UMONS
Université de Mons

Functionalization of Electron beam melting parts by Machining

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POLYTECH MONS
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Context

- AM ➔ booming field
- Rapid prototyping to production of “real” parts with required mechanical properties
- Electron Beam Melting
- Mechanical applications ➔ contact application

solid-solid (prosthesis)

fluid-solid (turbomachine)

Context

- Mechanical applications ➔ contact application
- ➔ from Ra = 25 µm to Ra = 1.6 -> 0.1 µm
- ➔ traditional machining
  - Dimension of the rough part (machining allowance)
- mass production
  - Capability analysis
  - Repeatability
  - Etc.

Goals

- Functionality of parts build by EBM process
- Finishing: traditional machining

➔ determination of the optimal cutting conditions

- Finished parts: geometrical and dimensional tolerances ➔ **Process capability** ➔ lack in the literrature

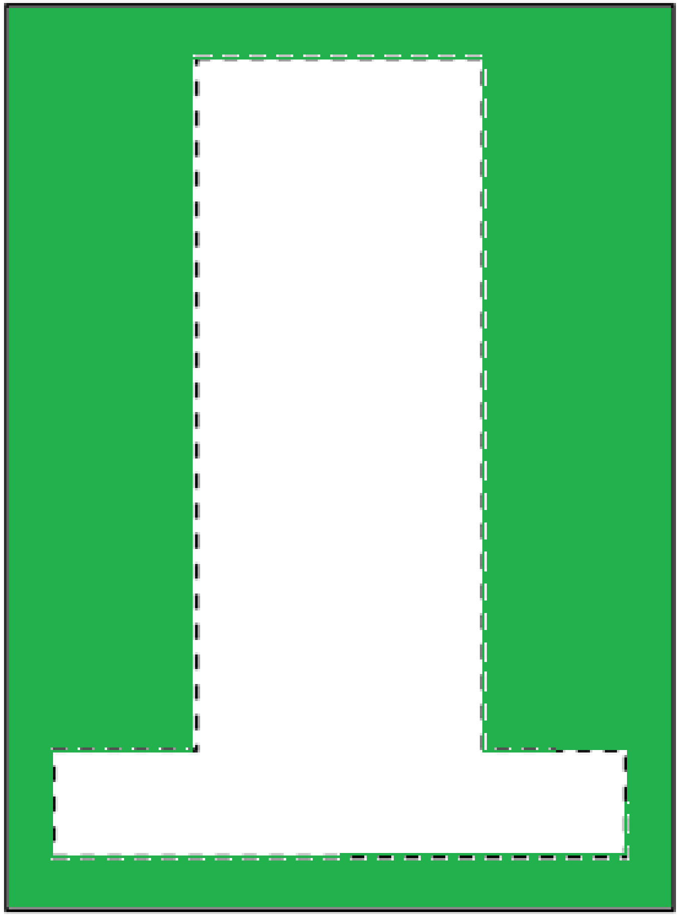
- EBM Process : Process characterization (metrological analysis) Definition of machining allowance

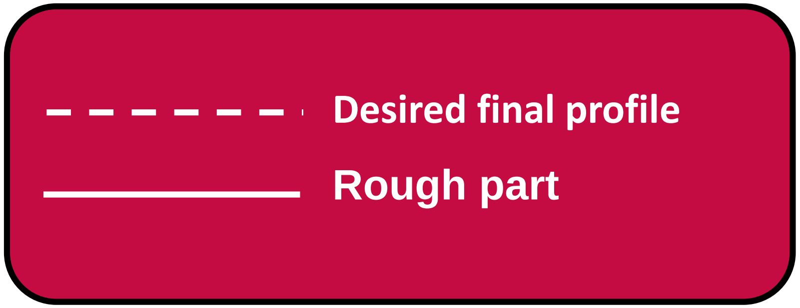
- Mechanical behavior of parts before and after finishing operation
  - Residual stresses
  - Static behavior
  - Etc.

Goals

Conventional machining

Traditional raw material





- Machining from a rough part
  - A lot of waste
  + Sure to be in the desired tolerances

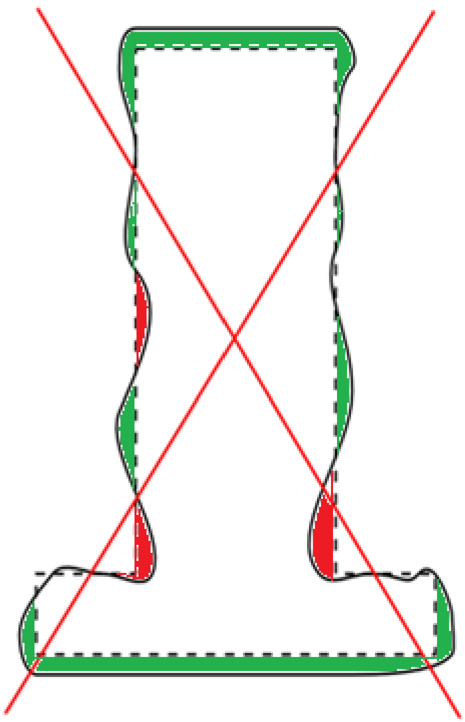
Goals

Conventional machining

EBM raw material

Desired final profile

Rough part

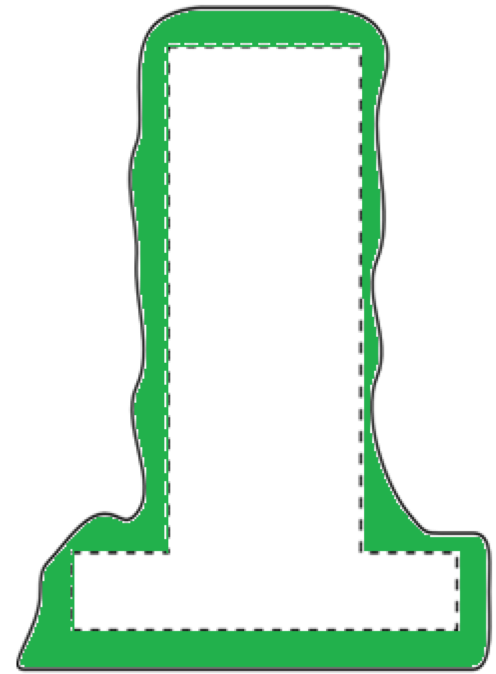


NOK

- Machining from an EBM rough part

  + Less waste produced
  + Reduction of the machining time
  – Not sure to be in the desired tolerances

➔ Need to better control the process



OK

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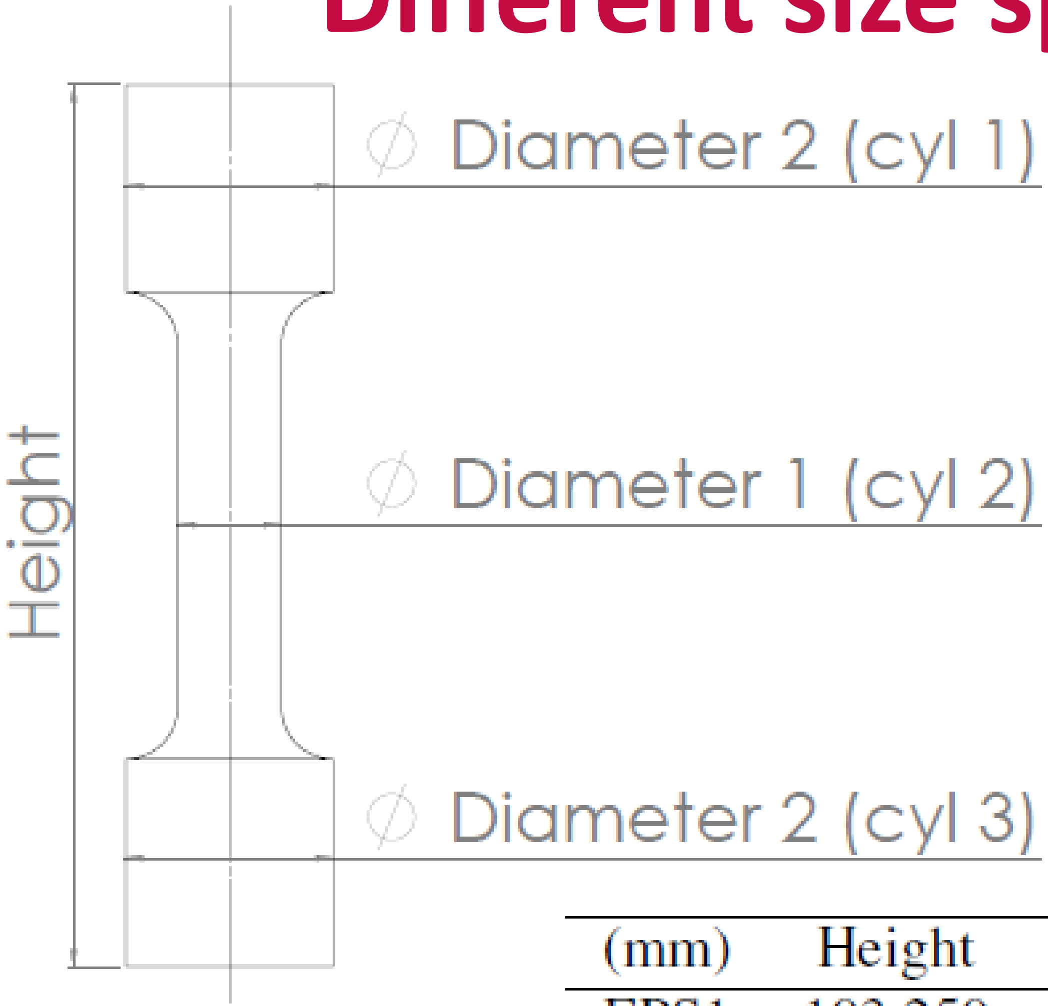
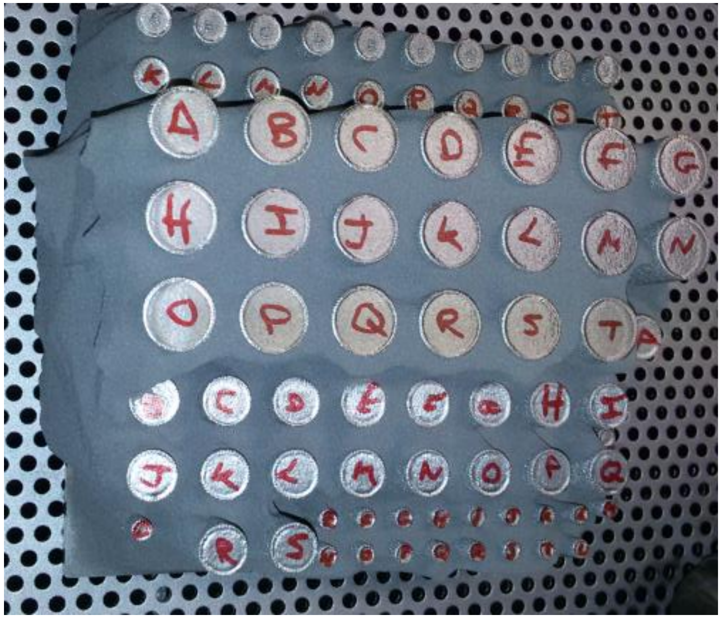
Outline

1. Process characterization
    1. Dimensional characterization
    2. Capability analysis
    3. Surface characterization
2. Machinability of EBM Samples
3. Residual stresses analysis (in progress)

Process Characterization

Different size specimens





(mm)	Height	Diameter 2	Diameter 1
EPS1	103.250	21.070	9.656
EPS2	81.949	15.405	7.059
EPS3	60.858	11.999	5.499
EPS4	54.934	6.905	3.165

Metrology

Macro

- Determination of the dimension

- Measuring equipment :

CMM Wenzel LH 54

- Precision:

U1 (µm) = 3 + L/300

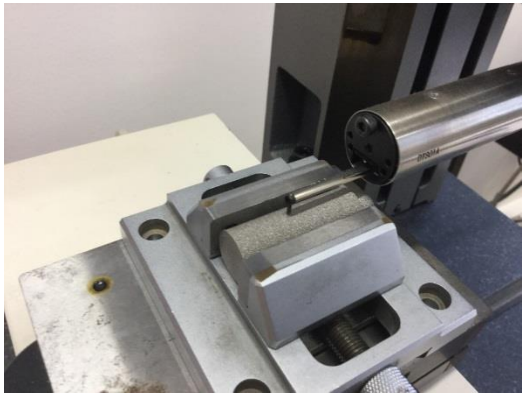
U3 (µm) = 3,5 + L/300

Micro

- Characterization of the surface finish

- Measuring equipment :

SURFCOM 1400D-3DF



Dimensional Characterization

		Number of parts	Target value (mm)	Systematic error (mm)	σ (mm)
EPS 1	Length	20	103.250	-0.088	0.124
	cyl1	20	21.070	+0.087	0.104
	cyl2	20	9.656	+0.055	0.122
	cyl3	20	21.070	+0.008	0.067
EPS 2	Length	19	81.949	- 0.568	0.114
	cyl1	19	15.405	+ 0.060	0.055
	cyl2	19	7.059	+0.099	0.089
	cyl3	19	15.405	+0.037	0.068
EPS 3	Length	13	60.858	-0.502	0.075
	cyl1	13	11.999	+0.108	0.083
	cyl2	13	5.498	+0.017	0.024
	cyl3	13	11.999	+0.107	0.094
EPS 4	Length	11	54.934	-0.054	0.105
	cyl1	11	6.905	+0.031	0.059
	cyl2	11	3.165	+0.118	0.130
	cyl3	11	6.905	+0.016	0.081

