Rapid Manufacturing Research at the Catholic University of Leuven

E. Yasa, T. Craeghs, M. Badrossamay, J.-P. Kruth
Department of Mechanical Engineering, Catholic University of Leuven, Leuven, Belgium
(evren.yasa@mech.kuleuven.be, jean-pierre.kruth@mech.kuleuven.be)

Abstract - **Additive layer manufacturing (LM) is commonly used for manufacturing prototypes (RP), tools (RT) and functional end products (RM) in a wide range of industries including medicine, automotive and aerospace industries. One of the key advantages of RM over conventional machining is the elimination of molds, dies, and other forms of tooling, and the consequent eradication of tooling restrictions. Moreover, almost infinite geometrical complexity, mass customization, individualization and material flexibility give RM other superior properties. For RM to prosper, the limitations of existing additive processes must be overcome, e.g. limitations such as repeatability, reliability, surface finish, material properties and productivity. At the University of Leuven, selective laser melting/sintering (SLM/SLS) of metals, ceramics and polymers is studied aiming to develop the process to a level enabling RM of complex and customized parts in a competitive way. In order to achieve this overall goal, a monitoring and control system of SLM/SLS for metals is installed in an in-house developed machine to process metals. Laser re-melting and selective laser erosion (SLE) are employed during or after SLM/SLS in order to improve surface quality and density as well as to modify the microstructure and mechanical properties. For medical applications, design and manufacturing of scaffolds and dental prostheses with required mechanical properties are conducted including the investigation of the influence of structural parameters (porosity, cell size and cell shape) on the cell growth. In order to widen the palette of applicable materials, K.U.Leuven does not only focus on metallic materials, but also on direct or indirect SLM of ceramics as well as machine modifications such as pre-heating modules and deposition systems necessary to handle ceramics**.

Keywords – **Rapid Manufacturing, Selective Laser Melting**

I. INTRODUCTION

Layered Manufacturing, which was also referred to as Rapid Prototyping in the past, is the most common name given to a host of related technologies that are used to fabricate three-dimensional physical objects directly from CAD data sources. These methods are unique in that they add and bond materials in layers to form objects. Layered manufacturing goes back to the late 1980's and early 1990s with a clear breakthrough in 1994 [1]. In 1994, the machine sales took off exponentially as shown in Figure 1 [2]. The initial purposes of layered manufacturing processes were visualization and basic testing. Then, the layered manufacturing processes started to be used for other purposes such as fabrication of complex geometries which are used as end-products with required mechanical properties. Today, distinction is made between Rapid Prototyping (RP) and Rapid Manufacturing (RM) whereas Rapid Tooling (RT), production of functional tool components produced in a layerwise manner, can be considered as a sub-category of RM [1]:

- RP means the production of prototypes, visual design aids, touch, feel, fit and assembly test parts, etc., that are used in the product development phase and are not meant to be equivalent to real production parts at all levels.
- RM means the production of functional parts that are meant to be used as end products with various basic requirements in terms of mechanical, material or other properties.

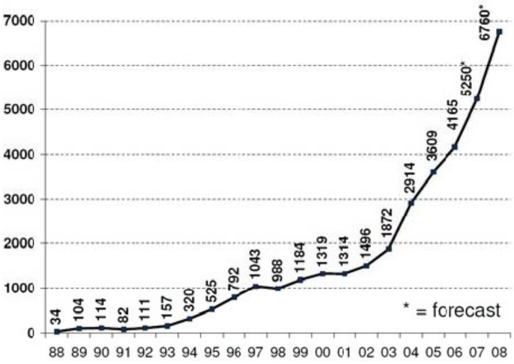


Figure 1: Yearly additive system unit sales worldwide [2]

The most popular layered manufacturing processes are photo-polymerisation (Stereolithography (SLA) and its derivates), ink-jet printing (IJP), 3D printing (3DP), Fused Deposition Modelling (FDM), Selective Laser Sintering or Melting (SLS/SLM) and to a lesser extend Laminated Object Manufacturing (LOM and similar sheet stacking processes) and Laser Cladding (LC) processes [3]. Since many of those processes do not allow common engineering materials to be processed with sufficient mechanical properties, they are mainly limited to Rapid Prototyping**.** In the prospect of Rapid Manufacturing, SLS/SLM seems to be the most versatile process, capable of processing engineering polymers, metals, ceramics and a wide range of composites.

At the University of Leuven, the work on Rapid Prototyping and Rapid Manufacturing has started in early 1990s with RP of polymers processed with ink-jet printing and stereolithography yielding patents about curtain recoating and colour SLA and a spin-off company called Materialise which is now a worldwide known RP company with over 700 of employees. Later, the work on metals has been started with Electron Beam Melting (EBM) and Selective Laser Sintering [4]. The work on metals did not only focus on processes but also machine construction was one of the important topics and resulted in an own-made SLS/SLM machine with a 500W Nd:YAG laser. By the purchase of DTM Sinterstation 2000, the work started to cover SLS of polymers, steels (i.e. Rapidsteel and Laserform), hard metals and titanium. Moreover, the in-house built machine has always been kept up-to-date and re-built with new laser sources, new powder handling/deposition systems and a monitoring and control system. Now, the machine employs a 300W fiber laser with a special software developed to control the machine. In 2005, a new machine, Concept Laser M3 Linear, was added to the laboratory resulting in new opportunities such as the production of dental frameworks in Ti and CoCr, industrial application of tool steel and stainless steel as well as the combined (hybrid) process of SLM and Selective Laser Erosion (SLE). In 2008, a new spin-off company, called Layerwise, was incorporated specializing in RP&RM of metals. Recently, new research topics have been initiated, e.g. SLM/SLS of ceramics.

