EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-E

High-Temperature Reactor Components and Systems

CONTRACT N°
FIKI-CT-2001-00177

Deliverable D41-b for "Tribology in Helium Environment"
Realization of elementary tests

Carole FALCAND

FRAMATOME ANP

FRANCE

Dissemination level: RE
Document N°: HTR-E- 05/12 – D – 5 – 3 – 1 – 2/2

Status: Final
Deliverable D 41-b
FRAMATOME ANP identification: NFTM R05.1109

REACTEURS
CENTRE TECHNIQUE

FRAMATOME ANP
B.P. 13 - 71380 SAINT-MARCEL - France
Tél. (33) 03 85 90 30 44
Fax. (33) 03 85 90 31 51

AFAQ ISO 9001 VERSION 2000
N° QUAL/2002/19028

AREVA

NFTM R05.1109

MODIFICATIONS	
INDICE	DATE
0	28/02/2006

HTR-E / WP5

FRAMATOME ANP'S CONTRIBUTION TO DELIVERABLE D41

REALIZATION OF ELEMENTARY TESTS

(EC reference: HTR-E- 05/12 – D – 5- 3 – 1 – 1/2)

KEY WORDS

HTR-E
Tribology
Helium
Tests

DISTRIBUTION
Niveau de protection
~~NORM (normal)~~
FILT (filtré)
~~CONF (confidentiel)~~

N° Réseau : 178661

Nature document :

DIFFUSION	FONCTION	NAME	SIGNING	DATE
D. BESSON (NFPVEI)	Writer	C. FALCAND		10/02/06
L. CACHON (CEA DER/STPI/LCFI)	Checker	J.Ph. VERNOT		14/02/06
D. BUCKTHORPE (NNC)	Approver	G. BERTHOLLON		28/02/2006
TFCM				
TFC				

REVISIONS

Ind.	***Date***	***Parag.***	***Page***	***Appen-dix***	***Revision object***
0	28/02/2006				Document edition

ABSTRACT

Within the framework of the European Program HTR-E, work package 5, this document is part of deliverable D41 representing Framatome ANP contribution. The aim of the task 3.1 was the realization of elementary tests. The tests are realized by two partners: CEA and FRA ANP.

FRA ANP tests have been realized with the following parameters:

- The ambiance of tests is pure Helium at atmospheric pressure;
- The normal load applied is constant on each test;
- Six couples of materials have been characterized.

The results are given in the form of friction coefficient, wear depth, profilometry and wear coefficient.

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FIGURES

TABLES

APPENDICES

1. REFERENCES

[1] HTR-E-04/04-D-5-2-1 Deliverable D40 for « Tribology in Helium Environment »

[2] HTR-E-05/06-M-5-0-7 Minutes of WP5 – 7th meeting for « Tribology in Helium Environment » in Manchester

[3] HTR-E-05/12-M-5-0-8 Minutes of WP5 – 8th meeting for « Tribology in Helium Environment » in Le Creusot

2. INTRODUCTION

Within the framework of the European Program HTR-E, work package 5, this document is part of deliverable D41 representing Framatome ANP contribution. The aim of the task 3.1 was the realization of elementary tests. The tests are realized by two partners: CEA an FRA ANP. The repartition of tests is given in the tables here after issued from [1]:

N°	Component / contact	Environment	Material 1	Material 2	Temper. (°C)	Load (MPa)	Covered length (m)	Velocity (cm/s)	Tribometer FANP	Tribometer CEA	Remark
2	Reference test	Pure He	HR230	HR230	500	5	200	1			
4	Liner / Liner	Pure He	HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	500	5	200	1			5MPa = limit load for liner; 900°C for PBMR, same procurement
6			HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	900	5	200	1			
8		Pure He	HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	500	5	200	1			
10			HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	900	5	200	1			
12	Liner / Liner	Pure He	HR230 + SiC	HR230 + SiC	500	5	200	1			
14			HR230 + SiC	HR230 + SiC	900	5	200	1			
16		Pure He	HR230 + Cr_3C_2	HR230 + Cr_3C_2	500	5	200	1			
18			HR230 + Cr_3C_2	HR230 + Cr_3C_2	750	5	200	1			
20	Internals / vessel or Internals / block support	Pure He	9%Cr	9%Cr	250	50	200	1			
22			9%Cr	"	500	50	200	1			
24		Pure He	9%Cr + TiC	9%Cr	250	50	200	1			
26			9%Cr + TiC	"	500	50	200	1			
28			9%Cr + WC/NiCr	9%Cr	250	50	200	1			

Table 1: Tests in pure He

N°	Component / contact	Environment	Material 1	Material 2	Temper. (°C)	Load (MPa)	Covered length (m)	Velocity (cm/s)	Tribometer FANP	Tribometer CEA	Remark
2	Reference test	He + impurities	HR230	HR230	500	5	200	1			
4	Liner / Liner	He + impurities	HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	500	5	200	1			5MPa = limit load for liner; 900°C for PBMR, same procurement
6			HR230 + ZrO_2/Y_2O_3	HR230 + ZrO_2/Y_2O_3	900	5	200	1			
8	Liner / Liner	He + impurities *	HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	500	5	200	1			
10			HR230 + ZrO_2/CaO	HR230 + ZrO_2/CaO	900	5	200	1			
12	Liner / Liner	He + impurities	HR230 + SiC	HR230 + SiC	500	5	200	1			
14			HR230 + SiC	HR230 + SiC	900	5	200	1			
16	Liner / Liner	He + impurities	HR230 + Cr_3C_2	HR230 + Cr_3C_2	500	5	200	1			
18			HR230 + Cr_3C_2	HR230 + Cr_3C_2	750	5	200	1			
20	Internals / vessel or Internals / block support	He + impurities	9%Cr	9%Cr	250	50	200	1			
22			9%Cr	"	500	50	200	1			
24		He + impurities	9%Cr + TiC	9%Cr	250	50	200	1			
26			9%Cr + TiC	"	500	50	200	1			
28			9%Cr + WC/NiCr	9%Cr	250	50	200	1			

Table 2 : Tests in He+impurities

The tests are continuous (no dwell motion), and realized on fresh materials (no pre-oxydation).

All FRA ANP tests are realized on a classical pin on disk tribometer. This apparatus has been adapted to inject gas near the samples to realize tests in helium atmosphere. In temperature, reactions between the tribometer materials and the gas, and particularly when impurities are present in the gas, can happen. Of this fact, we don't test the good proportion of impurities. A new tribometer has been developed to realize tests in a representative environment. The materials in contact with the gas are neutral. But it was not available for this programme. That's why we used only pure helium in the pin on disk tribometer. The pure gas doesn't react with the apparatus surfaces.

3. DESCRIPTION OF FRA ANP PIN ON DISK TRIBOMETER

General features (see Figure 1):

- Fixed pin and rotating disk;
- Thermal housing around the disk;
- Normal load generated by free mass or spring;
- Little capacity for test in humid or lubricated environment;
- Contact forces (normal and tangential) measured by train gauge sensors.

Performances:

- Normal load up to 2,5 daN (estimated contact pressure: from 2 MPa to 600 MPa);
- Sliding speed: 1 to 250 mm/s;
- Temperature up to 600°C;
- Working environment: liquid (at low temperature) or gas;
- Nature of contact: typical sphere on plate or piece of real components;
- Measurement of temperature, displacement (wear evolution), normal and tangential forces, distance covered with personal computer during test.

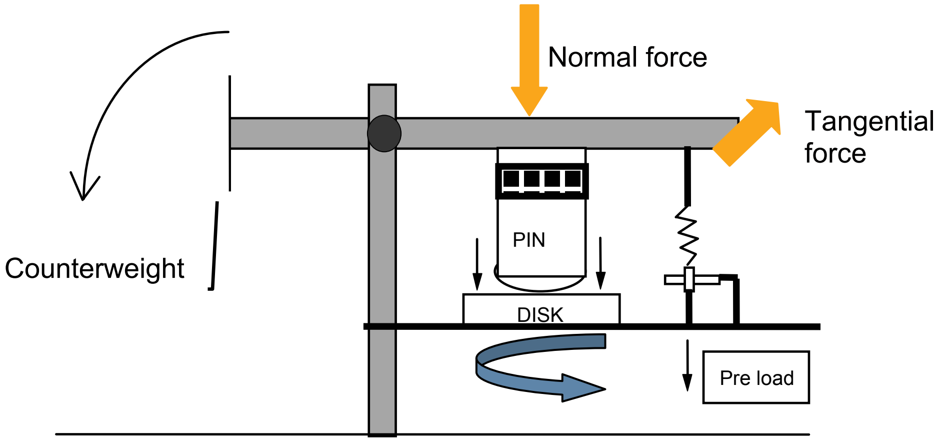


Figure 1: FRAMATOME ANP pin-on-disk tribometer

4. ENVIRONMENT

For the need of this test campaign, the tribometer has been modified to add a gas injection as near as possible from the contact. The gas is conducted from the bottle to the tribometer by a stainless steel tube, and then is sent in an alumina tube that is pre-heated, to inject the gas at a temperature near the expected temperature of the contact. See Figure 2 and Figure 3.

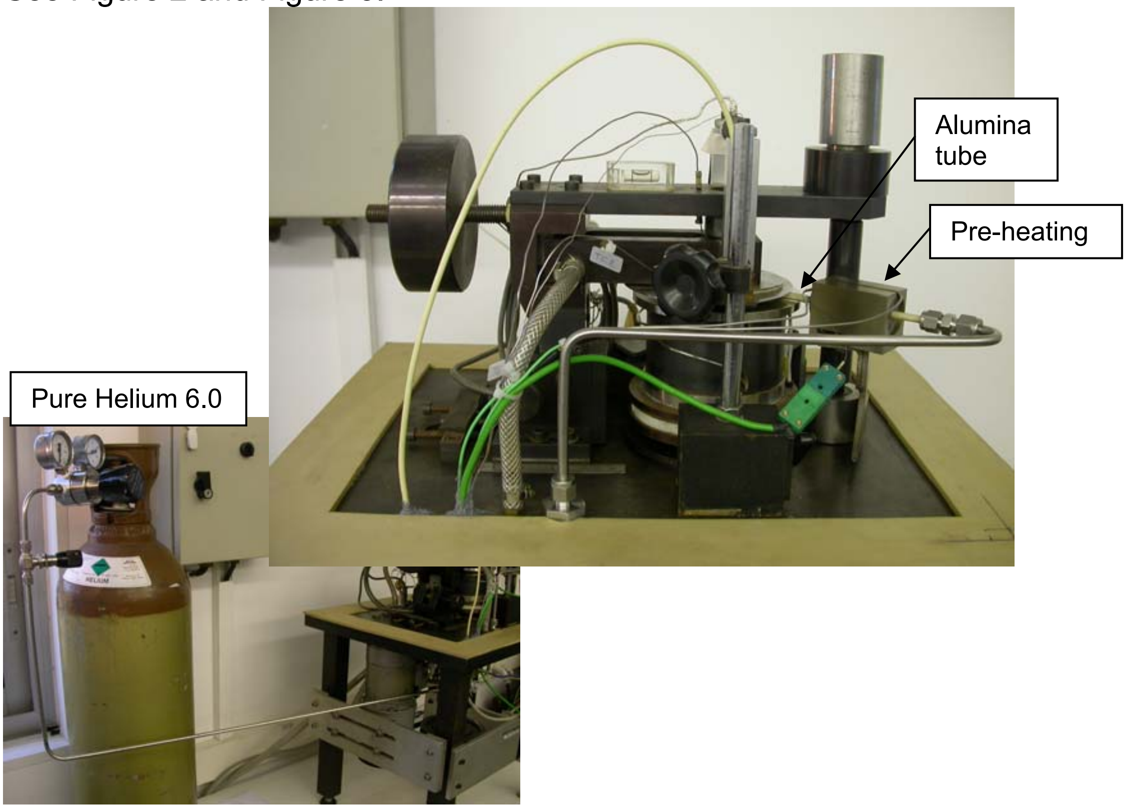


Figure 2: gas injection in the tribometer

The gas used is scientific helium 6.0 (99.9999% pure He). It contains only one ppm of impurities.

The tests are realized at atmospheric pressure.

Figure 3: Pin on disk tribometer

5. SAMPLES

All samples are identified by a number engraved on the diameter. One side is identified by a symbol (Δ).

5.1. First series of tests (see Table 1)

For this series of tests, the base material is HR230, and the contact pressure is 5 MPa. To get this value with a load around 20 N, the contact dimension is limited at ∅ 2.25 mm (Figure 4). The pin rubbing surface is flat.

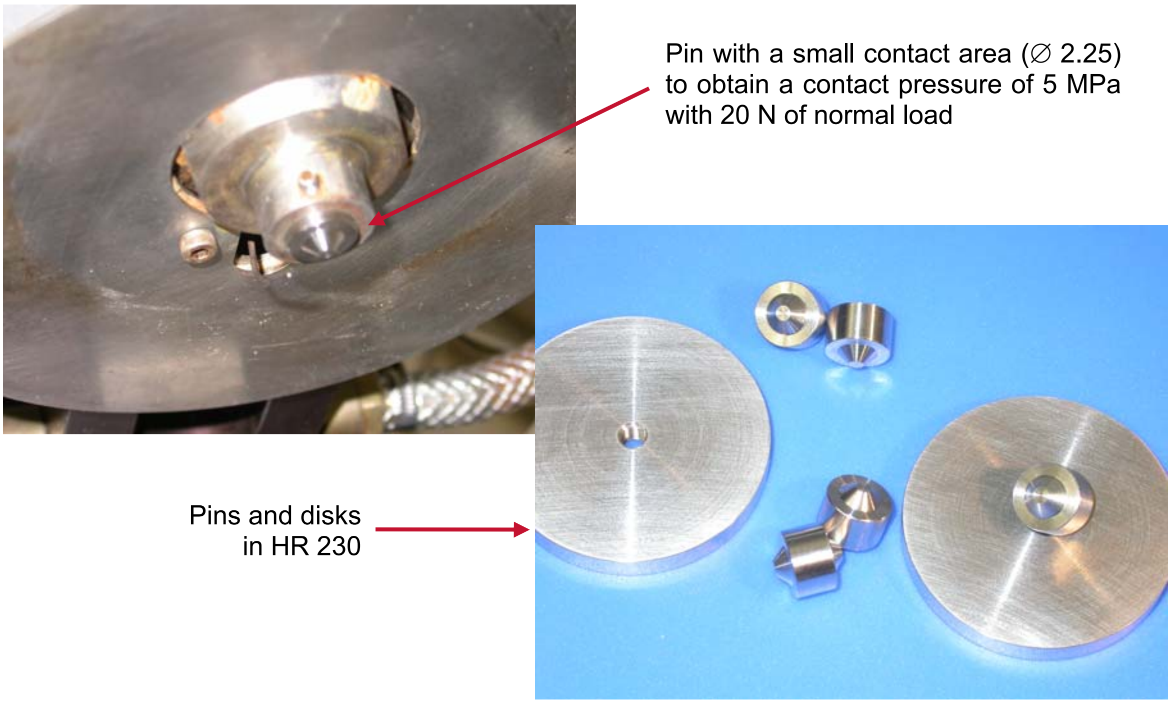


Figure 4: samples HR230

Three materials are tested: HR230, a deposit of ZrO_2 - Y_2O_3 and a deposit of ZrO_2 - Y_2O_3 + CaF_2 as solid lubricant (Figure 5). The choice of CaF_2 rather than CaO was that it was more easily feasible, and with good performance fore-seeable (in accordance with CEA). The coatings are constituted of a NiCrAlY sub-layer (100 µm) and the zirconia coating with or without solid lubricant (200 to 230 µm after grinding).

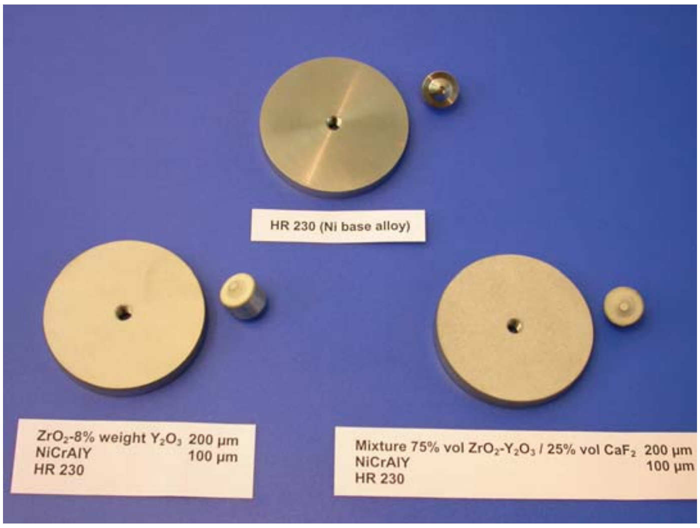


Figure 5: samples with or without coating

The coatings are exactly the same as CEA's ones. They are deposited by Low Pressure Plasma Spray. The composition of Yttria zirconia is ZrO_2 - 8% weight Y_2O_3

For the test with zirconia+solid lubricant, the composition is as follow:
75% vol. ZrO_2 - Y_2O_3 / 25% vol. CaF_2
In this series, both samples are coated (pin and disk).

5.2. Second series of tests (see Table 2)

For this series of tests, the base material is Z10CDVNb9.1 (named 9%Cr 1%Mo), and the contact pressure is 50 MPa. To get this value with a maximal load of 22 N, the contact dimension is limited at ∅ 0.75 mm (Figure 6).

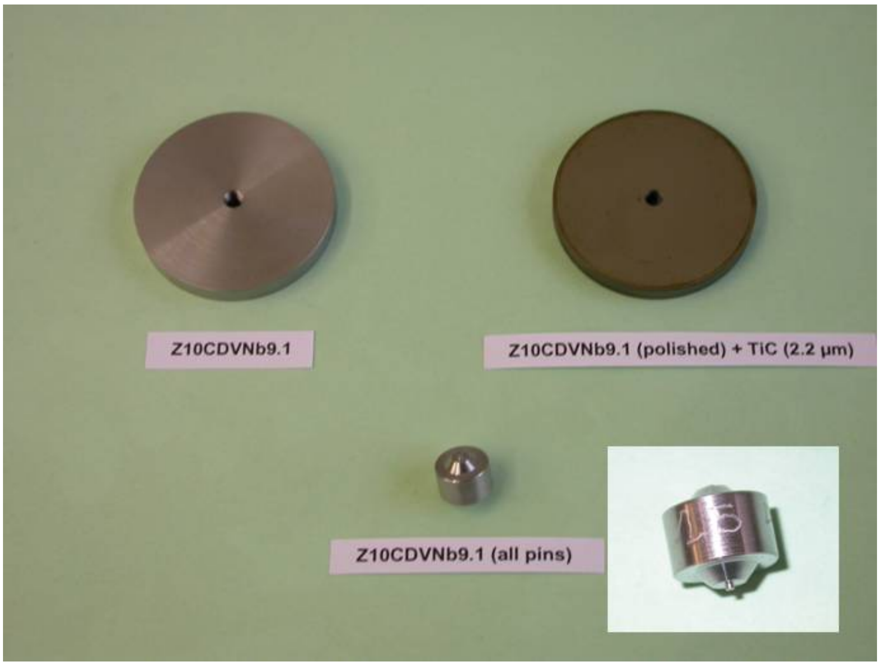


Figure 6: samples based on Z10CDVNB9.1

Three materials are tested: Z10CDVNb9.1, a deposit of WC/NiCr (SDG2005), and a deposit of TiC.
Only the disk is coated on both sides. Pins are Z10CDVNb9.1.
Under WC/NiCr denomination was LW5 [1]. This coating was deposit by Detonation Gun. The company who realized this coating now is Praxair, and they improved their deposition process, that is now called Super Detonation Gun (SDG). The composition is the same as in the past (tested by NNC): 25% (weight) WC, 70% mixed WC_3 / Cr_2C_3, 5% Ni. With the new process, the coating is compacter, has a better adhesion, that allows thinner layers. The thickness of the coating is 80 µm, and his name is SDG2005.
The deposit of TiC is realized by magnetron sputtering. This coating can only be deposited in thin layer. In our application, the problem is the important difference of expansion coefficient between Z10CDVNb9.1 ($11.8.10^{-6}$ at 200°C, $13.00.10^{-6}$ at 500°C) and TiC. The TiC thickness is 2.2 µm. With thicker layer (5 µm), the coating cracks, due to thermal stresses.

6. MEASUREMENTS

During the tests, the following parameters are registered continuously:

- Tangential load (Ft) with a strain gauges sensor - capacity 50 N, accuracy < 1% FS;
- Displacement of the pin with an Eddy current sensor, accuracy < 1% FS – when the signal increases, you have wear, when it decreases, you can have a third body in the contact. This measurement called “wear depth” gives the total wear pin + disk;
- Several temperatures with R type thermocouples:
  - TC1 in the near of Ft sensor;
  - TC2 in the near of the displacement sensor;
  - TC He, the gas outlet.

The temperature is controlled just over the disk surface (1 mm). A previous calibration allows us to know the contact temperature.

The data acquisition is realized by a National Instruments AT MIO 64E3 card, and the Labview programme is called “Acq format tableur et SGL-2.2”.

Results are presented in curves of:

- Friction coefficient (ratio between the tangential force and normal load) versus the covered length;
- Wear depth versus the covered length.

After the tests, SEM analyses have been realized when needed (particularly on zirconia coatings). The wear volume of disks (table 3) has been determined from 2D profilometries (4 profiles at 90°). All profilometry measurements are in Appendix 1.
Pins have been weighted to get wear coefficients (table 4).

7. TEST RESULTS

All tests are realized twice.

7.1. Reference test: HR230 on HR230

The aim of this first test is to compare the results issued from both tribometers (CEA and FRA ANP). The test conditions are the same.

Two tests have been realized, at CEA test conditions (CEA realized his test first, so we decided to use the same parameters to compare the results):

7.1.1. Test 1

Test conditions:

- Load: 5 MPa

- Sliding speed: 19.2 mm/s
- Sliding Diameter: 15.25 mm
- Covered length: 70 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 1	**Pin**	**Disk**
Identification	1 Δ	3 Δ
Material	HR230	HR230

The test has been limited at 70 m due to a problem with the heating device.
The Figure 7 shows the evolution of wear depth and friction coefficient during the test.

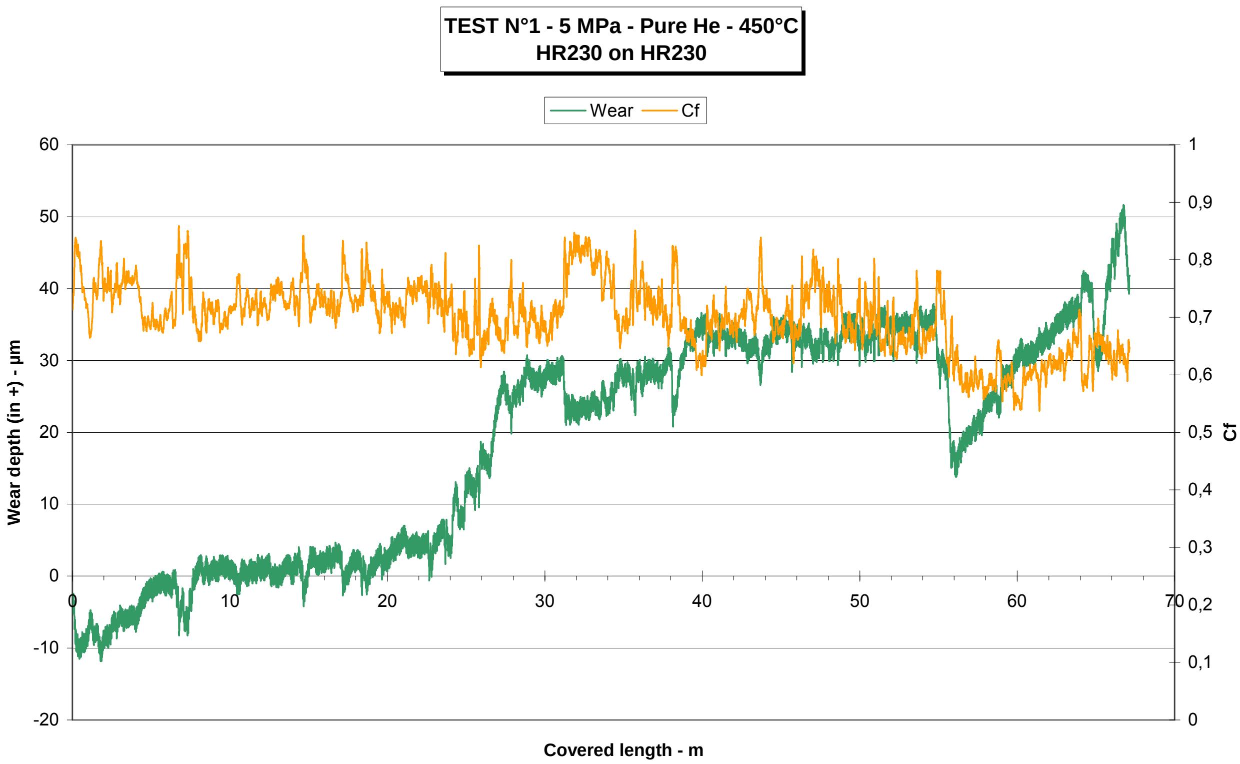
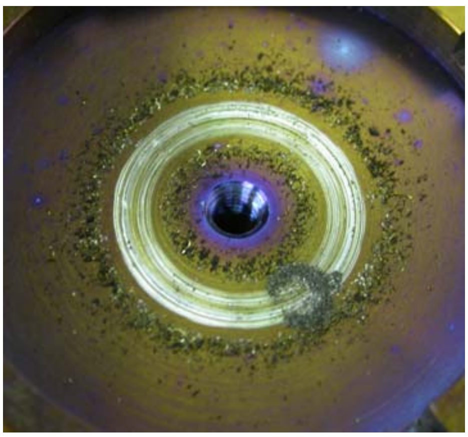


Figure 7: Wear and friction coefficient evolution - Test 1

Figure 8: Samples at the end of the test, before dismounting - Test 1



The mean value of friction coefficient is 0.70, and the wear is important.
The pictures of the samples before dismounting show the amount of debris created during the test (see Figure 8) and the sample wear. The worn volume on the disk is 1.81 mm^3 and the maximal depth (measurements on 4 profiles) is 37 µm.