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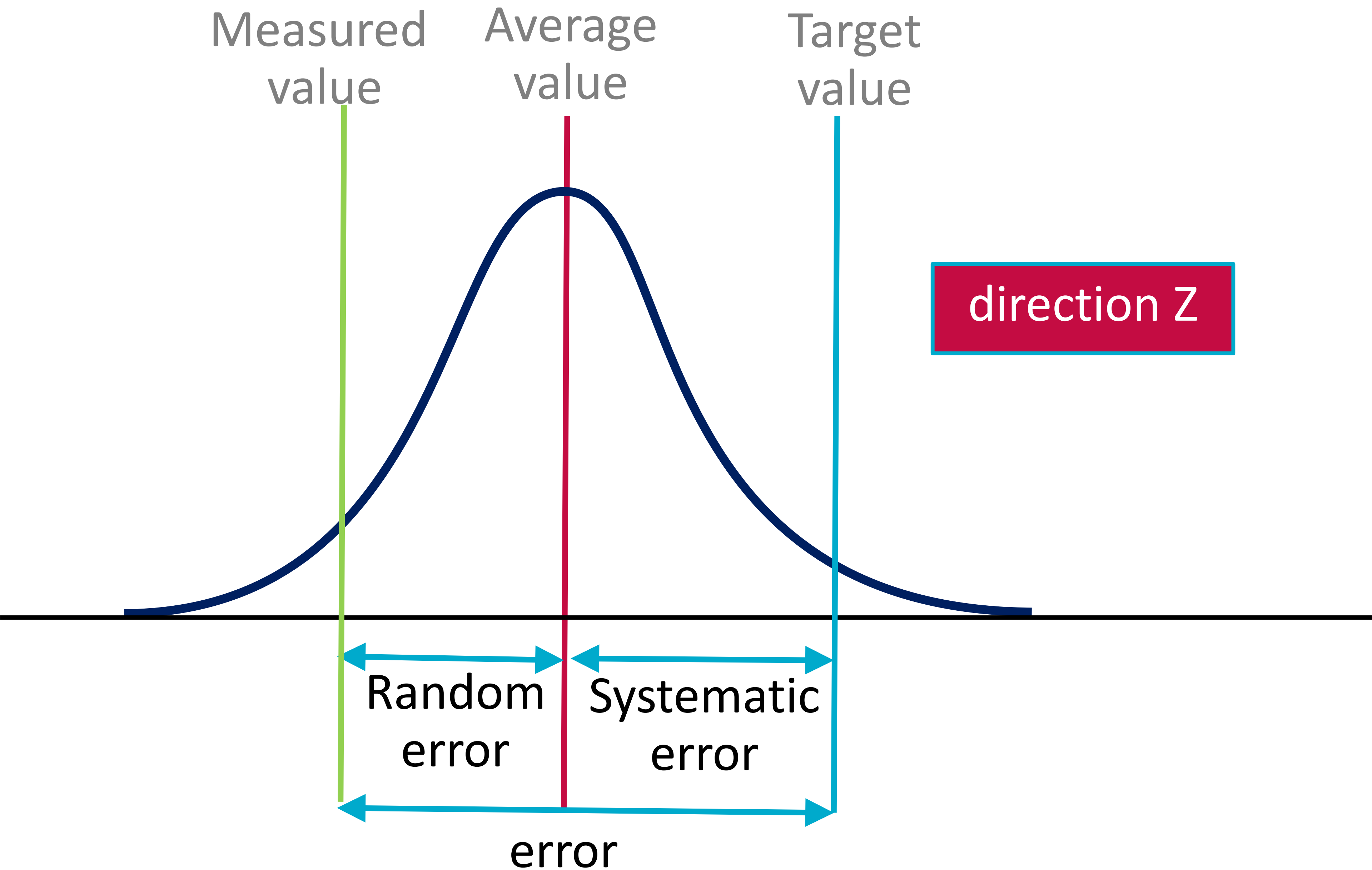
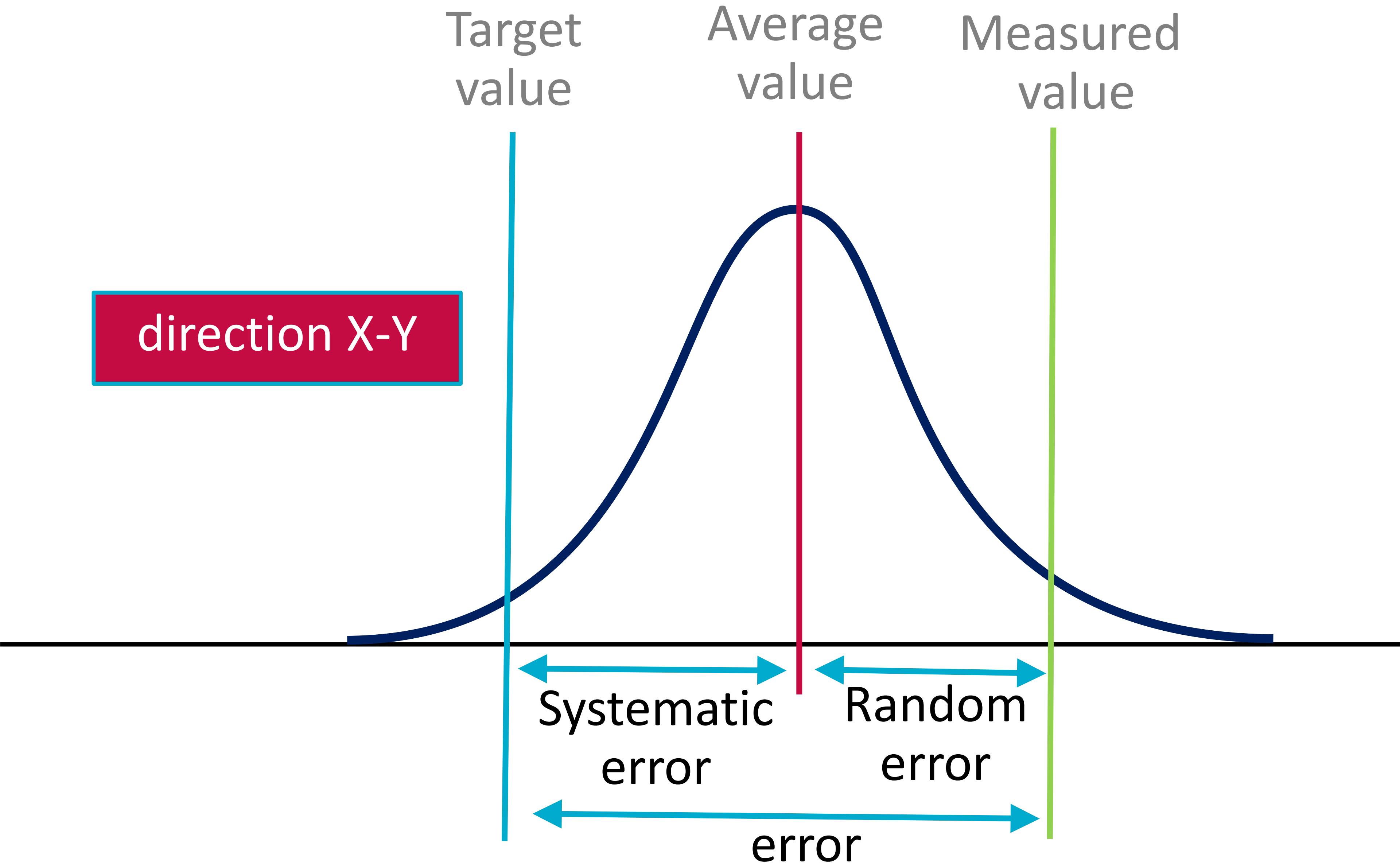


Dimensional Characterization



Capability Analysis

- Capability Analysis
- ➔"Long term performance level of a process after it has been brought under statistical control. It is the ability to produce a product that will consistency meet the design requirement and customer expectation"
- The capability is linked to Upper Specification Limit (USL) and Lower Specification Limit (LSL)

Capability Analysis

Dimension Nominale mm		Degrés de tolérance normalisés																	
		IT1	IT2	IT3	IT4	IT5	IT6	IT7	IT8	IT9	IT10	IT11	IT12	IT13	IT14	IT15	IT16	IT17	IT18
Au-dessus de	Jusqu'à et y compris	Tolérances µm											Tolérances mm						
-	3	0,8	1,2	2	3	4	6	10	14	25	40	60	0,1	0,14	0,25	0,4	0,6	1	1,4
3	6	1	1,5	2,5	4	5	8	12	18	30	48	75	0,12	0,18	0,3	0,48	0,75	1,2	1,8
6	10	1	1,5	2,5	4	6	9	15	22	36	58	90	0,15	0,22	0,36	0,58	0,9	1,5	2,2
10	18	1,2	2	3	5	8	11	18	27	43	70	110	0,18	0,27	0,43	0,7	1,1	1,8	2,7
18	30	1,5	2,5	4	6	9	13	21	33	52	84	130	0,21	0,33	0,52	0,84	1,3	2,1	3,3
30	50	1,5	2,5	4	7	11	16	25	39	62	100	160	0,25	0,39	0,62	1	1,6	2,5	3,9
50	80	2	3	5	8	13	19	30	46	74	120	190	0,3	0,46	0,74	1,2	1,9	3	4,6
80	120	2,5	4	6	10	15	22	35	54	87	140	220	0,35	0,54	0,87	1,4	2,2	3,5	5,4
120	180	3,5	5	8	12	18	25	40	63	100	160	250	0,4	0,63	1	1,6	2,5	4	6,3
180	250	4,5	7	10	14	20	29	46	72	115	185	290	0,46	0,72	1,15	1,85	2,9	4,6	7,2
250	315	6	8	12	16	23	32	52	81	130	210	320	0,52	0,81	1,3	2,1	3,2	5,2	8,1
315	400	7	9	13	18	25	36	57	89	140	230	360	0,57	0,89	1,4	2,3	3,6	5,7	8,9
400	500	8	10	15	20	27	40	63	97	155	250	400	0,63	0,97	1,55	2,5	4	6,3	9,7
500	630	9	11	16	22	32	44	70	110	175	280	440	0,7	1,1	1,75	2,8	4,4	7	11
630	800	10	13	18	25	36	50	80	125	200	320	500	0,8	1,25	2	3,2	5	8	12,5
800	1000	11	15	21	28	40	56	90	140	230	360	560	0,9	1,4	2,3	3,6	5,6	9	14
1000	1250	13	18	24	33	47	66	105	165	260	420	660	1,05	1,65	2,6	4,2	6,6	10,5	16,5
1250	1600	15	21	29	39	55	78	125	195	310	500	780	1,25	1,95	3,1	5	7,8	12,5	19,5
1600	2000	18	25	35	46	65	92	150	230	370	600	920	1,5	2,3	3,7	6	9,2	15	23
2000	2500	22	30	41	55	78	110	175	280	440	400	1100	1,75	2,8	4,4	7	11	17,5	28
2500	3150	26	36	50	68	96	135	210	330	540	860	1350	2,1	3,3	5,4	8,6	13,5	21	33

Cpk Value	Sigma Value	Area under Normal Curve	Non Conforming ppm
0.1	0.3	0.235822715	764177.2851
0.2	0.6	0.451493870	548506.1299
0.3	0.9	0.631879817	368120.1835
0.4	1.2	0.769860537	230139.4634
0.5	1.5	0.866385542	133614.4576
0.6	1.8	0.928139469	71860.531
0.7	2.1	0.964271285	35728.7148
0.8	2.4	0.983604942	16395.0577
0.9	2.7	0.993065954	6934.0461
1.0	3.0	0.997300066	2699.9344
1.1	3.3	0.999033035	966.9651
1.2	3.6	0.999681709	318.2914
1.3	3.9	0.999903769	96.231
1.333	3.999	0.999936360	63.6403
1.4	4.2	0.999973292	26.7082
1.5	4.5	0.999993198	6.8016
1.6	4.8	0.999998411	1.5887
1.666	4.998	0.999999420	0.5802
1.7	5.1	0.999999660	0.3402
1.8	5.4	0.999999933	0.0668
1.9	5.7	0.999999988	0.012
2.0	6.0	0.999999998	0.002