In this paper, a review of the recent work conducted in the field of SLM of metals at the University of Leuven is presented.

II. RESEARCH ACTIVITIES

This section is divided into five main sub-sections in order to explain each research topic separately and more in detail. The research areas, subject to this paper, are the process monitoring and control system for SLM, productivity enhancement of the SLM process, laser surface re-melting (LSR) and combined process of SLM and SLE (Selective Laser Erosion). Other main research topics are shortly summarized in the last sub-section.

A. *Process Monitoring and Control System*

In all manufacturing processes, feedback control opens new opportunities to control part quality. Thus, an in-process system based on a high speed CMOS camera and photodiode has been developed at K.U.Leuven (see Figure 2). The figure shows the monitoring system mounted on the own-built SLM machine of K.U.Leuven with its main components. The system is capable of observing the melt pool at all times during the process regardless of the movement of the laser spot since the camera and photodiode look at the process through the beam deflection unit. According to Planck’s law, the emitted radiation from the melt pool depends on the temperature of the melt pool [6].

The CMOS camera and photodiode can extract information from the melt pool radiation. The photodiode integrates all melt pool radiation whereas the CMOS camera provides a two-dimensional image from which the melt pool geometry can be extracted as shown in Figure 3. Some post-processing steps such as thresholding and filtering of tiny particles around the melt pool are needed before the extraction of melt pool geometry giving the melt width, area or length.

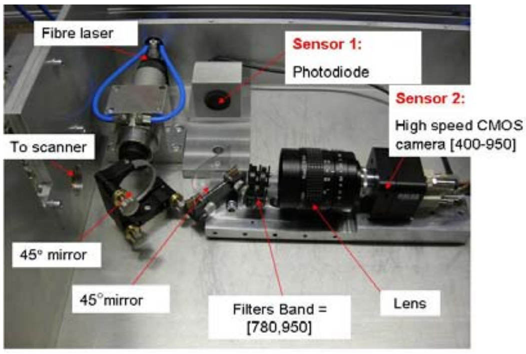


Figure 2: Monitoring system

Using the monitoring and control system based on the camera and photodiode, many problems can be detected during or after the process. For instance, the build can be stopped if it will not succeed due to some problems such as excessive powder feed and insufficient melting of the thick layers. Stopping the build may prevent any possible material waste and extra effort to re-cycle the deposited and unused powder. Moreover, the bulk parts are generally black boxes and do not give any information (e.g. density) about their interior unless any destructive methods are used. However, insight can be obtained from the information derived from the two main sensors (CMOS camera and photodiode). Moreover, the monitoring system can be used to detect local overheating problems and to solve them with the feedback control.

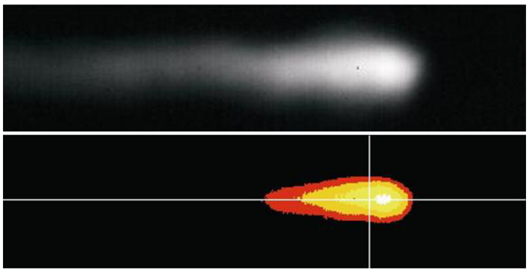


Figure 3: Raw image of the melt pool (top), melt pool geometry after post-processing (bottom)

Building overhang structures is generally a significant limitation during layer additive processes as depicted in Figure 4. The border conditions of the conductive heat transport have a very large influence on melt pool dimensions when three dimensional parts are produced by SLM. At solid-supported zones, the conductive heat transport will be large depending on the bulk material's heat conductivity. However, at powder-supported zones, the heat conduction rate may be more than 100 times smaller than the corresponding bulk conductivity and this is encountered during scanning of an overhanging structure [6]. This results in too large heat input when a powder-supported zone is scanned. Thus, a very large melt pool is formed sinking in the supporting powder material due to gravity and capillary forces. The details of avoiding bad quality overhang structures during SLM are published elsewhere [5].

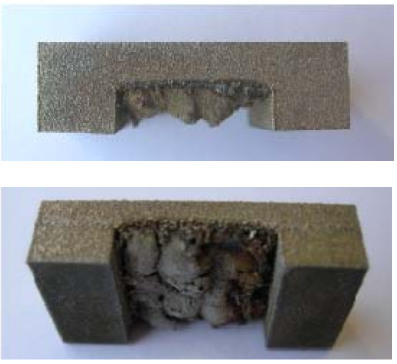


Figure 4: Overhang structures made by SLM

In order to evaluate the real-life performance of the feedback system, a benchmark study has been conducted regarding overhang structures. A benchmark geometry including different sizes of rectangular and circular holes has been designed and produced from stainless steel powder with and without control (See Figure 5). The results are depicted in Figure 6. As evident, the holes made with feedback control exhibit less dross formation for all cases. The feedback control system regulates the energy input given to the powder and automatically adapts it to the state of the material underneath the scanned zone.