7.1.2. Test 2

Test conditions:

- Load: 5 MPa
- Sliding speed: 15.2 mm/s
- Sliding Diameter: 15.25 mm
- Covered length: 103 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 2	**Pin**	**Disk**
Identification	2 Δ	4 Δ
Material	HR230	HR230

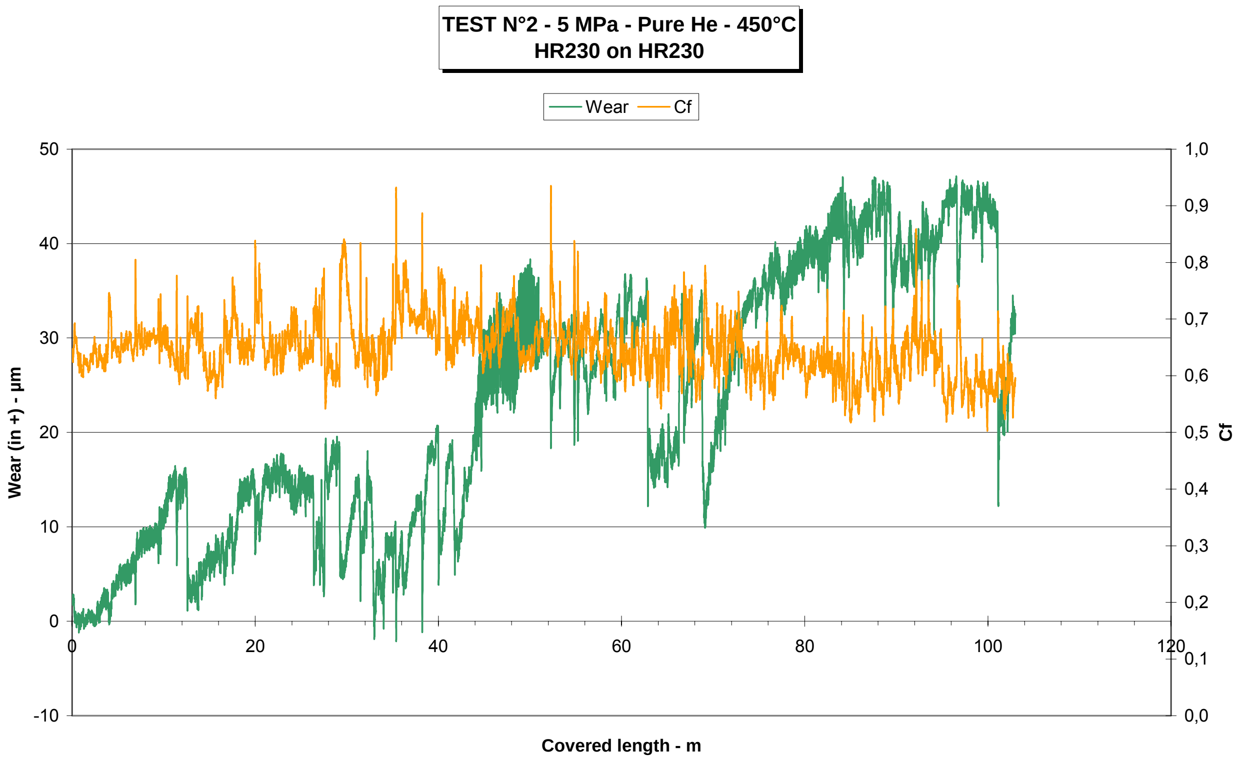


Figure 9: Wear and friction coefficient evolution – Test 2

The Figure 9 shows the evolution of wear depth and friction coefficient during the test.

The mean value of friction coefficient is 0.65, and the wear is important.

The samples before dismounting (Figure 10) are similar to those from test 1. The worn volume is a bit higher: 3.01 mm^3, idem for the maximal depth: 49 µm, but the covered length is 103 m. The wear coefficients are similar.

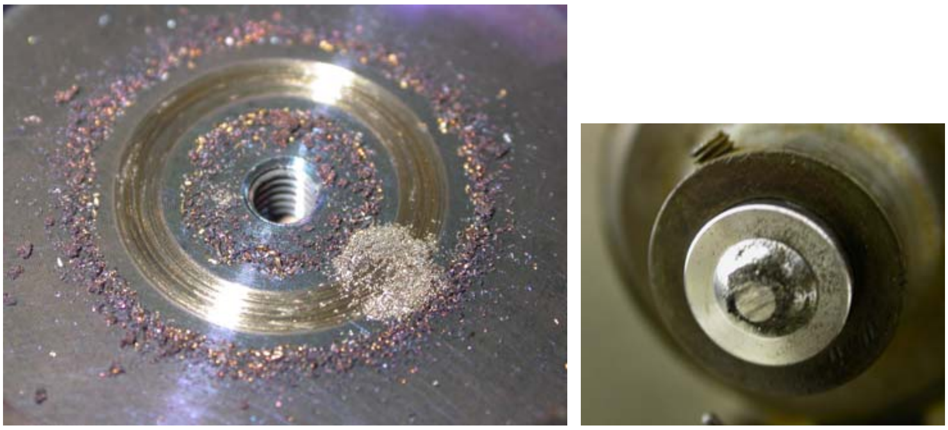


Figure 10: Samples at the end of the test, before dismounting - Test 2

The measurements during the tests 1 and 2 are compared in the graph Figure 11. The reproducibility of friction coefficient is very good. The kinetic of wear is the same at the beginning on 25 m, and is a bit different after, but it depends on the debris creation.

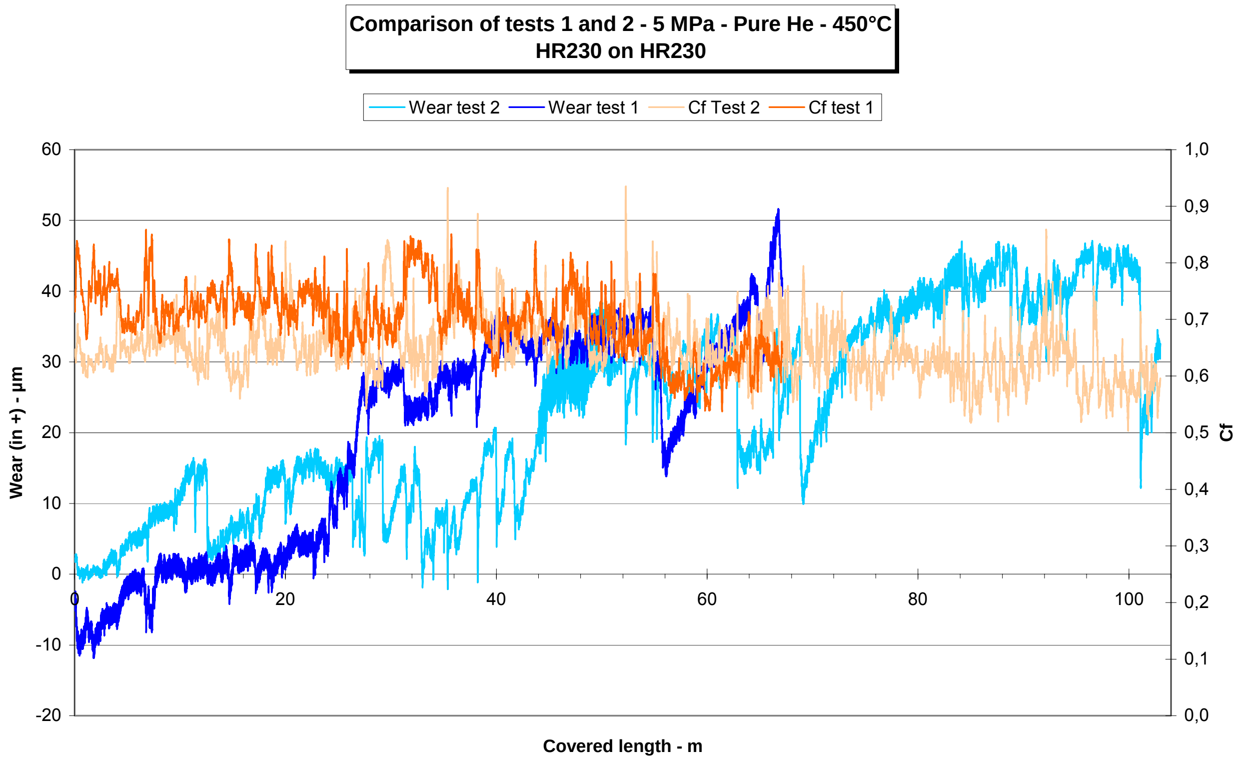


Figure 11: Comparison of tests 1 and 2

7.2. HR230+ZrO_2/Y_2O_3 on HR230+ZrO_2/Y_2O_3

7.2.1. Test 5

Test conditions:

- Load: 5 MPa
- Sliding speed: 17.8 mm/s
- Sliding Diameter: 20 mm
- Covered length: 200 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 5	**Pin**	**Disk**
Identification	4	2 Δ
Material	HR230 + NiCrAlY + ZrO_2/Y_2O_3	HR230 + NiCrAlY + ZrO_2/Y_2O_3

The Figure 12 shows the evolution of wear depth and friction coefficient during the test.

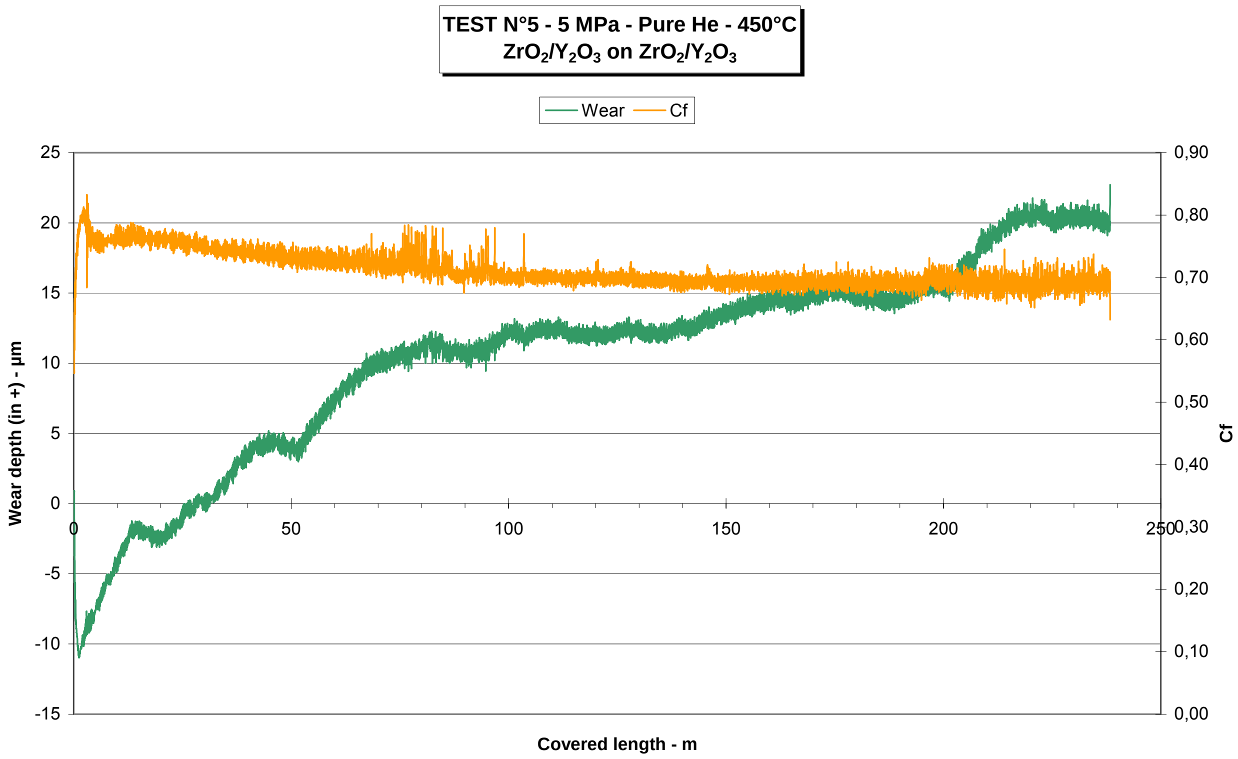


Figure 12: Wear and friction coefficient evolution – Test 5

The friction coefficient is rather high with a mean value of 0.71.

The pictures of samples (Figure 13) show a small amount of debris on the pin. The wear on the disk is small but measurable (1.53 mm^3) for a sliding distance of 238 meters. The maximal depth is 17.5 µm.

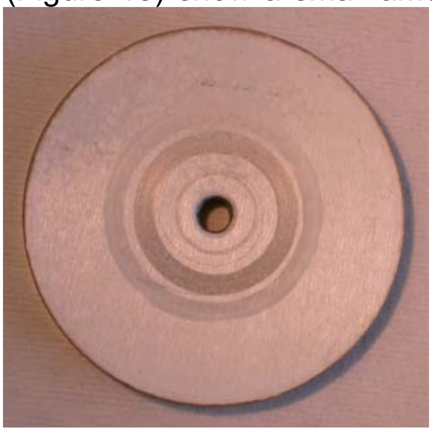


Figure 13: pictures of samples from test 5 before cleaning

7.2.2. <u>Test 6</u>

Test conditions:

- Load: 5 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20 mm
- Covered length: 200 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

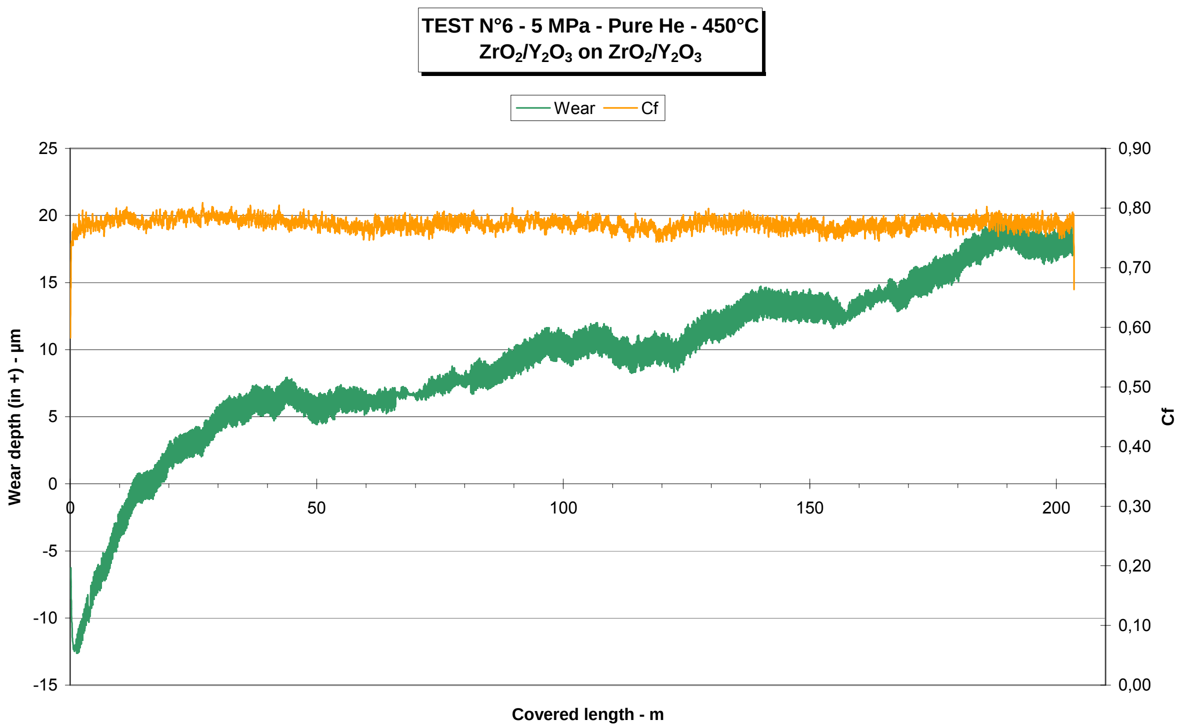


Figure 14: Wear and friction coefficient evolution – Test 6

Test 6	**Pin**	**Disk**
Identification	5	2
Material	HR230 + NiCrAlY + ZrO_2/Y_2O_3	HR230 + NiCrAlY + ZrO_2/Y_2O_3

The Figure 14 shows the evolution of wear depth and friction coefficient during the test. The mean value of friction coefficient is 0.77.

The pictures of samples (Figure 15) show a very low wear with a smaller amount of debris than in test 5. The track on the disk is not regular. The wear volume on the disk is not measurable. That confirms the visual observation.

Figure 15: Pictures of samples from test 6

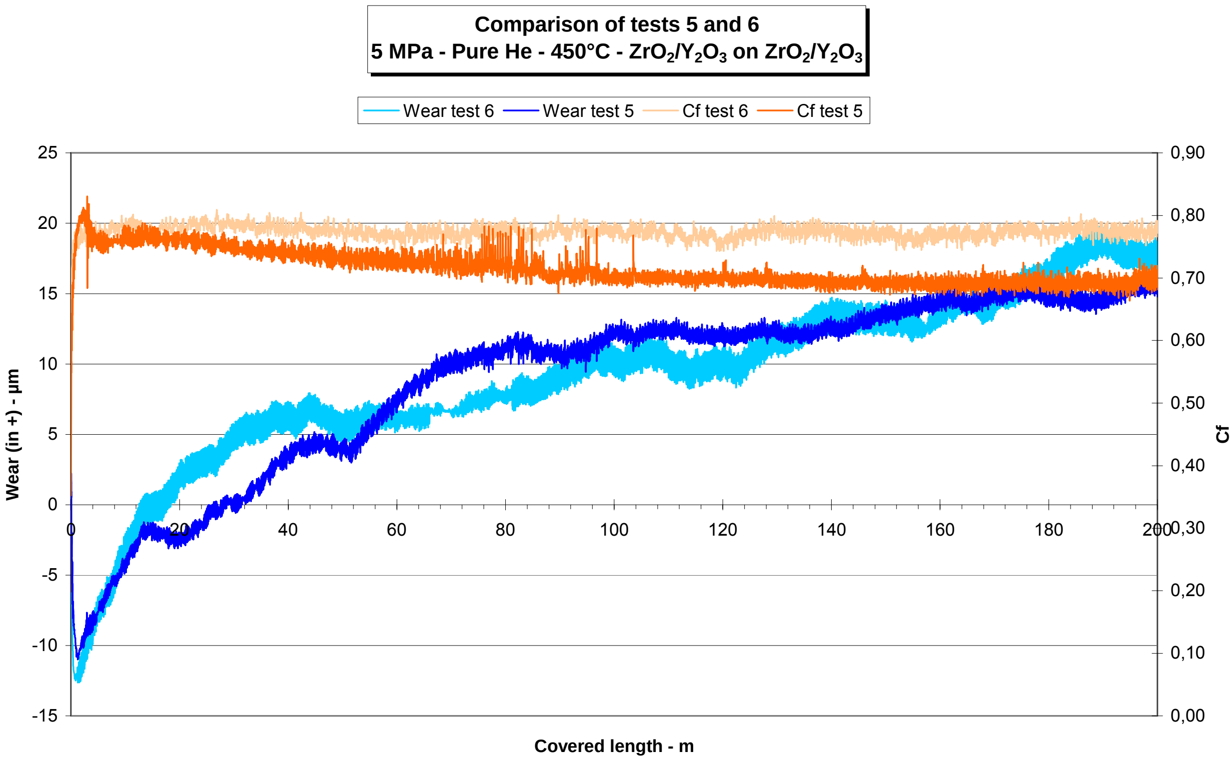


Figure 16: Comparison of tests 5 and 6

The measurements during tests 5 and 6 are compared in the graph Figure 16. The evolutions of wear depths are similar.

In test 5, the friction coefficient decreases slowly, while it stays constant in test 6. The mean level of friction coefficient is 0.74.

The SEM analyses are realized on disk 2 from test 6. The observation of the surface out of the wear track (Figure 17) shows the grinding marks. In the wear track (Figure 18), the surface is run over. On 2D profile measurements, there's no change in the roughness. (See Appendix1 pages 6 and 7)

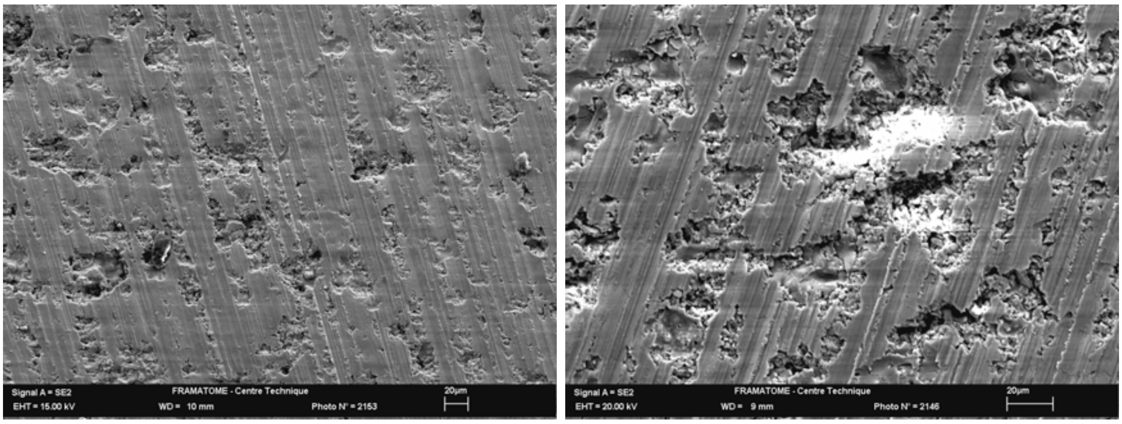


Figure 17: Disk surface 2 (test 6) out of the wear track

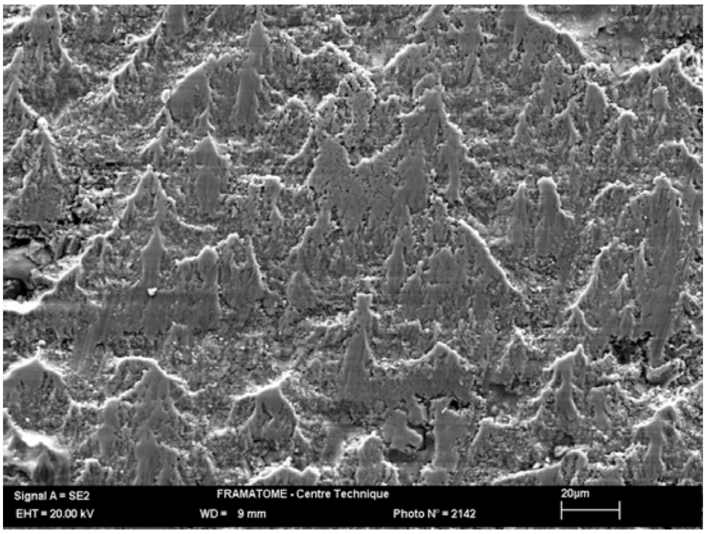


Figure 18: Wear track surface (Test 6)

7.3. HR230+ZrO_2/Y_2O_3/CaF_2 on HR230+ZrO_2/Y_2O_3/CaF_2

7.3.1. Test 7

Test conditions:

- Load: 5 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20 mm

- Covered length: 200 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 7	**Pin**	**Disk**
Identification	3 Δ	1 Δ
Material	HR230 + NiCrAlY + $ZrO_2/Y_2O_3/CaF_2$	HR230 + NiCrAlY + $ZrO_2/Y_2O_3/CaF_2$

The Figure 19 shows the evolution of wear depth and friction coefficient during the test. During the first phase (up to 80 m), the friction coefficient is very low (between 0.3 and 0.4), and the wear depth is stabilized.