NOK

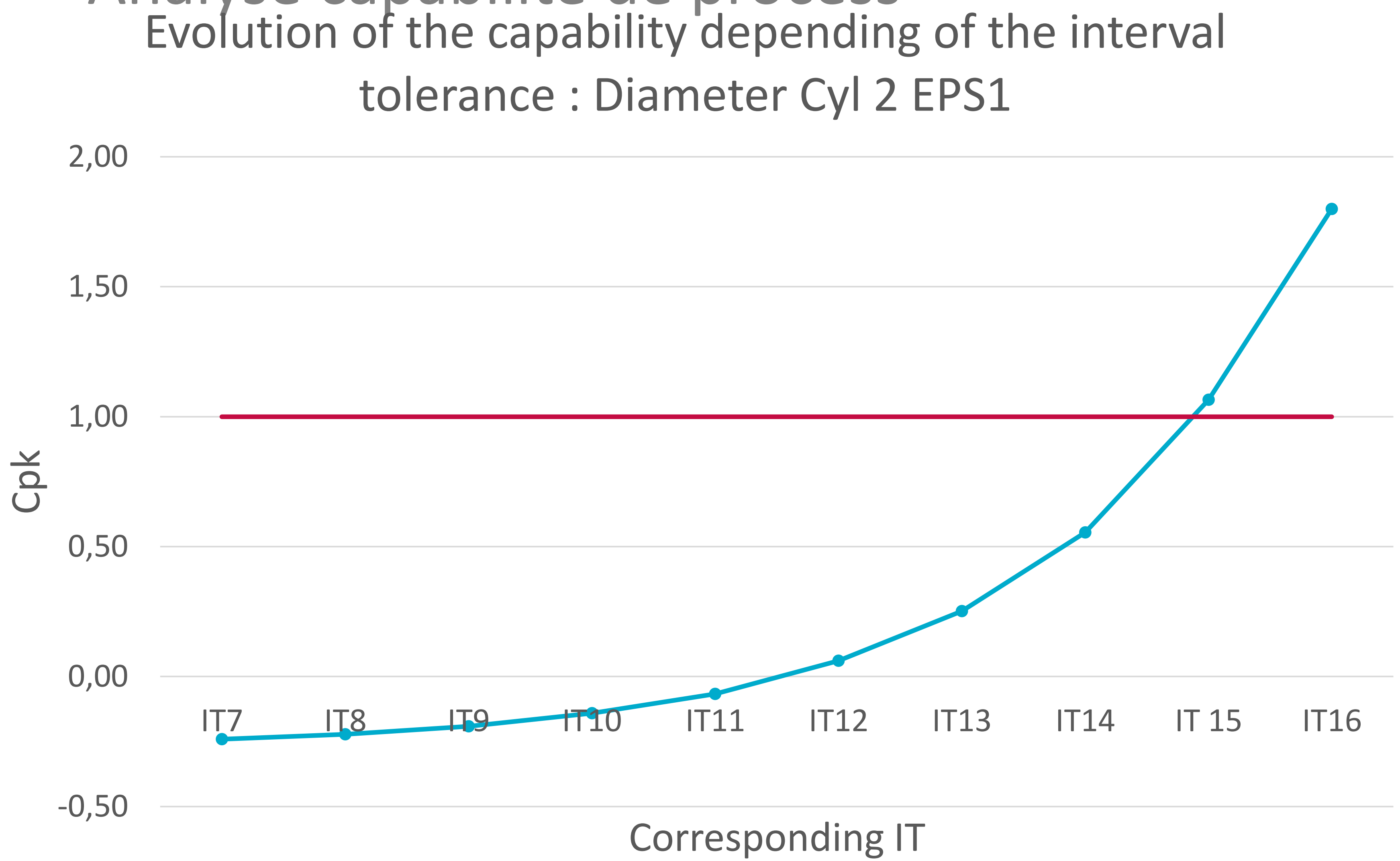
OK

$$C_p = \frac{USL - LSL}{6\sigma}.$$

$$C_{pk} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right)$$

Capability Analysis

- Analyse capabilité de process



Capability Analysis

- Capability analysis of EBM process

C_{pk}		IT11	IT12	IT13	IT14	IT15	IT16	ARCAM
EPS1	Height	0.06	0.23	0.49	0.93	1.64	2.72	0.30
	Cyl2	-0.07	0.06	0.25	0.55	1.07	1.80	0.14
EPS2	Height	-1.39	-1.19	-0.91	-0.41	0.39	1.59	-1.12
	Cyl2	-0.01	0.20	0.47	0.96	1.77	2.98	0.44

- The nearest process is sand casting (IT 11 to 16 and Roughness 6,3 to 50 *Ra*).

➔ Compare with CT class (ISO8062)

Capability Analysis

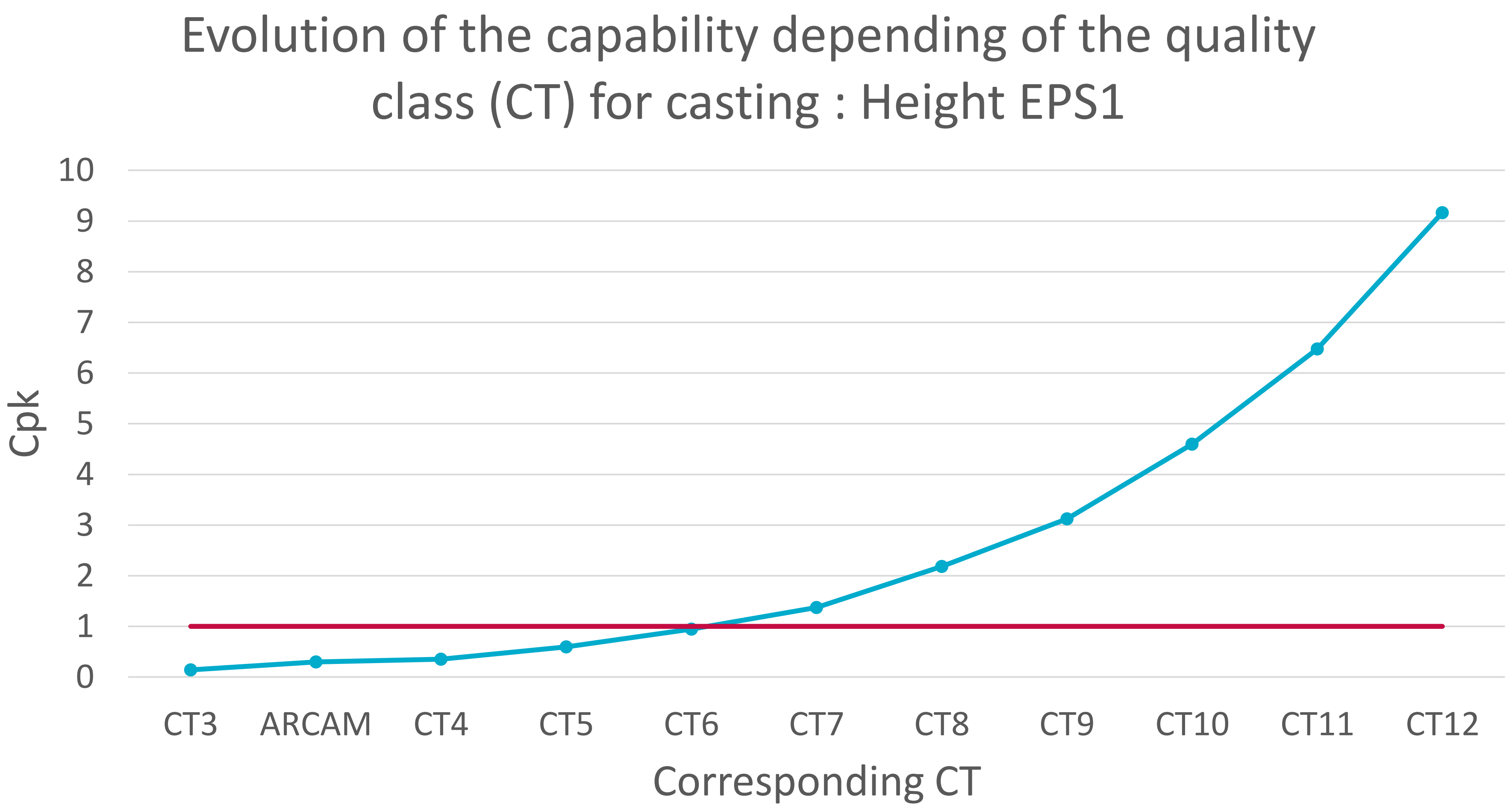
- ISO 8062 Standard (Casting parts)

Tableau 1 — Tolérances des pièces moulées

Cote nominale de la pièce brute mm		Tolérance générale des pièces moulées[1] mm															
		Qualité de tolérance des pièces moulées CT															
au-delà de	jusqu'à inclus	1[2]	2[2]	3	4	5	6	7	8	9	10	11	12	13	14	15	16
—	10			0,18	0,26	0,36	0,52	0,74	1,0	1,5	2,0	2,8	4,2	—	—	—	—
10	16			0,20	0,28	0,38	0,54	0,78	1,1	1,6	2,2	3,0	4,4	—	—	—	—
16	25			0,22	0,30	0,42	0,58	0,82	1,2	1,7	2,4	3,2	4,6	6	8	10	12
25	40			0,24	0,32	0,46	0,64	0,90	1,3	1,8	2,6	3,6	5,0	7	9	11	14
40	63			0,26	0,36	0,50	0,70	1,0	1,4	2,0	2,8	4,0	5,6	8	10	12	16
63	100			0,28	0,40	0,56	0,78	1,1	1,6	2,2	3,2	4,4	6	9	11	14	18
100	160			0,30	0,44	0,62	0,88	1,2	1,8	2,5	3,6	5,0	7	10	12	16	20
160	250			0,34	0,50	0,70	1,0	1,4	2,0	2,8	4,0	5,6	8	11	14	18	22
250	400			0,40	0,56	0,78	1,1	1,6	2,2	3,2	4,4	6,2	9	12	16	20	25
400	630				0,64	0,90	1,2	1,8	2,6	3,6	5	7	10	14	18	22	28
630	1 000					1,0	1,4	2,0	2,8	4,0	6	8	11	16	20	25	32
1 000	1 600						1,6	2,2	3,2	4,6	7	9	13	18	23	29	37
1 600	2 500							2,6	3,8	5,4	8	10	15	21	26	33	42
2 500	4 000								4,4	6,2	9	12	17	24	30	38	49
4 000	6 300									7,0	10	14	20	28	35	44	56
6 300	10 000										11	16	23	32	40	50	64

Capability Analysis

- Analyse capabilité de process



Capability Analysis

- In casting :

Method	Quality of tolerance (CT)								
	Steel	Grey iron	Spheroidal graphite iron	Malleable iron	Copper alloy	Zinc alloy	Light metal alloy	Nickel alloy	Cobalt alloy
Hand Sand Casting	11 to 13	11 to 13	11 to 13	11 to 13	10 to 12		9 to 11		
Automatic Sand Casting	8 to 10	8 to 10	8 to 10	8 to 10	8 to 10		7 to 9		
Permanent and semi-permanent mould castings		7 to 9	7 to 9	7 to 9	7 to 9	7 to 9	6 to 8		
Die Casting					6 to 8	4 to 6	5 to 7		
Investment Casting	4 to 6	4 to 6	4 to 6		4 to 6		4 to 6	4 to 6	4 to 6

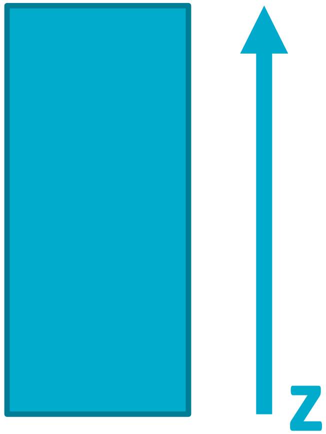
Capability Analysis

- Definition of machining allowance
- In casting : $0.5mm \pm \frac{1}{2} IT$ Standard ISO 8062
- EBM ≈ Casting → IT = 15

$$0.5mm \pm \frac{1}{2} IT$$

Surface Characterization

- Surface Roughness measurement
- Variation of contours parameters (TA-Sirris-UMONS)



