previously sintered structure.

These complex phenomena necessitate the use of support structures, when parts are sintered directly in the process. Although the powder underneath the current layer supports the sintered layer to some extent, it does not prevent the layer from warping or moving from its place due to thermal stresses or recoating. However, due to the very thin layers, down facing surfaces with angles even below 30° can be sintered on loose powder. If the distance from the closest sintered adjacent structure is not more than about 4 mm, even surfaces with 0° angle can be sintered without a support structure.

SUPPORTS AND EXPOSURE STRATEGIES

The direct fabrication of metal parts has been on the verge of mass commercialization for a few years already, but the progress has been slow due to problems that prevent the effective use of the technology. These problems are the need for supports on down facing surfaces and the surface quality on these surfaces. Most commercial software used for support generation are made for Stereolithography (SLA) and their suitability for a direct metal sintering process is not optimized.

The main functions of the supports are to prevent sintering on loose powder, fix the part to the building platform and conduct excess heat away from the part. Sintering on loose powder can be prevented by using a very dense mesh extruded in z-direction that is metallurgically bonded to both the building platform and the actual part. If the mesh is too large, heat is not conducted away from the sintering zone quickly enough, which causes over melting. The over melting causes the formation of spherical droplets due to the surface tension of the liquid metal, which is also known as the balling phenomenon. If too many of these droplets are formed, the recoater may jam at this position during recoating of a new powder layer and can even break the support structure. The part has to be adequately bonded to the support in order to withstand the thermal stresses during the sintering. As mentioned previously, the stresses are mostly relaxed afterwards, but some remain in the matrix.

Fixing of the part and heat conduction benefit also from the dense mesh. However, in order to remove the support from the part easily the mesh cannot be too dense. In addition, the boundary between the support and the part has to be easily detectable and, even more importantly, easily breakable. This can be done by using serrated teeth on top of the support structure. With correct settings the teeth can be designed so that the support can be removed manually. However, this requires a slightly larger mesh for the support itself so that the bond between the support and the part is not too strong, i.e. the contact area between the support and the part becomes smaller. A drawback in using a larger mesh is that the surface quality on down facing surfaces becomes worse. If the support removal is not easy, machining has to be used, which usually lengthens the process chain to the extent that the use of an additive method may not be rational anymore. In conclusion, a proper support at the moment is a compromise between part fixing, heat conduction, support removal and surface quality.

The main drawback in the currently available support types is the poor surface quality on down facing surfaces. The use of supports based on sintering lines into a mesh is not very rational, because the line pattern and especially the teeth are copied onto the down facing surface. In addition, some hard to reach surfaces may have to be supported from another surface, which damages the surface quality of a surface that would otherwise be intact. Two examples of support marks on a surface can be seen in Figure 2. The figure on the left shows the marks of the support mesh as well as other marks on the vertical surface, which was used for supporting the other surface. The figure on the right shows support tooth marks after breaking off the support manually.

The most important factor in direct part manufacturing is that the user has to be aware of

Figure 2. Support marks on part surface after support removal.

how the part should be positioned for sintering. The correct positioning influences the resulting building time and also the post-processing time, as with correct positioning the amount of support can be minimized and the building time minimized. Another factor influencing on the amount of supports needed is the lack of variables in the exposure parameters. For example, with the EOS PSW process control software it is possible to use separate exposure parameters on the first layers on the down facing surfaces, i.e. downskin. However, there is a need to optimize certain other aspects of the building strategy to prevent e.g. the bulging material presented in Figure 2. At the moment, the best results in direct part fabrication are always compromises between the use of supports and exposure speeds and strategies.

CASES

Typical geometries that can be laser-sintered are conventionally produced by PM compacting, are cast or cannot be produced at all. In fact, the trend now seems to be that for some cases the conventional manufacturing methods are replaced by direct laser sintering by DMLS. Several applications require only a few components that would be very expensive to manufacture by conventional means. In these cases the parts could be produced by DMLS in just a few days without any tooling. Especially suitable for direct part manufacturing is the new 20 µm bronze powder, where a good mechanical strength is combined with an excellent surface quality.

There have been cases where direct laser-sintering has replaced conventional manufacturing totally. In a case where a customer needed 300 sets of a small locking device that consisted of three different parts (900 parts in total), casting was replaced by DMLS because of the speed and quality of the parts. At first the customer needed only a few prototypes, but after seeing the quality and consistency of the parts then decided to replace the whole series with the laser-sintered parts. Conventionally the customer would have needed three die-casting moulds or a number of investment casting "trees", both of which would have cost too much considering the number of parts and the lead-time would have been too long. With DMLS the project was carried out with 5 sintering jobs, which lasted 32 hours each. The supports were removed by snapping them off the part with pliers, which turned out to be a very fast method.

Figure 3 presents a fan wheel for a hand tool and a "spinning top" toy made of the same geometry. Both the parts are made of the 20 µm bronze-based material. The thin ribs in the fan

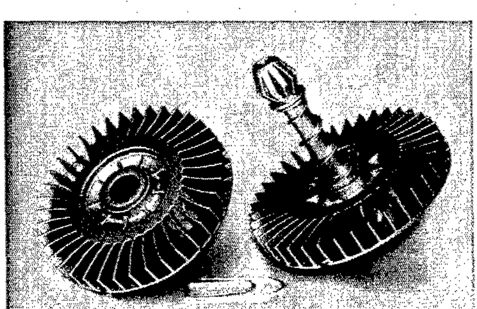

Figure 3. Parts made directly by DMLS. Fan wheel geometry by TransCAT GmbH.

wheel are only 0,6 mm thick, which is also the minimum feature thickness that can be fabricated with the technology. Injection molding inserts for the same geometry were also made and successful moldings were produced. The spinning top was made as a demonstration model of the technology, because it presents well the limits in detail resolution, but also the possibilities of freeform fabrication, because the part would be very difficult to make even by casting.

CONCLUSIONS

The state of the Rapid Tooling and Manufacturing industry has changed a lot over the past decade. For DMLS it has meant expansion of material selection from bronze to steel materials and also reduction of the layer thickness from 100 μm to 20 μm. The properties of the sintered materials have improved significantly: the tensile strength has increased from 200 N/mm^2 to 600 N/mm^2 and the surface roughness has reduced from nearly 10 μm to about 2-3 μm. The improved properties have widened the application field from the original injection molding to direct part manufacturing. In addition, the technology has shifted from a prototyping method permanently to a production method also. This applies to both mold manufacturing and direct part manufacturing.

Today, more complex shapes and more varieties of the same product are produced. Therefore, production costs would rise very much if conventional technologies would be used in the production. This serves as a driving force for further development of the DMLS process for rapid manufacturing. There is still need for an even better surface quality, accuracy, different materials and a faster process. Some of these problems could be resolved by simply developing a better software for support generation and by making some modifications to the exposure strategies in the EOS PSW software. The development work continues in this direction.

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