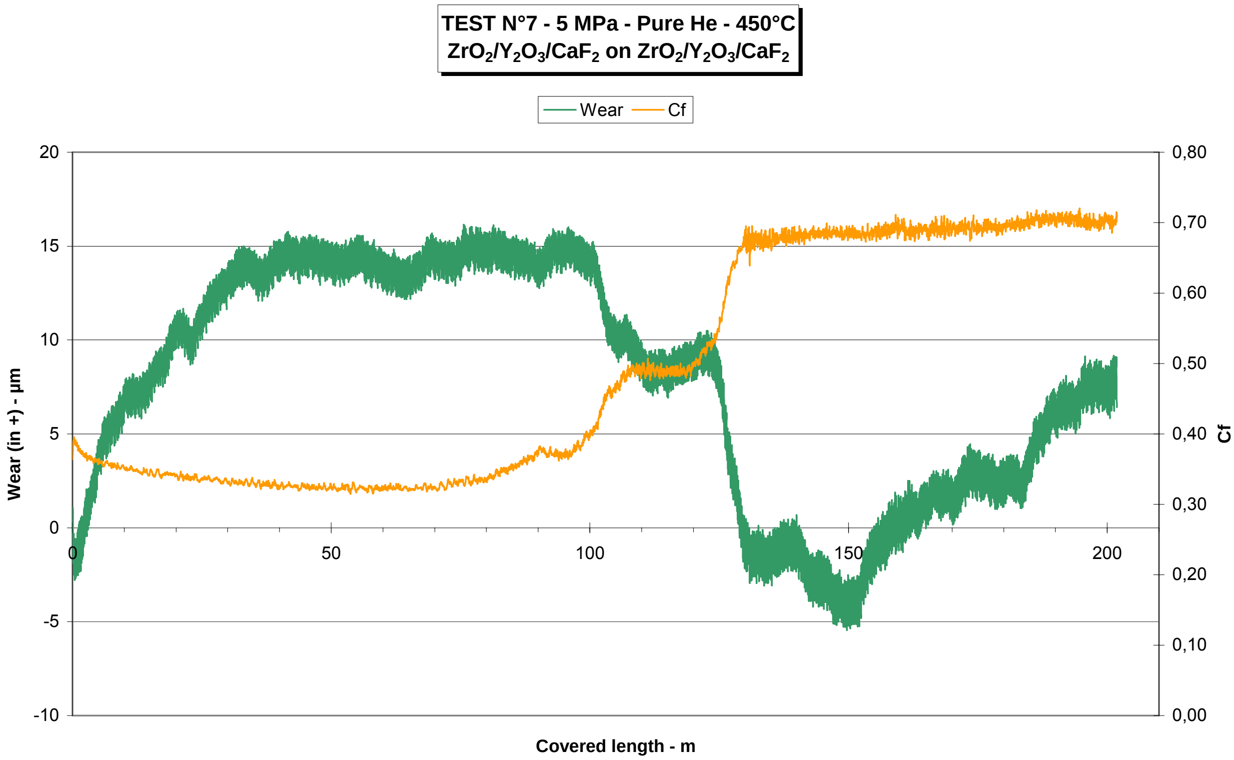


Figure 19: Wear and friction coefficient evolution – Test 7

Around 100 meters, there is a quick evolution of the friction coefficient that increase up to 0.7. In the same time, the wear depth decreases, that means that the distance between pin and disk increases.

Figure 20: pictures of samples from test 7 before dismounting

The explanation is that there is a creation of debris in the contact. After that, the behaviour of the contact is like in previous test 6.
The wear is very low but we can observe (Figure 20) a small amount of debris. The wear volume of the disk is not measurable by profilometry (see pages 2 and 3 of appendix1.

7.3.2. Test 8

Test conditions:

- Load: 5 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20 mm
- Covered length: 200 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 8	**Pin**	**Disk**
Identification	3	1
Material	HR230 + NiCrAlY + $ZrO_2/Y_2O_3/CaF_2$	HR230 + NiCrAlY + $ZrO_2/Y_2O_3/CaF_2$

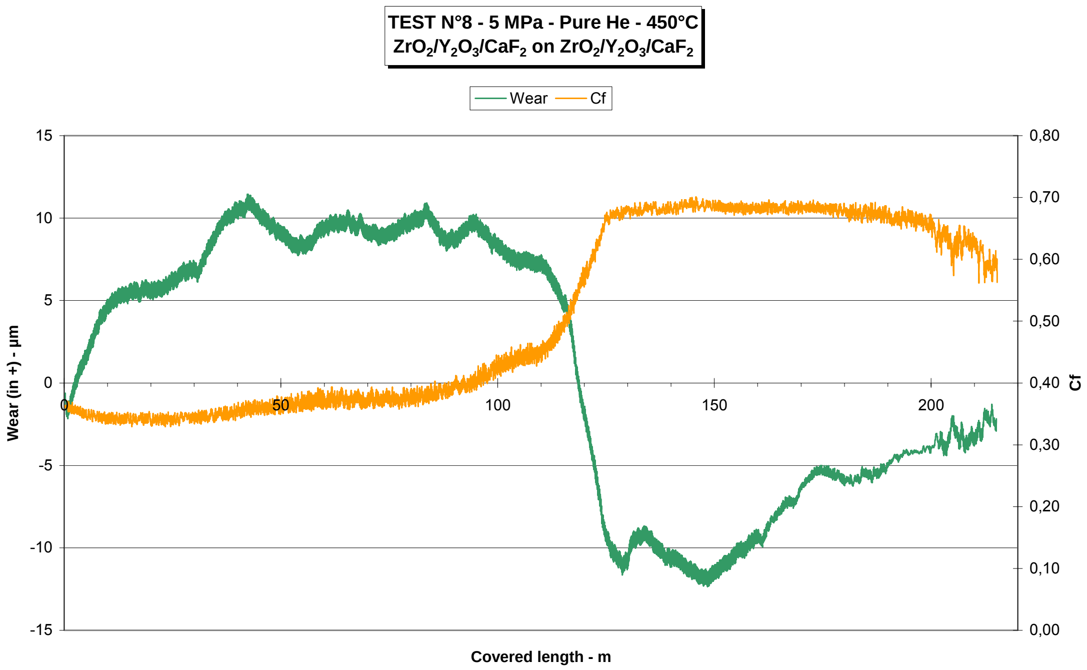


Figure 21: Wear and friction coefficient evolution – Test 8

The Figure 21 shows the evolution of wear depth and friction coefficient during the test. The same behaviour as in test 7 is observed. The pictures of the samples just after the test (Figure 22) are similar to those from test 7. A longer test could give us information about the behaviour of the coating, if the phenomenon is cyclic. The SEM analyses (Figure 23) show the disk surface out of the track and the wear track. The surface is less marked by grinding than in test 6. On the track, the surface is run over and very flat.

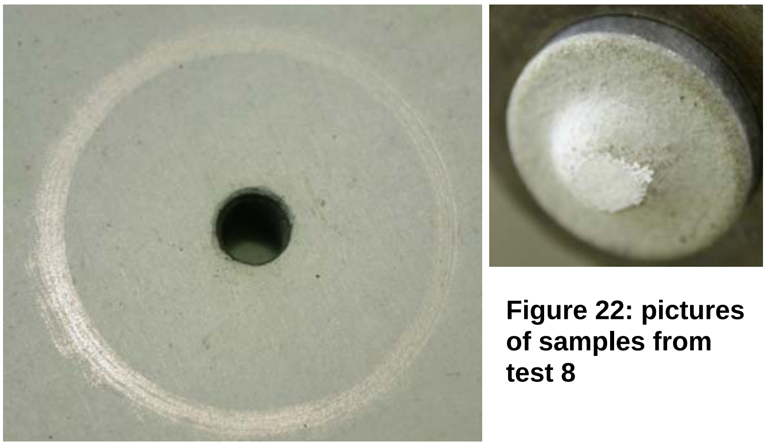


Figure 22: pictures of samples from test 8

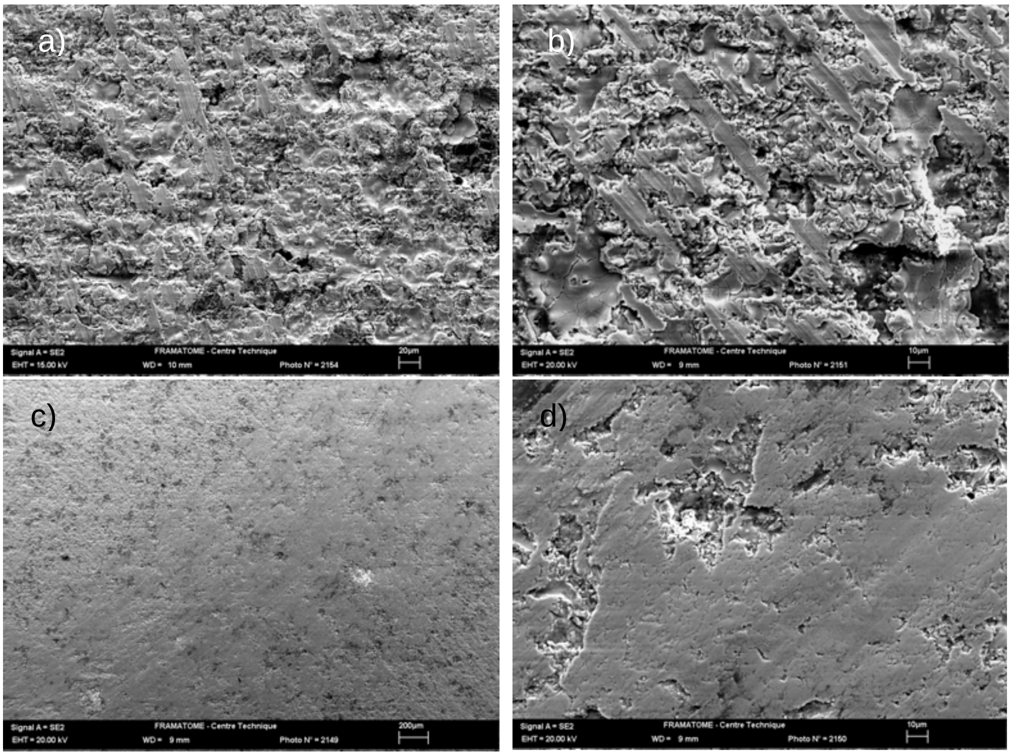


Figure 23: Disk 1Δ (test 7) surface - a) b) out of the wear track - c) d) observation of the wear track

The surface composition has been measured on the disk surface, out of the wear track (Figure 24). CaF_2 is well distributing on the surface. On the wear track (Figure 25), the extreme surface is free from CaF_2. But CaF_2 is present under the surface, in holes. That explains that the friction coefficient at the end of the test is the same as in tests 5 and 6, without solid lubricant.

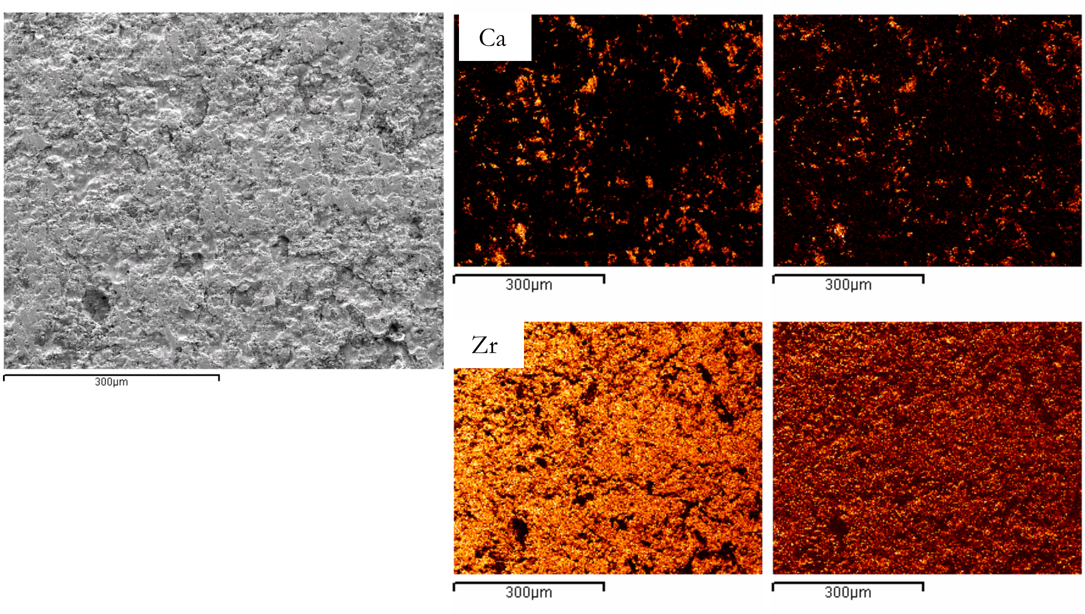


Figure 24: EDS on the disk surface out of the wear track

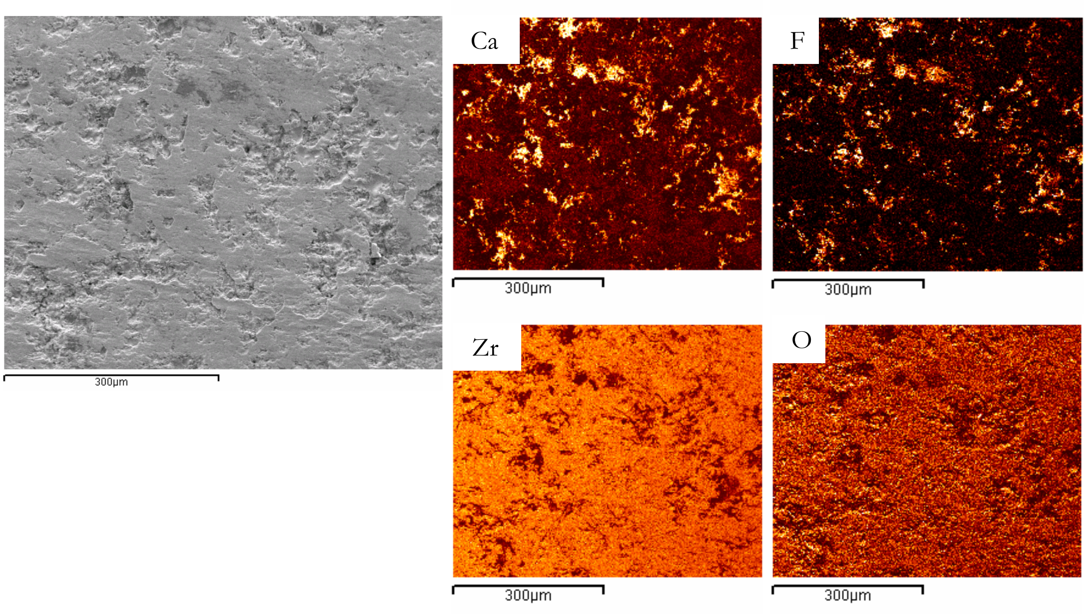


Figure 25: EDS on the wear track

The Figure 26 shows the good reproducibility of both tests.

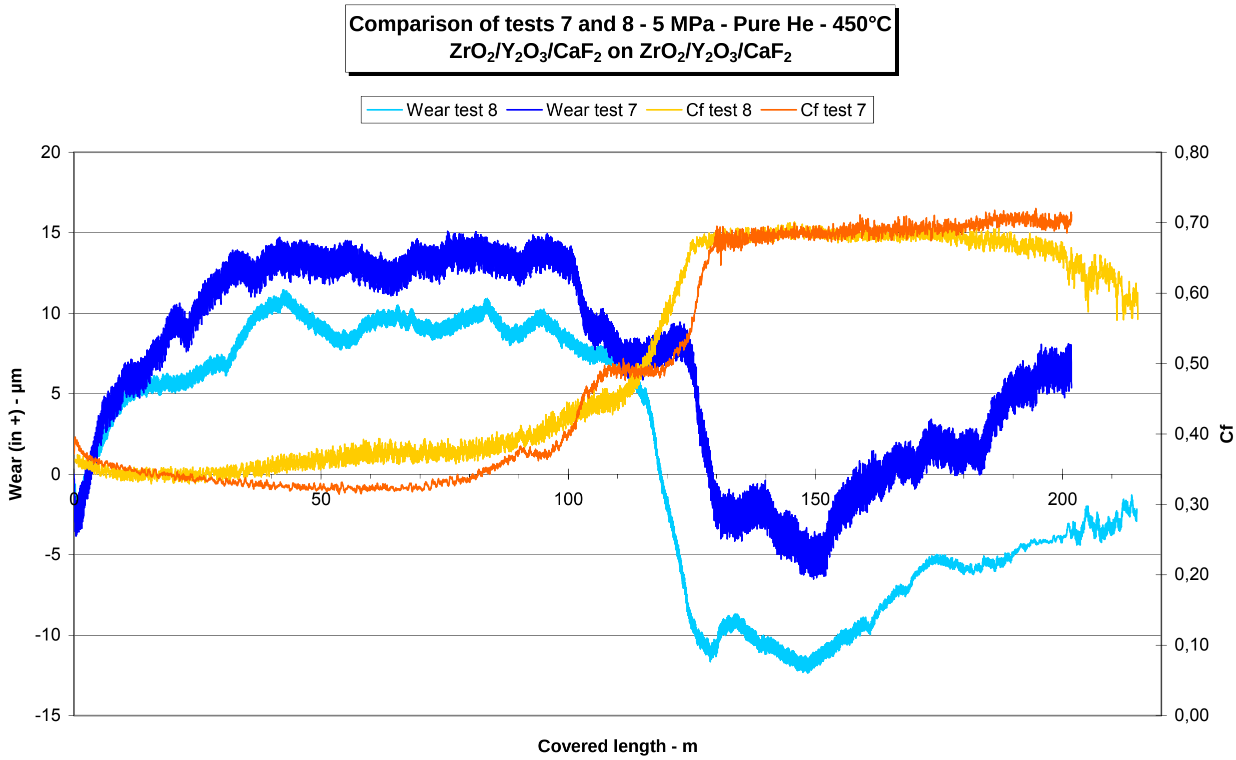


Figure 26 : Comparison of tests 7 and 8

7.4. Z10CDVNb91 on Z10CDVNb91

7.4.1. Test 9

Test conditions:

- Load: 50 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20 mm
- Covered length: 200 m
- Temperature: 250°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 9	**Pin**	**Disk**
Identification	13 Δ	13 Δ
Material	Z10CDVNb91	Z10CDVNb91

The Figure 27 shows the evolution of wear depth and friction coefficient during the test. At the beginning of the test, the pin has been broken, due to the important tangential force. The maximal flexion strain is 370 MPa, witch is a high value. Re = 480 MPa at 20°C and 331 MPa at 550°C, Rm = 367 MPa at 550°C. So the strain is near from mechanical resistance limits.

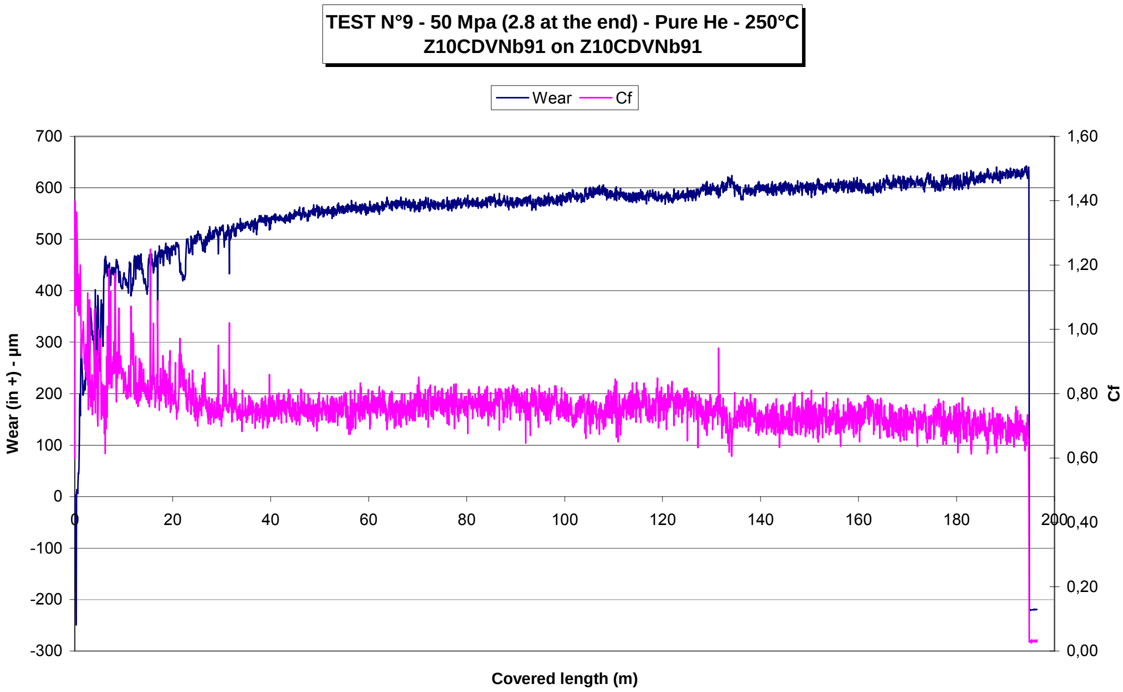


Figure 27: Wear and friction coefficient evolution – test 9

The Figure 28 shows the beginning of the test and the break in the wear curve at 0.3m. We don't know exactly what happened during the first 35 meters. After that, the diameter of the pin in contact with the disk is 3.2 mm (in regards of 0.75 mm at the beginning of the test). The contact pressure is then reduced to 2.8 MPa.

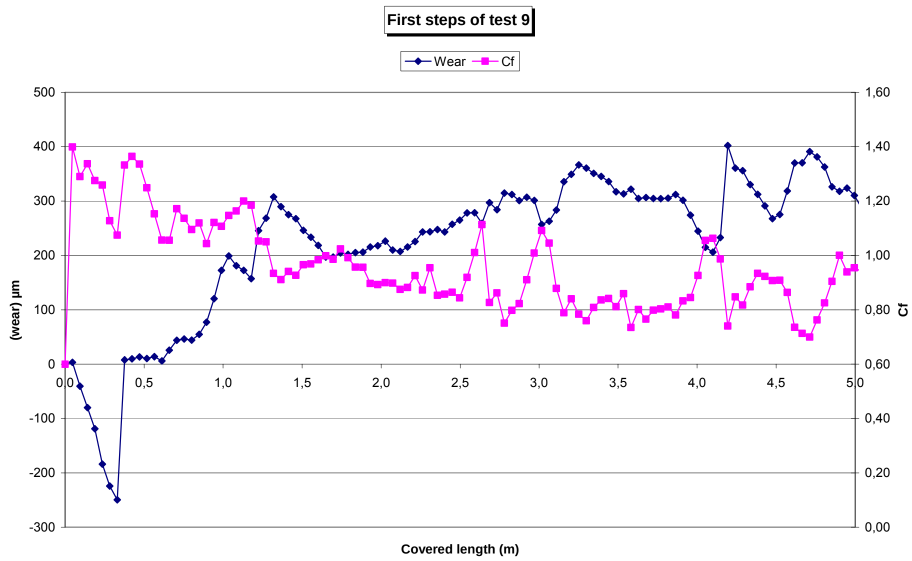


Figure 28: Beginning of test 9

The pictures (Figure 29) show a lot of debris on both pieces, agglomerated. The track of pin diameter 0.75 is not visible. That confirms the hypotheses that it has been broken at the beginning of the test.

Figure 29: Pictures of samples from test 9 before dismounting

To avoid the pin rupture, the contact pressure has been reduced to 10 MPa in the next tests.

7.4.2. Test 10

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20 mm
- Covered length: 200 m
- Temperature: 250°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 10	**Pin**	**Disk**
Identification	13	13
Material	Z10CDVNb91	Z10CDVNb91

The Figure 31 shows the evolution of wear depth and friction coefficient during the test. The debris created is visible on the pictures Figure 30. The wear volume is 2.03 mm^3, and the maximal depth observed on 4 profiles is 80 µm, for a sliding distance of 210 m.