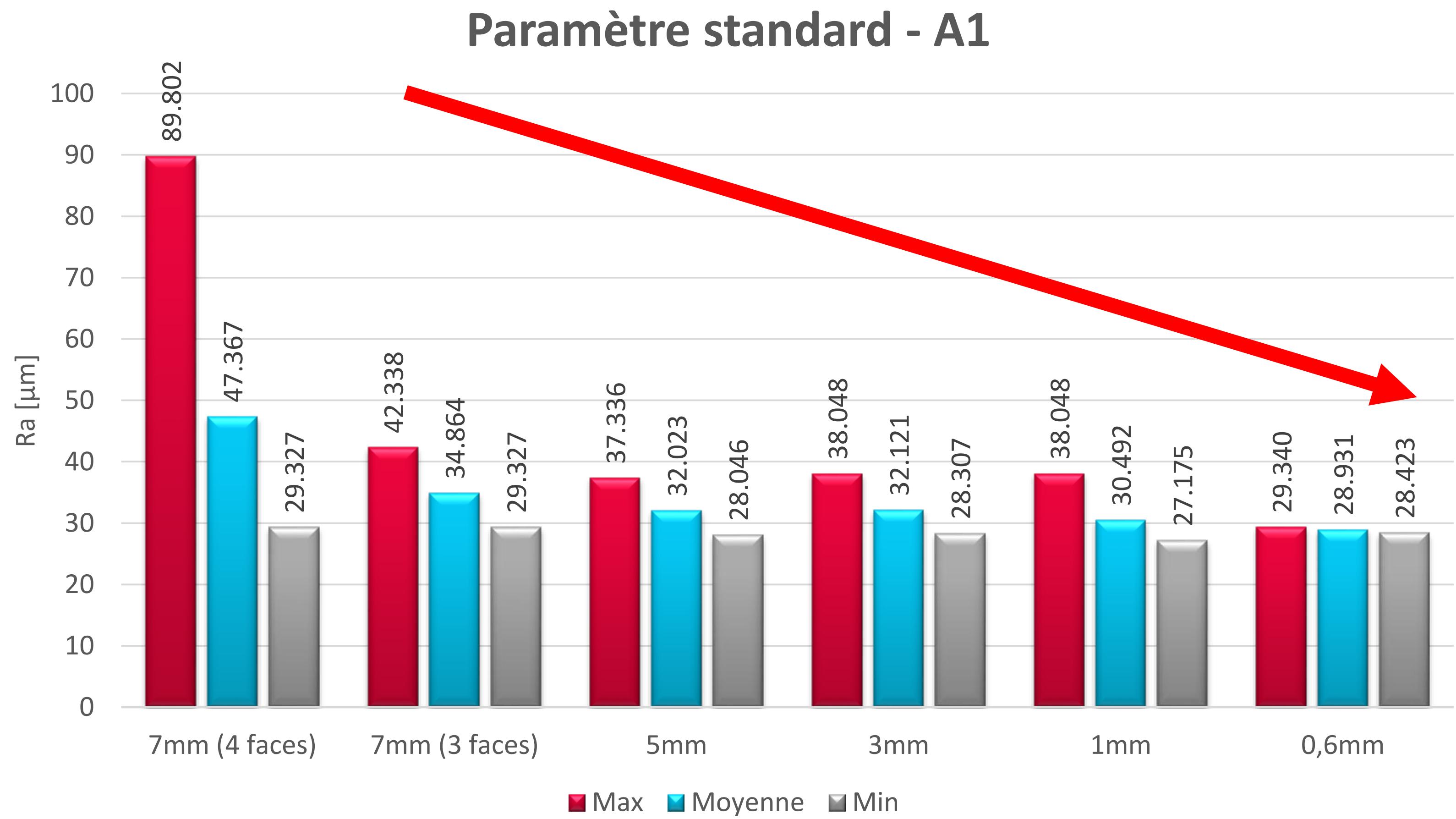
En résumé : plaque verticale 20*64mm variant :

- Épaisseur [mm] : 0,6 – 1- 3 -5 – 7
- 4 thèmes 50 um A2 : A2 50um – …
- Nombre de contours : 2 – 3 – 100
- Ordre des 2 contours / hatch : Outer to Inner – Inner to Outer
- Outer contour speed [mm/s] : 340 – 250 – 175 – 100
- Outer Focus offset [mA] : 0 – 3 – 10 – 15
- Outer current=Maxcurrent [mA] : 3 – 4 – 6 – 8
- Outer spots [#] : 10 – 20 – 40
- Double fusion (outer supplémentaire à la fin)
- Paramètre croisés vu que lié par densité d'énergie :

speed	I=Imax	FO		160202#
250	4	3		B2
250	4	10		D1
250	3	3		C6
250	3	10		C7
250	6	10		D2
175	4	3		B3
175	2	3		D5
175	2	10		D6
175	8	3		D3
175	8	15		D4

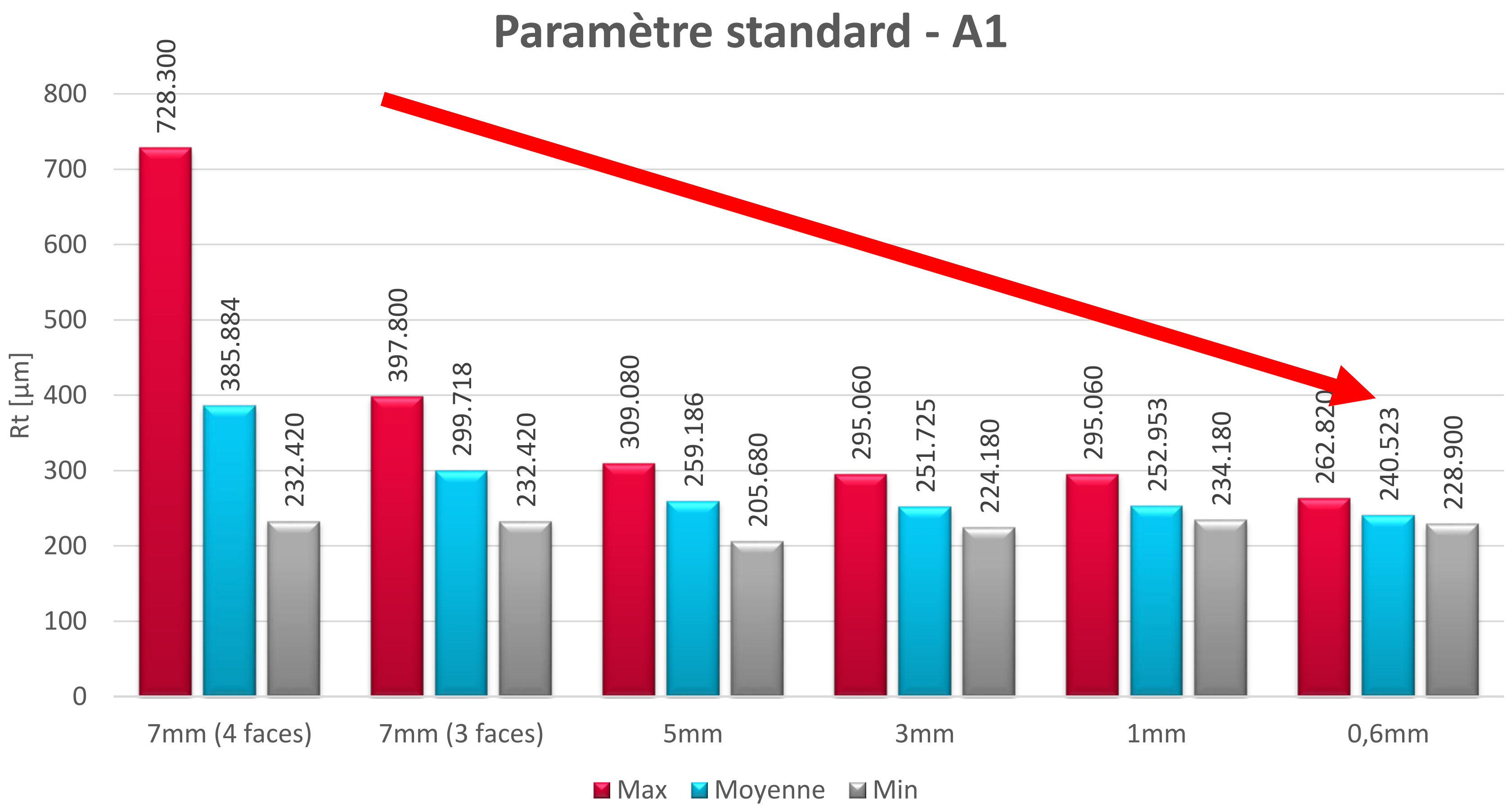
Surface Characterization

- Surface Roughness measurement
- Diminution of Ra with thickness' of the sample



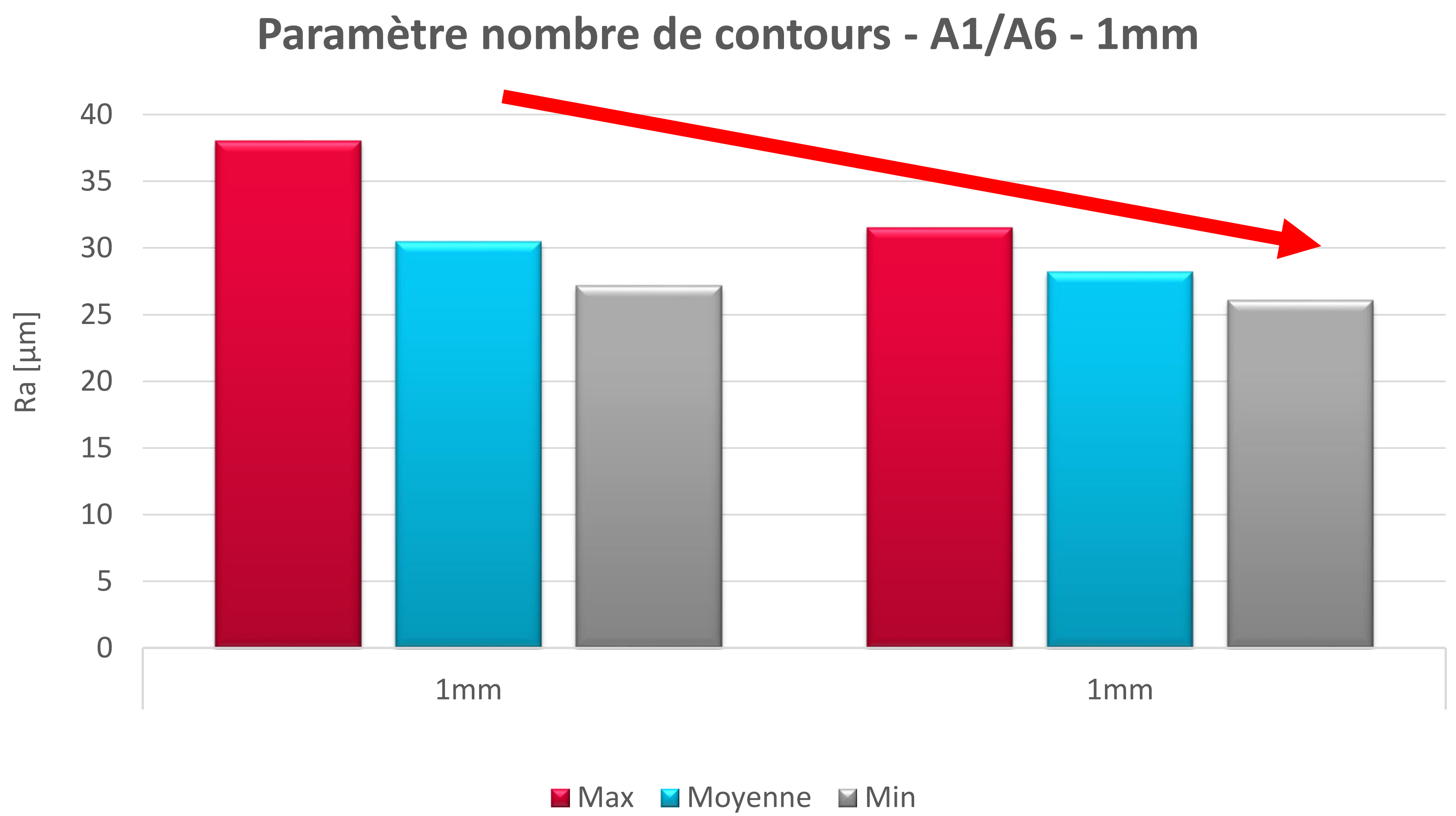
Surface Characterization

- Surface Roughness measurement
- Diminution of Rt with thickness' of the sample



Surface Characterization

- Surface Roughness measurement
- Influence of contour



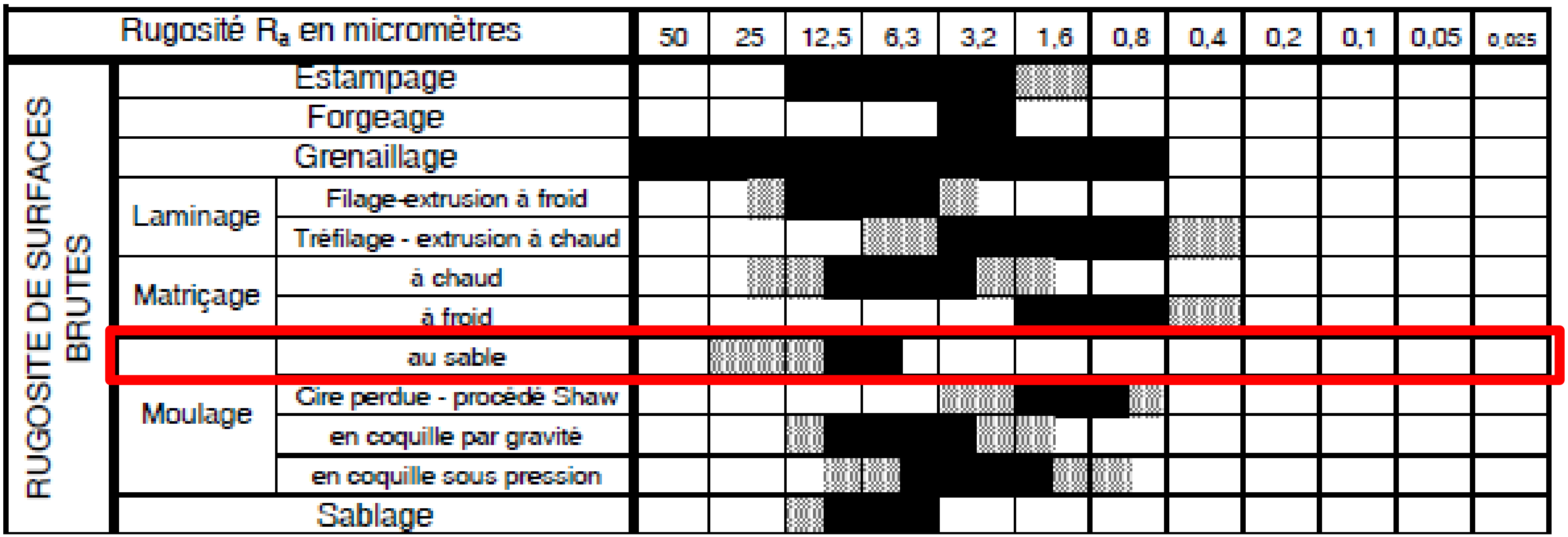
Surface Characterization

- Surface Roughness measurement
- Synthesis :
  - Contour numbers = 100 (A6)
    - 1mm ➔ better than standard (Ra and Rt)
    - 7mm ➔ idem
  - Contour inner to outer (A7)
    - 1mm ➔ better than standard (Ra and Rt)
    - 7mm ➔idem
  - Double fusion
    - Worst than Standard

Surface Characterization

- Surface Roughness measurement
- Ra = 25-35 µm ➔ Near Sand casting!