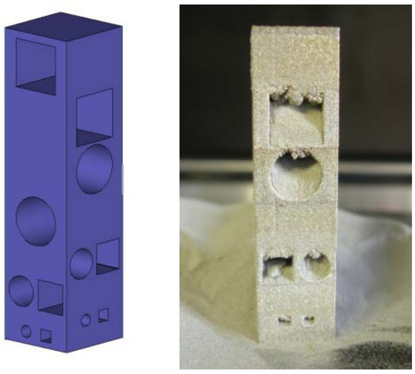


Figure 5: Benchmark design and production without feedback control

The monitoring and control system is not only used to cope with overhanging structures, but also to detect excessive oxygen in the chamber, any failure during the build due to insufficient or excessive layer thickness or wrong selection of process parameters. An example is given in Figure 7. The laser window which is located between the process chamber and the laser source gets dirty during the process resulting in the loss of laser power reaching the powder bed. This kind of failure is traceable from the average photodiode signals taken at the initial and end layers as shown in Figure 7. The reduced laser power results in a lower density at the top of the part compared to the bottom. Comparing the photodiode signals at different layers, it is possible to observe a decrease in melt pool area and to correct for this problem by increasing the laser power gradually.

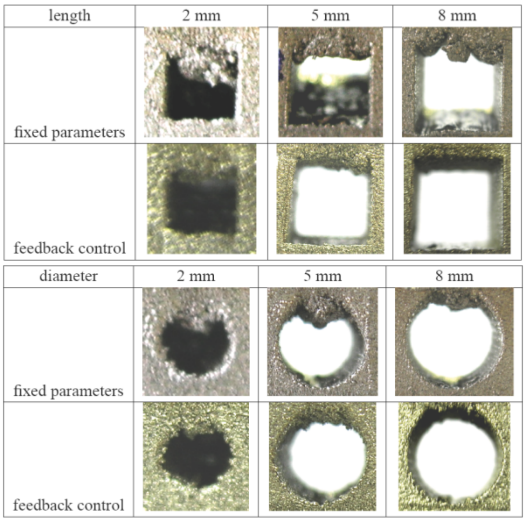


Figure 6: Comparison of parts produced with fixed parameters (without control) and with feedback control

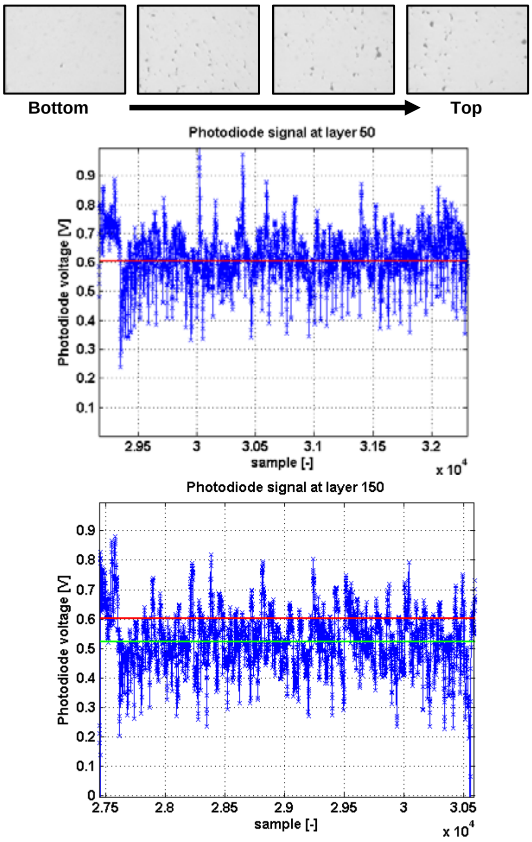


Figure 7: Decrease in the photodiode signal due to dirt on the laser window

Another example is given in Figure 8 illustrating a possible failure in the environmental conditions. Three tests are made using 316L stainless steel powder with nominal parameters optimized for density and productivity. The first test is carried out in ambient air whereas the second and third are conducted in argon atmosphere. The flushing of the chamber with argon was done once or twice in the second and third tests, respectively. As the figure suggests, the photodiode signal is more stable when SLM of steel is carried out in inert atmosphere compared to the case with excessive oxygen in the chamber.

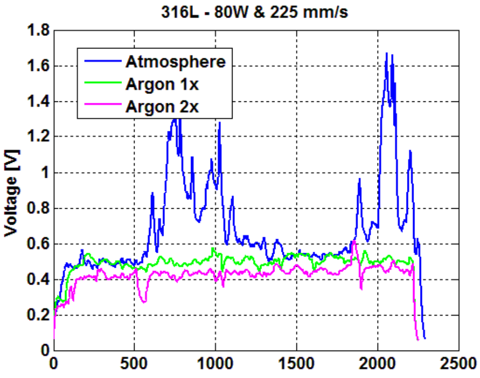


Figure 8: Comparison of photodiode signals received under different conditions

Finally the monitoring and control system has to assure the quality of the parts being produced. If the system detects problems during the process, the cause of this problem has to be removed or has to be cancelled out. In this way the system will contribute to the total quality control of the SLM process.

