TNO Industrial Technology

TNO report with the collaboration of AIMME

AIMME
INSTITUTO TECNOLÓGICO
METALMECÁNICO

Study about the rapid manufacturing of complex parts of stainless steel and titanium

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Contents

1 Introduction

Rapid manufacturing is the use of additive fabrication technology to directly produce useable products or parts. Geometric freedom, use of multiple materials, elimination of tooling, mass customization and lowered costs are some of the advantages of these processes. However a great accuracy, good mechanical properties and low prototype time[I1] are needed to be a competitive manufacturing process.

Since the origin of rapid manufacturing as an evolution of rapid prototyping many companies are developing processes and materials in this direction and applications fields are increasing as soon as new improvements are being reached.

Technology is advancing so fast that an updated of the state of the art is necessary.

The objective of this project is to test available and under development technologies for the rapid manufacturing of complex metal parts in order to know the currently state of the art

Getting to know advantages and limitations of these processes will make it possible to find potential manufacturing applications and to select the most suitable process for any customer needs.

For the performance of [I2]this project, several companies on different technologies will be asked to build the same part in metal as benchmarking. Parts will be built in steel or titanium alloys. Steel was the first commercially available material from many companies due its main application as rapid tooling, while titanium in many cases is still under development

Accuracy, detail capability and geometry limitations will be measured to test the quality of the parts.

Tensile and hardness test will be performed on building materials to determine mechanical properties.

Building time will be considered as the total amount of machine hours and secondary operations. Post processing like support removal and finishing processes will not be taken into account.

2 Technologies

2.1 3D Printing. ProMetal

The ProMetal 3D printing process is an indirect technology, which consists in jetting a binder onto a metal powder bed. Parts are built up layer by layer to near net shape. Upon completion, the "green" part is loaded into a sintering furnace that fuses the tool steel powder into a form that has 60 percent density, while burning off the binder. In a second furnace cycle, this porous structure is infiltrated with molten bronze via capillary action to reach full density.

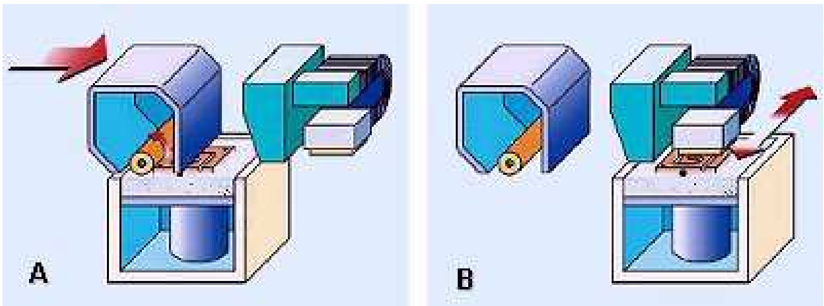


Figure 1 Courtesy of ProMetal

2.2 Selective Laser Melting. (SLM) MCP

SLM is a direct process based on a principle in such manner that the powder is applied in very thin layers on a building platform and melted due to the thermal influence of a laser beam. In each layer the laser beam generates the outline of the part that is being built by melting the powder particles, before the building platform is lowered and coated with a new layer of powder

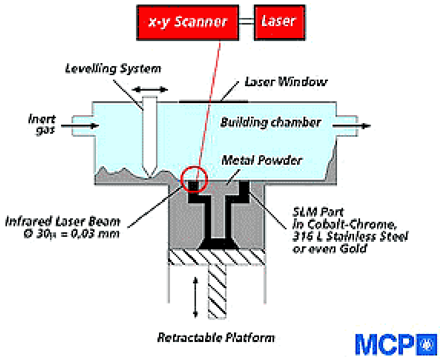


Figure 2 Courtesy of MCP

2.3 Laser Forming. Trumpf

In this process, like in MCP, the laser beam melts on the powder layer. Adjacent melting traces and stacked layers are welded together and the build platform is lowered by the set layer thickness. These steps are repeated until the entire component is complete.

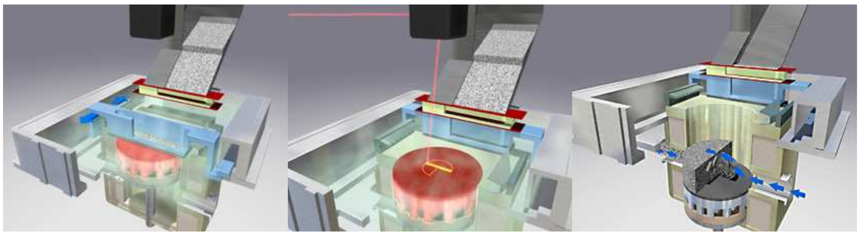


Figure 3 Courtesy of Trumpf

2.4 LaserCusing. Concept Laser

Like the previous direct processes, this method fused layer for layer single component metallic powder to produce an almost 100% component density. A patented exposure strategy allows the generation of solid and large-volume components without any deformation. A special surface post-treatment process, called micro blasting, directly after the construction process ensures the highest surface quality and hardness.

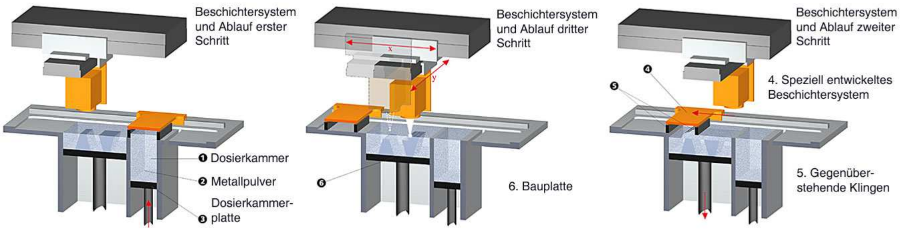


Figure 4 Courtesy of Concept laser GmbH

3 Benchmark model

This picture shows a 60*100*81 mm part which has been designed specifically to study the following features:

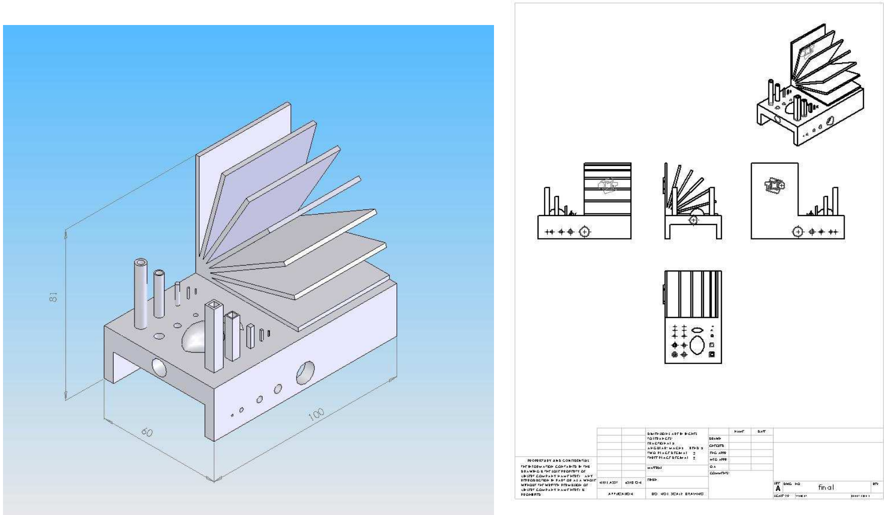


Figure 5 Benchmark model

3.1 Overhang

Many technologies have difficulties in building an overhang plane due to the process definition of layered wise production in a powder bed. Some of the processes can solve this problem by using support structures, which afterwards have to be removed by post machining. This solution will increase production time and the need of secondary operations. The benchmark part has been designed with a “table” shape whereby the overhang plane at the interior side is a building challenge.

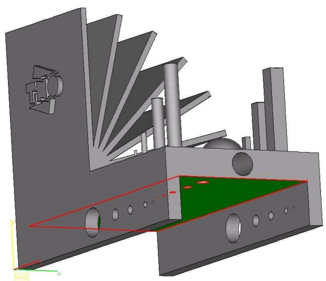


Figure 6 Overhang plane

Warpage

Warpage is the excessive distortional change in a processed part after it has been removed out of the powder bed at the end of the process. The term warpage is employed when a whole part is being bowed. The main cause for warpage is inhomogeneous shrinkage. Both shrinkage and warpage will depend on the material properties, part geometry and process conditions.