ETATS DE SURFACES – CAPACITES DES MOYENS DE PRODUCTION



Process Characterization

- Conclusions

Surface characterization

Ra = 30-35 µm

Sand Casting

Dimension characterization

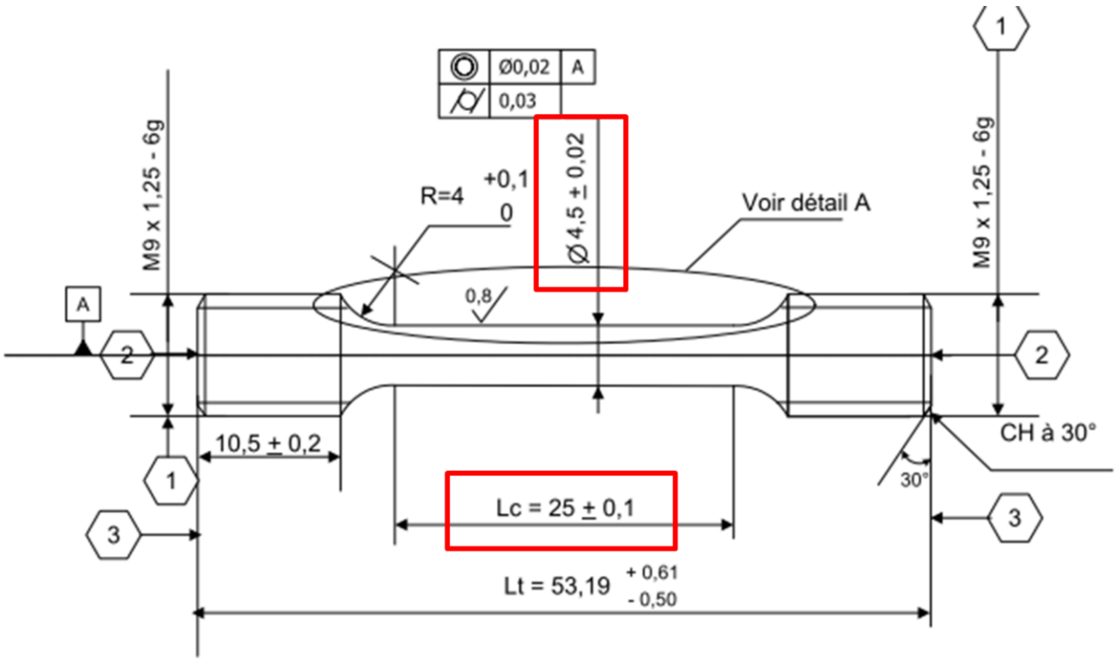
CT = CT7

Die Casting, Investment casting

Machining of EBM Samples

Machining of EBM Samples

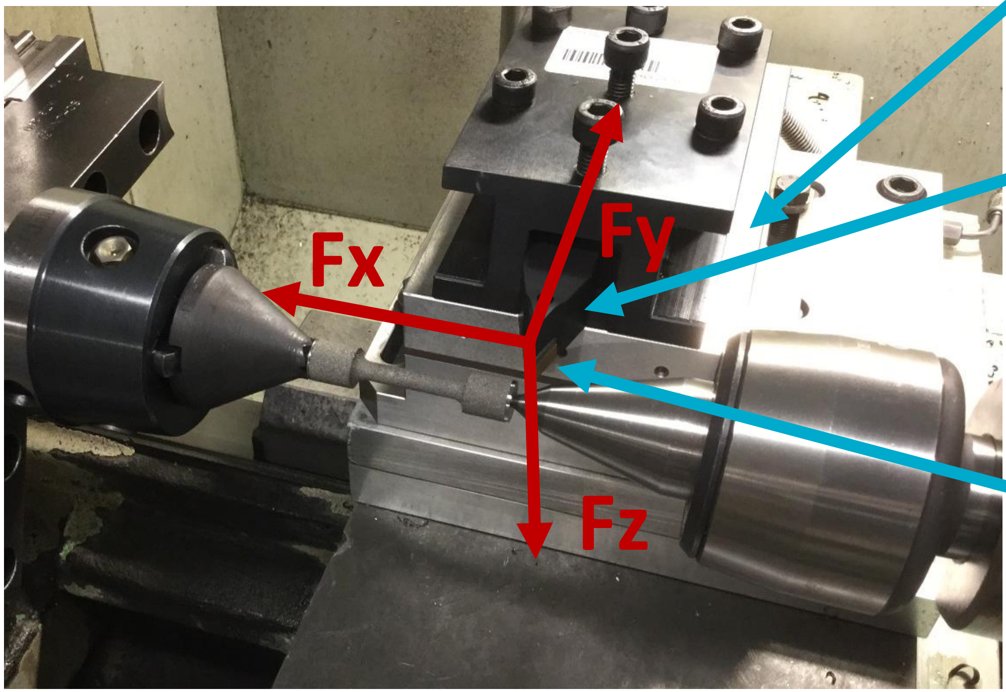
- Sample for tensile test
- ➔cutting forces measurement of Ti EBM + chips analysis



Experimental Setup

Machining Center :

- Weiller E35
- Max spindle speed 3000 RPM
- Spindle power of 11kW



Dynamometer Kistler 9257B

Tools Holder : SVVBN 2020K16

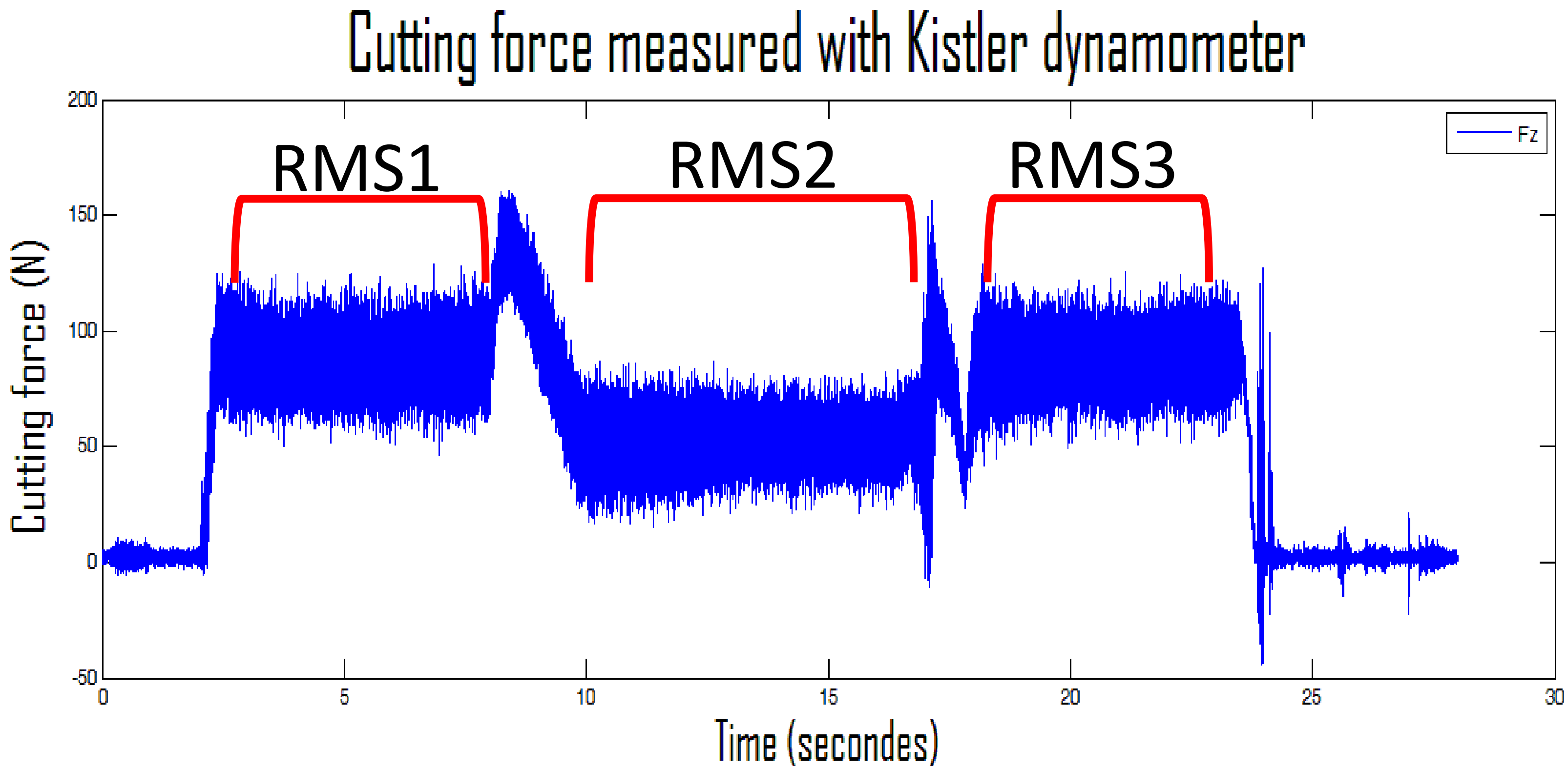
Tools : Cutting insert (VBMT 160404-FM2 (CP500))

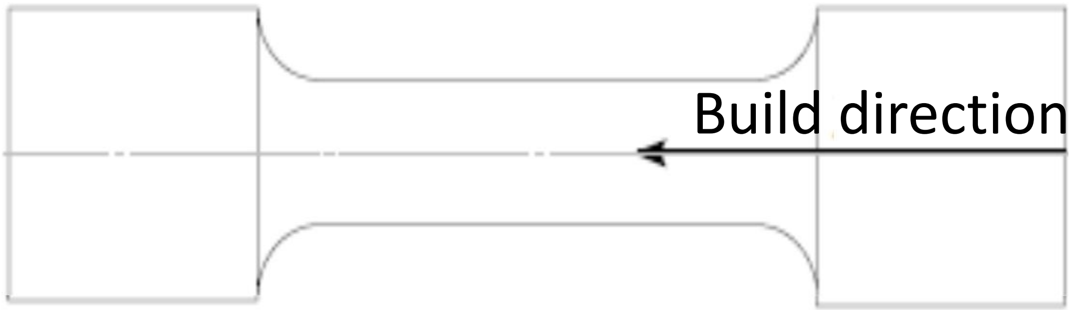
Machining of EBM Samples

- Different size of specimens
- Before and after HIP treatment
- We machined this specimens and measure the cutting force

Machining of EBM Samples

- Measurement





Machining of EBM Samples

- Comparison of the cutting forces between EBM titanium alloy with and without HIP treatment