Figure 30: Pictures of samples before cleaning - Test 10

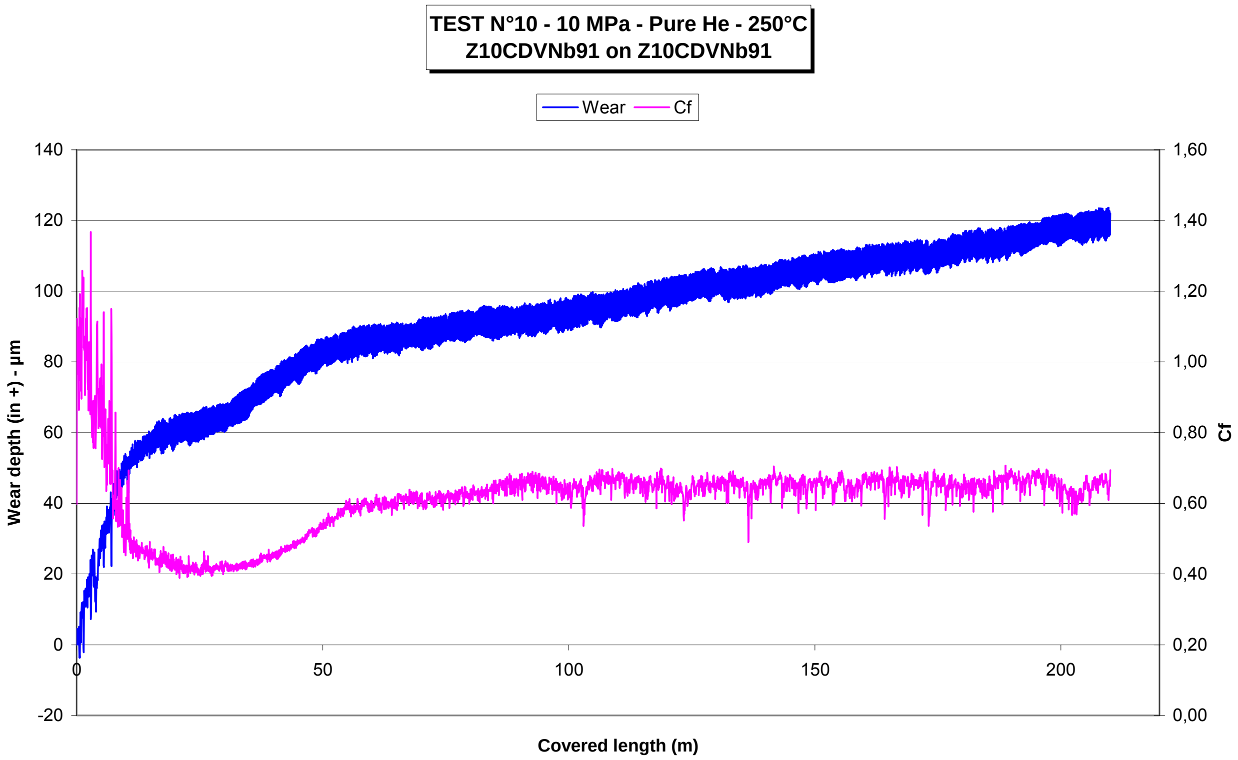


Figure 31: Wear and friction coefficient evolution – test 10

7.4.3. Test 11

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 16 mm
- Covered length: 200 m
- Temperature: 250°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

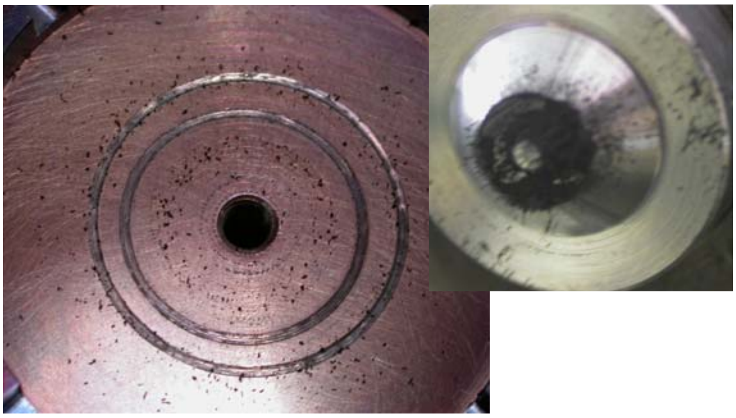


Figure 32: Pictures of samples before dismounting - Test 11

Test 11	**Pin**	**Disk**
Identification	10 Δ	13
Material	Z10CDVNb91	Z10CDVNb91

The Figure 33 shows the evolution of wear depth and friction coefficient during the test. The wear volume is 1.01 mm^3 for 201 m, with a maximal depth of 1 µm (always on 4 profiles). The pictures on Figure 32 show a lot of debris on the pin and on each side of the wear track. It's similar to test 10.

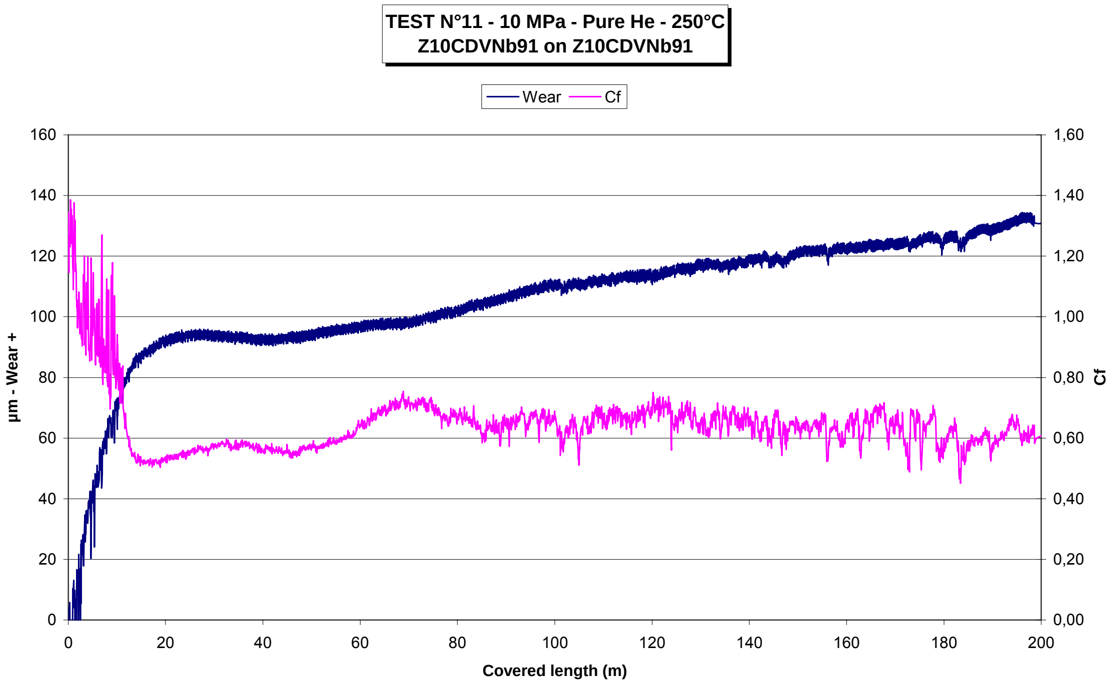


Figure 33: Wear and friction coefficient evolution – test 11

On Figure 34, the superposition of tests 10 and 11 shows another time the good reproducibility of tests. In the first 15 meters, the wear increases quickly, and the friction coefficient decreases from 1.1 to 0.5. Up to 80 meters, there is a stabilization phase, and then, the parameters are stable: the friction coefficient is constant at 0.65, and the wear increase regularly.

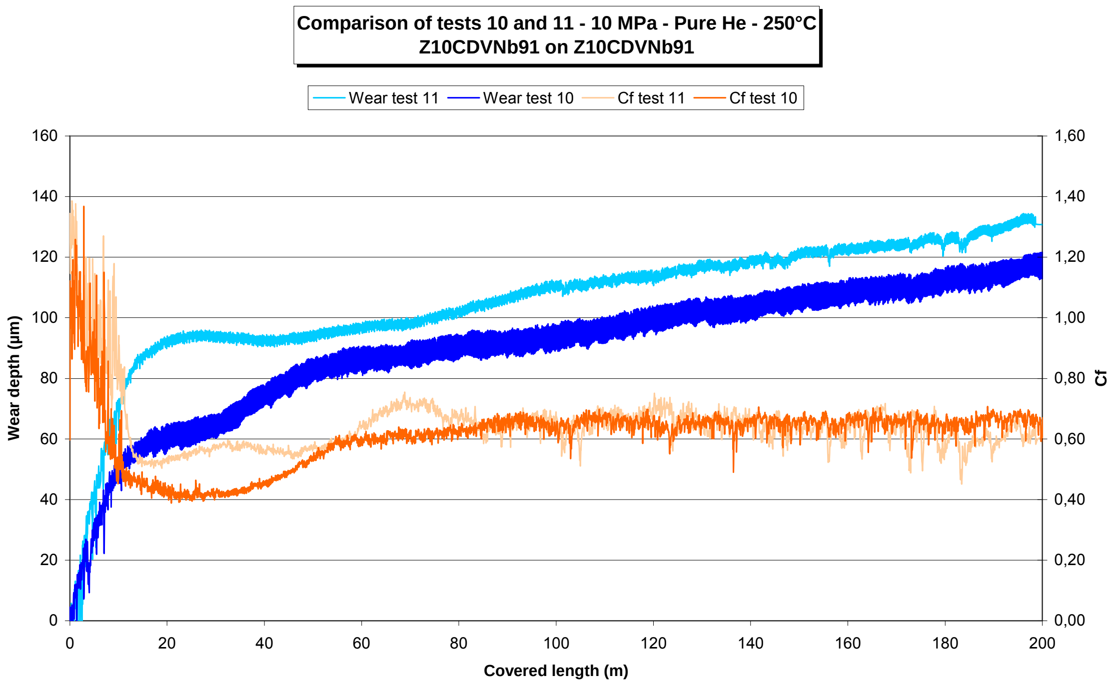


Figure 34: Comparison of tests 10 and 11

7.4.4. Test 16

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20 mm
- Covered length: 88 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 16	**Pin**	**Disk**
Identification	14 Δ	14 Δ
Material	Z10CDVNb91	Z10CDVNb91

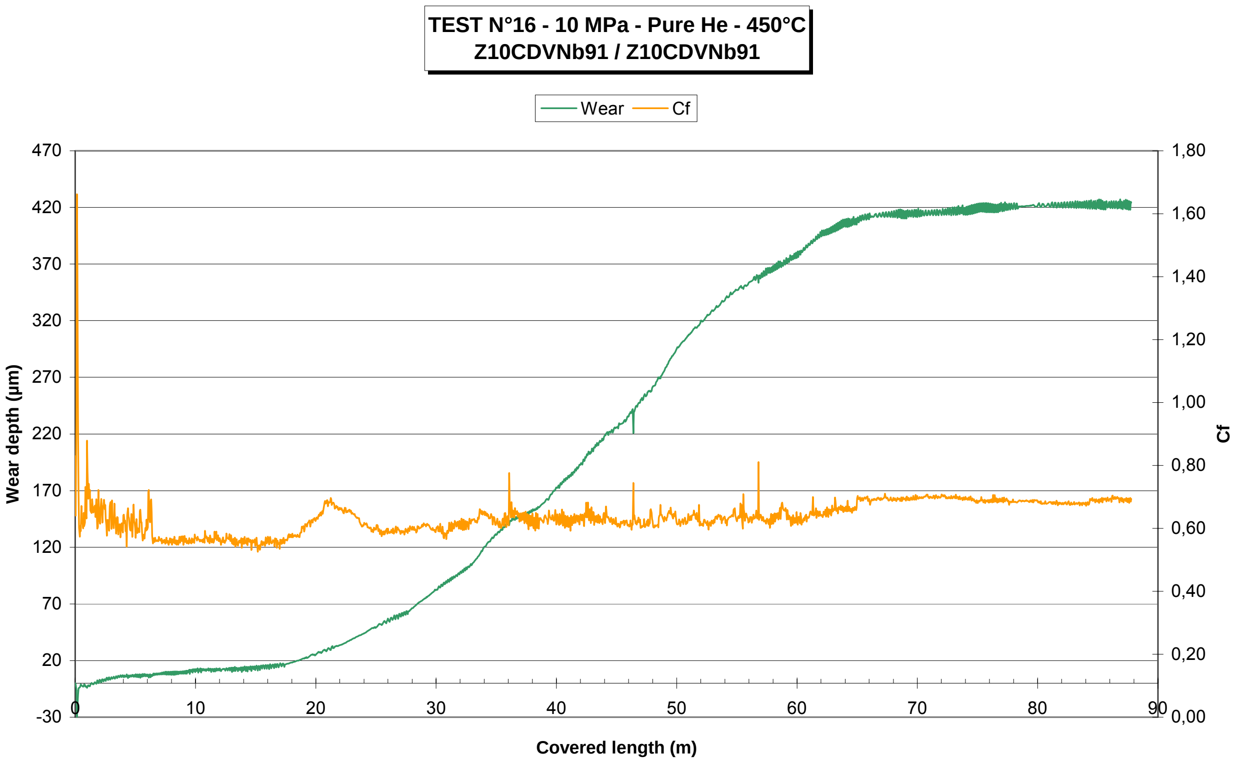


Figure 35: Wear and friction coefficient evolution – test 16

The Figure 35 shows the evolution of wear depth and friction coefficient during the test. In the first 18 m, the wear is low. After, the wear depth increases slightly, up to the complete wear of the pin diameter 0.75. At 65m, the pin is completely worn, and the wear speed (in depth) decrease due to the bigger surface of the pin in contact. The test has been stopped after 88 m covered.

The pictures of the samples (Figure 36) show debris on the pin, but also on the disk. The two tracks are visible on the disk: in the middle, the track due to the contact with the pin ∅ 0.75 mm, and around, the larger track ∅ 2.25 mm. In the middle of the worn pin, the position of ∅ 0.75 mm is visible. The wear volume is 0.59 mm^3 and the maximal depth is 40 µm.

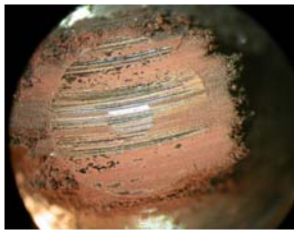


Figure 36: Pictures of samples before cleaning – Test 16

The comparison with test 10 (realized at 250°C) shows on Figure 37 a different behaviour of the contact. The wear in test 16 is much lower at the beginning of the test, and increase strongly (10 µm/m), while in test 10, the wear increase at 0.65 µm/m. The ration is more than 15. The friction coefficient is a bit higher, but not so different. It's more stable.

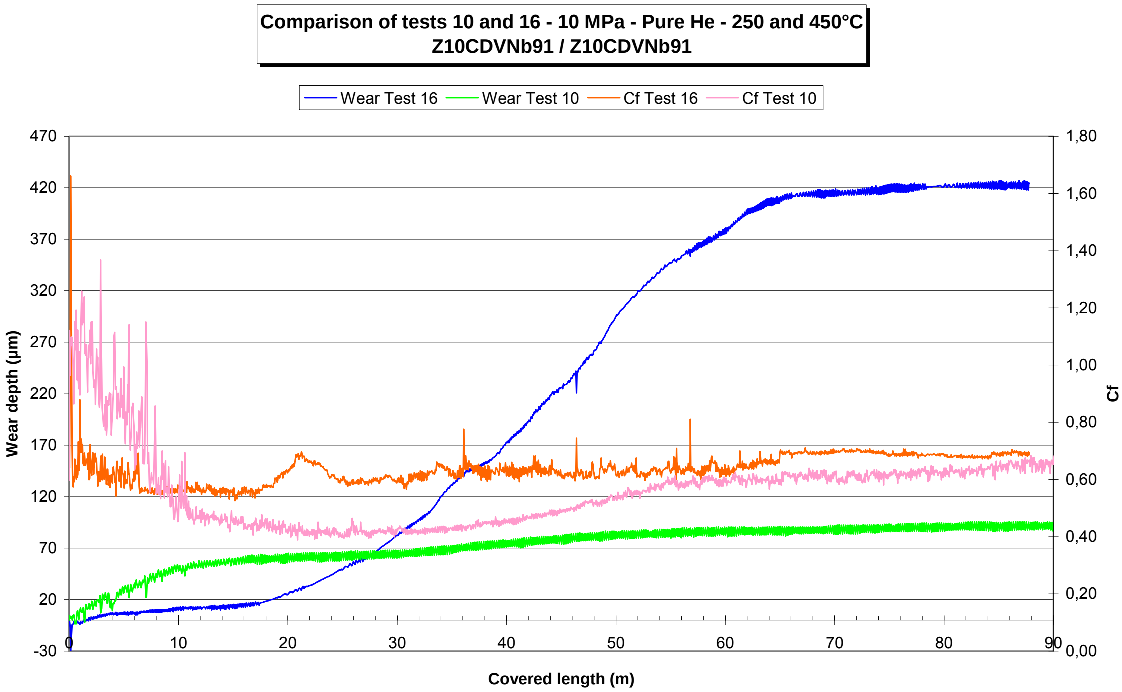


Figure 37: Comparison of tests 16 and 10

7.4.5. Test 17

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 16 mm
- Covered length: 200 m

- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 17	**Pin**	**Disk**
Identification	14	14
Material	Z10CDVNb91	Z10CDVNb91

The Figure 38 shows the evolution of wear depth and friction coefficient during the test.

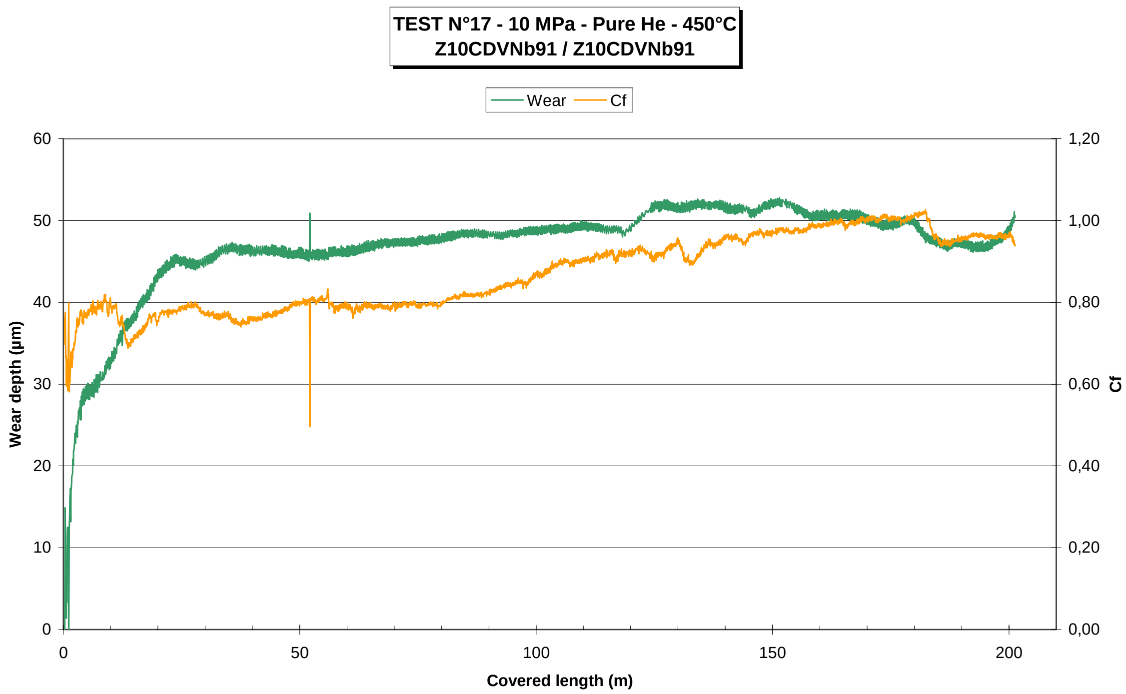


Figure 38: Wear and friction coefficient evolution – test 17

The pictures of the samples (Figure 39) show debris on the pin, but also on the disk. The pin is not completely worn.
The behaviour of the contact is completely different from test 16 (Figure 40).

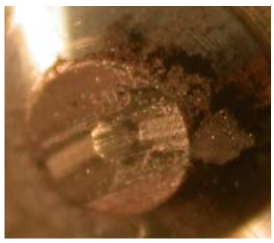


Figure 39: Pictures of samples - Test 17

The wear depth increases very slowly, and slower than during test 10 (Figure 41). The wear volume is 0.4 mm^3, and the maximal wear depth is 30 µm after 201 m.

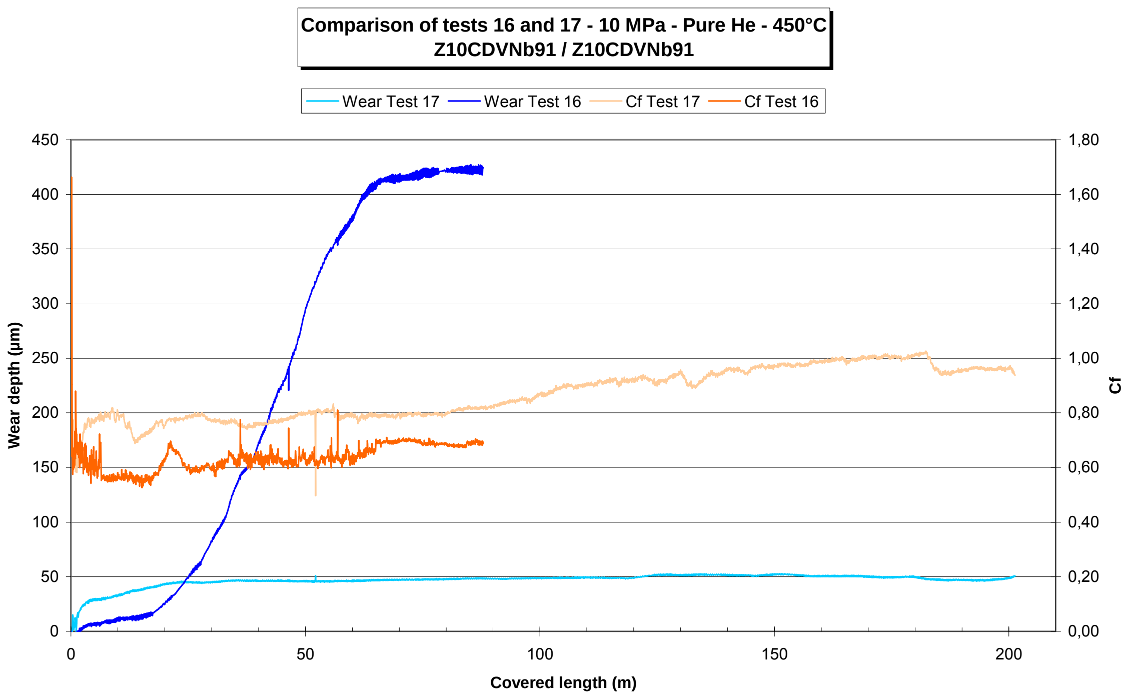


Figure 40: Comparison of tests 16 and 17

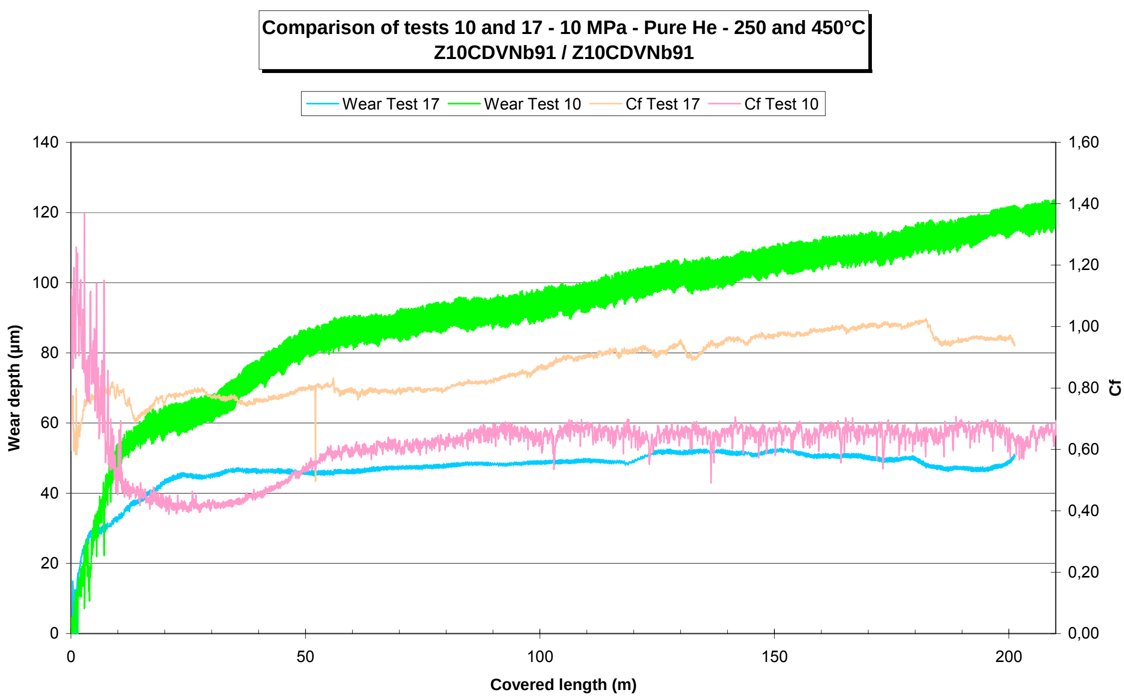


Figure 41: Comparison of tests 10 and 17

7.5. Z10CDVNb91 on Z10CDVNb91+WC/NiCr

7.5.1. Test 12

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 16 mm
- Covered length: 200 m
- Temperature: 250°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 12	**Pin**	**Disk**
Identification	12 Δ	12 Δ
Material	Z10CDVNb91	Z10CDVNb91+ SDG2005

The Figure 42 shows the evolution of wear depth and friction coefficient during the test. The friction coefficient increases slowly from 0.6 to 0.65.