Wall thickness transitions also exert influence on the heat transfer within a part. To evaluate this phenomenon the part has been designed with a “table” shape where there is a wall thickness transition from 10 to 5 mm.

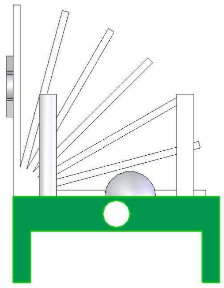


Figure 7 "Table" shape

3.2 Building angles

Due layers construction some technologies have difficulties in building features with a specific angle. In some of them supports may be needed. To study this capability an “open book” shape has been designed. The “sheets” are placed in angles of 0, 15, 30, 45, 60, 75 and 90 degrees.

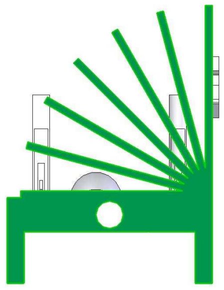


Figure 8 "Open book" shape

3.3 Wall thickness

Laser spot limits usually minimal wall thickness. In this part, elements with 2, 1 and 0.5 mm wall thickness have been designed to study this limitation. The “open book’s “sheets” have a 2 mm wall thickness and the two first circular and square towers have been designed hollow with 1 and 0.5 mm thickness.

3.4 Critical geometries: narrow and high details

There is a risk that the internal stresses will induce cracks where there are layer defects in high parts. Square and circular towers with heights of 30, 20, 10, 5 and 2.5 mm and different dimensions or diameters have been designed to analyze the risk of cracking. There are also towers with 1 and 0.5 mm diameter, which in some cases, may not be built due to minimal spot laser.

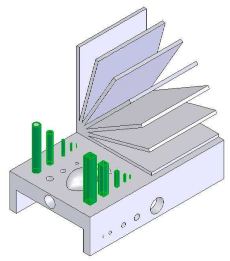


Figure 9 High and narrow details

3.5 Critical geometries: small through holes and Z- bonus.

In layer production technologies, part orientation is a very important building factor. Building features in XY plane is[I3] easier than making then in XZ or YZ plane due to layer slicing in Z direction. In some cases surfaces will become thicker than planned. On the other hand, small holes may not be built due to minimal spot laser.

To test detail capability through holes of 4, 3, 2, 1, and 0.5 mm diameter and 10 mm length have been placed at the top plane (XY). At the right and left plane (YZ) holes of 10, 4, 3, 2, and 1 mm with 5 mm length can be found. At the front plane (XZ) there is a through hole of 8 mm diameter and 100 mm length.

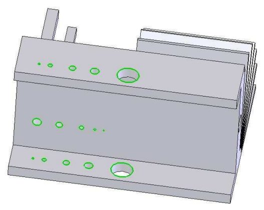


Figure 10 Holes in different directions

3.6 Critical geometries: curved areas

For layers production technologies it may be difficult to build curved areas due to layer slicing. Two elliptical areas with different dimensions have been placed at the top plane (XY) to test this capability.

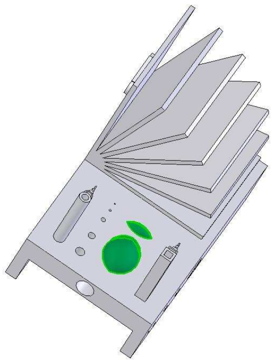


Figure 11 Curved areas

3.7 Mechanical properties

Some of the “open book’s “sheets” will be used to obtain specimens for a tensile and hardness test to determine mechanical properties.

4 Analysis and results

4.1 Building parameters and general observations

Due to the complex design of the benchmark model, it has been very difficult to find companies, which accepted this building challenge.

Following technologies and materials have participated in the study.

Steel Alloy				
Technology	**Equipment**	**Company**	**Alloy Name**	**Similar to commercial alloy**
LaserCusing	M3 Linear	Concept Laser GmbH	CL 20ES	AISI 316L Stainless Steel / DIN 1,4404
Selective Laser Melting	MCP Realizer SLM	MCP Tooling Technologies LTD	AISI 316L Stainless Steel / DIN 1,4404	
3DP Printing	R2	ProMetal	S4 (60% Stainless steel + 40% bronze)	AISI 420 Stainless steel / DIN 1.4021

Titanium Alloy				
Technology	**Equipment**	**Company**	**Alloy Name**	**Similar to commercial alloy**
Laserforming	Trumaform 250	Trumpf	TiAl 6 V4	

ProMetal

For the benchmark model the following build parameters were used:

Material: S4 (60% Stainless/ 40% Bronze)
Layer thickness: 100 µm. 616 layers.
Mode: printed 1 way

Due to the ProMetal process it was necessary to add a support for bronze infiltration. This support will be machined before testing.

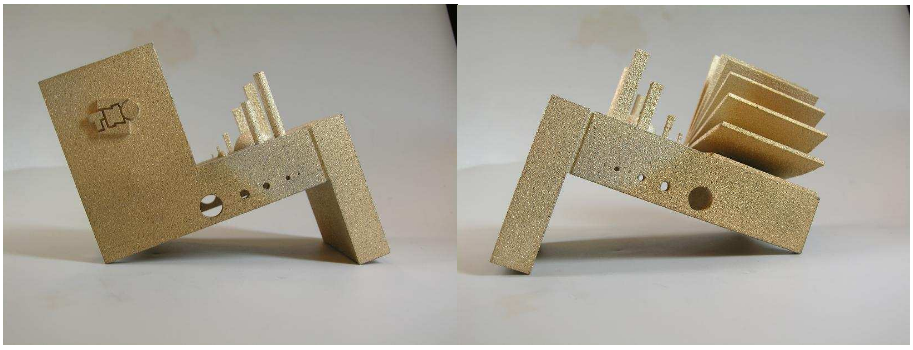


Figure 12 ProMetal part with supports

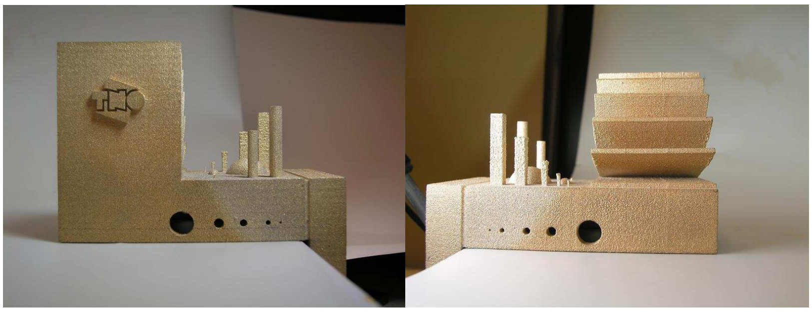


Figure 13 Left and right plane

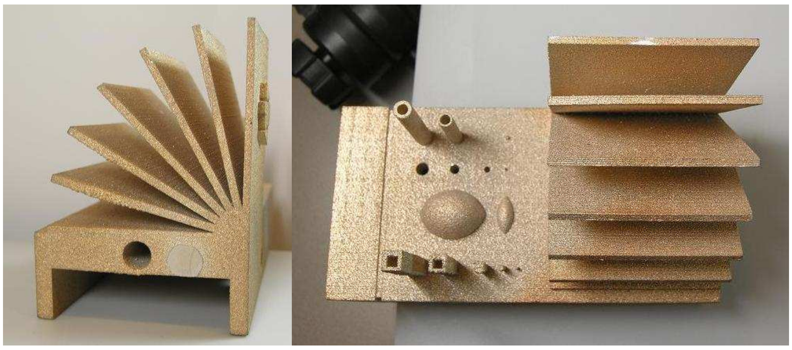


Figure 14 Back and top plane

Overhang, angle planes and logo were positive built without supports, but some features like the small holes and cylinders were missing at the top plane. Small through holes were positive built at right and left plane but not at front plane.

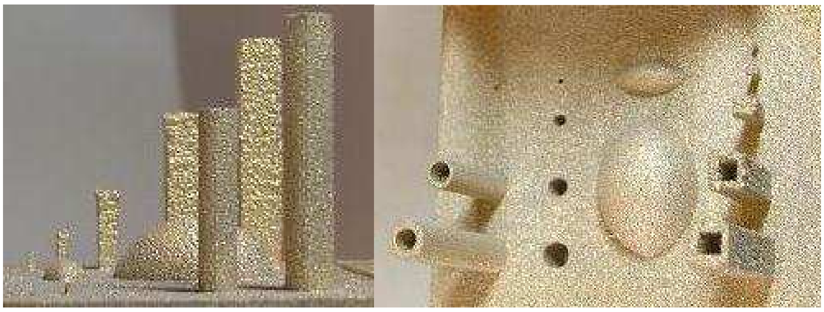


Figure 15 ProMetal benchmark features

Figure 16 Logo and through holes at right plane

MCP

For the benchmark model following build parameters were used:

Material: Stainless Steel 316L
Layer thickness: 75 µm

MCP had to add supports to build overhang, trough holes, logo and angle planes below 45 degrees. The part also needs to be removed from the building platform.