$$F_{Z\,RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {F_{zi}}^{2}}$$

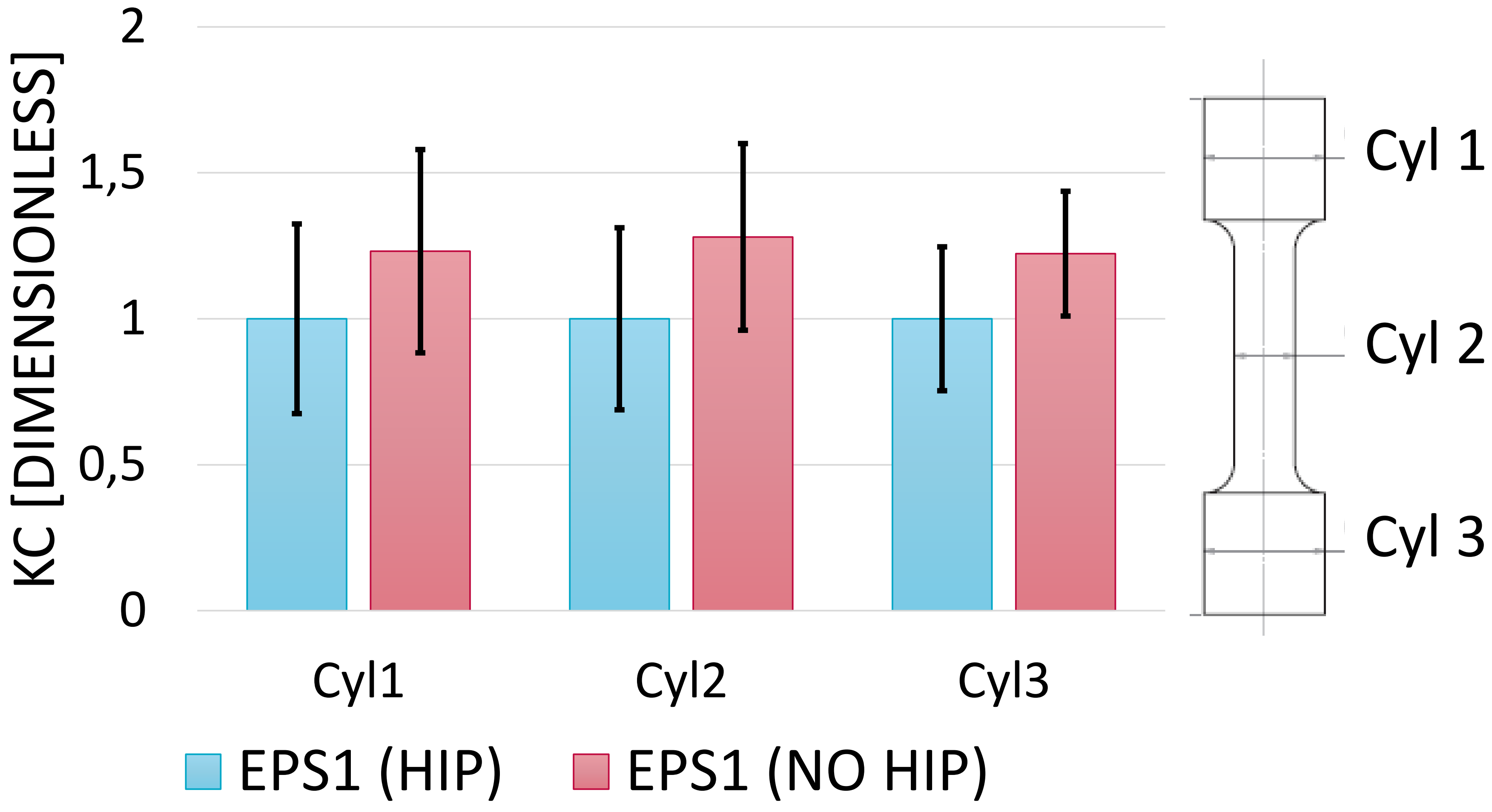
a_p = (vary depending of the sample)
f=0.08

$$K_c = \frac{F_{Z\,RMS}}{A}$$

$$A = a_p \,.\, f$$

$$a_p = \frac{D_{be} - D_{ef}}{2}$$

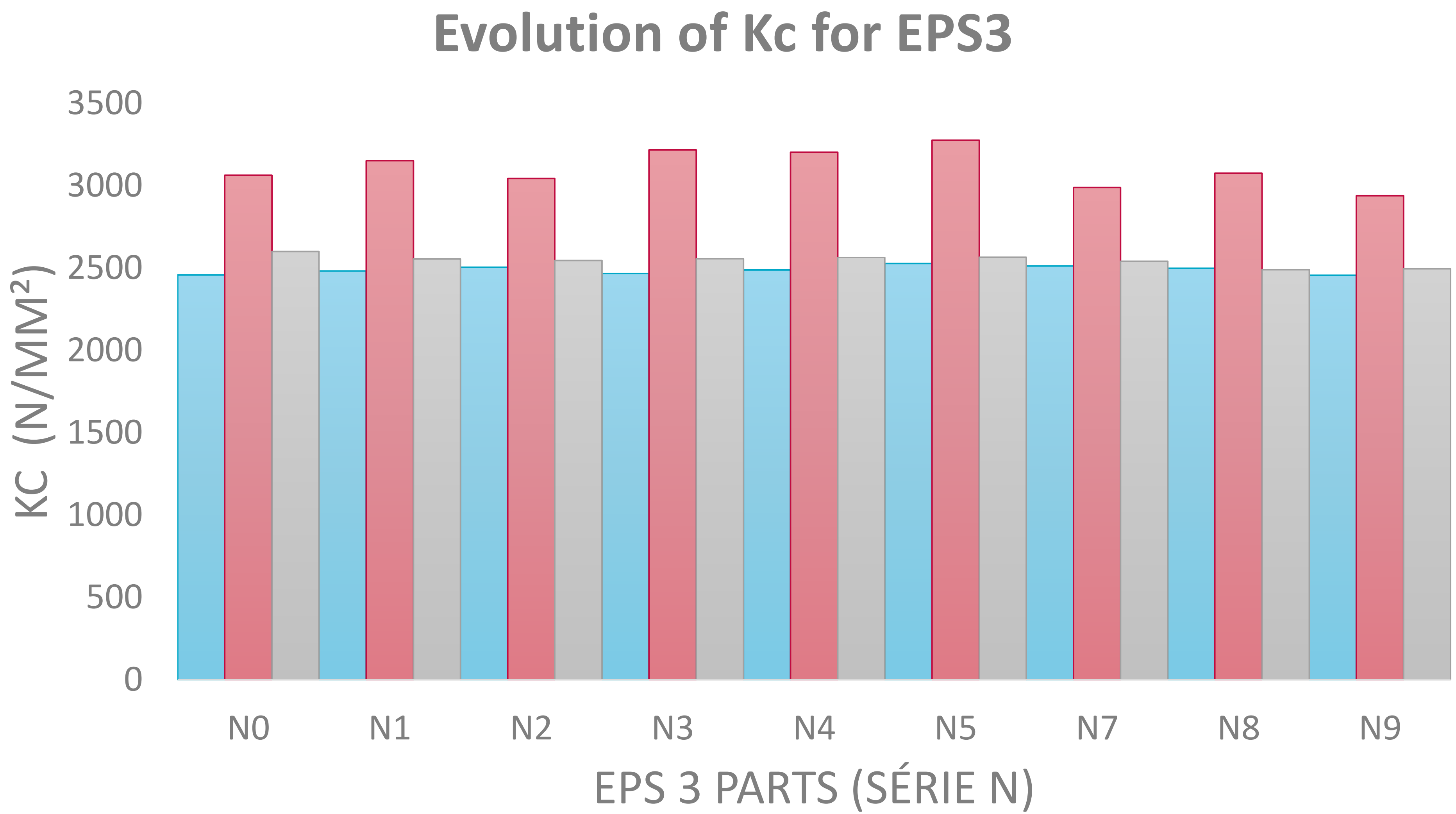
Machining of EBM Samples



Machining of EBM Samples

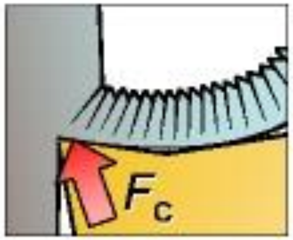
- 5 HIP and 5 No HIP
- Difference between HIP and No HIP is under experimental uncertainty
- ➔ HIP Has no significant influence on machining properties

