BENCHMARKING OF DIFFERENT SLS/SLM PROCESSES AS RAPID MANUFACTURING TECHNIQUES

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Abstract

Recently, a shift of Rapid Prototyping (RP) to Rapid Manufacturing (RM) has come up because of technical improvements of Layer Manufacturing processes. Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) techniques are no longer exclusively used for prototyping and the possibility to process all kind of metals yields opportunities to manufacture real functional parts, e.g. injection moulds (Rapid Tooling).

This study examines different SLS/SLM processes with regard to conditions that become very important for manufacturing, such as accuracy, material, mechanical properties, speed and reliability. A benchmark model is developed facilitating to test these conditions and to check the process limitations. This benchmark is manufactured by five SLS/SLM machines which differ in process mechanism, powder material and optimal process parameters. To find out process accuracy, a dimensional analysis is performed and the surface roughness is measured. Besides, the benchmarks are tested for their mechanical properties such as density, hardness, strength and stiffness. Finally, speed and repeatability are discussed as important factors for manufacturing.

This paper presents the state of the art in SLS/SLM and aims at understanding the limitations of different SLS/SLM processes to form a picture of the potential manufacturing applications of these processes.

Introduction

Selective Laser Sintering (SLS) and Selective Laser Melting (SLM) are layer-wise material addition techniques that allow generating complex 3D parts by selectively consolidating successive layers of powder material on top of each other, using thermal energy supplied by a focused and computer controlled laser beam [1, 2, 3, 6]. Different binding mechanisms can be responsible for the consolidation of the powder: Solid State Sintering, Liquid Phase Sintering, Partial Melting or Full Melting [4]. The competitive advantages of SLS/SLM are geometrical freedom, mass customization and material flexibility. In contrast to material removal techniques, complex shapes can be fabricated without the need for lengthy tool path calculations and remaining unprocessed powder can be reused.

Over the last decade SLS/SLM processes have gained a wide acceptance as Rapid Prototyping (RP) techniques. Due to technical improvements, better process control and the possibility to process all kind of metals, a shift to firstly Rapid Tooling (RT) and secondly Rapid Manufacturing (RM) came up in recent years [5, 6]. Many applications could take advantage of this evolution by using SLS/SLM not only for visual concept models and onetime functional prototypes, but also for tooling moulds, tooling inserts and end-use functional parts with long-term consistency.

To turn SLS/SLM processes into production techniques for real components, some conditions have to be fulfilled. Firstly, manufacturing applications increase the requirements on material and mechanical properties. The process must guarantee consistency over the entire product life cycle. Secondly, process accuracy, surface roughness and the possibility to fabricate geometrical features like overhanging surfaces and internal structures become very important for manufacturing. Finally, the breakthrough of SLS/SLM processes as Rapid Manufacturing techniques will depend on reliability, performance and economical aspects like production time and cost.

The presented work investigates if SLS/SLM processes, according to the state of the art, fulfil these manufacturing requirements and tries to show opportunities of new applications of direct metal manufacturing by means of SLS/SLM.

Materials and methods

This study examines SLS/SLM as direct metal manufacturing techniques by benchmarking of five different SLS/SLM processes. A benchmark model is developed facilitating to test manufacturing conditions and is fabricated by these SLS/SLM processes which differ in equipment, powder material, binding mechanism and process parameters. The produced benchmarks are tested for their mechanical properties such as density, hardness, strength and stiffness. Dimensional analyses are performed to check process accuracy and surface quality. Repeatability and economical aspects like speed and costs are discussed as important factors for manufacturing.

Benchmark model

The benchmark can not only be used to analyze the process limitations, but also to optimize each process iteratively. A few loops of benchmark tests can lead to optimal parameters. For example, offset and scaling values, used to compensate for thermal distortions and dimensional changes due to the laser beam spot size, can be optimized iteratively based on dimensional analyses of (successively) produced benchmark parts. The benchmark procedure must be performed for each combination of machine, powder material and process parameters, because geometrical and mechanical properties vary with these settings.

Figure 1 shows the benchmark model. Due to limited dimensions (50 x 50 x 9 mm^3), building time is reduced to draw conclusions about process limitations more rapidly. Mechanical tests will be performed on beams cut off from the left solid half of the part. The other half of the benchmark contains some geometrical features.