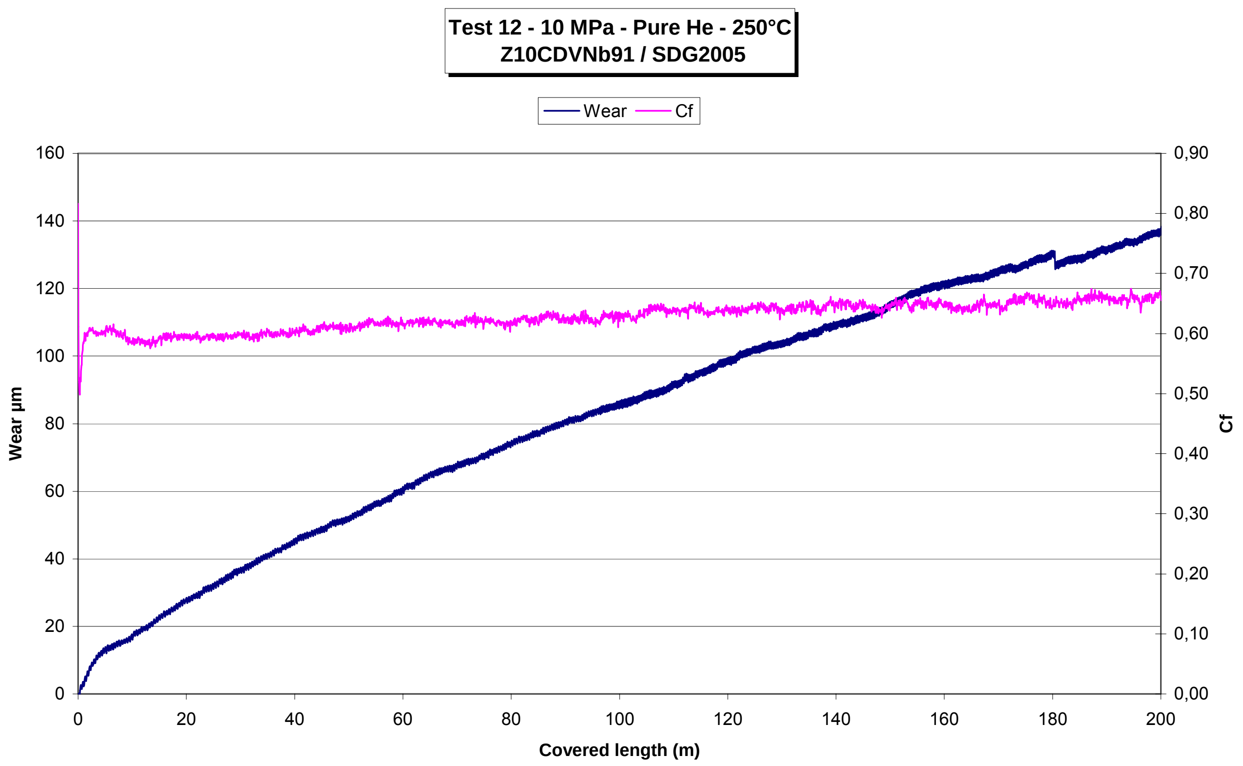


Figure 42: Wear and friction coefficient evolution – test 12

But the wear increase quickly. The pictures of Figure 43 show lots of debris on the pin, but no wear on disk track. This is confirmed by the profile measurements on the disk. The wear is not measurable. No debris is found on the disk.

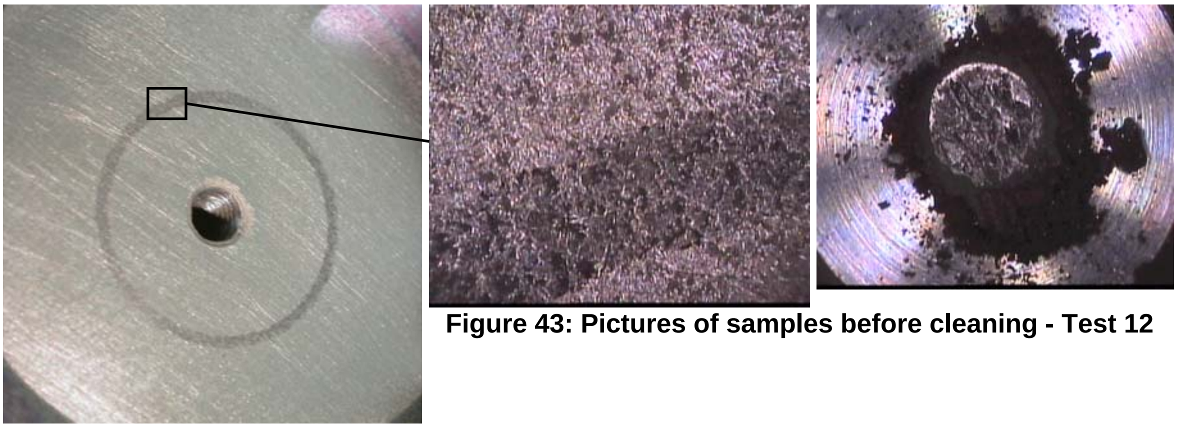


Figure 43: Pictures of samples before cleaning - Test 12

7.5.2. Test 14

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20.7 mm
- Covered length: 200 m
- Temperature: 250°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

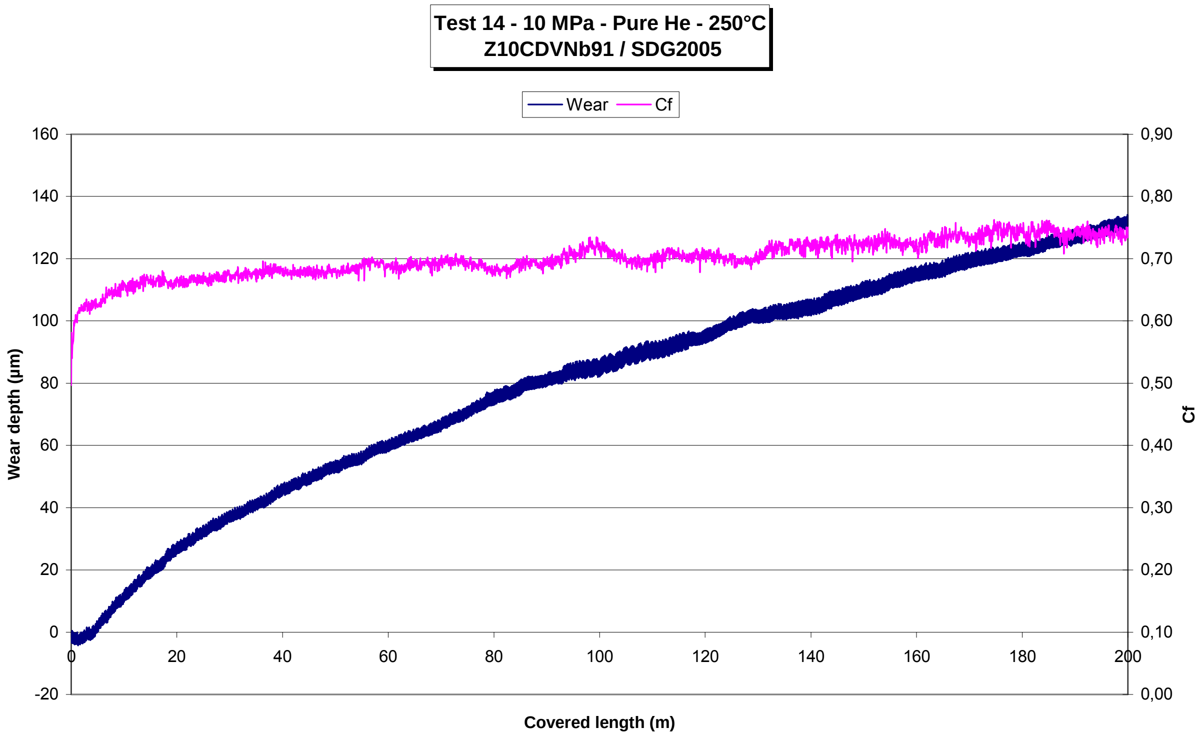


Figure 44: Wear and friction coefficient evolution – test 14

Test 14	**Pin**	**Disk**
Identification	12	12 Δ
Material	Z10CDVNb91	Z10CDVNb91+ SDG2005

The Figure 44 shows the evolution of wear depth and friction coefficient during the test, that are similar to those from test 12. Only the friction coefficient is a bit higher. The samples are similar also (Figure 45). Only the pin is worn. The wear on the disk is not measurable. The roughness is not modified in the wear track.

Figure 45: Pictures of samples before dismounting - Test 14

The comparison of tests 12 and 14 (Figure 46) show the same behaviour of the contact in both tests. The wear evolution is the same. The friction coefficient is a bit different: 0.65 at the end of the test 12, and 0.73 at the end of the test 14. The wears on pins are similar.

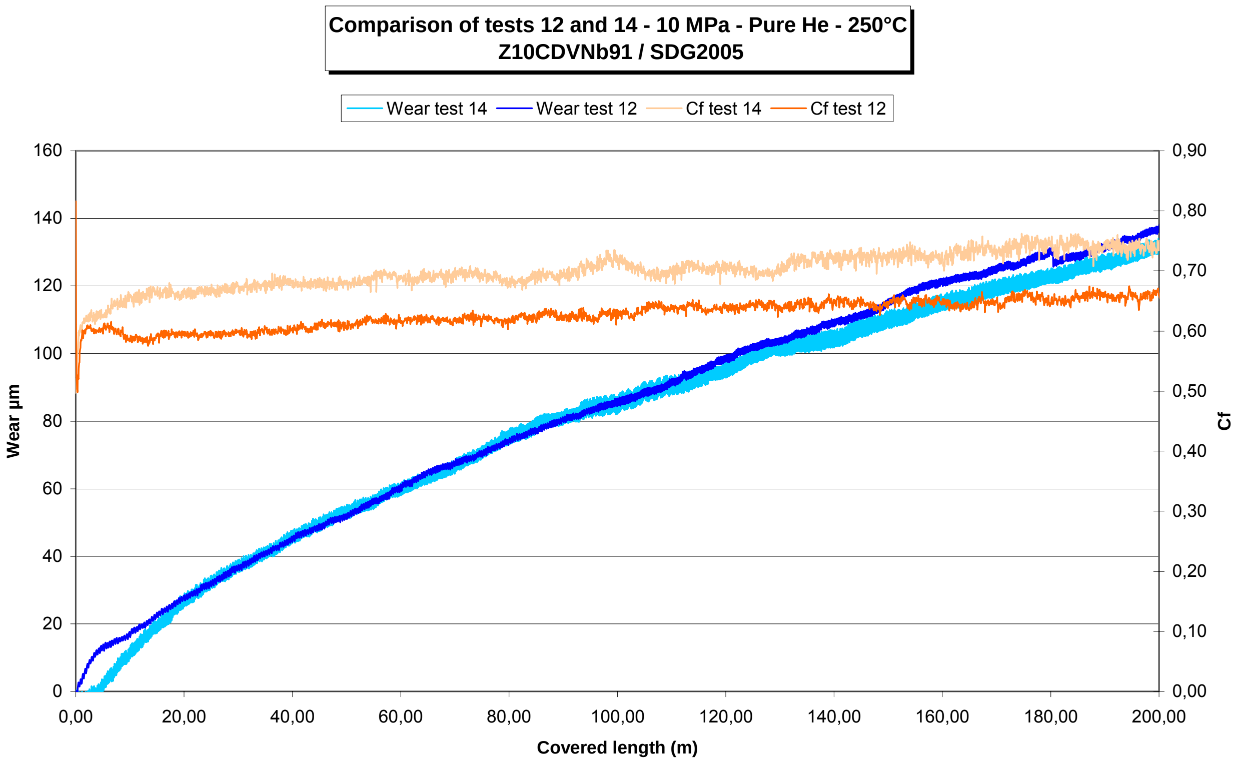


Figure 46: Comparison of tests 12 and 14

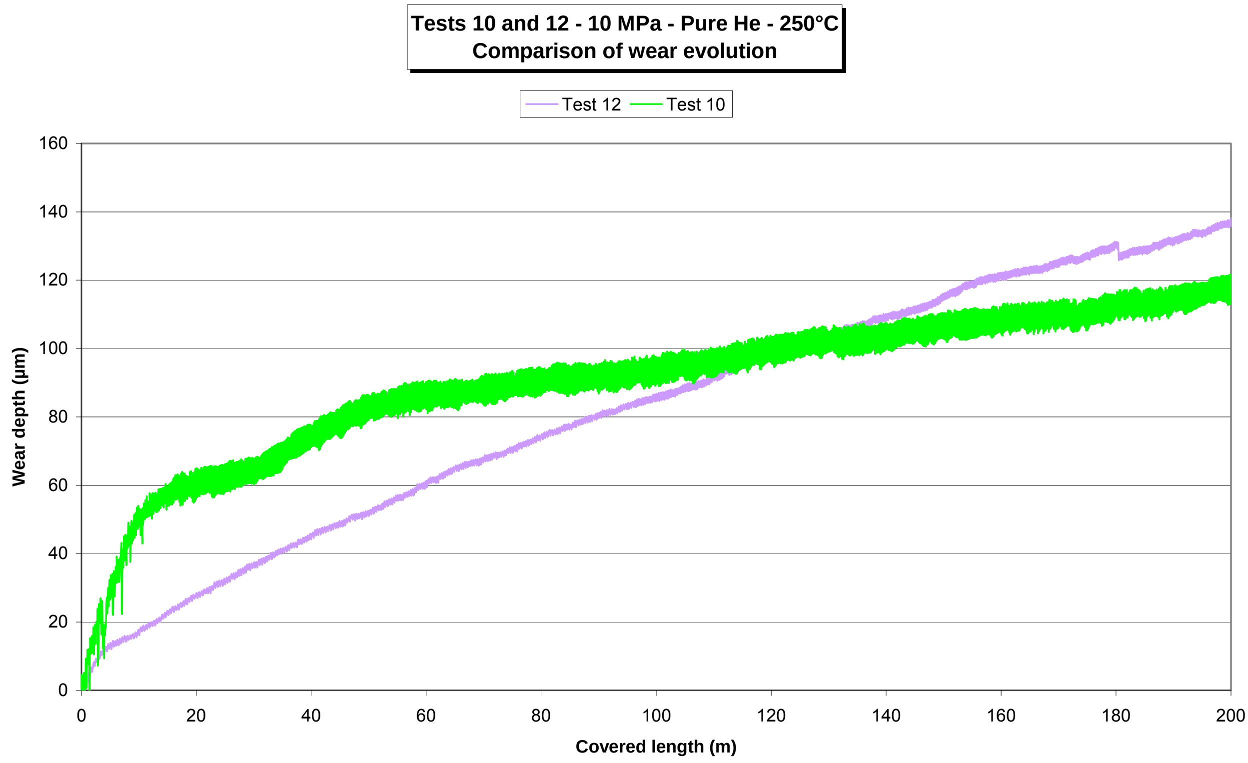


Figure 47: Comparison of tests 10 and 12

If we compare the wear evolution to test 10 (Figure 47), it's different. In the stable phase (after 60 m), the wear process is faster in test 12 than in test 10. This must be taken into account in the component design. The coated component is well protected, but the component in contact will be worn faster than against the not coated component in Z10CDVNb91.

7.6. Z10CDVNb91 on Z10CDVNb91+TiC

7.6.1. Test 13

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 16 mm
- Covered length: 200 m
- Temperature: 250°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 13	**Pin**	**Disk**
Identification	11 Δ	11 Δ
Material	Z10CDVNb91	Z10CDVNb91+TiC

The Figure 48 shows the evolution of wear depth and friction coefficient during the test. At 3 meters, there is a big step in the wear depth that decreases suddenly (Figure 49). An explanation could be the rupture of thin TiC film of 2.2 µm. The coating forms a third body in the contact that protects the surfaces. After, the wear increases slowly.

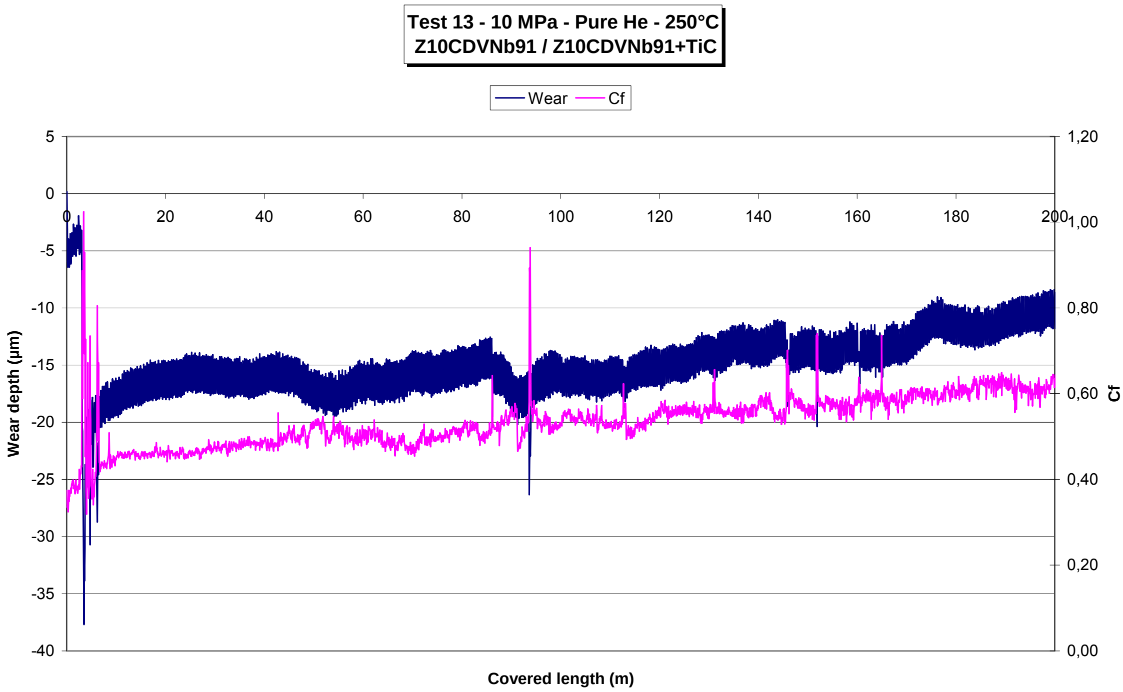


Figure 48: Wear and friction coefficient evolution - Test 13

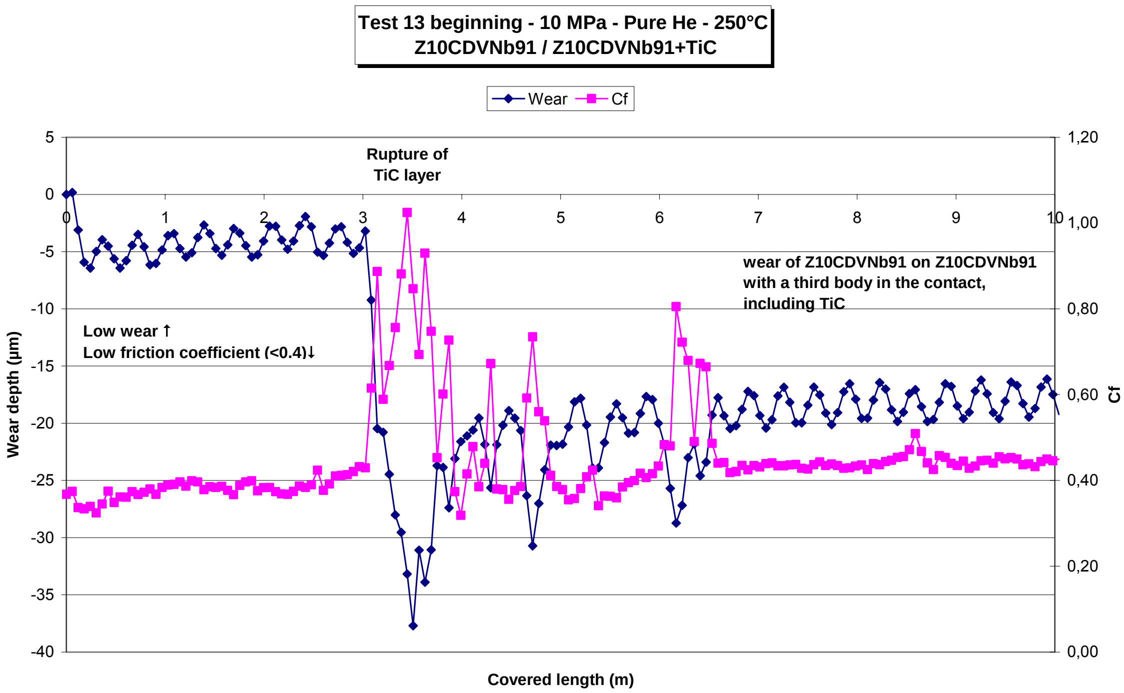


Figure 49: Beginning of test 13

The friction coefficient is lower than in other tests with pin in Z10CDVNb91: less than 0.4 at the beginning with TiC coating, and 0.6 at the end of the test. On pictures (Figure 50), the debris is on the pin. The wear volume on the disk is 0.36 mm^3, and the maximal wear depth is 25 µm (measured on 4 profiles), for a covered length of 207 m. The wear on the pin is less important than in previous tests 12 and 14.

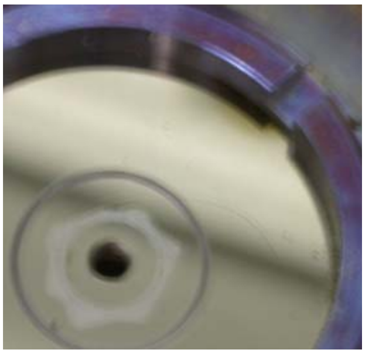



Figure 50: Pictures of samples from test 13

7.6.2. <u>Test 15</u>

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 20 mm
- Covered length: 200 m
- Temperature: 250°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 15	**Pin**	**Disk**
Identification	11	11 Δ
Material	Z10CDVNb91	Z10CDVNb91+TiC

The Figure 52 shows the evolution of wear depth and friction coefficient during the test. The behaviour of the contact is different from that of test 13.