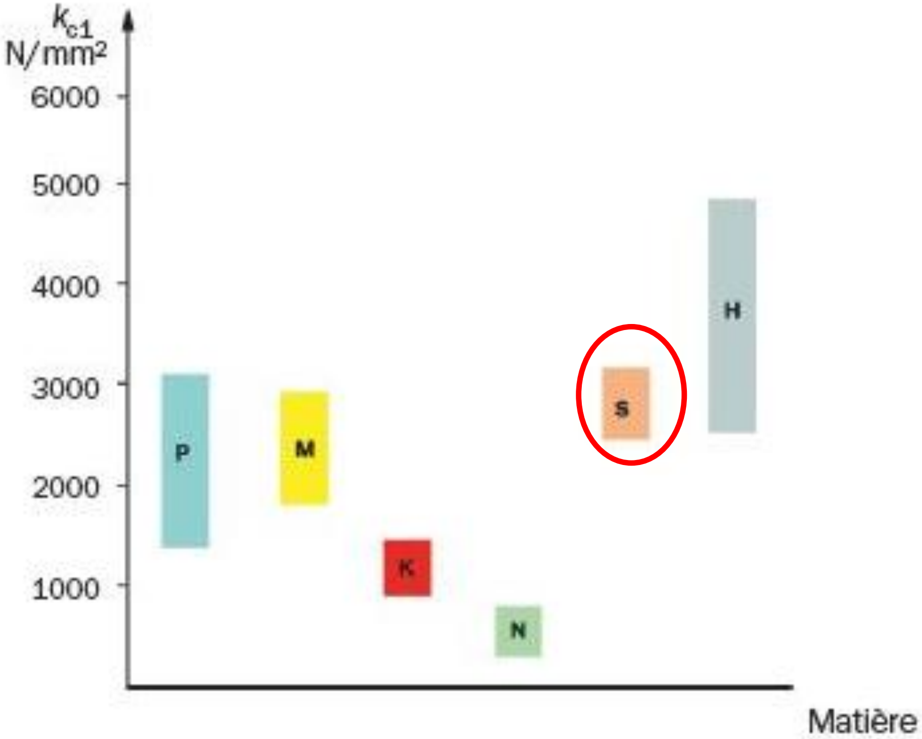
Machining of EBM Samples



- Kc similar to wrought titanium

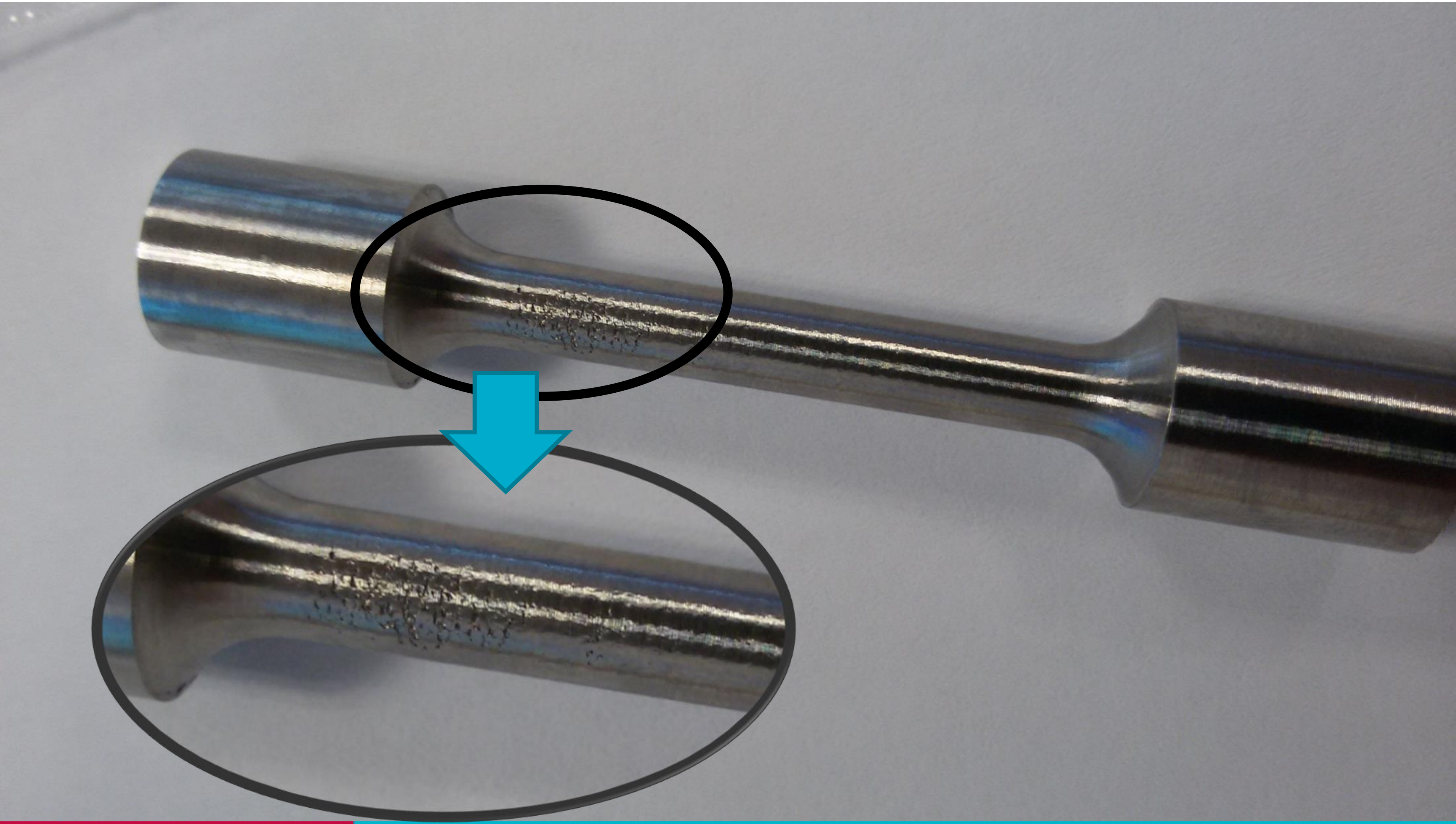
Machining of EBM Samples





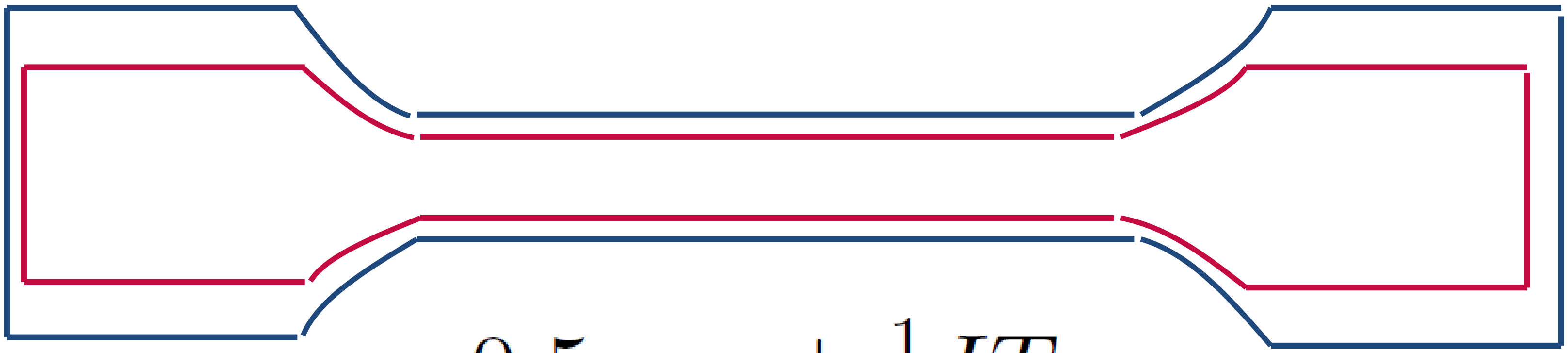
Machining of EBM Samples

- Verification of machining allowance



Machining of EBM Samples

- Verification of machining allowance

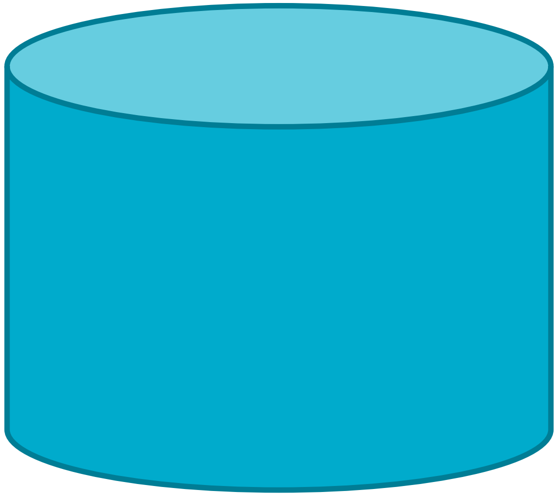


$$0.5mm \pm \frac{1}{2}IT$$

Befor machining : 12 mm and 5.5 mm
After machining : 10 mm and 4.5 mm

Machining of EBM Samples

- Future tasks
- Machining of simple geometry

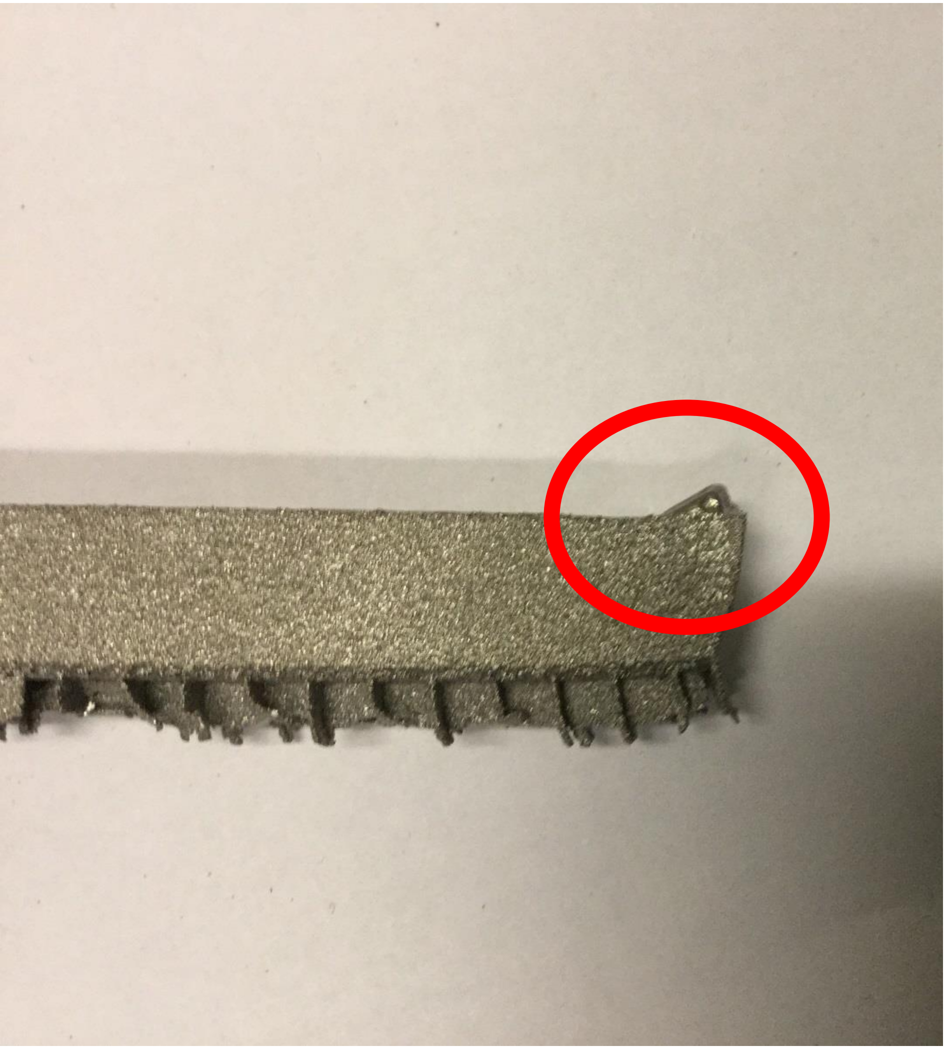


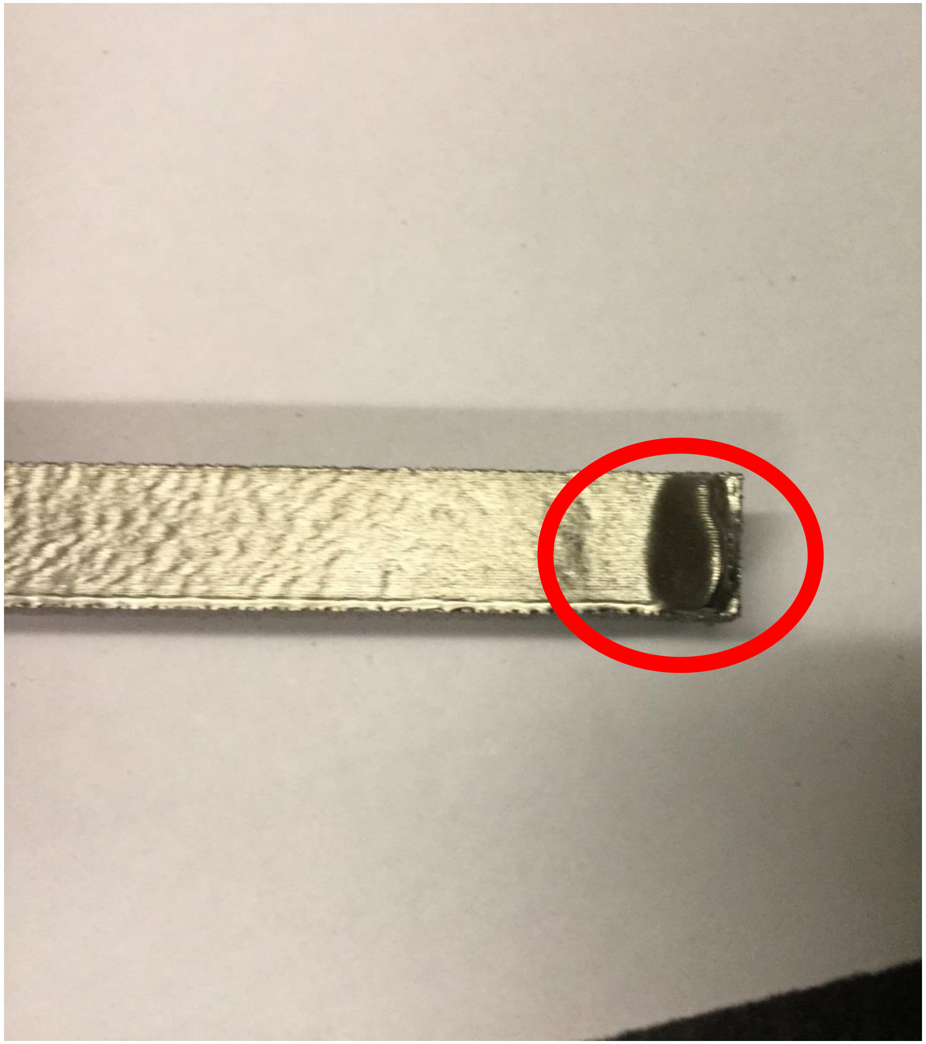
- Wear analysis?
- Cutting forces analysis
- Comparison with wrought Ti6Al4V

Residual stresses analysis (in progress)

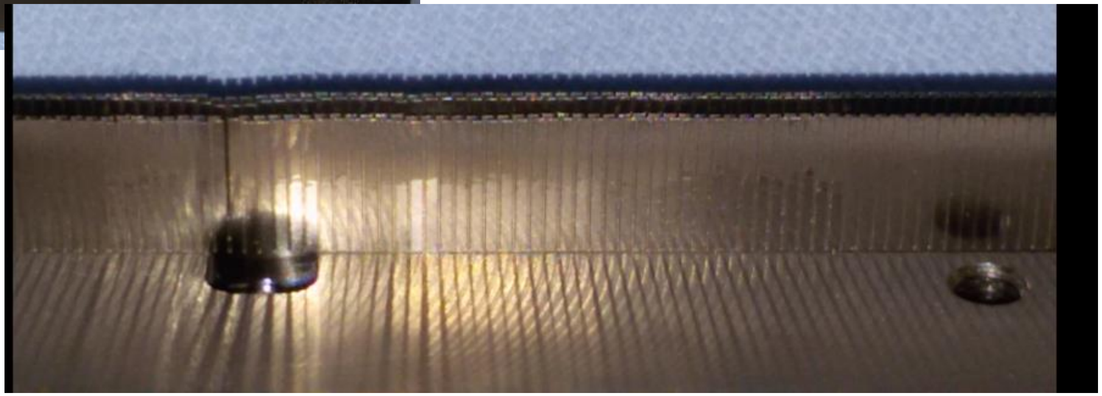
Residual stresses analysis

- Presence of residual stresses?





Residual stresses analysis



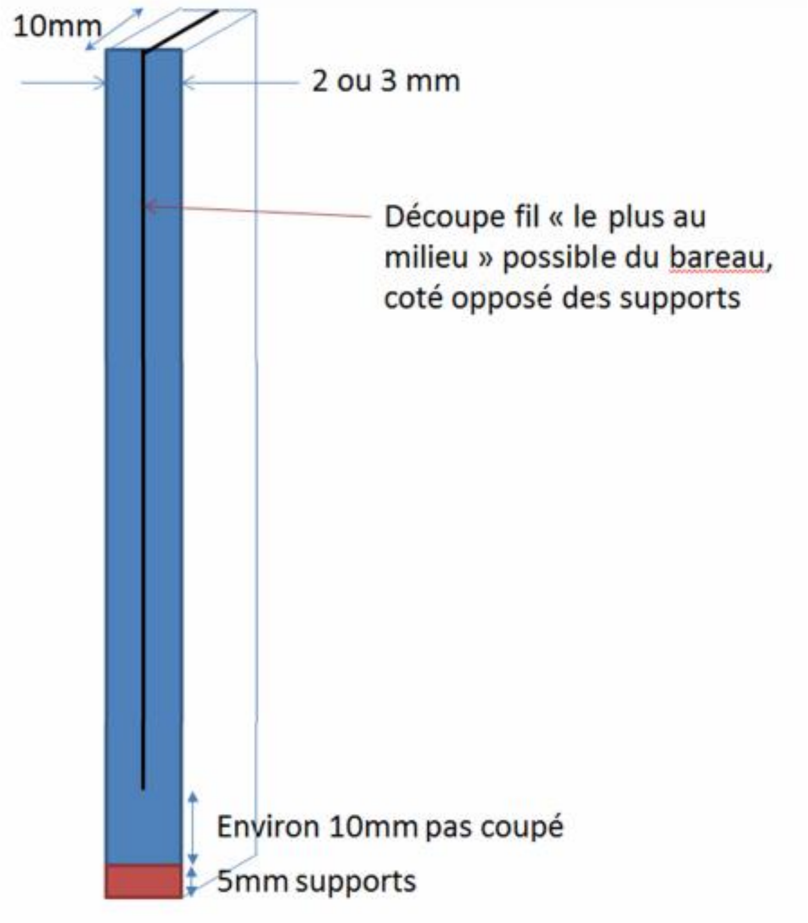
Presence of residual stresses?