The sloping plane and the rounded corner are introduced to verify the stair effect, inherent to the layer-wise production. Due to the contraction of molten material that solidifies and cools down and due to high thermal gradients during SLS/SLM processes, distortions like curling or delamination can appear [7, 8, 9, 10]. The presence of the thin plane with a thickness of 2 mm can indicate warpage due to thermal stresses. The feasible precision and resolution of the process are tested by small holes (ranging from 0.5 to 5 mm diameter), small cylinders (ranging from 0.5 to 5 mm diameter) and thin walls (ranging from 0.25 to 1 mm thickness). Sharp edges with angles from 14° to 45° are applied to the benchmark to check the influence of heat accumulation at the angle tips and to discover scanning errors. The integrated circular and rectangular overhanging surfaces can prove the possibility of producing overhangs without the need for support structures. All geometrical features can be used to measure process accuracy in x, y and z-direction.

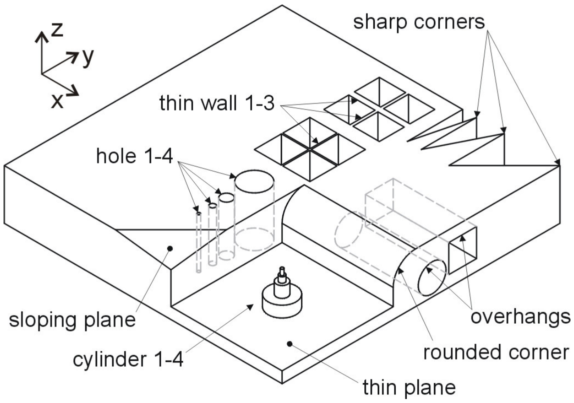

Fig. 1. Benchmark model

Test methods

The surface roughness of the as-processed benchmark samples is measured along different directions using a Taylor Hobson Form Talysurf roughness meter. R_a and R_t values are measured using a cut-off length of 2.5 mm. The solid half of the produced benchmarks is cut by wire-EDM (Electrical Discharge Machining) into appropriate blocks for mechanical testing.

Density is measured according to the Archimedes principle by weighing the samples in air and subsequently in ethanol to measure the volume. A coating with lacquer avoids absorption of ethanol by the specimen. The density of the sample can be calculated based on the mass of the solid, the mass of the lacquer, the mass of the coated sample in ethanol, the density of ethanol and the density of the lacquer. Micrographs are taken at various magnifications on a Philips SEM XL30 FEG and help to understand the presence and size of pores.

Three point bending tests are carried out using an Instron 4467 machine, according to the ASTM B312 standard, to determine the bending yield strength and the Young's modulus of the part. The samples are polished to reduce the possibility of notch effects on the bending test. The average micro-hardness is measured on a universal testing machine using a Vickers indentation with a load of 100 g ($HV_{0.100}$).

Experimented SLS/SLM processes

The benchmark is manufactured by five SLS/SLM machines, which differ in laser source, optics, powder deposition, scanning equipment and environment control system. Process parameters, such as layer thickness, laser power and scanning strategy are optimized for each process depending on the applied binding mechanism [4] and chosen powder material [11]. Table 1 sums up some important specifications of the five SLS/SLM processes. Other materials are possible for each machine.

Nr	Equipment	Binding mechanism	Material	Layer thickness / Laser power
1	3D Systems DTM	Liquid phase sintering (polymer binder)	Polymer coated stainless steel	80 µm 10 W
2	Concept Laser	Full melting	Hot work tool steel	30 µm 100 W
3	Trumph	Full melting	Stainless steel 316L	50 µm ≤200 W
4	MCP-HEK	Full melting	Stainless steel 316	50 µm 100 W
5	EOS	Partial melting	Bronze based	20 µm 221 W

Table 1. Specifications of experimented processes

In this study three different binding mechanisms are found. The first mechanism is Liquid Phase Sintering where the polymer coating of the powder grains, liquefied by the laser beam, acts as a binder for the structural stainless steel grains. This technology needs a furnace cycle as an additional step, in which the polymer is burnt out and the green part is further sintered and infiltrated with bronze. The second consolidating method is Partial Melting. This technology doesn't exhibit a clear distinction between binder and structural material, but molten and non-molten material areas can be distinguished after fusing the powder mixture. The third binding mechanism is Full Melting. Near full density is reached within one step by melting the metal powder completely by the laser beam, thus avoiding lengthy post processing steps. Other binding mechanisms are possible for SLS/SLM processes, but not tested in this study [4, 5].