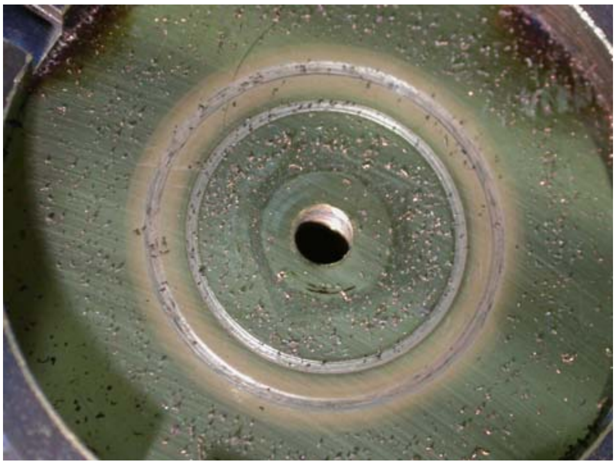
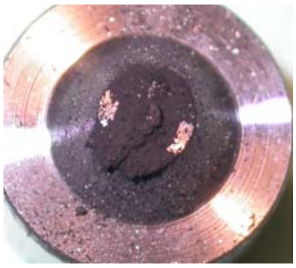



Figure 51: Picture of the samples before cleaning - Test 15

The 40 first meters are disturbed (Figure 53). After 23 meters, the behaviour is the same as with not coated Z10CDVNb91 (see comparison with test 10 in Figure 54). The beginning of wear Z10CDVNb91 on Z10CDVNb91 is similar as in test 10, up to 60 m. After the friction coefficient is stabilized to a value of 0.9, higher than in test 10. The wear volume on the disk is 2.54 mm^3, and the maximal wear depth is 81 µm (measured on 4 profiles), for a covered length of 191 m. Theses values are similar to those from tests 10 and 11 without coating.

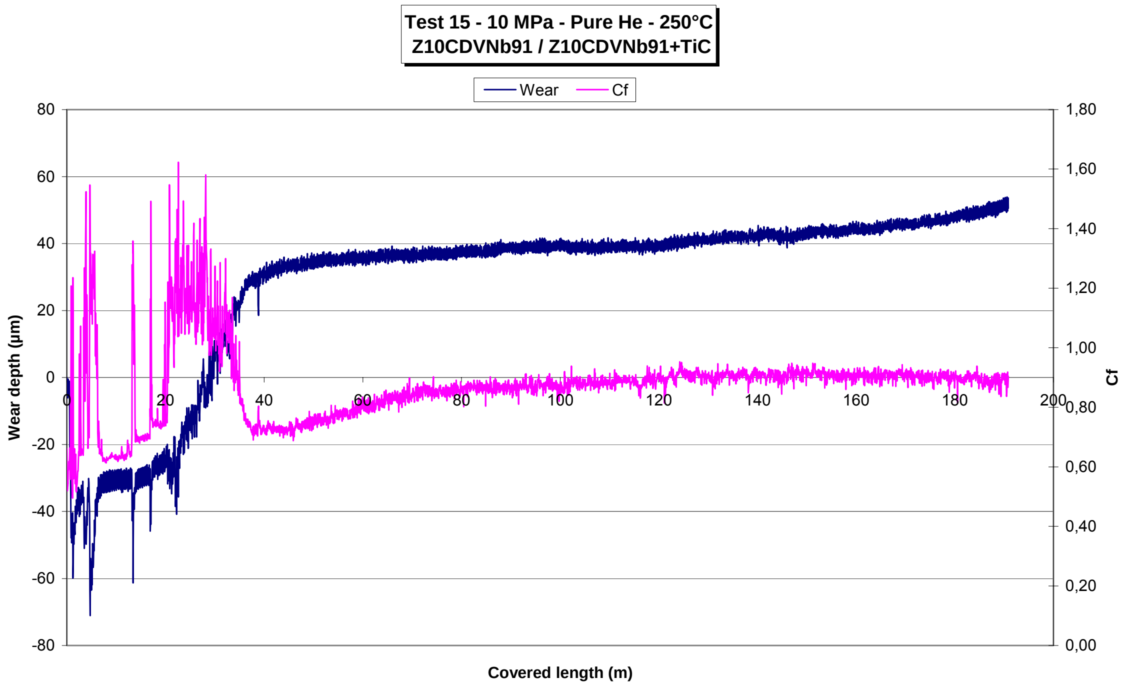


Figure 52: Wear and friction coefficient evolution - Test 15

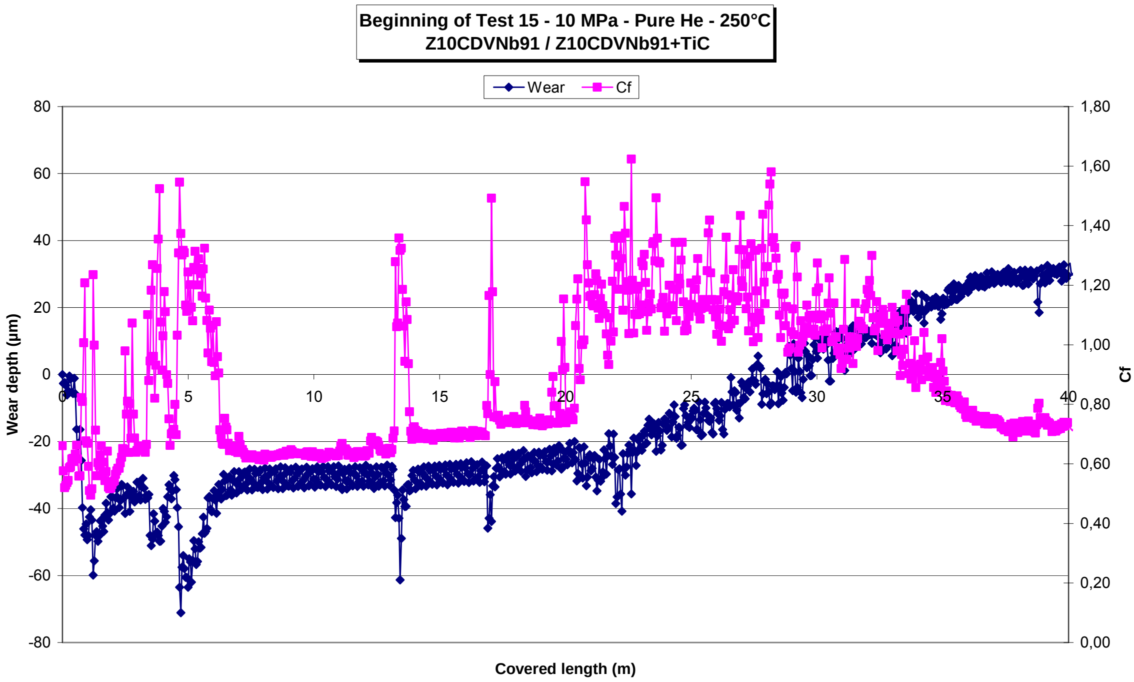


Figure 53: Beginning of test 15

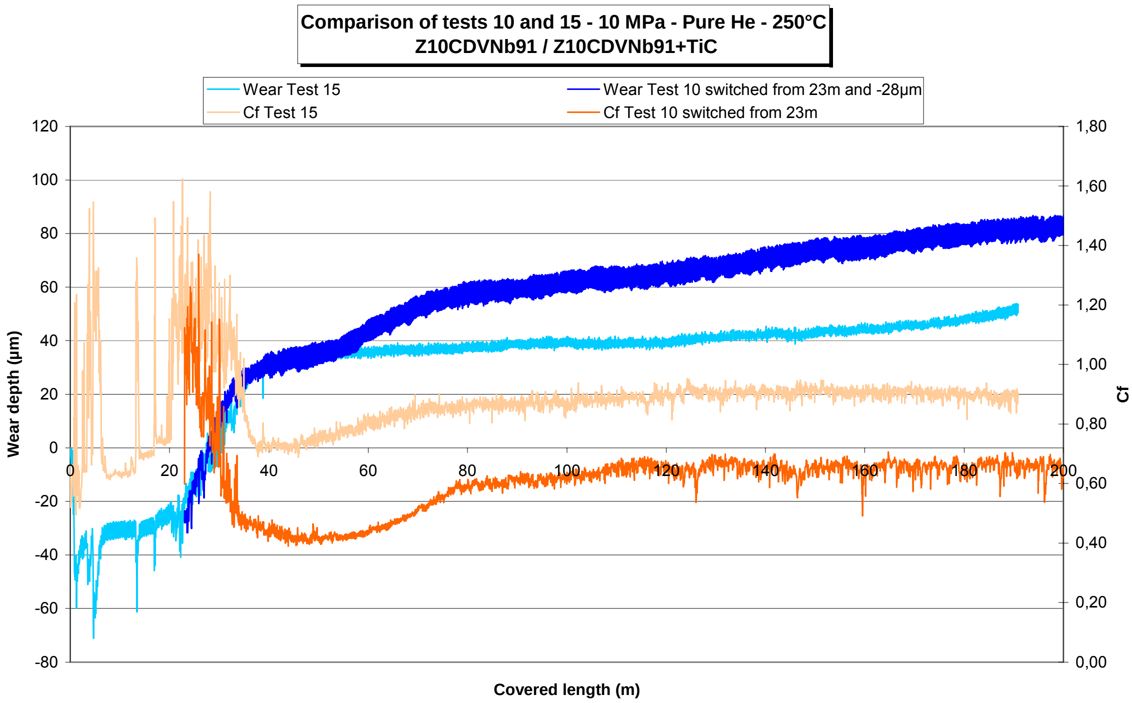


Figure 54: Comparison of tests 10 and 15

The pictures Figure 51 show debris on the disk, even though there was no debris on the disk in test 13. The pin is covered with debris, coming from the contact.

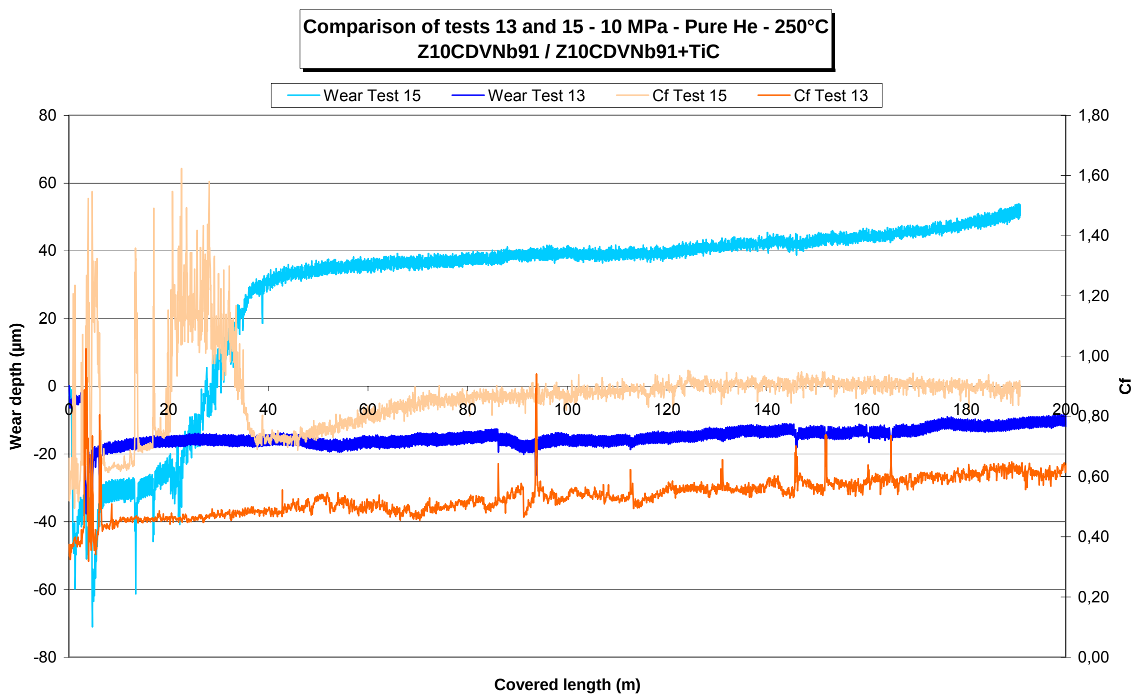


Figure 55: Comparison of tests 13 and 15

The Figure 55 presents the different behaviour of contact between tests 13 and 15.

7.6.3. Test 18

Test conditions:

- Load: 10 MPa
- Sliding speed: 15.7 mm/s
- Sliding Diameter: 16 mm
- Covered length: 200 m
- Temperature: 450°C
- Environment: Pure helium (scientific helium 6.0: 1 ppm impurities)

Test 18	**Pin**	**Disk**
Identification	15 Δ	11
Material	Z10CDVNb91	Z10CDVNb91+TiC

The Figure 56 shows the evolution of wear depth and friction coefficient during the test. The behaviour is similar as during test 16. The coating is broken in the first rotations. The pin is completely worn. It is not useful to realize a second test in these conditions. The coating is to thin, and we test the behaviour of Z10CDVNb91 on itself.

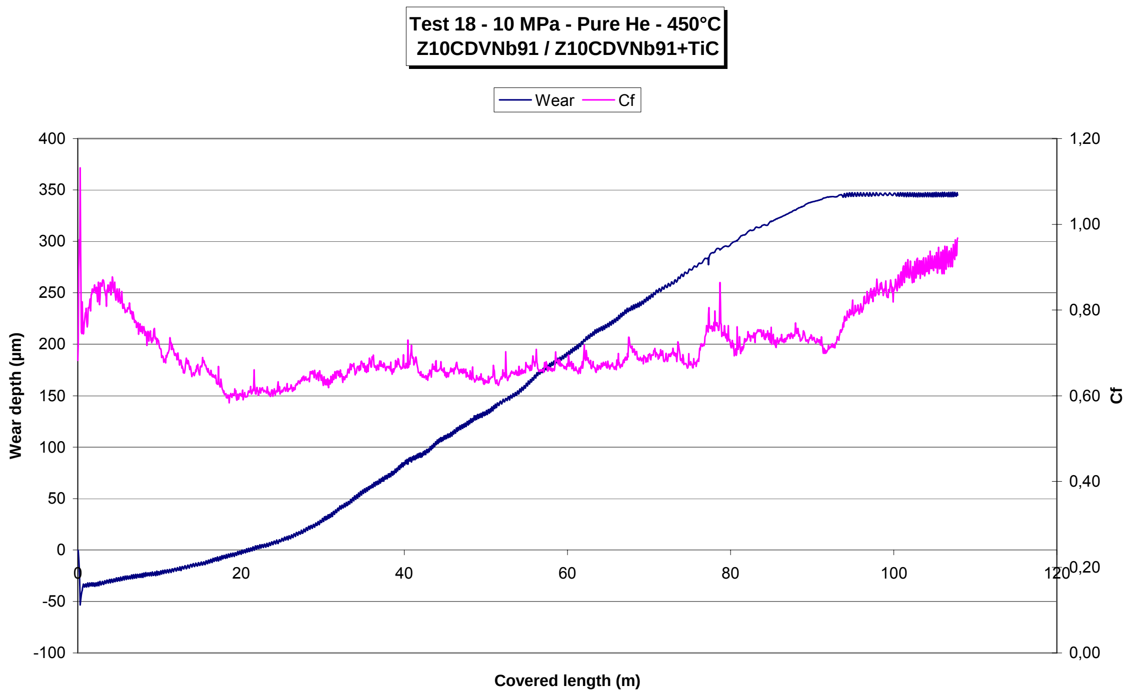


Figure 56: Wear and friction coefficient evolution - Test 18

8. CONCLUSION

A test campaign has been conducted to test the tribological behaviour of material couples considered for HTR reactors.

The tests concerned six couples of materials.

The main results are listed below:

The friction coefficient is relatively high (near 0.7) in all tests (except with the solid lubricant).

The pin on disk tribometer don't represent a real contact (it's a "standard" contact), but it allows to characterize couple of materials easily and rapidly. It is useful in the study of coatings for example, to evaluate the adhesion of the deposit…

In some cases, the wear is important, particularly in contacts metal/metal. With zirconia coatings, the surfaces are few worn. The tungsten carbide coating is resistant to wear, but the counterpart is well worn. The TiC coating was to thin to be correctly characterized. It could be interested to test another deposition process (like PACVD).

Table 3

Wear volume and wear coefficient of disk from 2D-profilometry measuremants

Test number	Material	Disk reference	Temperature (°C)	Wear						Sliding distance (mm)	Normal load (N)	Wear coefficient * ($m^3/(N.m)$)
				track width (mm)	Internal diameter (mm)	External diameter (mm)	Mean diameter (mm)	wear volume (mm^3)	Maximal depth (µm)			
1	HR230	3 Δ	450	2,46	12,18	17,10	14,64	1,81	37,41	67111	20,01	1,35E-12
2	HR230	4 Δ	450	2,35	12,40	17,13	14,76	3,01	49,47	103013	19,90	1,47E-12
5	HR230 + NiCrAlY + ZrO2/Y2O3	2 Δ	450	2,00	18,80	22,81	20,81	1,53	17,49	238302	19,90	3,22E-13
6	HR230 + NiCrAlY + ZrO2/Y2O3	2	450	1,22	19,92	22,35	21,14	NM	NM	203575	19,90	
7	HR230 + NiCrAlY + ZrO2/Y2O3/CaF2	1 Δ	450	2,03	19,05	23,11	21,08	NM	NM	201879	19,90	
8	HR230 + NiCrAlY + ZrO2/Y2O3/CaF2	1	450	1,99	18,87	22,85	20,86	NM	NM	215262	19,90	
9	Z10CDVNb91	13 Δ	250	3,50	17,86	24,83	21,34	8,63	109,4	196784	22,11	1,98E-12
10	Z10CDVNb91	13	250	0,74	20,31	21,85	21,08	2,03	79,88	210078	4,43	2,18E-12
11	Z10CDVNb91	13	250	0,73	15,48	16,91	16,20	1,01	54,48	201054	4,43	1,14E-12
12	Z10CDVNb91+ WC/NiCr	12 Δ	250	0,74	15,36	16,83	16,10	NM	NM	205843	4,43	
13	Z10CDVNb91+TiC	11 Δ	250	0,76	15,20	16,73	15,97	0,36	25,29	207407	4,43	3,95E-13
14	Z10CDVNb91+ WC/NiCr	12 Δ	250	0,79	19,90	21,48	20,69	NM	NM	208600	4,43	
15	Z10CDVNb91+TiC	11 Δ	250	0,82	19,68	21,34	20,51	2,54	81,15	190852	4,43	3,01E-12
16	Z10CDVNb91	14 Δ	450	1,27	19,43	21,93	20,68	0,59	39,69	87839	4,43	1,53E-12
17	Z10CDVNb91	14	450	1,75	14,04	17,40	15,72	0,41	30,34	201298	4,43	4,60E-13
18	Z10CDVNb91+TiC	11	450	2,15	14,06	18,26	16,16	NM (Transfer)	10,76	107847	4,43	

NM Not Measurable

* Wear coefficient is defined as the ratio between wear volume and the product of normal load by sliding distance

Table 4

Wear volume and wear coefficient of pin from 2D-profilometry measuremants

Test number	Material	Pin reference	Temperature (°C)	Weight loss (mg)	Wear wear volume (mm^3)	Maximal depth (µm)	Sliding distance (mm)	Normal load (N)	Wear coefficient ($m^3/(N.m)$)
1	HR230	1 Δ	450	NW			67111	20,01	
2	HR230	2 Δ	450	**0,06**	0,01		103013	19,90	3,26E-15
5	HR230 + NiCrAlY + ZrO2/Y2O3	4	450	**4,04**	0,86		238302	19,90	1,81E-13
6	HR230 + NiCrAlY + ZrO2/Y2O3	5	450	**0,44**	0,09		203575	19,90	2,31E-14
7	HR230 + NiCrAlY + ZrO2/Y2O3/CaF2	3 Δ	450	**0,81**	0,17		201879	19,90	4,29E-14
8	HR230 + NiCrAlY + ZrO2/Y2O3/CaF2	3	450	**4,27**	0,91		215262	19,90	2,12E-13
9	Z10CDVNb91	13 Δ	250	Broken			196784	22,11	
10	Z10CDVNb91	13	250	NW	0,07	**150**	210078	4,43	7,12E-14
11	Z10CDVNb91	10 Δ	250	NW	0,04	**90**	201054	4,43	4,47E-14
12	Z10CDVNb91	12 Δ	250	NW	0,07	**150**	205843	4,43	7,27E-14
13	Z10CDVNb91	11 Δ	250	NW	0,06	**130**	207407	4,43	6,25E-14
14	Z10CDVNb91	12	250	NW	0,07	**150**	208600	4,43	7,17E-14
15	Z10CDVNb91	11	250	NW	-0,04	**-80**	190852	4,43	
16	Z10CDVNb91	14 Δ	450	NW	0,20	**460**	87839	4,43	5,23E-13
17	Z10CDVNb91	14	450	NW	0,19	**440**	201298	4,43	2,18E-13
18	Z10CDVNb91	15 Δ	450				107847	4,43	

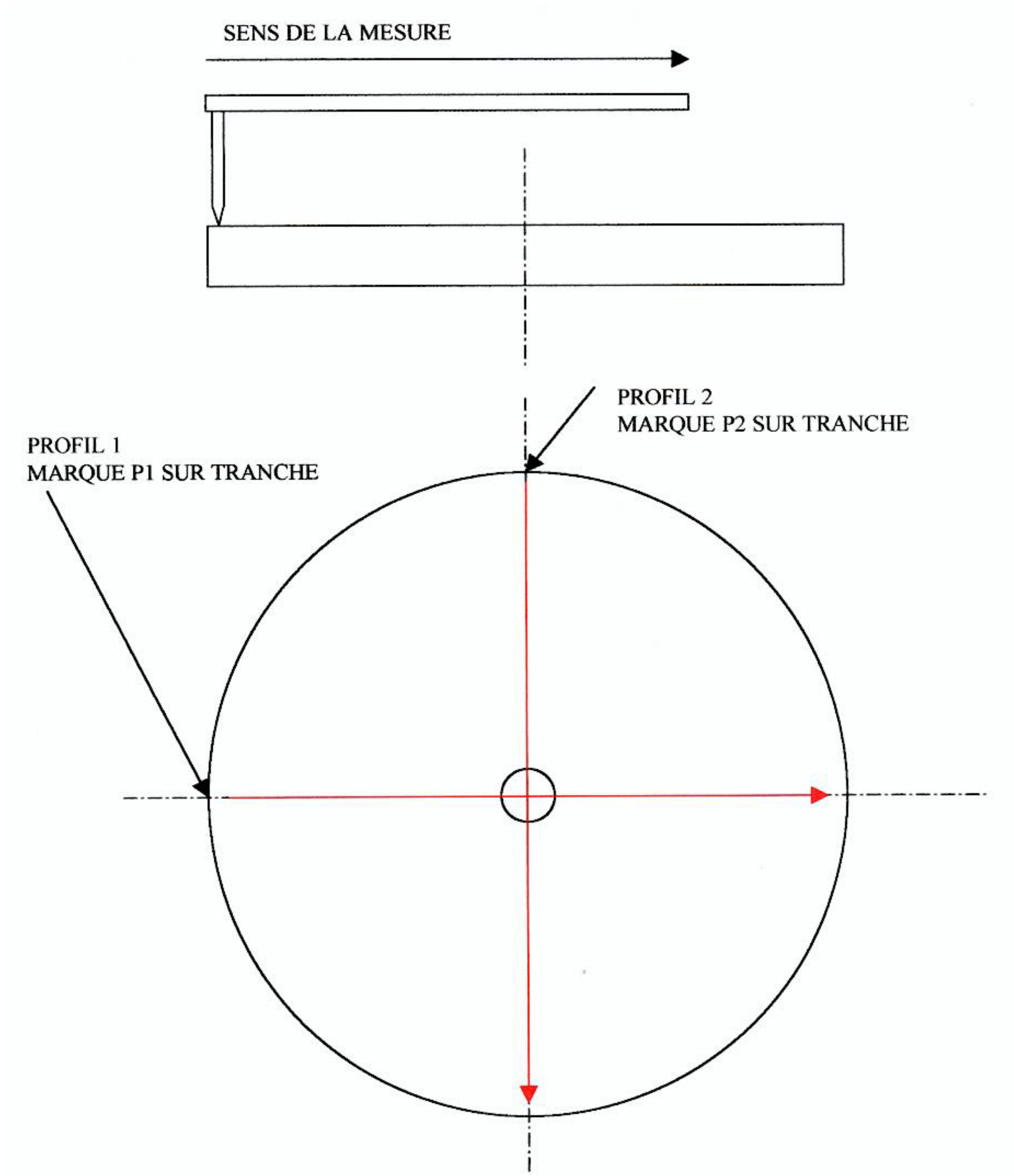
NW Not Weighted

In **Bold**, values considered for wear volume calculation

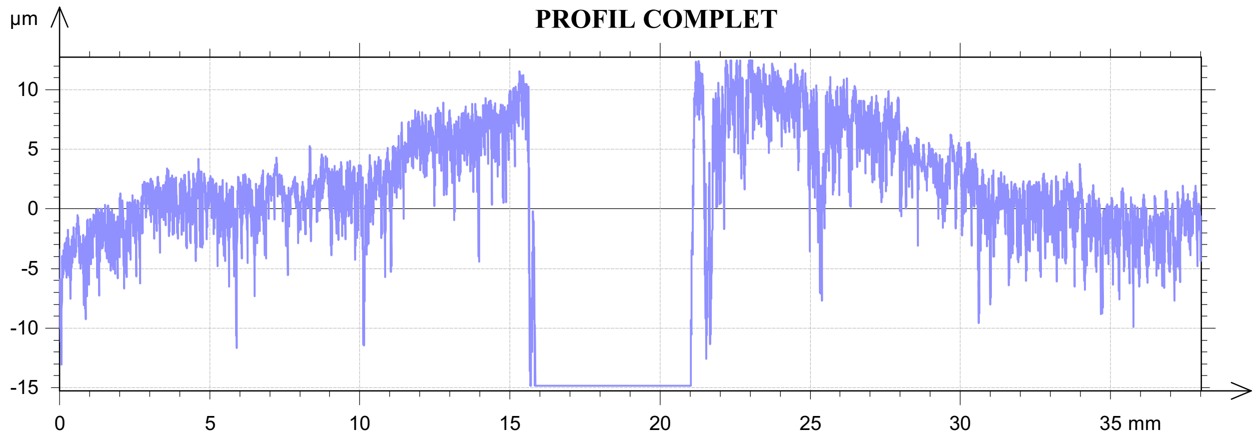
APPENDIX 1: Disk Profilometry

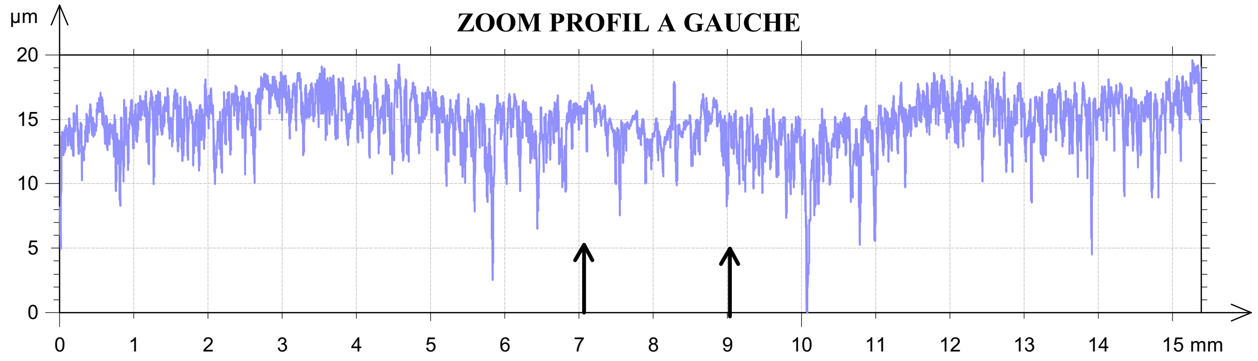
This document collects all measured profiles.