Figure 17 MCP part with supports at left and front plane

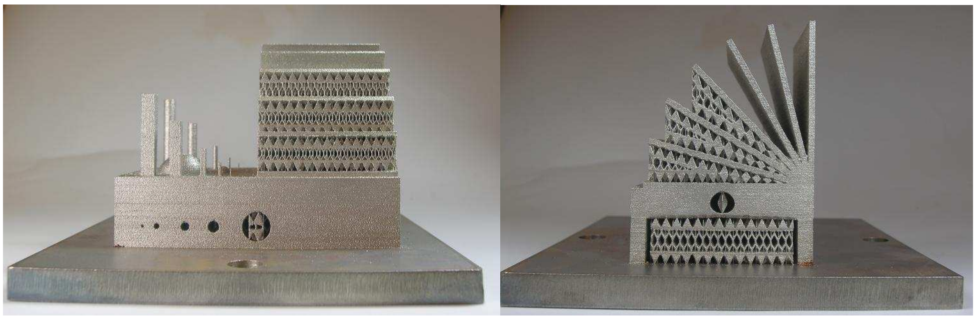


Figure 18 Right and back plane

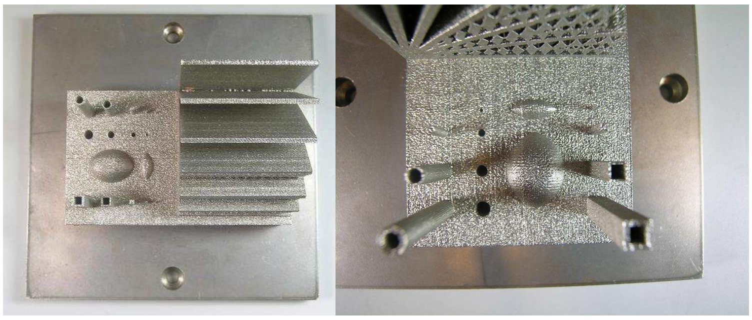


Figure 19 Top plane

The effect of Z-bonus and warpage is remarkable[I4] at front plane

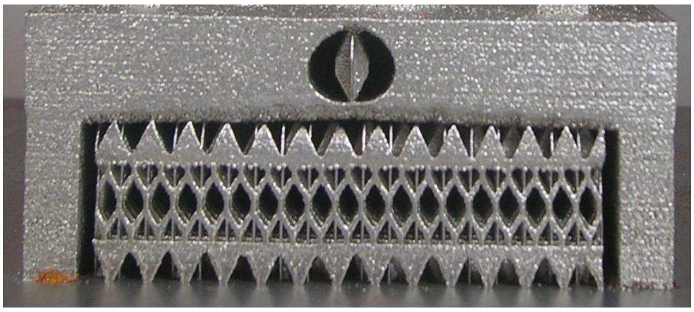


Figure 20 Warpage and Z-bonus

All features at top plane were positive built.

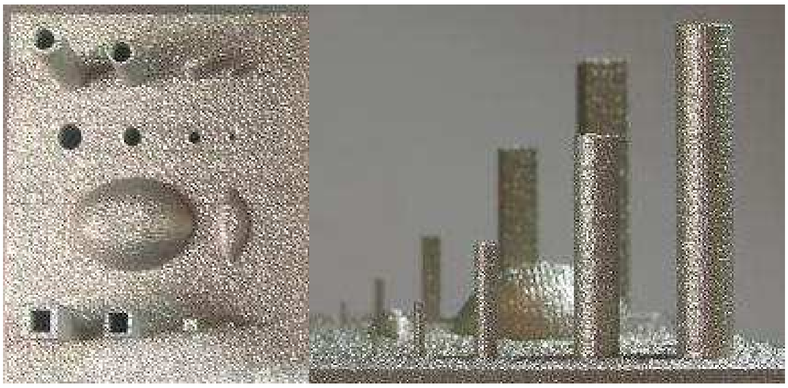


Figure 21 MCP benchmark features

Concept Laser

For the benchmark model following build parameters were used:

Material: Stainless Steel 316L
Layer thickness: 30 µm
Finishing process: Micro blasting

Concept Laser built the part rotated over 135 degrees and used supports which were removed after building.

Figure 22 Concept Laser building orientation

Due this building orientation, warpage and Z-bonus cannot be studied.

In some critical geometries the effects of the supports can be noticed due this building orientation. There is also a deviation from the vertical plane in the angle plane supposed to be built at 90 degrees, in one of the “book’s sheets”.

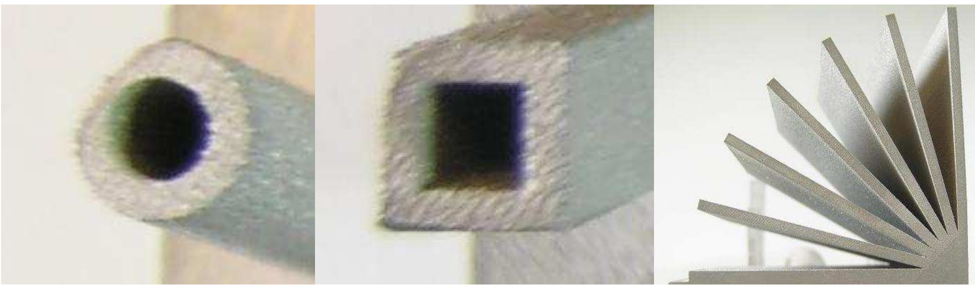


Figure 23Effects of the building orientation

It was also necessary to add a support structure to the file to build the overhang plane. Holes were made to reduce support-building time. Due this added support, holes are not through.

Through holes at front plane were positive built.

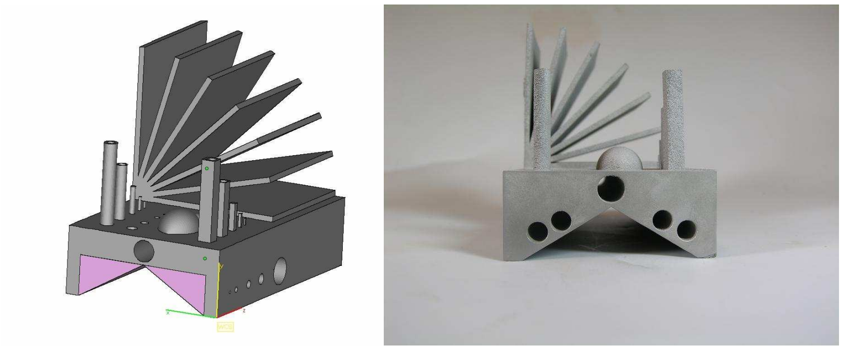


Figure 24 Concept Laser part with support

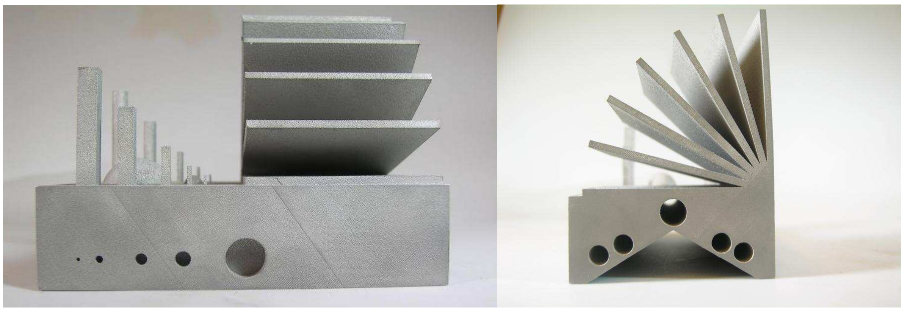


Figure 25 Right and back plane

Logo and all details at top plane were positive built.