B. Production Rate Enhancement

Productivity is one of the issues related to economical aspects of SLM that plays a key role for further applications of SLM as a competitive manufacturing technology. Productivity of SLM is directly connected to the scanning speed; a process parameter that in turn has been increased significantly in recent years [7]. SLM is however carried out at scanning speeds much lower than the speed range normally used in SLS since SLM calls for much higher laser energy densities. It is also not enough just to melt (partially or full) the surface of a powder bed, but also to ensure a strong adherent to the previous layers [8]. On the other hand, it has been realized that it is unlikely to make SLS/SLM to be commercially viable for high volume parts with simple geometries because of high production time along with high costs of machines and materials [9]. Thus, at K.U.Leuven, it is aimed to improve the productivity of standard alloy steels by a parametric study of selective laser melting without sacrificing part properties, i.e. part density and surface quality. The study aims to enhance the productivity by increasing the layer thickness or scan speed from the default values recommended by machine-makers. Two types of commercial steel powders, namely AISI 316L stainless steel and hot work maraging steel 300, are examined. The influences of processing parameters on the mentioned parameters are studied. Two machines were utilized in this work: Concept Laser M3 Linear machine and EOSINT M270.

The recommended values for 316L stainless steel by Concept Laser are a layer thickness of 30 μm with a scan speed of 360 mm/s and a scan spacing of 126 μm. Two kinds of maraging steel powder, commercially available from Concept Laser and EOS were processed on a Concept Laser M3 Linear and an EOSINT M270, respectively. EOS recommends a layer thickness of 30-40 μm with a scan speed of 750 mm/s and a scan spacing of 100 μm whereas the recommended values are a layer thickness of 30 μm and a scan speed of 200 mm/s for Concept Laser M3 Linear machine.

After the test specimens were produced, density was measured according to the

Archimedes method by weighing the samples in air and subsequently in a fluid (ethanol). A coating with lacquer was also applied to avoid ethanol absorption at lower densities. Presented density results in the next paragraphs are arithmetic means of three measurements at each processing condition and are expressed as relative density by taking materials' bulk density. 8.0 kg/cm^3 for 316L stainless steel and 8.1 kg/cm^3 for the maraging steel are taken as the bulk density.

The total build time, including powder deposition time, laser scanning time and file loading time, is the dominant component of laser processing activity which in turn is a representative criteria for economical aspect of SLM process. Other activities during an SLM process cover handling of raw material, CAD file loading and modifications of the file (e.g. orientation of parts, support generation, etc.), slicing as well as post-processes such as re-cycling of un-used powder, part removal from the machine and from the base plate, EDM (electro-discharge machining) cutting, sand blasting of produced parts, etc. A rough estimation for the total production time is given in the following equations:

$$t_{total} = t_{depos} + t_{scan} + t_{dead} \qquad (1)$$

$$t_{depos} = n_{layers} \cdot t^{*}_{depos} \qquad (2)$$

$$t_{scan} = \sum_{i=1}^{n_{layer}} \sum_{j=1}^{n_{part}} \frac{A^{scan}_{i,j}}{U \cdot s} \qquad (3)$$

where

t_{depos} : total time for powder deposition

t_{scan} : total time for scanning

t_{dead} : total file loading time

n_{layers} : number of layers defined by the height of the part divided by the layer thickness $n_{layers} = h / t_{layer}$

t^{*}_{depos} : time to deposit one layer of powder (an SLM machine characteristic)

n_{part} : number of parts being built

$A^{scan}_{i,j}$: area of part *j* in layer *i* being scanned

U: scan speed

s: scan spacing

From these equations, it is evident that the number of layers, which depends on the layer thickness, is the most dominant parameter governing all terms in the total production time equation (1). The scan speed and scan spacing are also key factors determining the time for scanning. The scanned area and the height of the part are fixed parameters dictated by the design. Note that the time needed to move the scan head during the build (Concept Laser M3 Linear machine only) is not taken into account and generally depends only on the size of the scanned area for each layer. The only possibility to enhance the productivity is thus to change the layer thickness, scan speed or scan spacing.

The experimental results, shown in Figure 9, depicts the relationship between the scan speed and relative density obtained at three different layer thicknesses for 316L stainless steel processed on Concept Laser M3 Linear machine. At sufficiently low scan speeds, the relative density is almost independent of the layer thickness for in the selected range of the layer thickness, and a maximum of 99% relative density is achievable. At higher scan speed values, a higher layer thickness results in less density. However, the layer thickness can be increased if the scan speed is sufficiently lowered to achieve the same density values.

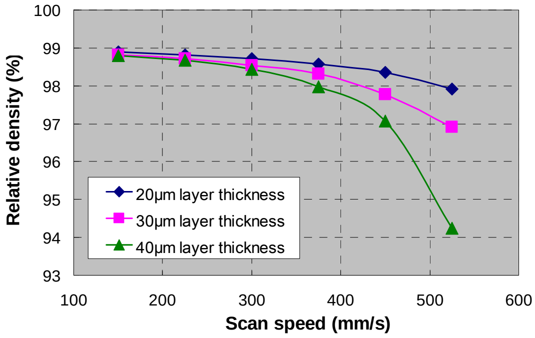


Figure 9: Effect of scan speed on the relative density for 316 L stainless steel processed on Concept Laser M3 Linear