Results and discussion

Geometrical features, mechanical properties and economical aspects are tested as important manufacturing requirements for each fabricated benchmark. This study doesn't aim at comparing results between the tested SLS/SLM techniques, because the processes differ in powder material, equipment and aimed focus; accuracy, speed or mechanical properties. This study is meant to understand the limitations of SLS/SLM and to find potential manufacturing applications.

Geometrical features

Manufacturing applications increase the requirements on process accuracy and demand the possibility to produce all kinds of geometrical features. Table 2 summarizes the dimensional analysis performed on all benchmarks manufactured by the different SLS/SLM processes. Figure 2 shows some pictures of specific geometrical features.

To guarantee high accuracy the processes must take into account the laser beam spot size and thermal distortions due to successive melting and resolidification of metal material. Scaling and offset parameters, as well as scanning strategies anticipate these dimensional changes. By spending more time and effort on optimizing these parameters, higher process accuracy could be reached by a few more loops of benchmark tests. Hereby, one has to take into consideration cost and time efforts versus required accuracy.

With regard to feasibility and geometrical resolution, holes with a diameter of 0.5 mm can not be built because the enclosed loose powder is melted by the surrounding heat. The minimum thickness of thin walls (figure 2b) corresponds with one scan track and is thus limited by the laser beam spot size. Cylinders with a diameter smaller than 0.5 mm can not be produced because of insufficient strength of the scanned feature to resist forces during powder deposition (figure 2a).

nominal dimension	**process 1**	**process 2**	**process 3**	**process 4**	**process 5**
Length 50 mm	50.59	50.08	50.12	50.78	50.16
Width 50 mm	50.22	50.09	50.11	50.73	50.18
Height 7 mm	7.05	6.96	7.12	7.12	7.03
Hole 1 ∅ 5 mm	5.03	4.87	4.84	4.67	4.83
Hole 2 ∅ 2 mm	1.96	1.97	1.95	1.72	1.77
Hole 3 ∅ 1 mm	Badly built	Badly built	0.95	Badly built	0.90
Hole 4 ∅ 0.5 mm	Not built	Not built	Not built	Not built	Not built
Cylinder 1 ∅ 5 mm	4.95	5.03	4.96	5.35	5.12
Cylinder 2 ∅ 2 mm	1.90	2.05	1.97	2.23	2.10
Cylinder 3 ∅ 1 mm	0.97	1.06	1.02	1.25	1.12
Cylinder 4 ∅ 0.5 mm	Not built	Not built	Badly built	0.64	0.63
Wall 1 1 mm	0.97	1.23	1.04	1.34	1.16
Wall 2 0.5 mm	0.71	Not built	0.55	0.76	0.68
Wall 3 0.25 mm	Not built	Not built	0.33	0.47	0.47
Stair effect	Bad	Good	Bad	Bad	Good
Curling	Good	Good	Bad	Good	Good
Sharp corners	Too short	Good	Too short	Too short	Good
Overhangs	Good	Badly built	Badly built	Badly built	Badly built
R_a – x (µm) R_t – x (µm)	2.03 13.80	5.39 35.75	16.71 148.57	11.16 76.43	10.45 67.81
R_a – y (µm) R_t – y (µm)	2.09 19.80	6.25 47.55	16.42 131.64	9.00 62.52	10.72 75.42

Table 2. Geometrical analysis of benchmarks

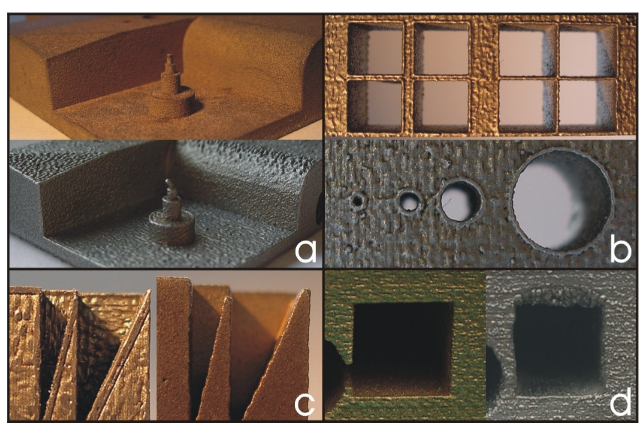

Fig. 2. Geometrical features of benchmarks: (a) Upper: good cylinders and limited stair effect (proc. 5), lower: bad cylinders and stair effect (proc. 3); (b) Thin walls and holes for proc. 3; (c) Left: good sharp corners (proc. 2), right: too short edges (proc. 1); (d) Left: good overhang (proc. 1), right: bad overhang (proc. 4).