Residual stresses analysis

5 pièces EBM

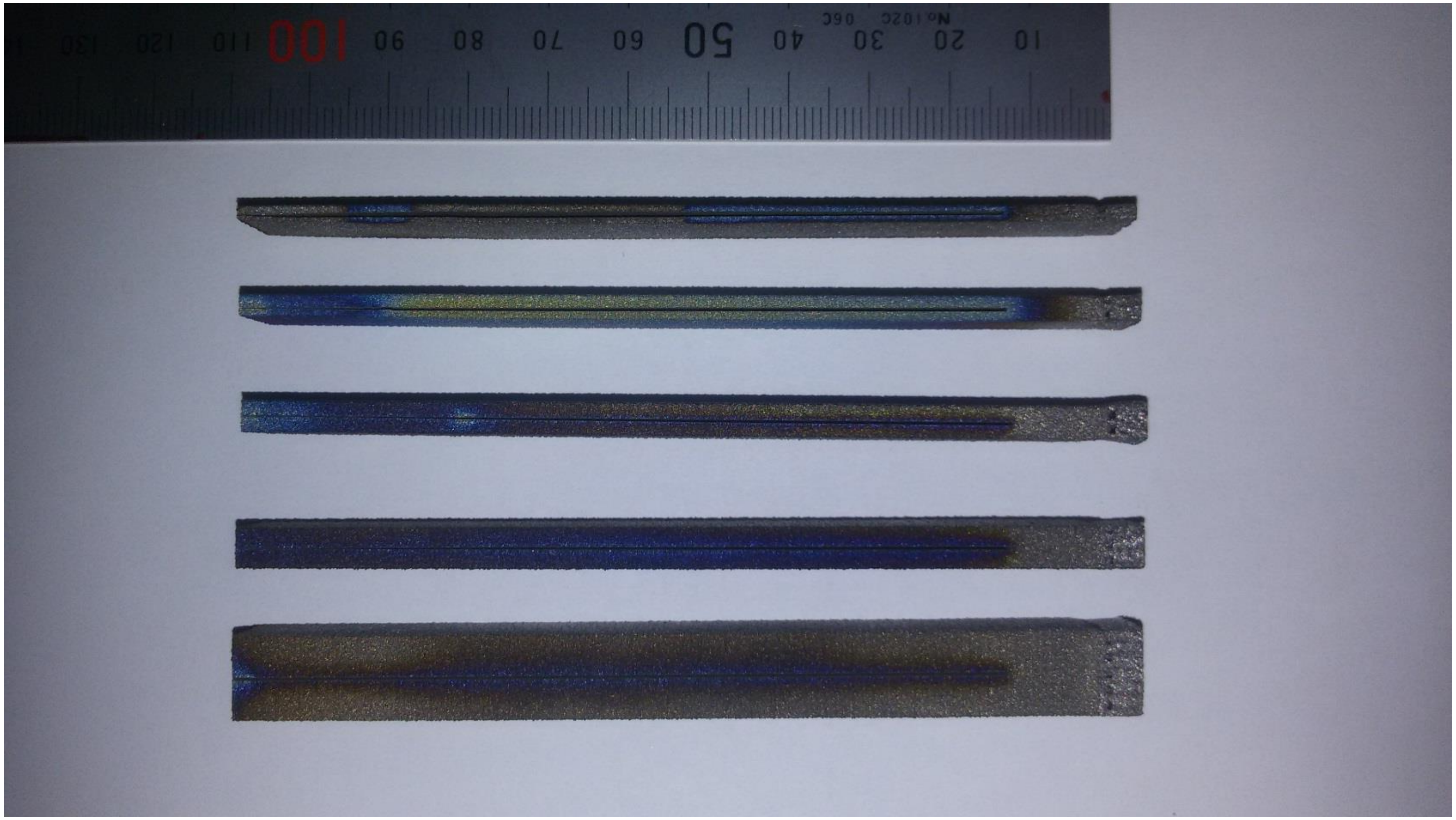
2x10x107, 3x10x107, 4x10x107, 5x10x107, 10x10x107

➔ Découpe fil



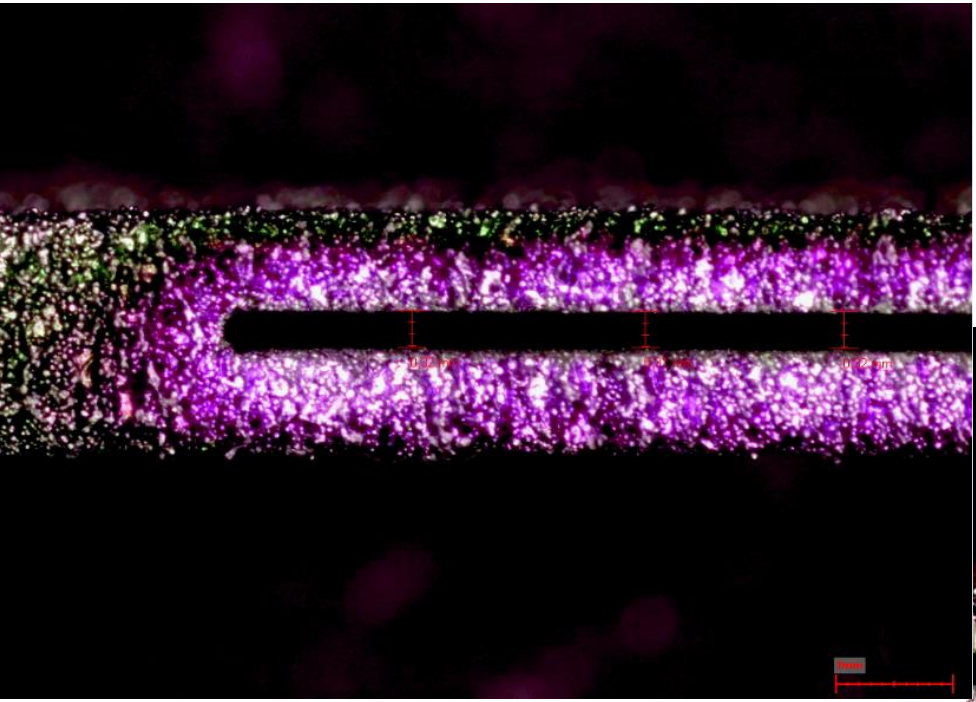
Residual stresses analysis

Results

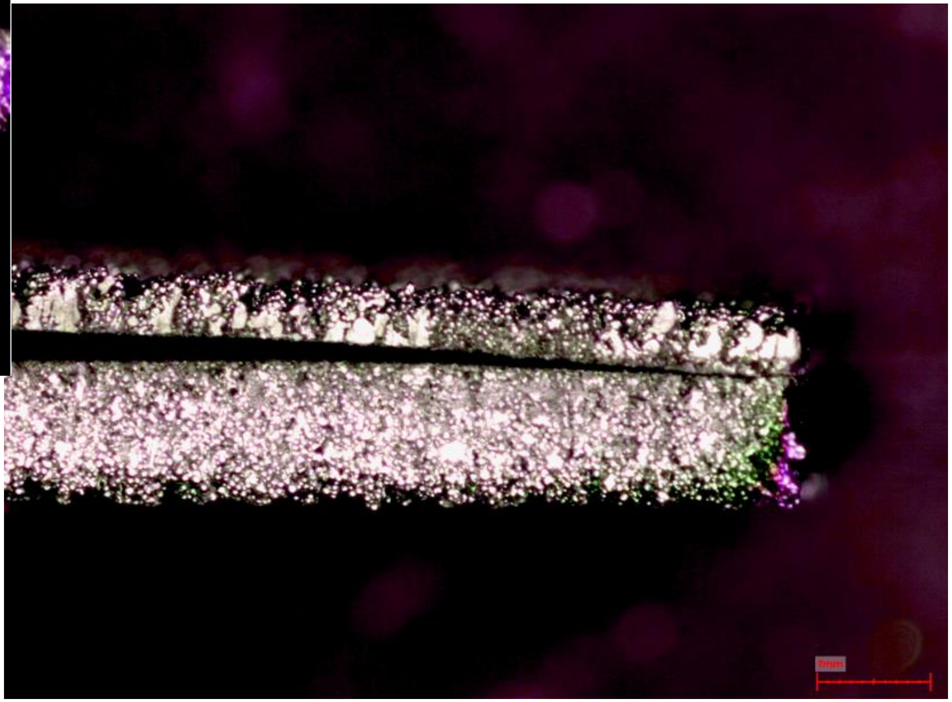


Residual stresses analysis

Results : 2 mm



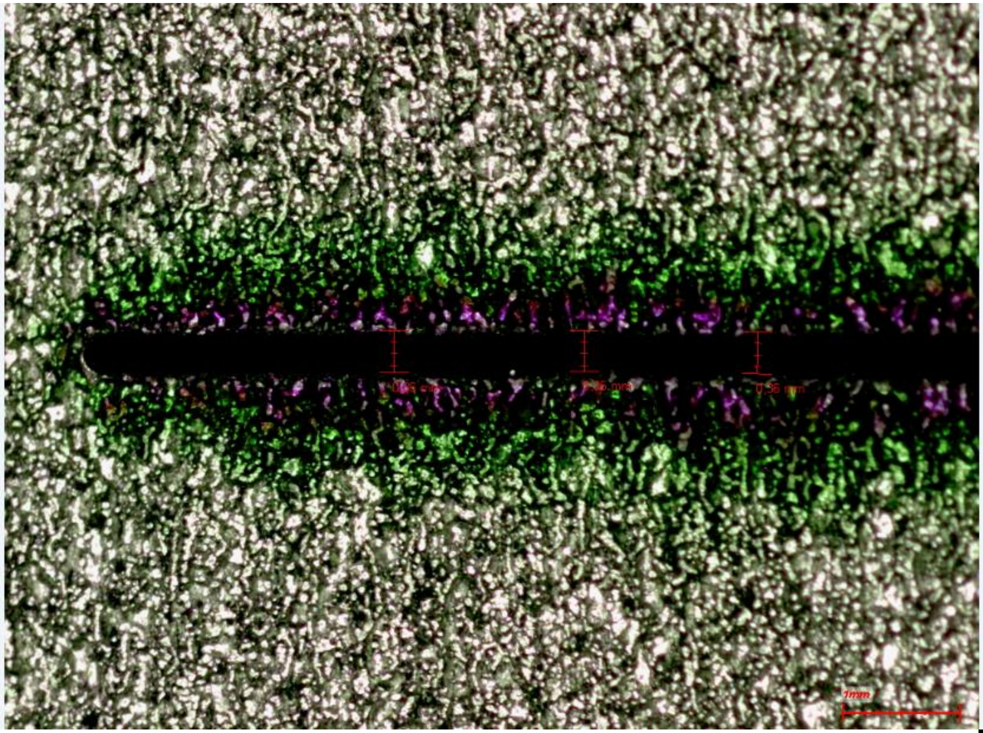
Touch



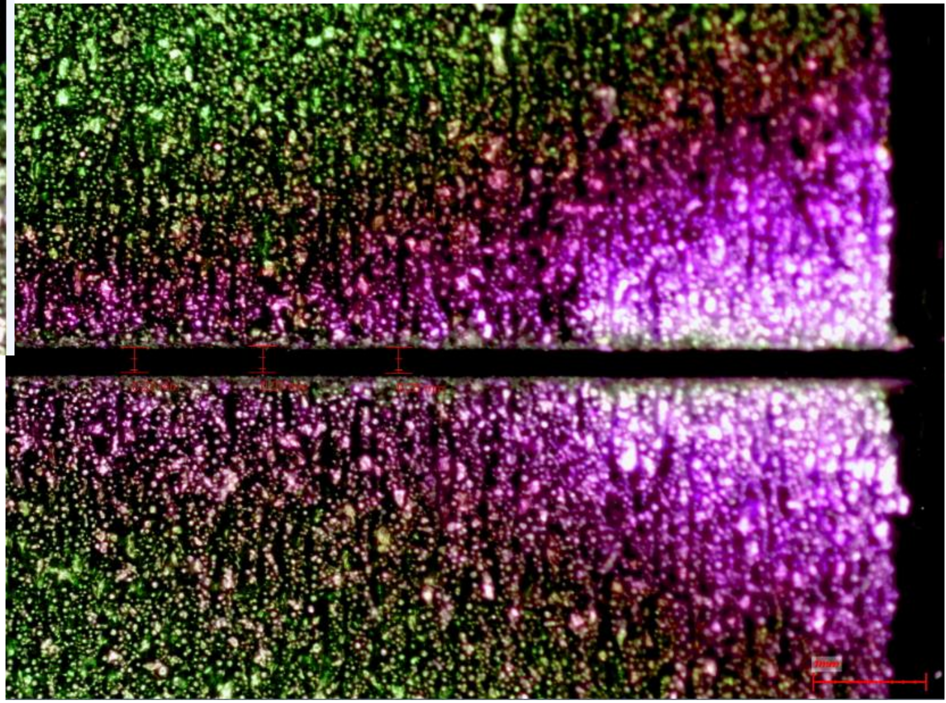
Begin = 0 mm
End = 0,33 mm

Residual stresses analysis

Results: 10 mm



Don't Touch



Begin = 0,23 mm
End = 0,33 mm

Residual stresses analysis

- Different methods:
  - Crack compliance method;
  - Finite element method;
  - DRX method.

Conclusions and future work

Conclusions and future work

- Different analysis were done
  - Dimension characterization
  - Capability analysis
    - ➔CT 7
  - Surface characterization
  - Machinability of EBM Samples

Conclusions and future work

- Future work
  - Residual stresses analysis :
    - Crack compliance method;
    - Finite element method;
    - DRX method.

UMONS
Université de Mons

Functionalization of Electron beam melting parts by Machining

Promoteurs académiques : Prof. E. Rivière, Prof. E. Filippi

POLYTECH MONS

Ir. Adrien Dolimont