Figure 10 shows how the density changes when powders with different particle size distributions are used for the same powder material (316 L stainless steel). The fine powder consists of powder particles having a diameter of 25 µm and half of the particles have a diameter less than 16.6 µm. The coarse powder has a wider particle size distribution between 25 and 53 µm, and half of the coarse particles has a diameter less than 42.5 µm. On Concept Laser M3 Linear, the obtained relative density from larger particles is slightly higher than the density from finer particles at lower speed range, i.e. up to around 300 mm/s. This is presumably related to the higher packing density and flowability of larger particles size with respect to the fine powders with the narrower particle size distribution. As the scan speed moves to higher values, on the other hand, the laser material interaction time is reduced, which in turn causes a reduction in the melt pool size. For the fine powder, however, less pronounced melt volume reduction is predictable since finer particles melt faster. Consequently, processing at higher scanning speeds may result in greater melt volume for finer powder. The latter phenomenon might be a possible explanation for slightly higher attainable densities at higher scanning speed. These results suggest a higher productivity by using finer powders.

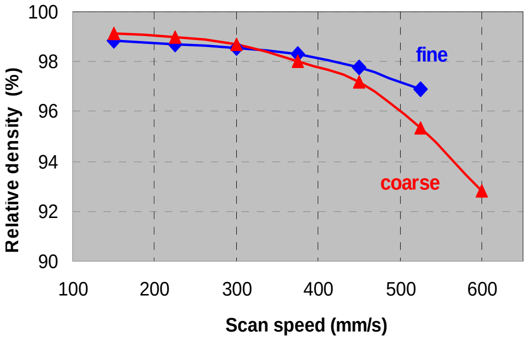


Figure 10: Effect of the particle size on density for 316L stainless steel on Concept Laser M3 Linear

Figure 11 and Figure 12 depict the results for the maraging steel processed on Concept Laser M3 Linear machine with four different layer thicknesses and on EOSINT M270 for two different layer thicknesses, respectively. The scan speed range investigated on EOSINT M270 machine is much wider than the one on Concept Laser M3 Linear since the laser sources are different. EOSINT M270 employs a fiber laser with a maximum output power of 200 W whereas the laser source of the Concept Laser M3 Linear is an Nd:YAG laser with a maximum power of 100 W.

The results depict the same conclusions as obtained with 316L stainless steel powder (see Figure 9). However, it is seen that a scan speed range (500-1000 mm/s) exits for EOSINT M270 where a maximum density is reached regardless of the layer thickness. The optimum scan speed (750 mm/s) overlaps with the recommended value by EOS Company (see Figure 12). On Concept Laser M3 Linear machine, the density decreases significantly when the layer thickness increases at high scan speed region (Figure 11). However, there is also a tendency to converge to the same density value at different layer thicknesses towards the low scan speed region. Therefore, higher layer thickness values can be selected in order to enhance the productivity especially at low scan speed region since it is observed that the obtained density is almost independent of the layer thickness in that zone for all experiments.

The research on this topic also includes the investigation of the influence of the process parameters on the surface quality. However, the results are not taken in the scope of this paper because of length of the paper, but are reported in [10]. Increasing the layer thickness at the cost of reducing the scan speed increases the productivity for the materials tested in the scope of this paper without any loss in the surface quality. However, it is important to note that the resolution along the building axis is reduced when bigger layer thicknesses are selected, e.g. the stair effect is more pronounced.

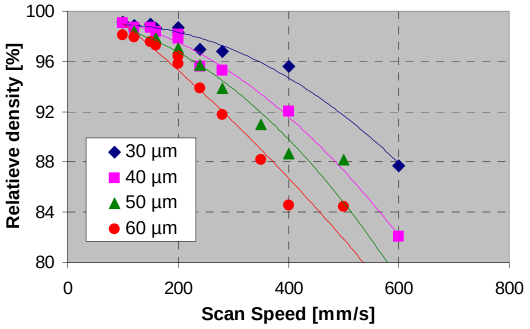


Figure 11: Effect of scan speed on the relative density for maraging steel 300 processed on Concept Laser M3 Linear

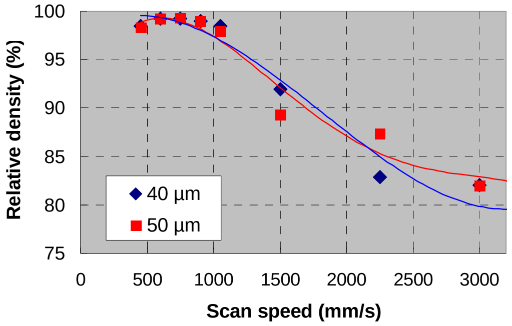


Figure 12: Effect of scan speed on the relative density for maraging steel 300 processed on EOSINT M270

C. Laser Surface Re-melting

Although the SLM process provides many advantages compared to conventional machining, low surface quality is one of the major drawbacks encountered in the process. Secondly, in spite of the fact that the process is capable of making almost full dense (~98%) parts, little residual porosity may be still problematic for some applications where high strength is necessary. In the scope of this study, laser re-melting is employed during SLM process to overcome these problems. After scanning a layer and melting the powder, the same slice is scanned again before putting a new layer of powder. This solution increases the production time but on the other hand, it can be the ultimate solution for applications where a density of 98% is not sufficient. Laser re-melting can also be applied only for the top surfaces if it is aimed to enhance the surface quality. In this case, it is named as Laser Surface Re-melting (LSR).