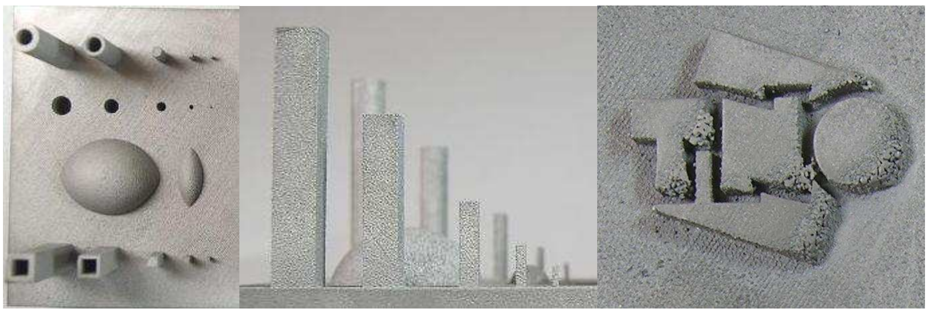


Figure 26 Concept Laser benchmark features

Trumpf

For the benchmark model following build parameters were used:

Material: TiAl 6 V4
Layer thickness: 50 µm

Trumpf had to add supports to build overhang, trough holes and angle planes below 45 degrees. No supports were needed to build the logo.

Figure 27 Trumpf benchmark model with supports

Figure 28 Right and back plane

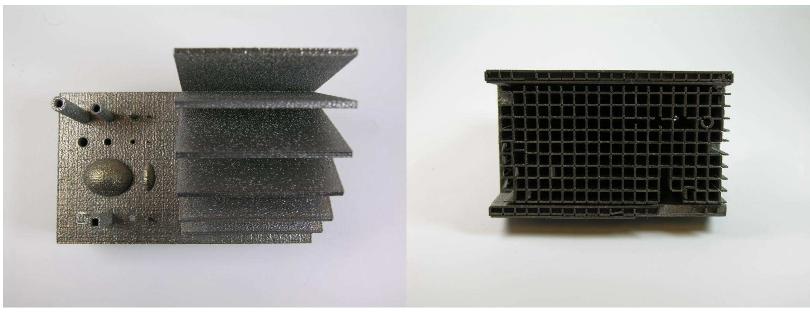


Figure 29 Top and bottom plane

There is a thickness defect at angle planes and warpage at front and back plane.

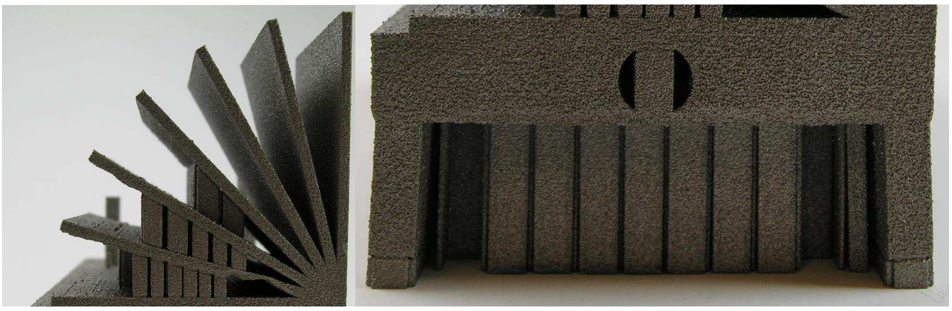


Figure 30 Thickness defect and warpage

Logo and most of the critical geometries at top plane were positive built but some geometries like tetrahedrons were missing.

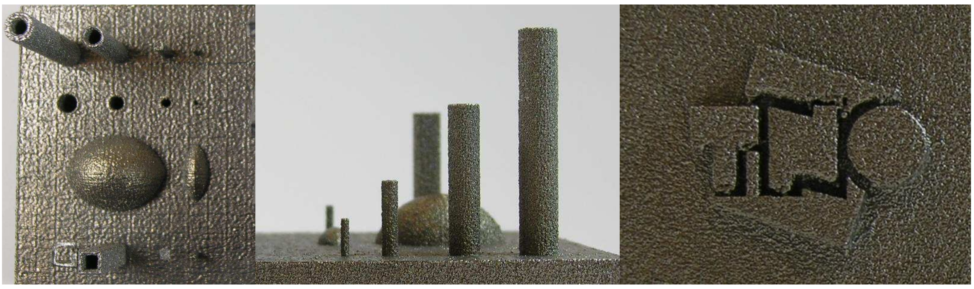


Figure 31 Benchmark details

4.2 Dimensional accuracy

Testing procedure

A digital calliper was used to test accuracy. All dimensions were averaged after five times measurements.

Each critical dimension has been analysed separately and compare between technologies.

Parts have been scanned and compared with the stl file.

A table with the deviation average and standard deviation by company is included at the end of this study.

Main dimensions

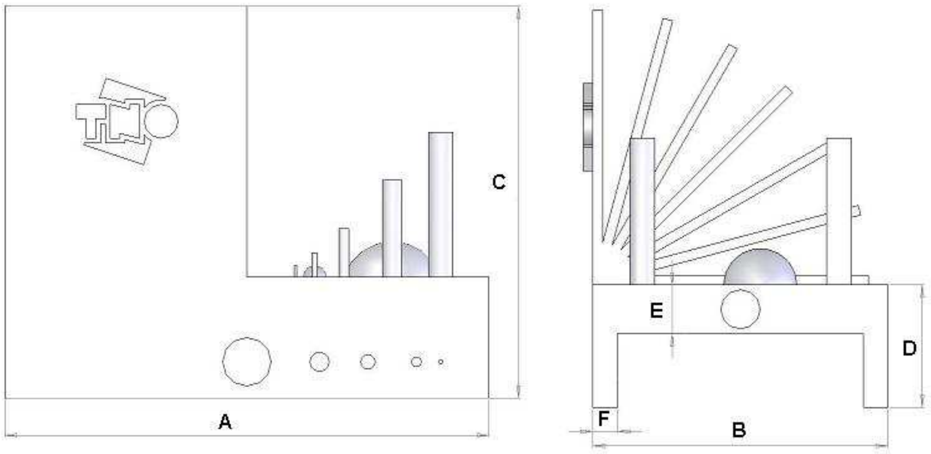
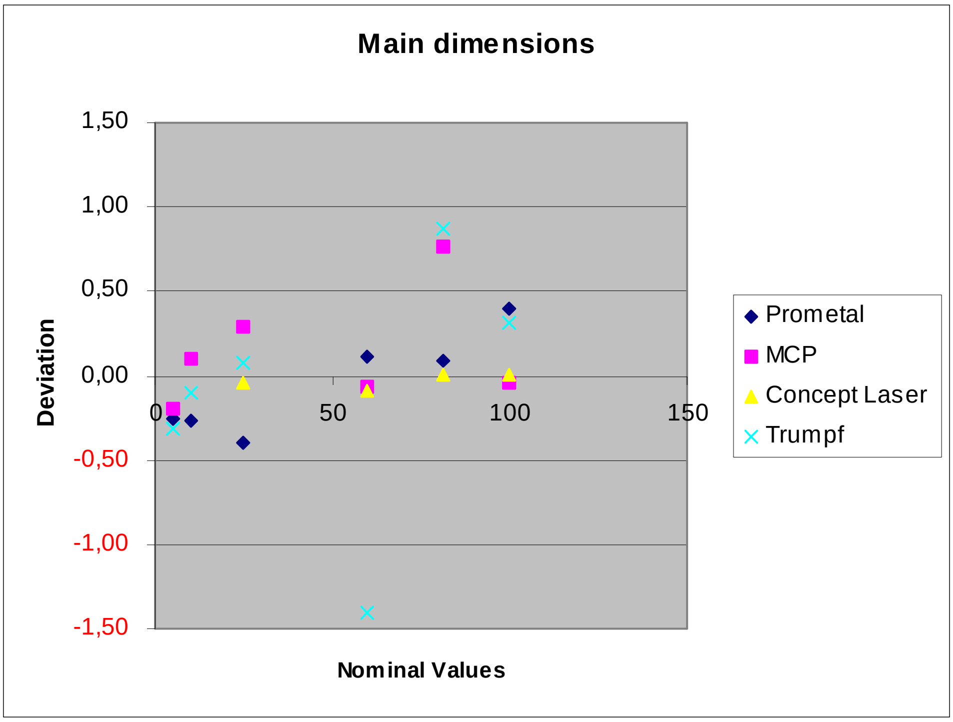
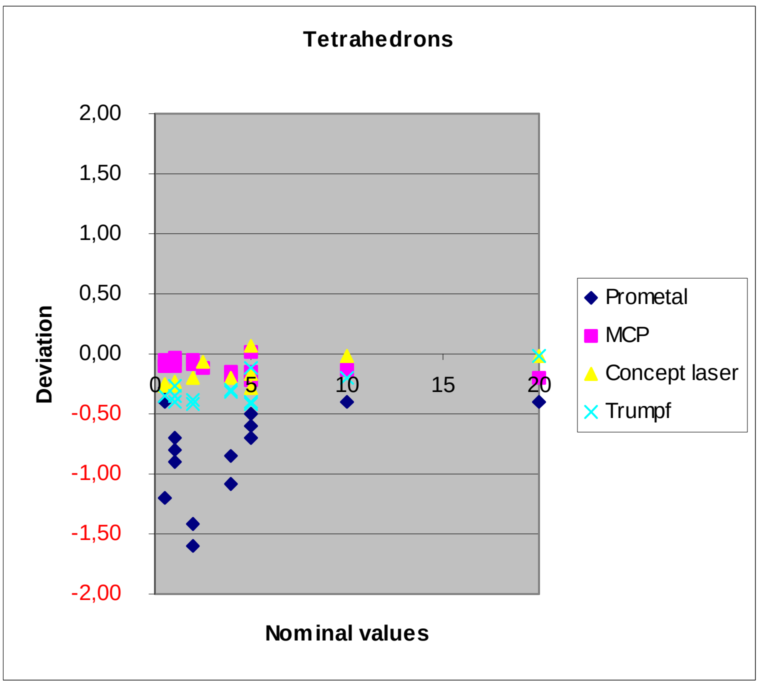