The stair effect, appearing on the sloping plane and the rounded corner due to the layer-wise manufacturing (fig. 2a), varies proportionally with the layer thickness. The layer thickness is a fixed process parameter dependent on the powder grain size. A possible solution to decrease the layer thickness is a combined process. Firstly the layer is scanned with the usual layer thickness. Next this layer is partly taken away by laser erosion. Alas, material removing by means of laser light requires high intensity laser pulses. Only process 2 is suited for this laser erosion, thanks to its integrated Q-switched module in the laser.

Curling due to thermal stresses is avoided by fully supporting the part with a base plate. Process 3 suffers from warpage of the thin plane because the component was built on a fine grid support structure. Sharp corners (figure 2c) can only be created when heat accumulation is avoided by a successful scanning strategy (i.e. exposure path of the laser beam) and when no scanning errors occur at the real edge of the feature. Near-horizontal overhanging surfaces (figure 2d) are not directly possible for processes with metal melting as binding mechanism. Since the laser beam penetrates deeply into the powder bed, bottom surfaces are not finished well and support structures are necessary to guarantee adequate process continuation.

The roughness of the top surface is measured in two perpendicular directions (X,Y), because different values could be expected according to the scan direction. However, these benchmark tests show that surface roughness is independent of the measurement direction. Process 1 guarantees a very low surface roughness due to the bronze infiltration during the furnace cycle. Process 2 shows a smooth top surface due to an ultrasonic filing post process. The other processes can also take advantage of a simple surface after-treatment. For example the surface roughness of the benchmark produced by process 5 has been reduced by shot peening to a R_a-value of 3.80 µm and a R_t-value of 29.80 µm.

Mechanical properties

Table 3 shows the results of mechanical tests performed on all benchmarks manufactured by the different SLS/SLM processes. For most tests the measured value compares to the value stated by the manufacturer.

The density tests prove that SLS/SLM techniques are able to produce near full dense objects. Figure 3 contains micrographs taken from cross sections of the parts. Remaining porosities are clearly visible as black spots. The light coloured zones in the sample of process 1 correspond to the bronze infiltrant surrounding the dark stainless steel particles. Only little amount of pores appear for process 3 thanks to the beneficial effect of the available preheating system. Slower cool down rates allow gas inclusions to escape from the melt pool before solidification of the material. Process 5 uses different scanning parameters for the outer shell and the core of the part. For gain of time the core is scanned much faster and some layers are even not scanned, yielding a porous structure (right half of picture of process 5 in fig. 3). The outer shell is intended to have the highest density and the highest strength.

For all processes micro-hardness is rather high because the melt pool cools down very rapidly when the laser beam has passed. The measured values for the Young's modulus are low in comparison with the stated values of the manufacturers. In this study the Young's modulus is determined based on a bending test, what can be a possible reason for this difference. The yield strength tests prove that SLS/SLM processes fulfil the requirements of strength for manufacturing.

Mechanical property	process 1	process 2	process 3	process 4	process 5
Density (kg/m^3) measured	7 750	8 025	7 870	7 900	7 650
µ-hardness ($HV_{0.100}$) stated	187	420	202	-	117
µ-hardness ($HV_{0.100}$) measured	176 ± 10	398 ± 12	251 ± 6	233 ± 5	185 ± 20
Young's modulus (GPa) stated	137	-	-	-	80
Young's modulus (GPa) measured	37	62	49	54	30
Yield strength (MPa) stated	305	1000	500	-	400
Yield strength (MPa) measured	218	1410	535	598	320