The parameters used during laser melting of the powder are the standard values optimized for maximum density on Concept Laser M3 Linear machine (scan speed 380 mm/s, laser power 105 W, scan spacing 125 µm and the spot diameter 200 µm) from 316L stainless steel powder. After SLM of each layer, the same slice is scanned with a different set of re-melting parameters. While changing some parameters such as scan spacing, scan speed, number of re-melting layers or laser power, some parameters were kept constant throughout the experiments: a spot size of 200 µm as well as a scan strategy of all 0° hatch lines. With a spot size of 200 µm, a pump current of 39 A corresponds to a laser power of 105 W whereas a pump current of 35 A corresponds to 85 W. The scan spacing factor (a_1) determines the scan spacing between two consecutive scan lines. As a_1 decreases, the scan lines are located closer to each other. In the laser re-melting experiments to enhance the density, the scan speed is changed in the range of 50 to 200 mm/s whereas a scan spacing factor is varied between 5% and 20% of the spot diameter. The effect of the laser power is investigated in the ranges of 85 to 105 W as well as two different numbers of re-melting layers.

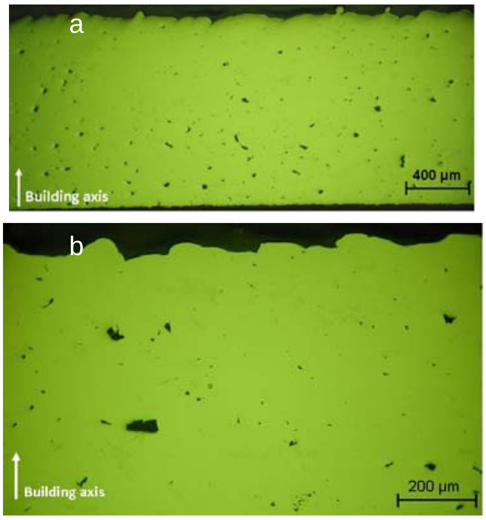
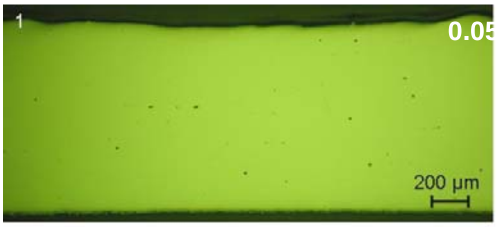


Figure 13: Cross-section of an SLM part a) 4x magnification b) 10 x magnification

The cross-section of a SLM part without any re-melting process observed with an optical microscope is shown in Figure 13. The black spots throughout the part are the pores that are created during the SLM process. They are homogeneously distributed and can be formed due to several reasons such as decrease in the solubility of the dissolved elements in the molten pool during cooling and solidification and evaporation of elements with a high vapor pressure [6]. Besides those melting and solidification phenomena, an insufficient surface quality can cause low density as well: High roughness peaks and valleys that are formed after each layer can avoid the coater to deposit a homogenous powder layer. Moreover, the laser energy may be not enough to melt the new layer completely since the depth of the powder in some regions will be thicker. Morgan et al. has already found that a rough surface causes the entrapment of gas upon deposition of a new powder layer. When the new layer is being scanned, the gas is superheated and expands rapidly removing the liquid metal above it, thus creating a pore [11].



35 A, 200 mm/s, a1 = 0.1, 1 layer

35 A, 200 mm/s, a1 = 0.1, 3 layers

35 A, 200 mm/s, a1 = 0.2, 3 layers

35 A, 200 mm/s, a1 = 0.2, 1 layer

Figure 14: Optical microscopy images of the laser re-molten parts with different parameters

In order to get a quantitative comparison between applying different laser re-melting parameters and only SLM parts, the densities of the parts are measured using cross-sectional images obtained with optical microscopy. In order to achieve this, first the pictures are converted to black and white images using a constant threshold value. Then the ratio of the number of black pixels to the one of the white pixels is calculated for each image giving the porosity. For every set of parameters, at least three pictures taken at different locations of the cross-section are used.

All parameter sets of laser re-melting improve the density when compared to only SLM result. The average porosity of only SLM parts is about 0.77% whereas the densest re-molten part obtained with a parameter set has a porosity of 0.032% as shown in Figure 14 where the optical microscope pictures of some parameter sets are depicted. The laser re-melting parameters for each part are given under the image. In Figure 14, the parts look almost fully dense which is also validated from the porosity percentages shown on right top corners.

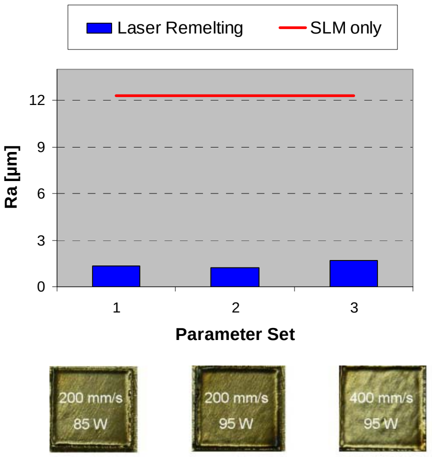


Figure 15: Roughness values with laser re-melting and only SLM parts

In the ranges that are subject to this study, higher re-melting scan speed (200 mm/s) in combination with low laser power (85 W) resulted in better density values. Applying the re-melting multiple times 1 or 3 times after each layer does not significantly change the porosity for low laser energy inputs to the substrate.