Figure 32 Main dimensions

Nominal Values		ProMetal		MCP		Concept Laser		Trumpf	
A	**100**	99,60	0,40	100,04	-0,04	99,99	0,01	99,68	0,32
B	**60**	59,89	0,11	60,06	-0,06	60,09	-0,09	61,40	-1,40
C	**81**	80,91	0,09	80,23	0,77	80,99	0,01	80,13	0,87
D	**25**	25,40	-0,40	24,71	0,29	25,04	-0,04	24,92	0,08
E	**10**	10,27	-0,27	9,90	0,10			10,10	-0,10
F	**5**	5,25	-0,25	5,20	-0,20			5,32	-0,32



Tetrahedrons



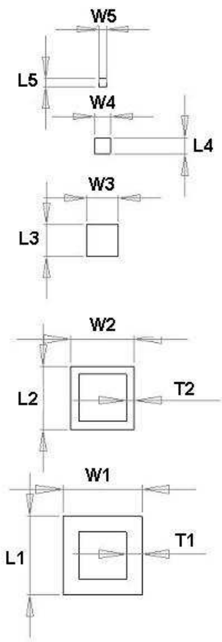
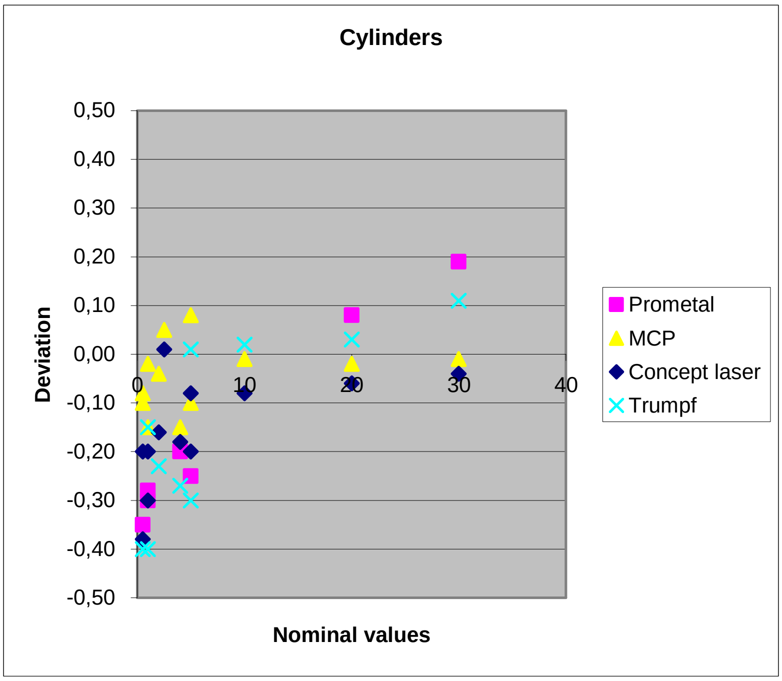


Figure 33 Tetrahedrons

Nominal Values		ProMetal		MCP		Concept laser		Trumpf	
L1	**5**	5,60	-0,60	5,21	-0,21	5,17	-0,17	5,40	-0,40
W1	**5**	5,70	-0,70	5,15	-0,15	5,28	-0,28	5,42	-0,42
T1	**1**	1,80	-0,80	1,10	-0,10	1,27	-0,27	1,40	-0,40
I1	**30**	29,80	0,20	30,12	-0,12	29,96	0,04	30,17	-0,17
L2	**4**	5,08	-1,08	4,18	-0,18	4,20	-0,20	4,32	-0,32
W2	**4**	4,85	-0,85	4,15	-0,15	4,20	-0,20	4,30	-0,30
T2	**1**	1,70	-1,20	0,60	-0,10	0,75	-0,25	0,85	-0,35
I2	**20**	20,40	-0,40	20,20	-0,20	20,01	-0,01	20,01	-0,01
L3	**2**	3,41	-1,41	2,08	-0,08	2,20	-0,20	2,41	-0,41
W3	**2**	3,60	-1,60	2,05	-0,05	2,20	-0,20	2,39	-0,39
I3	**10**	10,40	-0,40	10,14	-0,14	10,01	-0,01	10,20	-0,20
L4	**1**	1,70	-0,70	1,05	-0,05	1,23	-0,23	1,35	-0,35
W4	**1**	1,90	-0,90	1,04	-0,04	1,25	-0,25	1,27	-0,27
I4	**5**	5,50	-0,50	4,98	0,02	4,94	0,06	5,12	-0,12
L5	**1**	0,90	-0,40	0,60	-0,10	0,77	-0,27		
W5	**1**	0,78	-0,28	0,55	-0,05	0,77	-0,27		
I5	**3**	2,60	-0,10	2,62	-0,12	2,56	-0,06		

Cylinders



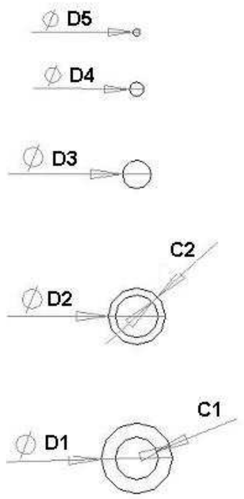


Figure 34 Cylinders

Nominal Values		ProMetal		MCP		Concept laser		Trumpf	
D1	5	5,25	-0,25	5,10	-0,10	5,20	-0,20	5,30	-0,30
C1	1	1,30	-0,30	1,15	-0,15	1,30	-0,30	1,40	-0,40
H1	30	29,81	0,19	30,01	-0,01	30,04	-0,04	29,89	0,11
D2	4	4,20	-0,20	4,15	-0,15	4,18	-0,18	4,27	-0,27
C2	0,5	0,85	-0,35	0,60	-0,10	0,88	-0,38	0,90	-0,40
H2	20	19,92	0,08	20,02	-0,02	20,06	-0,06	19,97	0,03
D3	2			2,04	-0,04	2,16	-0,16	2,23	-0,23
H3	10			10,01	-0,01	10,08	-0,08	9,98	0,02
D4	1	1,28	-0,28	1,02	-0,02	1,20	-0,20	1,15	-0,15
H4	5			4,92	0,08	5,08	-0,08	4,99	0,01
D5	0,5			0,58	-0,08	0,70	-0,20		
H5	2,5			2,45	0,05	2,49	0,01		