Table 3. Mechanical analysis of benchmarks

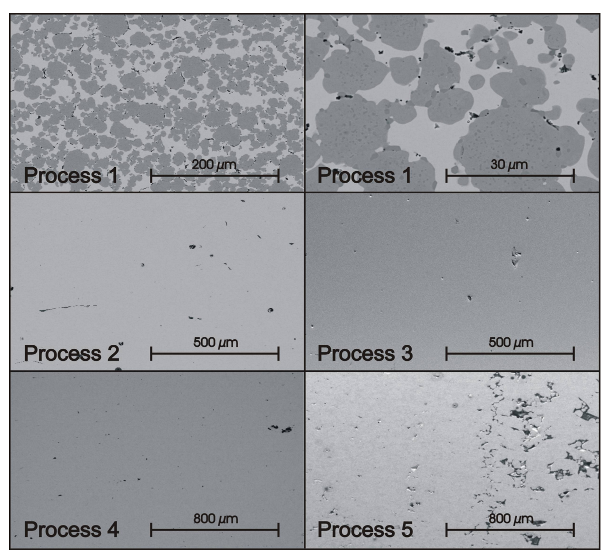

Fig. 3. Micrographs of cross sections of benchmarks

Reliability and economical aspects

The possibility of using SLS/SLM processes for industrial applications of direct metal manufacturing depends not only on geometrical and mechanical properties, but also on reliability, production time and costs. During the study repeatability has been checked for process 1 and process 2. Dimensional and mechanical analyses of a second and third part, made during other build sessions with the same parameters, revealed similar values, demonstrating the repeatability.

Table 4 indicates the production time of the benchmarks. Production time consists of powder depositioning time, scanning time and file loading time. The total powder depositioning time is proportional to the number of layers, thus proportional to layer thickness and build height. The total scanning time depends on scan speed, scan spacing and part dimensions. Geometrical complexity and number of scan vectors are the major determinants for file loading time. The furnace cycle of process 1 takes 24 hours. Production time of process 5 is relatively low due to the faster scanning of the core of the part.

During the last decade productivity of SLS/SLM processes has increased with a factor 10 [6] due to higher feasible scan speeds with equal or better quality of the part. A few hours of process time still seems rather long in comparison with production time of conventional manufacturing techniques, but complex shapes can be fabricated without the need for lengthy tool path calculations or the production of complex moulds. As no manpower is required during the process, production costs are mainly determined by machine hours. When more parts are fabricated during the same build session, depositoning time and consequently production cost will decrease for each part.

process 1	process 2	process 3	process 4	process 5
3 + 24 h	9 h	4.5 h	8.5 h	4.5 h

Table 4. Production time of benchmarks

Potential applications and challenges

The competitive position of SLS/SLM as manufacturing techniques relative to conventional methods depends on geometrical complexity and required quantity. The tested layer manufacturing processes will never substitute classical material removal processes completely. Suitable applications are characterized by medium to high geometrical complexity and rather low quantities. For example, geometrical freedom and mass customization give an excellent prospect to medical applications like individualized implants, dental prostheses and bone scaffolds. Performance of mould inserts can be increased by using SLS/SLM processes and incorporating conformal cooling channels. Other market segments like aerospace industry can take advantage of new opportunities of manufacturing by SLS/SLM: e.g. single part production, production of complex hollow light weight structures.

Even though SLS/SLM can already be used for a wide range of applications, further work needs to be done. The most important challenge is to reach high process accuracy for any geometrical shape. By splitting up the part according to specific geometrical features (e.g. overhangs, sharp corners, small details, core of the part, etc.), different process parameters can be applied for different regions of the part to reach high precision of each feature. This process accuracy advance should be accompanied with further progress in material properties and productivity.

Conclusions

This paper has demonstrated possibilities and limitations of different SLS/SLM processes as rapid manufacturing techniques for functional metal components. A benchmark model was developed and produced by five different SLS/SLM systems to test manufacturing requirements. A dimensional analysis was performed to measure process accuracy and to check the precision of specific geometrical features. Density tests and bending tests proved the ability of SLS/SLM to produce parts with good mechanical properties. Economical aspects like production time and costs were discussed.

Since high geometrical complexity and low quantity are determining factors for potential applications, medical parts and tooling inserts are highly suitable for manufacturing by SLS/SLM. The real breakthrough of SLS/SLM in other industries will depend on further improvements of process accuracy and productivity.

Acknowledgements

This research was supported by national funding provided by OSTC, FWO and K.U.Leuven-GOA.

Keywords

Rapid Manufacturing, Selective Laser Sintering, Selective Laser Melting, state of the art, benchmarking.

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