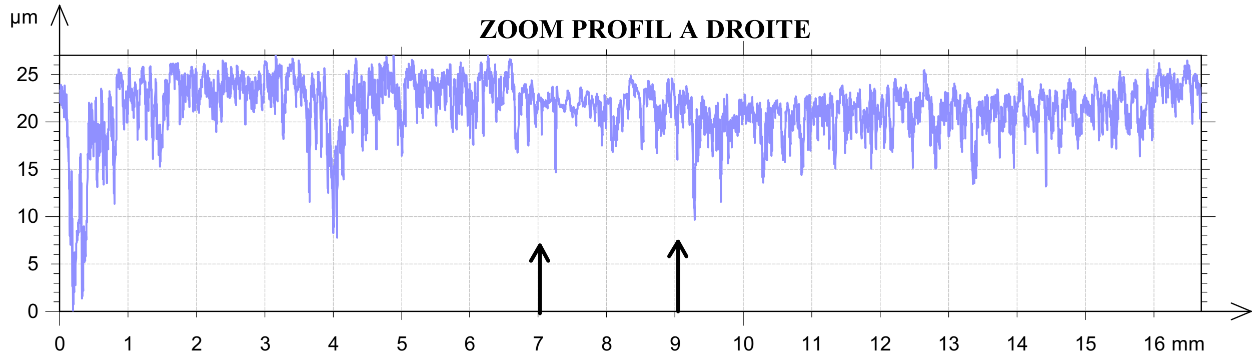
On each disk, two profiles are measured as seen on the scheme below:



DISQUE REPERE 1
(FACE GRISE - PROFIL NUMERO 1)

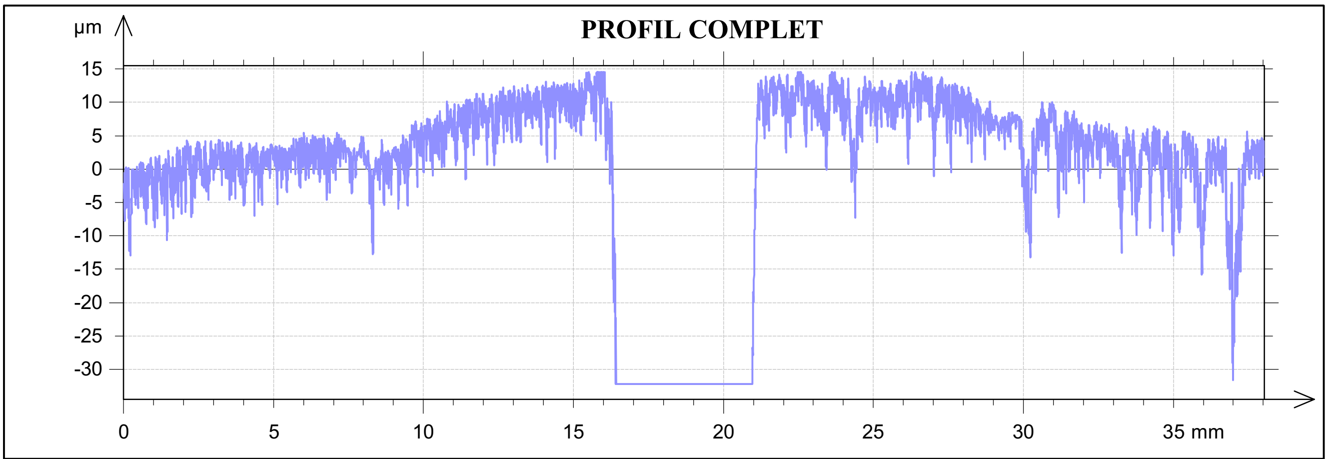


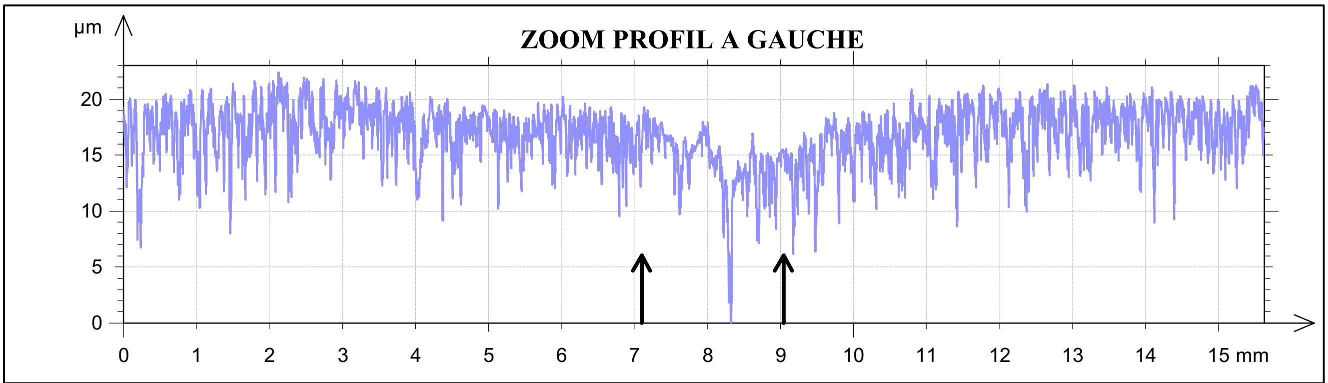


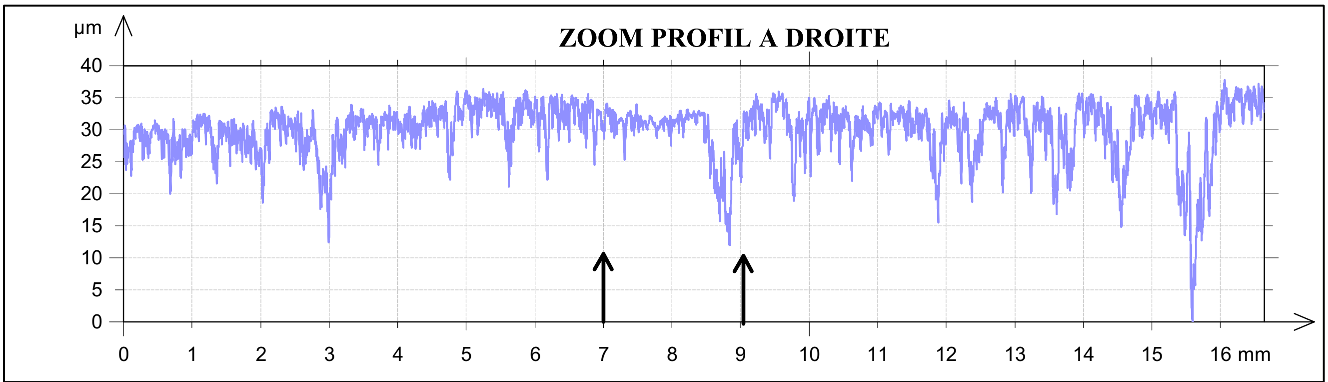


USURE A GAUCHE : **Largeur 2.047 mm**
USURE A DROITE : **Largeur 2.027 mm**
Usure sur diamètre int de **19.051 mm** et diamètre extérieure de **23.125 mm**
L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 1
(FACE GRISE - PROFIL NUMERO 2)

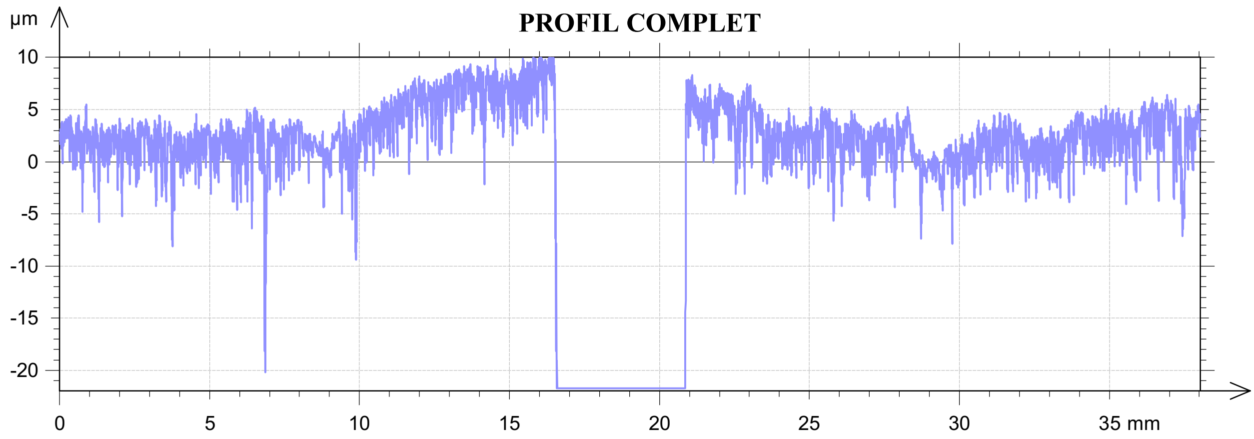


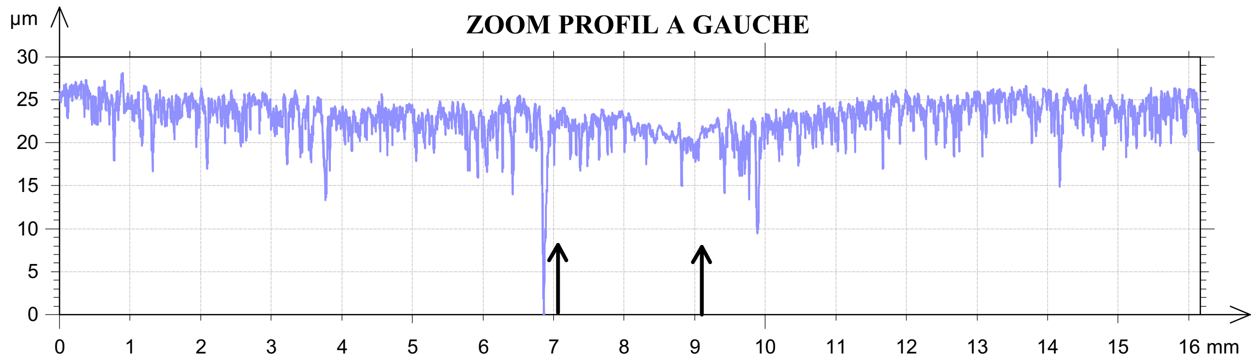


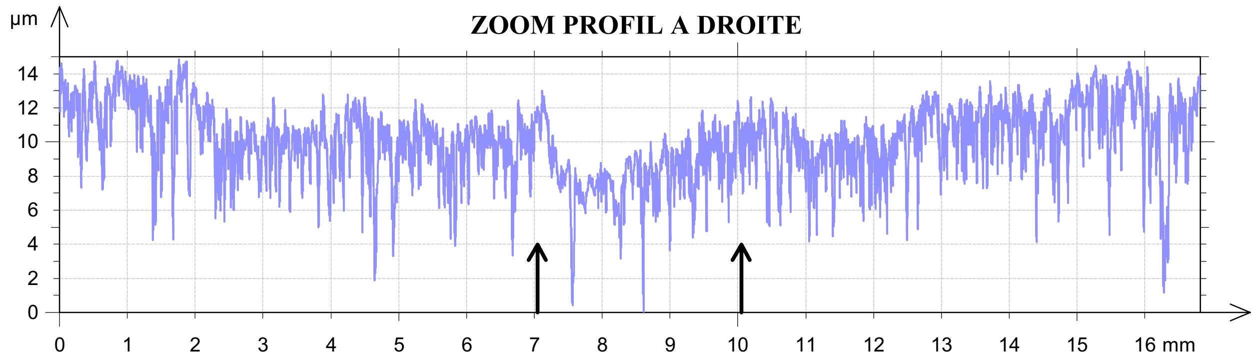


USURE A GAUCHE : **Largeur 2.026 mm**
USURE A DROITE : **Largeur 2.020 mm**
Usure sur diamètre int de **19.048 mm** et diamètre extérieure de **23.094 mm**
L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 1
(FACE BLANCHE - PROFIL NUMERO 1)

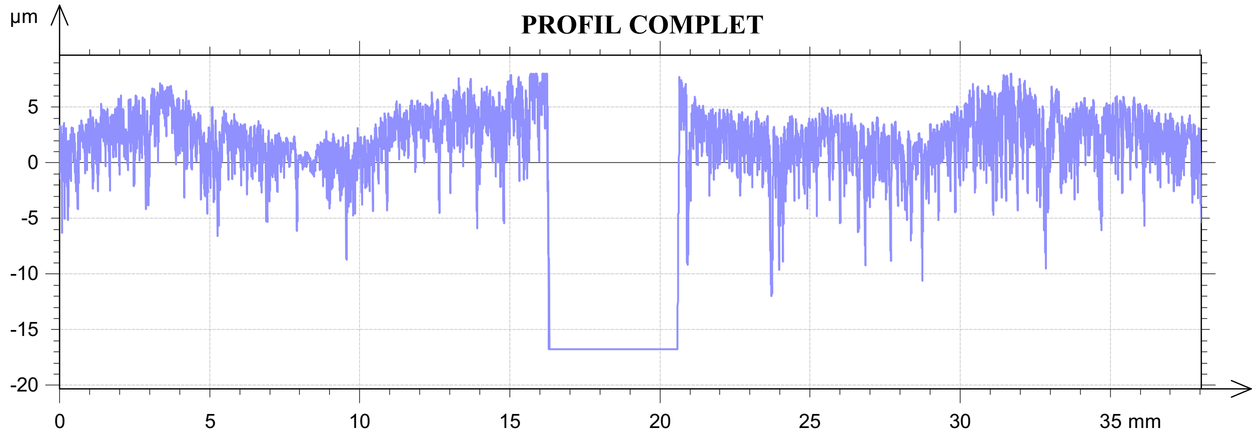


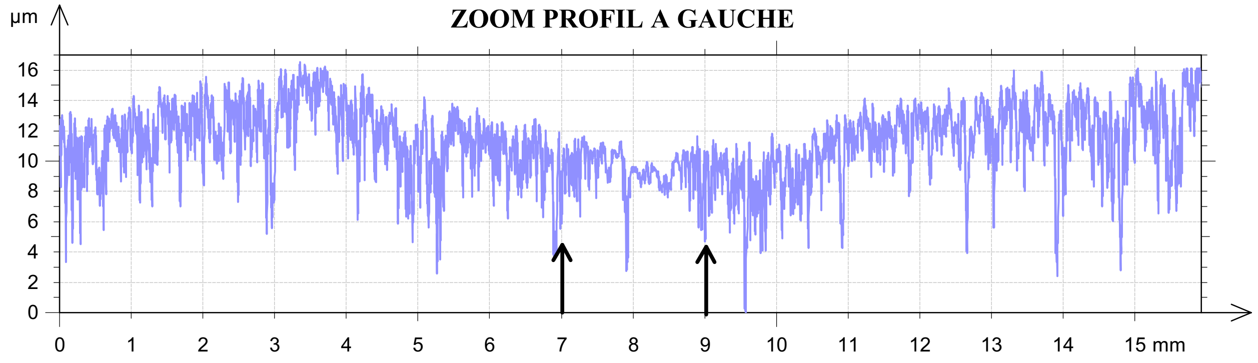


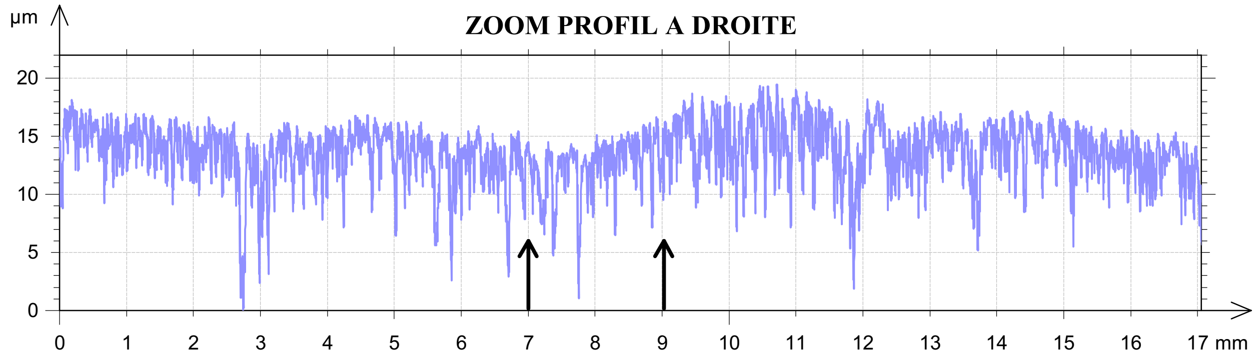


USURE A GAUCHE : **Largeur 1.886 mm**
USURE A DROITE : **Largeur 2.035 mm**
Usure sur diamètre int de **18.845 mm** et diamètre extérieure de **22.766 mm**
L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 1
(FACE BLANCHE - PROFIL NUMERO 2)

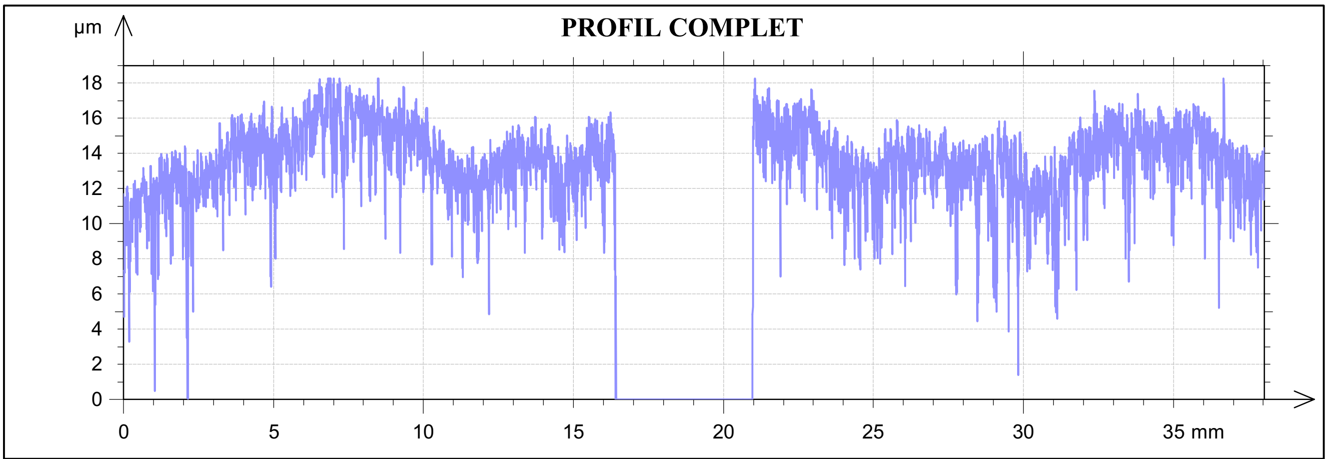


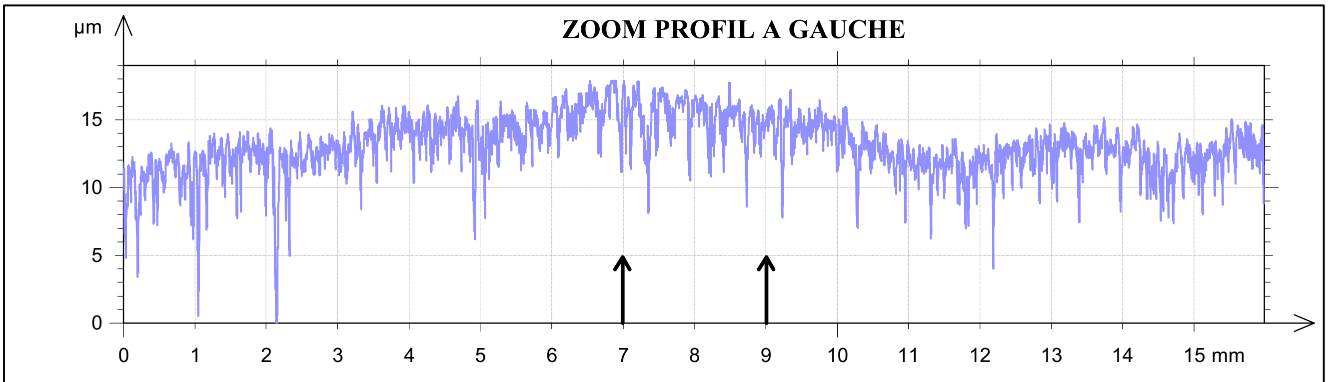


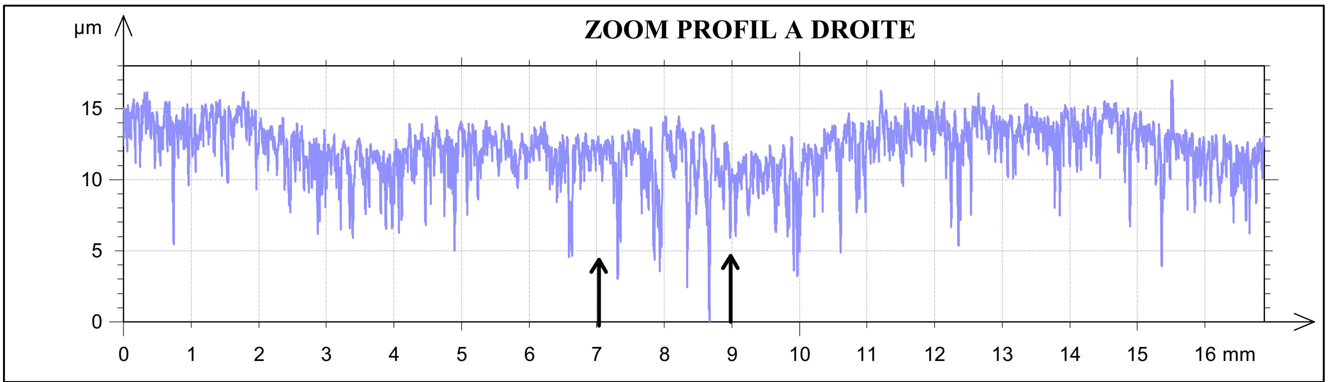


USURE A GAUCHE : **Largeur 1.984 mm**
USURE A DROITE : **Largeur 2.055 mm**
Usure sur diamètre int de **18.896 mm** et diamètre extérieure de **22.935 mm**
L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 2
(FACE GRISE - PROFIL NUMERO 1)