Angles

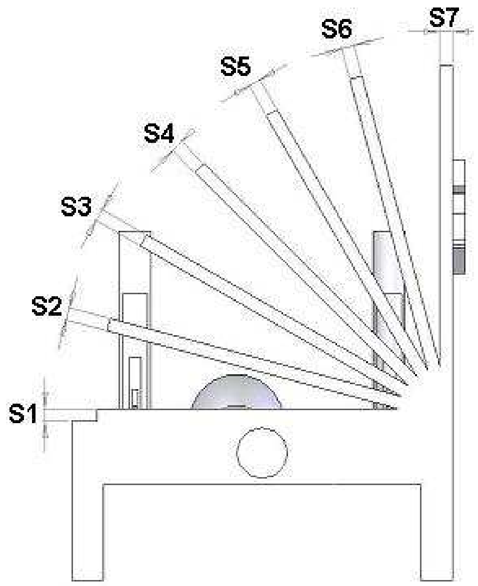
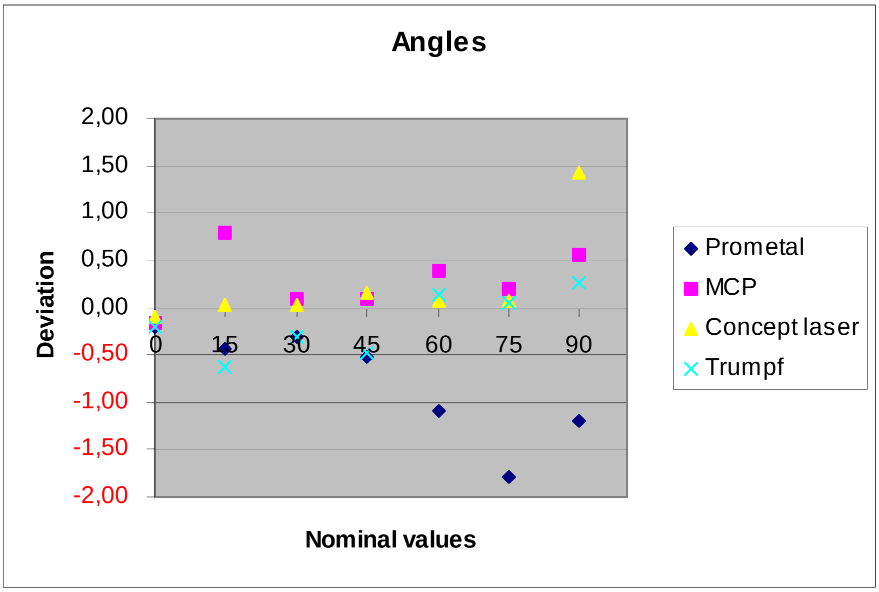
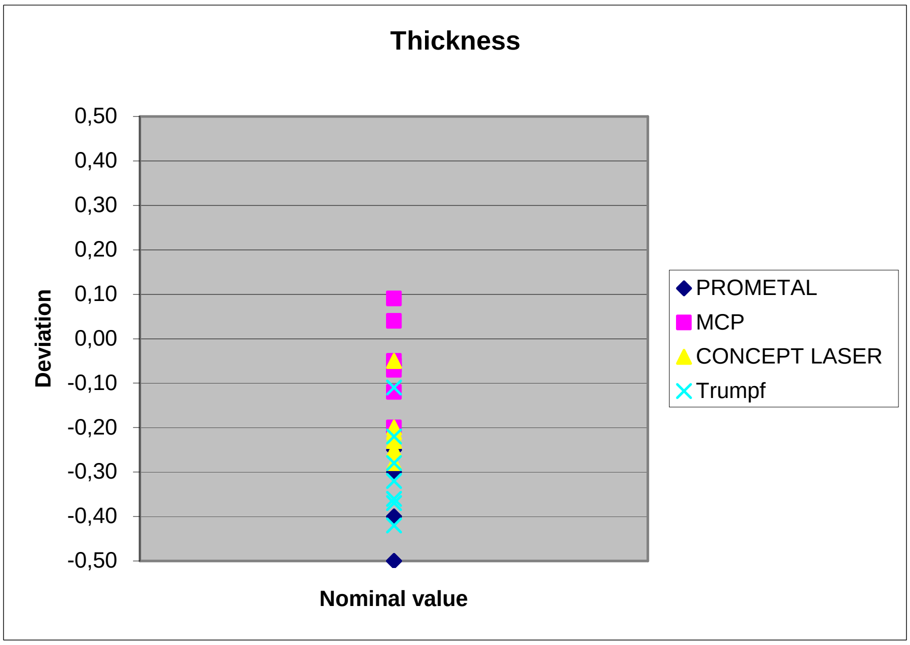


Figure 35 Angles

Nominal Values		ProMetal		MCP		Concept Laser		Trumpf	
A1	0	0,21	-0,21	0,16	-0,16	0,09	-0,09	0,21	-0,21
A2	15	15,44	-0,44	14,20	0,80	14,97	0,03	15,62	-0,62
A3	30	30,31	-0,31	29,90	0,10	29,97	0,03	30,3	-0,30
A4	45	45,51	-0,51	44,90	0,10	44,85	0,15	45,47	-0,47
A5	60	61,09	-1,09	59,60	0,40	59,93	0,07	59,87	0,13
A6	75	76,79	-1,79	74,80	0,20	74,93	0,07	74,95	0,05
A7	90	91,19	-1,19	89,43	0,57	88,58	1,42	89,73	0,27

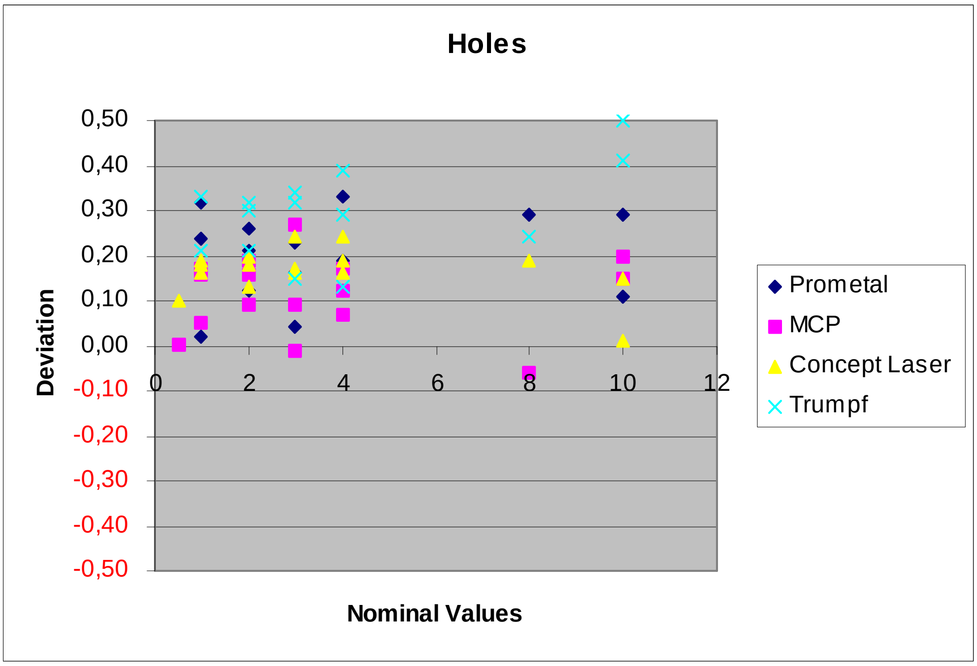


Thickness



Nominal Values		PROMETAL		MCP		CONCEPT LASER		Trumpf	
S1	2	2,06	-0,06	1,96	0,04	2,05	-0,05	2,11	-0,11
S2	2	2,5	-0,50	1,91	0,09	2,2	-0,20	2,32	-0,32
S3	2	2,4	-0,40	2,2	-0,20	2,28	-0,28	2,42	-0,42
S4	2	2,5	-0,50	2,12	-0,12	2,25	-0,25	2,22	-0,22
S5	2	2,4	-0,40	2,07	-0,07	2,21	-0,21	2,28	-0,28
S6	2	2,3	-0,30	2,06	-0,06	2,23	-0,23	2,36	-0,36
S7	2	2,25	-0,25	2,05	-0,05	2,22	-0,22	2,37	-0,37