For surface quality improvement, the last slice is exposed to Laser Surface Re-melting (LSR) for 10 times with a grid scanning strategy. Each LSR scanning was rotated 90 degrees with respect to the previous one in order to improve the surface quality. All laser re-molten surfaces exhibited a better surface quality compared to only SLM parts. The details of surface quality improvement are reported in [12, 13]. The best results obtained with LSR are plotted in Figure 15 where the average roughness (R_a) of an only SLM part measured on the top surfaces is shown with a horizontal line at about 12 μm with a standard deviation of 2 μm. After LSR, R_a value decreases from 12 μm to 1.5 μm. A low scan spacing factor (a_l of 0.1 or 0.4) together with a medium scan speed (200-400 mm/s) and a medium to high laser power (85–95 W) results in better surface quality compared to other parameter sets. The cross-sections of an only SLM part and a part with LSR (parameter set 2 in Figure 15) are compared in Figure 16: the enhancement of the top surface by LSR is evident.

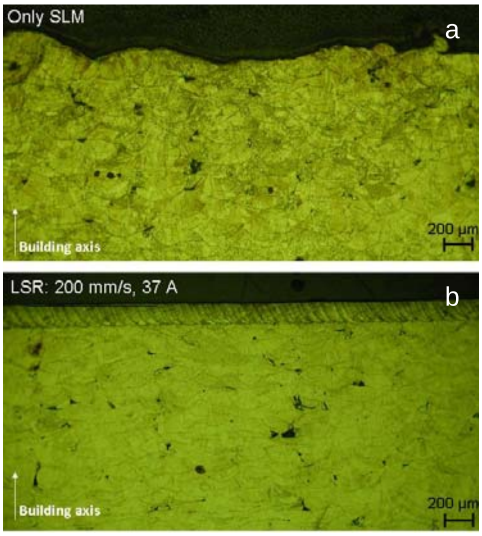


Figure 16: Surface quality enhancement with laser re-melting a) only SLM part b) Laser re-molten part with 200 mm/s and 95 W exhibiting a very smooth surface

D. Combined Process of Selective Laser Melting (SLM) and Selective Laser Erosion (SLE)

Selective Laser Erosion (SLE) is one of the research topics studied at K.U.Leuven in order to employ as a sole process or as a complementary process to enhance the SLM process. The main application areas of SLE in industry are laser marking or laser engraving processes in order to make permanent traces on a surface. At K.U.Leuven, the influence of process parameters such as laser power, scan speed, pulse frequency, scan spacing and scan strategies are studied on the outputs of SLE process in addition to the investigation of the physical phenomena behind laser erosion process [14, 15].

When employed as a complementary process, the combined process of SLE and SLM gives the opportunity to increase the resolution along the building axis of SLM and to enhance the surface quality. Additionally, SLE is capable of producing very tiny structures, of which the dimensions are limited to the diameter of the laser beam. The principle of the combined process of SLM and SLE is illustrated in Figure 17. Selective Laser Erosion can be applied after each or a number of SLM layers in order to increase the resolution along the building axis by reducing the layer thickness. For instance, the stair effect, appearing on sloping planes and rounded corners due to layerwise manufacturing varies proportionally with the layer thickness which is normally a fixed parameter in SLM, dependent on the powder particle size. Thus, a possible solution to decrease the layer thickness is a combined process. Firstly the layer is scanned with the usual layer thickness (30 µm). Next, this layer is partly taken away by laser erosion. Alas, material removing by means of laser light requires high intensity that is obtained by laser sources that can provide laser pulses with high energy intensity. Not only the stair effect is reduced in this manner, but also the micromachining capability of SLM is enhanced. In the experiments carried out on the Concept Laser M3 Linear machine with 316L powder, none of thin walls that have a thickness of less than 0.5 mm could be successfully made by SLM. However, the walls were built with success when combined process of SLM and SLE was applied. The results are also depicted in Figure 17.

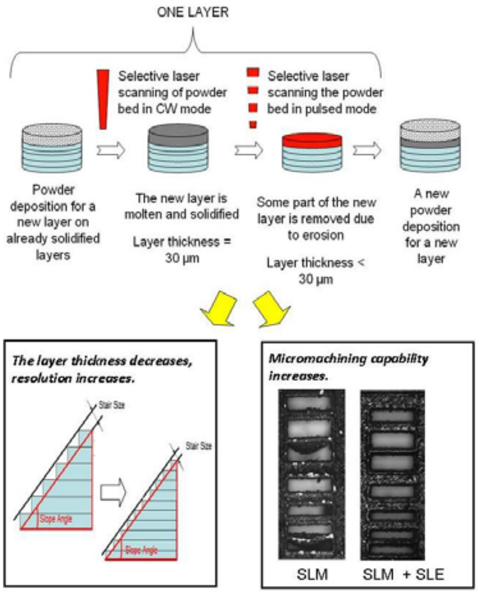


Figure 17: Combined Process of SLM and SLE where SLE is applied during SLM process