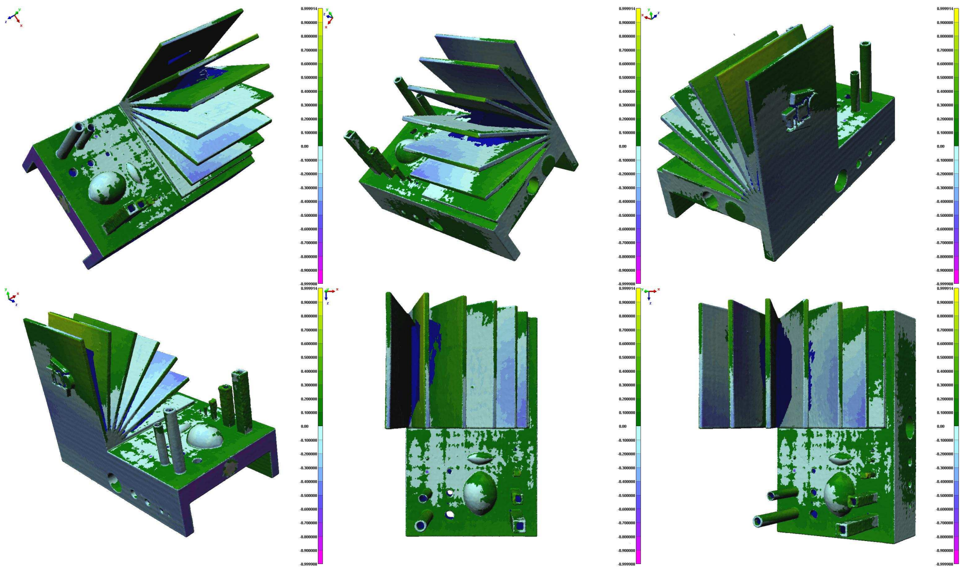
Holes



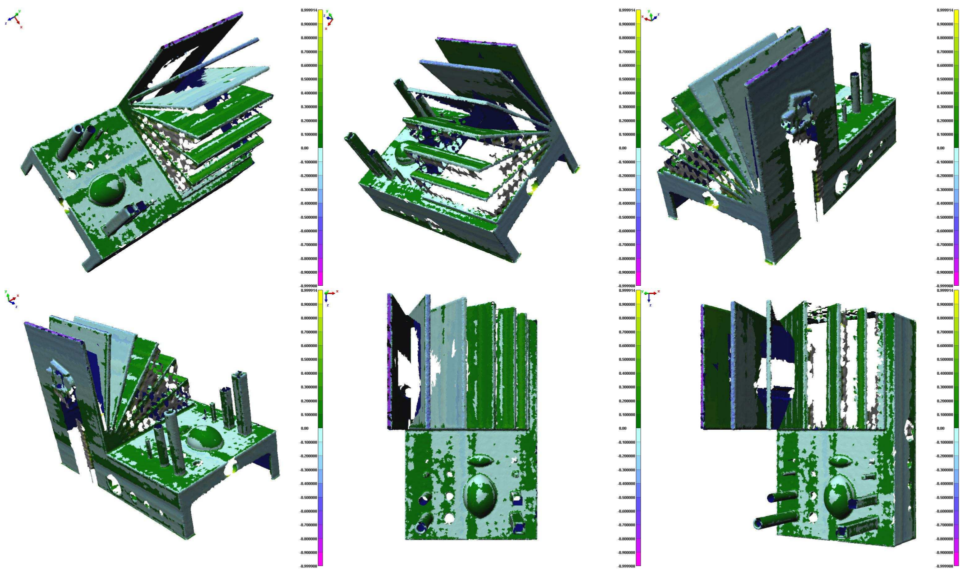
Holes	Nominal Values		ProMetal		MCP		Concept Laser		Trumpf	
XY (top)	**B1**	4	3,81	0,19	3,83	0,17	3,84	0,16	3,87	0,13
	B2	3	2,77	0,23	2,91	0,09	2,828	0,17	2,85	0,15
	B3	2	1,74	0,26	1,91	0,09	1,869	0,13	1,68	0,32
	B4	1	0,76	0,24	0,949	0,05	0,836	0,16		
	B5	0,5			0,498	0,00	0,4	0,10		
YZ (right)	**R1**	10	9,89	0,11	9,85	0,15	9,987	0,01	9,5	0,50
	R2	4	3,88	0,12	3,93	0,07	3,81	0,19	3,61	0,39
	R3	3	2,96	0,04	2,73	0,27	2,76	0,24	2,66	0,34
	R4	2	1,88	0,12	1,84	0,16	1,8	0,20	1,7	0,30
	R5	1	0,98	0,02	0,83	0,17	0,81	0,19	0,67	0,33
YZ (left)	**E1**	10	9,71	0,29	9,8	0,20	9,85	0,15	9,59	0,41
	E2	4	3,67	0,33	3,88	0,12	3,76	0,24	3,71	0,29
	E3	3	2,84	0,16	3,01	-0,01	2,84	0,16	2,68	0,32
	E4	2	1,79	0,21	1,81	0,19	1,82	0,18	1,79	0,21
	E5	1	0,68	0,32	0,84	0,16	0,82	0,18	0,79	0,21
XZ	**F1**	8	7,71	0,29	8,06	-0,06	7,81	0,19	7,76	0,24

Scan accuracy results

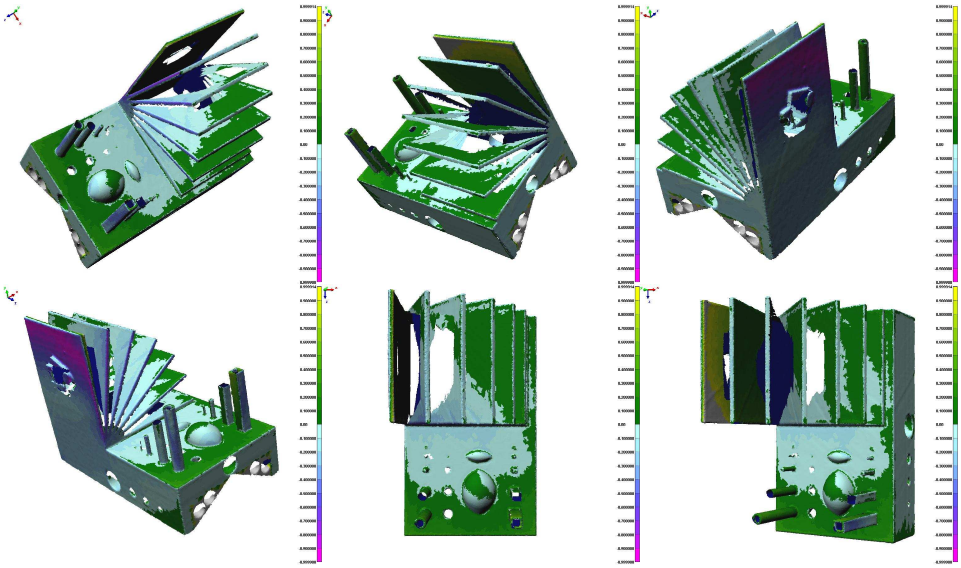
ProMetal



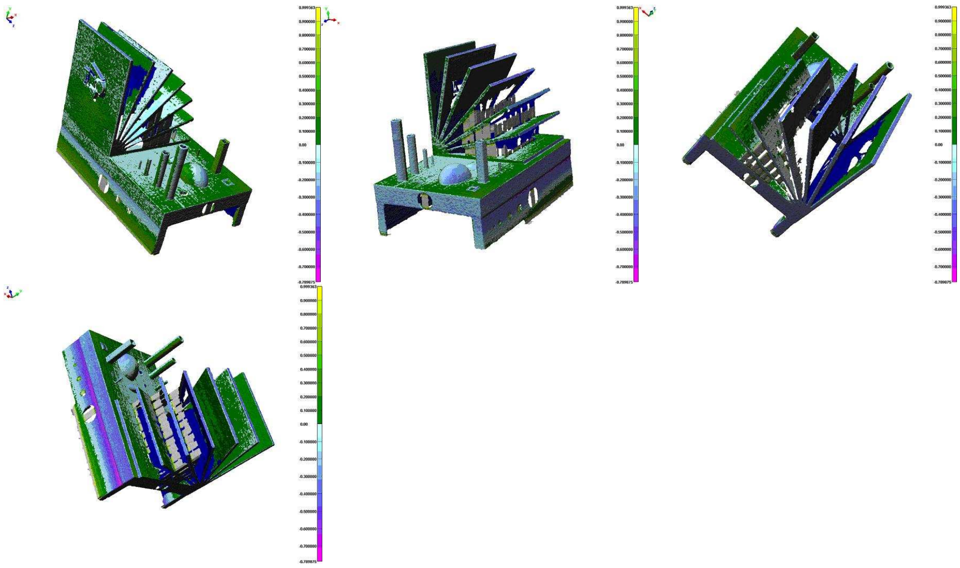
MCP



Concept Laser



Trumpf:



Average and standard deviation

	ProMetal	MCP	Concept Laser	Trumpf
Average Deviation	0,44	0,14	0,16	0,30
Standard Deviation	0,39	0,15	0,18	0,21

4.3 Building time

Building time was considered as the total amount of machine hours and secondary operations but no finishing processes. Time required to remove supports and part from the building platform has not been considered.

Following values were provided by companies and have not been checked by the technicians of the project.

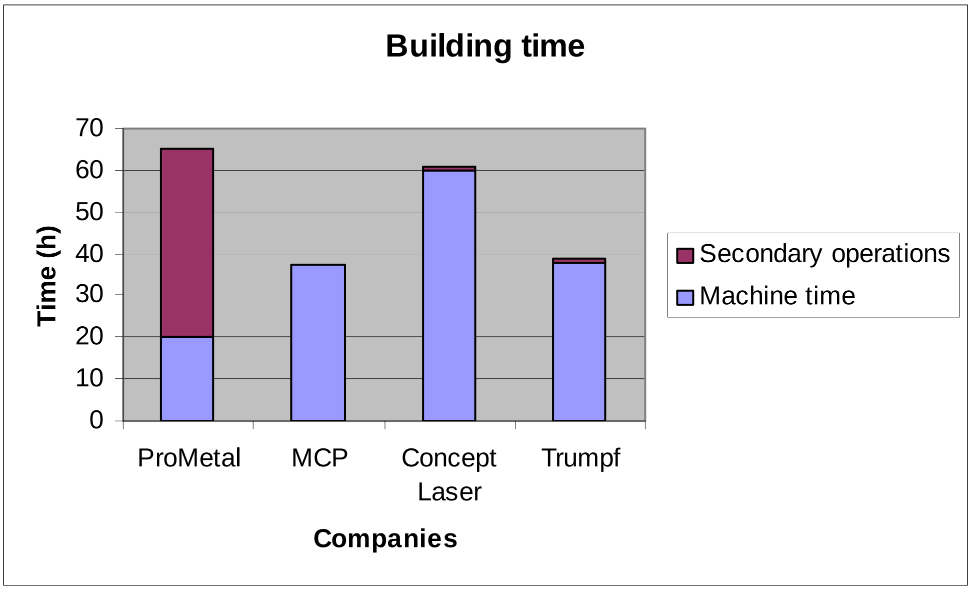


Figure 36 Building time

4.4 Mechanical properties

Hardness test

Hardness Vickers test was made according to UNE EN ISO 6507-1/98

Equipment used was durometer: Wolper V-Testor 2 con I_0= 8.2 HV 5

Tensile test

According to the standard ISO 6892, specimens were prepared from cutting some of the book's sheets of the part, with the following dimensions.

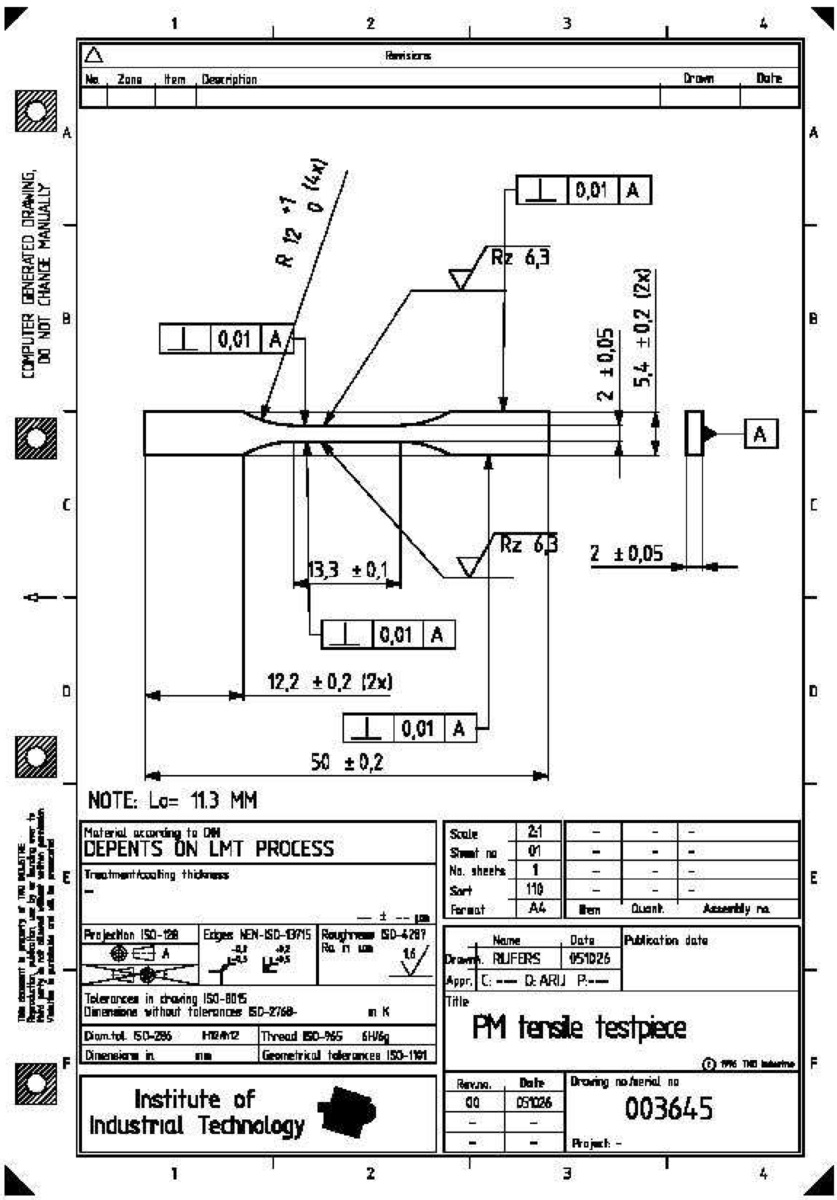


Figure 37 Tensile test piece drawing

Steel Alloy										
Technology	**Company**	**Alloy Name**	**Similar to commercial alloy:**	**Hardness (Vickers)**	**Conversion to Hardness (Rockwell C)**	**Material data Sheet Hardness**	**Tensile strength (MPa)**	**Material Data Sheet Tensile strength (MPa)**	**Elongation at Break**	**Material Data Sheet Elongation at Break**
Laser Cusing	Concept Laser	CL 20ES	AISI 316L Stainless Steel / DIN 1,4404	232,6	19,54 (HRC)	20 (HRC)	648,76	650	30,52	25
Selective Laser Melting	MCP	AISI 316L Stainless Steel / DIN 1,4404		212,4		237 (Vickers)	626,82	627	20,84	24
3D Printing	ProMetal	Stainless steel + bronze	AISI 420 Stainless steel / DIN 1.4021	256,8	23,25 (HRC)	25-30 (HRC)	358,73	682	0,56	2,3

Titanium Alloy										
Technology	**Company**	**Alloy Name**	**Similar to commercial alloy:**	**Hardness (Vickers)**		**Material data Sheet Hardness**	**Tensile strength (MPa)**	**Material Data Sheet Tensile strength (MPa)**	**Elongation at Break**	**Material Data Sheet Elongation at Break**
Laser Forming	Trumpf	TiAl 6 V4		415,6		420 (Vickers)	1165,42	1080-1090	3,59	5,8-6,2

5 Conclusions

Due to the complex design of the benchmark model, it has been very difficult to find companies, which accepted this building challenge. Therefore the effort of the companies, which have accepted this job, is very appreciated.

In this report has been checked [I5]that it is possible to build complex parts in stainless steel and titanium, and advantages and limitations of the technologies studied can be extended to complex production parts.

Excepted the ProMetal benchmark model built by 3DP printing technique, all models required supports for building. These supports structures are very difficult to be removed, especially in benchmark models built by Trumpf using Laserforming and MCP (Selective Laser Melting technique). In this case, it is also difficult to remove the MCP benchmark model from the platform. Concept Laser benchmark model was built in another orientation and the supports needed were removed by provider. The remaining supports can be machined without difficulty.

Dimensional accuracy was very good in MCP and Concept laser benchmark models with the best average and standard deviation for MCP. However in this model, the Z-bonus effect, which means that holes are not round due to layer construction at Z-axis, and warpage is remarkable. There was also warpage in the Trumpf model. All critical geometries were positive built in MCP and Concept Laser models, and some of them were missing in Trumpf and ProMetal models.

Building time was considered as the total amount of machine hours and secondary operations but no finishing processes. Time required to remove supports and parts from the building platform has not been considered. Building time values were provided by companies and have not been checked by the technicians of the project.

To determine mechanical properties, tensile and hardness test have been performed on building materials. Tensile strength, elongation and hardness obtained have been compared with material data sheets provided by companies, reaching in most cases the expected values.

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