Moreover, SLE can be applied only on top surfaces after the parts are produced by SLM as illustrated in Figure 18. In this manner, the surface quality of SLM parts can be improved in terms of average and total roughness values about 50%. Moreover, three-dimensional geometries with very fine details can be engraved on SLM parts. Due to the beam diameter used in SLM (180 µm) and risk of collisions of built forms with hard coater blades, tiny structures having dimensions less than 0.5 mm are difficult to be made during SLM. However, SLE only depends on removal of material by vaporization and the only limitation is the laser beam's diameter. On Concept Laser M3 Linear, it is possible to adjust the laser beam's diameter to 2 settings with the use of an aperture: approximately 75 µm and 180 µm. In order to achieve small details, the small aperture (75 µm) is generally utilized in SLE where the dimensional limitation is thus about 75 µm.

E. Other research activities

Other than the research activities mentioned in previous sections, production of lightweight structures as well as dental implants and bone scaffolds from biomedical materials such as CoCr and Ti alloys, SLM of ceramics and residual stresses formed during SLM are other areas that the RM/RP group of K.U.Leuven concentrates on. Some produced samples for dental frame and bone scaffolds are shown in Figure 19 and Figure 20. Morphological and mechanical characterization of Ti6Al4V scaffolds produced with Selective Laser Melting (SLM) is one of the undertaken research topics. Scaffolds with different pore sizes are designed and manufactured. Pore size measurements obtained by light microscopic and CT imaging show significant differences between designed and produced pore size values, but no significant difference within scaffolds batches produced over time is found. Compression tests, performed on cylindrical porous structures, result in a low inter batch variability of the stiffness. This work show that for SLM produced Ti6Al4V scaffolds the designed morphological (pore and beam size) values differ from the produced values but that the process is consistent. Taking the offset between designed pore value and real pore value in to account, it is concluded that SLM can build structures with controlled pore and beam size dimensions with controllable mechanical properties. More information about this work can be found in [16, 17]. Regarding the dental implants, [18] should be referred to.

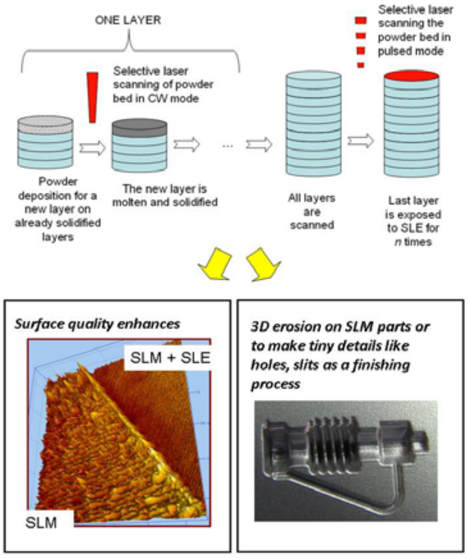


Figure 18: Combined Process of SLM and SLE where SLE is applied after SLM is completed

The work on ceramics has been initiated in 2008 and is now concentrated mostly on machine modifications necessary for melting of ceramics which have very high melting points compared to metals and high susceptibility to cracks. A pre-heating system, which can increase the temperature of the powder bed up to at least 1000 °C, becomes a necessary component of a SLM machine to process ceramics. The coating of ceramic powder particles also needs special handling. After the machine modifications are completed, more attention will be given to processability of different ceramic powders and different types of consolidation phenomena will be studied.

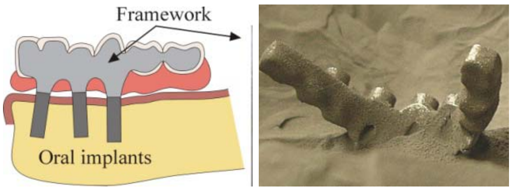


Figure 19: Ti dental frame

In the SLM process, during melting and solidification, the metal experiences very large thermal gradients causing high thermal stresses which can induce cracks, or undesired decrease in the strength of the parts. By changing standard parameters like scan pattern or process parameters, the thermal stresses can be reduced. To achieve this goal, a new measuring method was defined to compare the curvature of test parts after cut from the base plate in an easy way. A new method, named as Bridge Curvature Method, is defined. As a initial output of this study, changes which reduce the high temperature gradients, like short scan vectors and preheating of the base plate results in lower residual stresses. Besides, the orientation of the parts plays an important role on the residual stresses. More information can be found in [19].

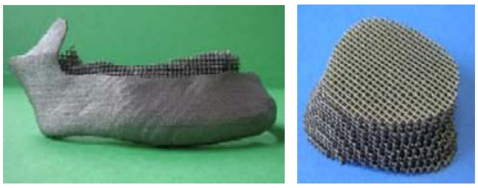


Figure 20: Bone scaffolds

III. SUMMARY

This paper summarizes the research activities of the Rapid Prototyping/Manufacturing group at the University of Leuven which is located in Leuven, Belgium. The main purpose of RP/RM research activities at K.U.Leuven is to develop the SLM/SLS processes of metals, ceramics and polymers enabling RP/RM of complex and customized parts in a competitive way with conventional manufacturing methods. The paper gives an overview of research activities investigated and studied at K.U.Leuven to achieve this overall goal.

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