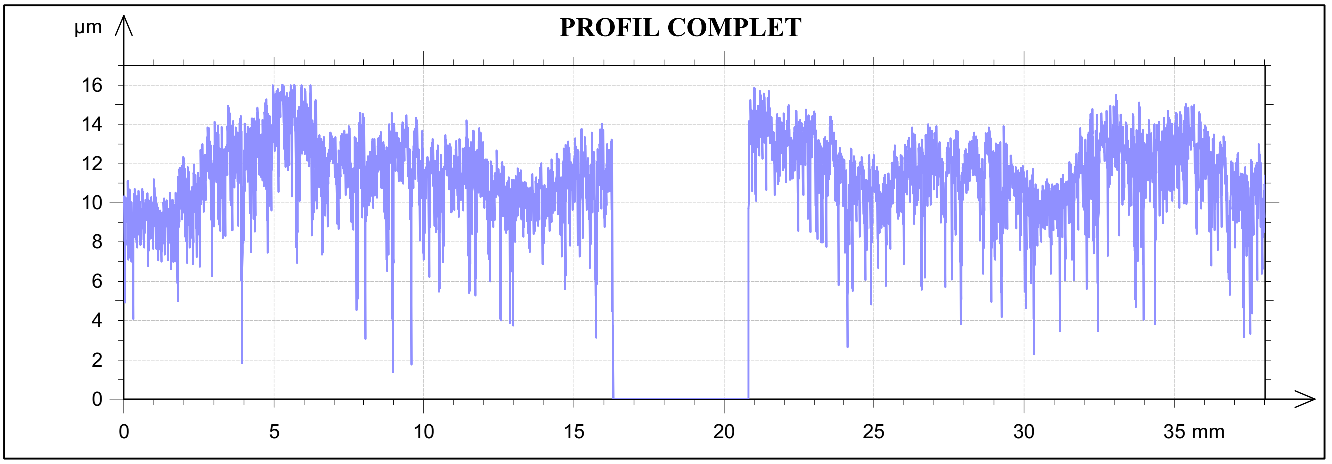


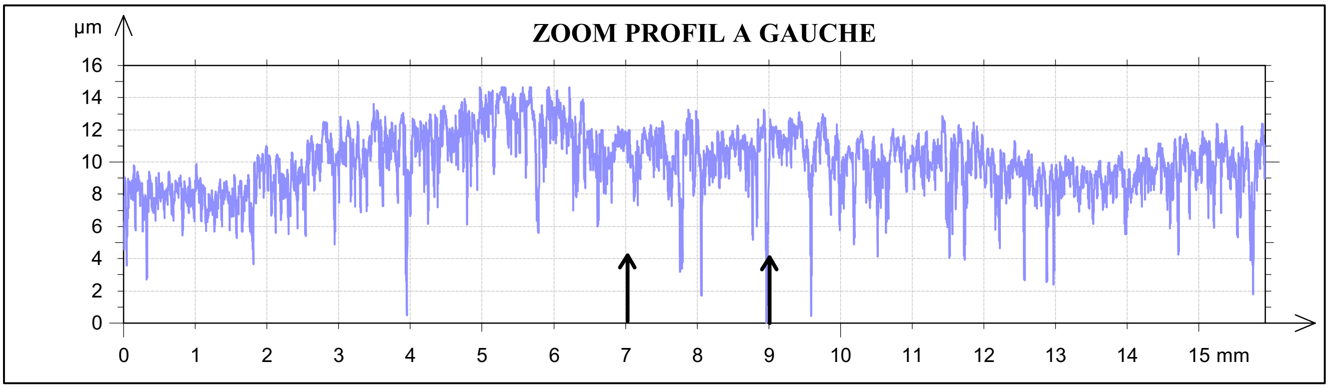


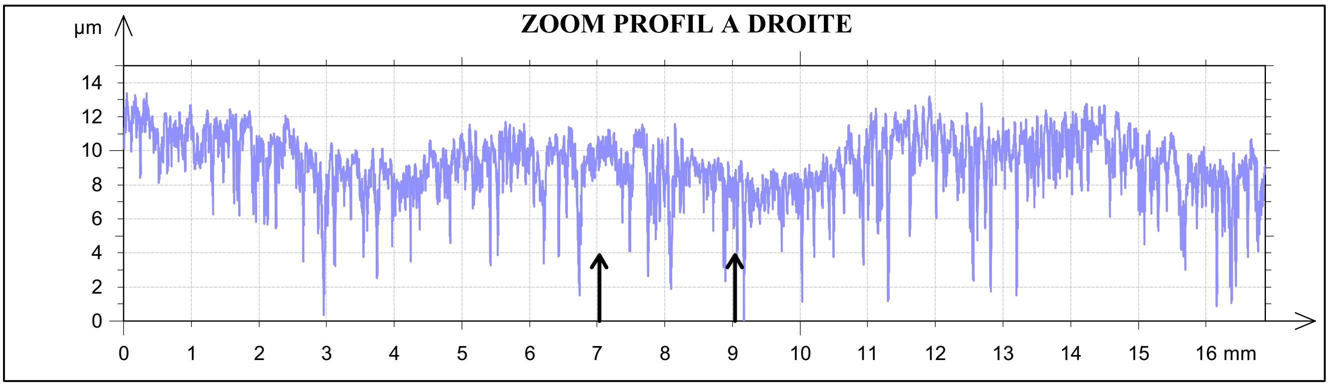


USURE A GAUCHE : **Largeur 1.724 mm**
USURE A DROITE : **Largeur 1.275 mm**
Usure sur diamètre int de **19.749 mm** et diamètre extérieure de **22.748 mm**
L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 2
(FACE GRISE - PROFIL NUMERO 2)



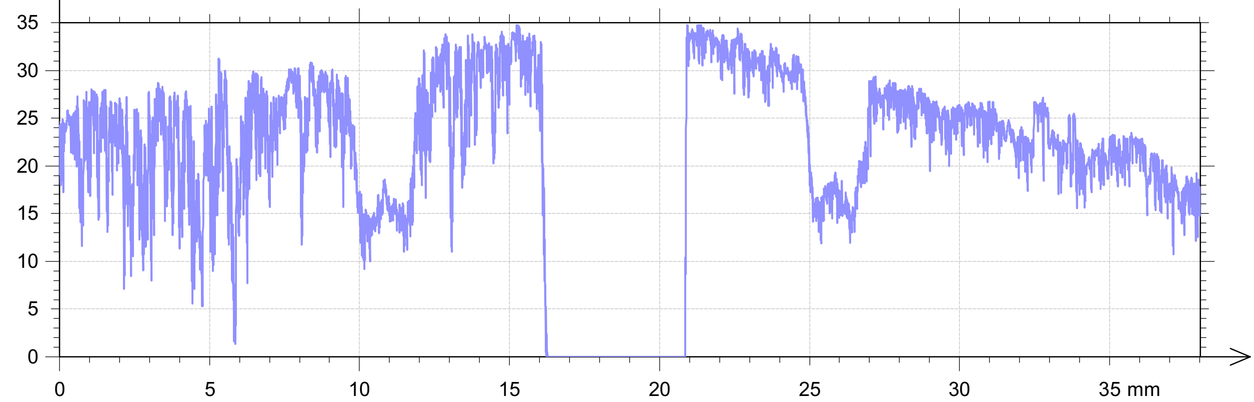




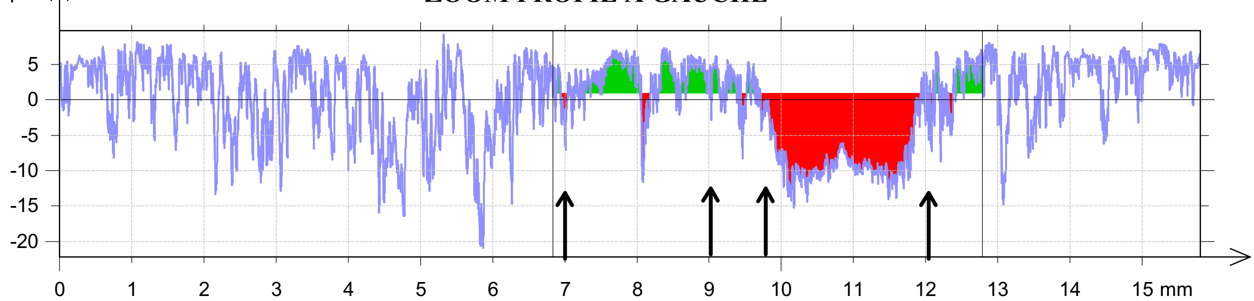
USURE A GAUCHE : **Largeur 1.040 mm**
USURE A DROITE : **Largeur 0.834 mm**
Usure sur diamètre int de **20.086 mm** et diamètre extérieure de **21.960 mm**
L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 2
(FACE BLANCHE - PROFIL NUMERO 1)

PROFIL COMPLET



ZOOM PROFIL A GAUCHE



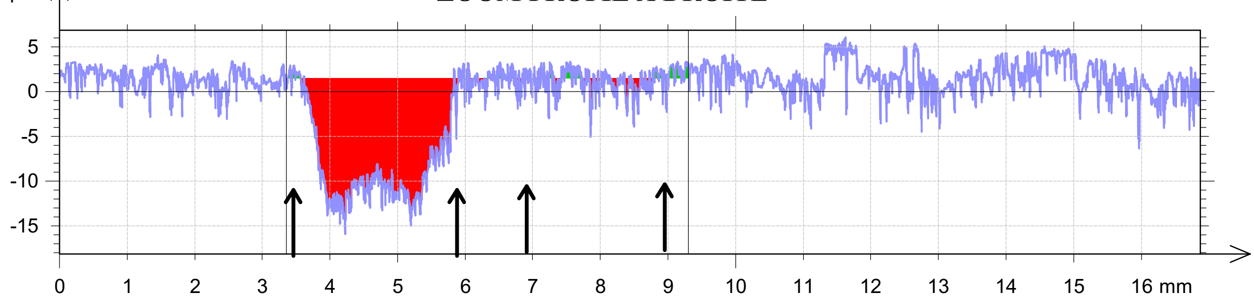
Profondeur maximum : 16.26 µm

Surface du trou : 24312 µm2

Hauteur maximum : 6.362 µm

Surface repoussée : 8394 µm2

ZOOM PROFIL A DROITE



Profondeur maximum : 17.49 µm

Surface du trou : 26747 µm2

Hauteur maximum : 1.779 µm

Surface repoussée : 1248 µm2

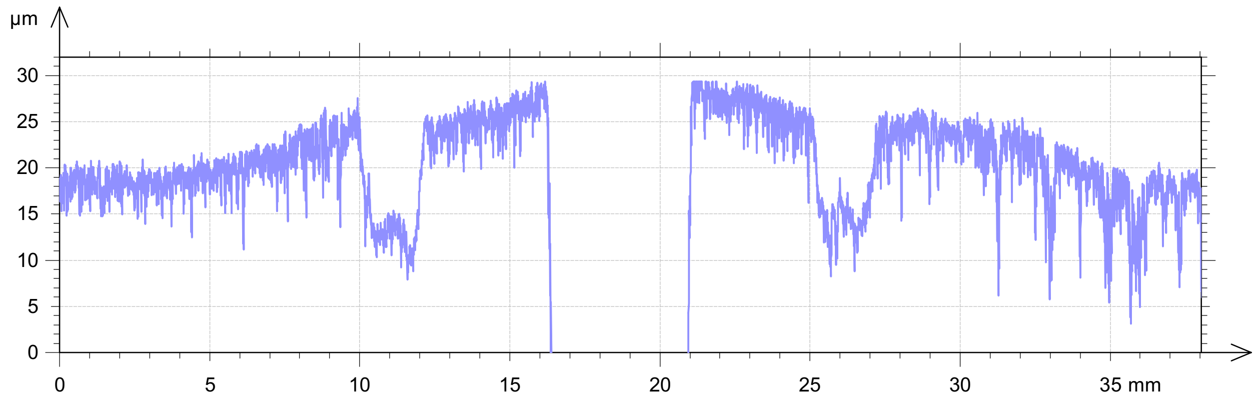
USURE A GAUCHE	Usure extérieure: **Largeur 2.060 mm**	Usure intérieure: **Largeur 2.273 mm**
USURE A DROITE	Usure extérieure: **Largeur 2.013 mm**	Usure intérieure: **Largeur 2.233 mm**

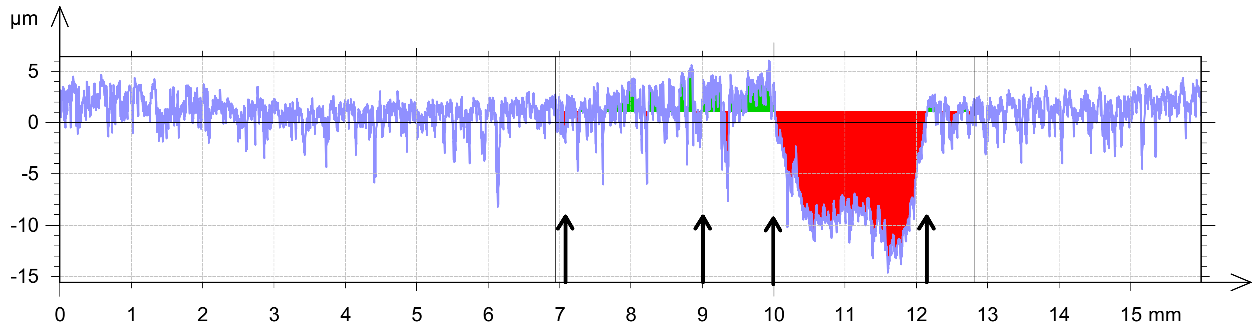
Usure extérieure sur diamètre int de **18.786 mm** et diamètre extérieure de **22.859 mm**
Usure intérieure sur diamètre int de **12.829 mm** et diamètre extérieure de **17.335 mm**

L'usure extérieure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

 Conçu avec la technologie Mountains

DISQUE REPERE 2
(FACE BLANCHE - PROFIL NUMERO 2)



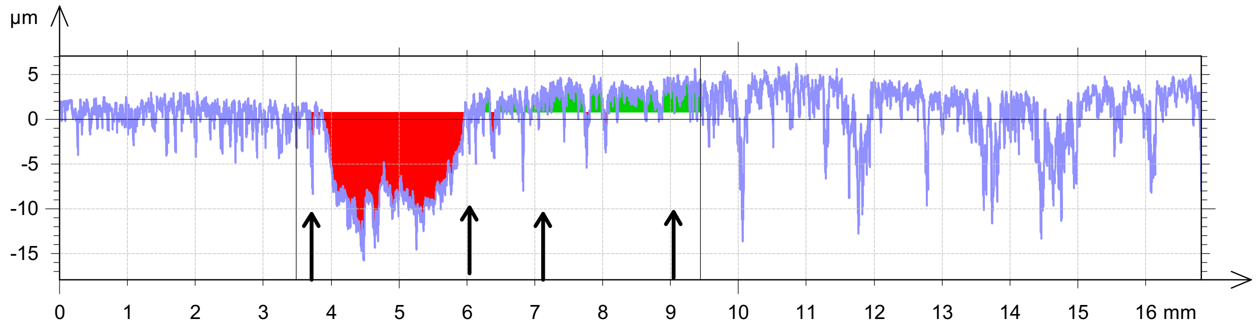


Profondeur maximum : 15.77 µm

Hauteur maximum : 4.899 µm

Surface du trou : 21851 µm2

Surface repoussée : 3641 µm2



Profondeur maximum : 16.69 µm

Hauteur maximum : 4.755 µm

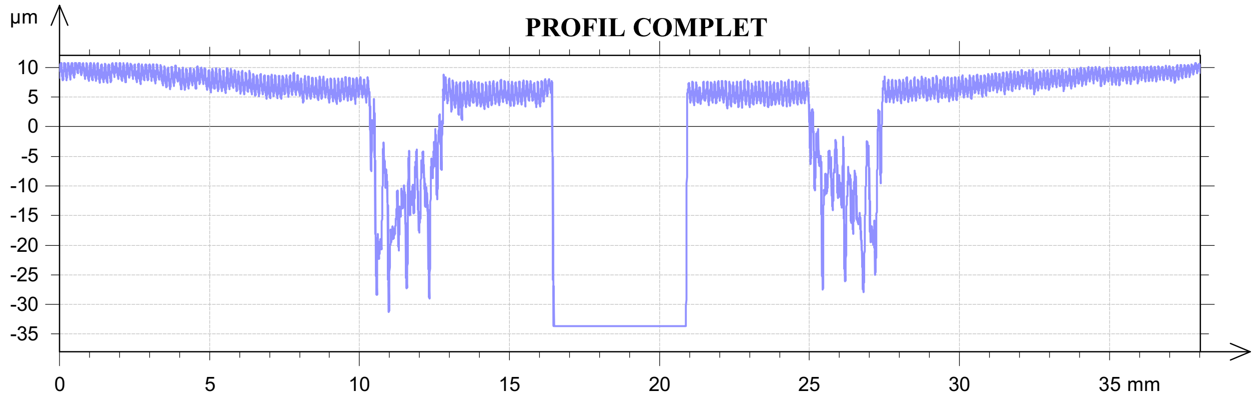
Surface du trou : 20587 µm2

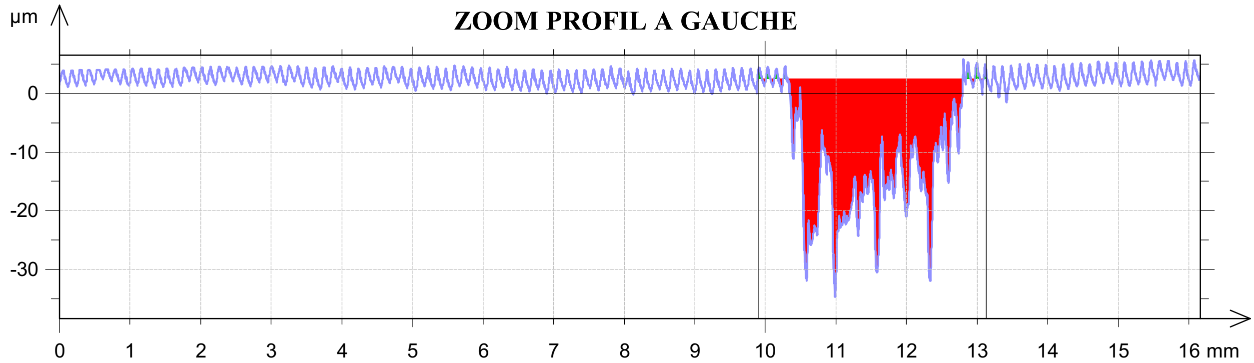
Surface repoussée : 5382 µm2

USURE A GAUCHE Usure extérieure: **Largeur 1.917 mm** Usure intérieure: **Largeur 2.189 mm**
USURE A DROITE Usure extérieure: **Largeur 2.025 mm** Usure intérieure: **Largeur 2.193 mm**
Usure extérieure sur diamètre int de **18.822 mm** et diamètre extérieure de **22.764 mm**
Usure intérieure sur diamètre int de **12.889 mm** et diamètre extérieure de **17.271 mm**

L'usure extérieure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 3
(PROFIL NUMERO 1)



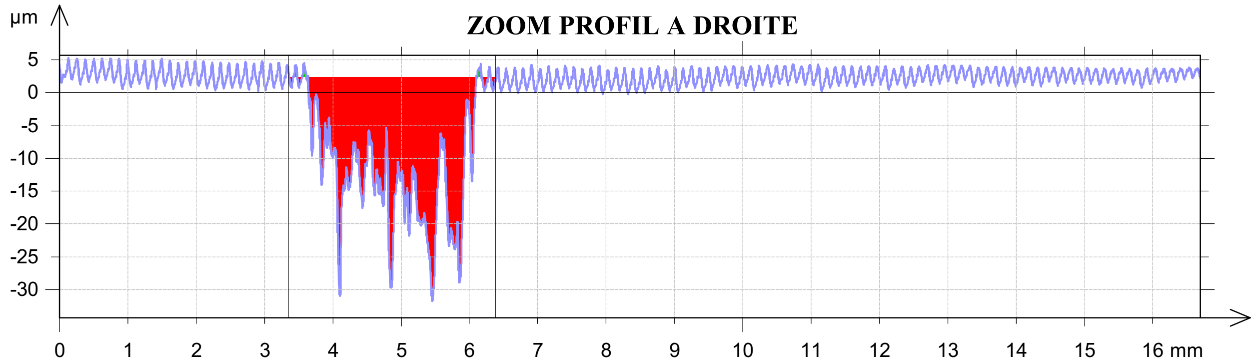


Profondeur maximum : 37.41 µm

Hauteur maximum : 3.203 µm

Surface du trou : 0.04439 mm2

Surface repoussée : 469.2 µm2



Profondeur maximum : 34.2 µm

Hauteur maximum : 2.021 µm

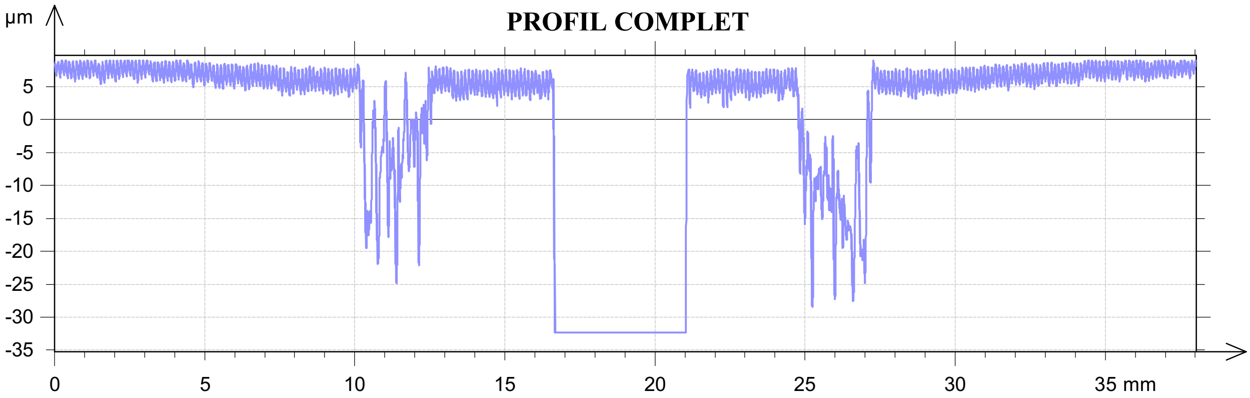
Surface du trou : 0.04138 mm2

Surface repoussée : 214.5 µm2

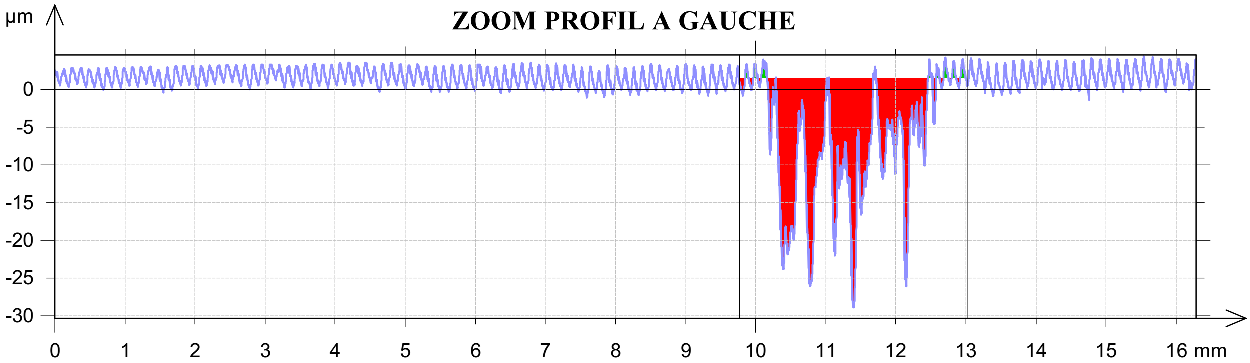
USURE A GAUCHE : **Largeur 2.446 mm**
USURE A DROITE : **Largeur 2.488 mm**
Usure sur diamètre int de **12.140 mm** et diamètre extérieure de **17.090 mm**

DISQUE REPERE 3
(PROFIL NUMERO 2)

PROFIL COMPLET



ZOOM PROFIL A GAUCHE



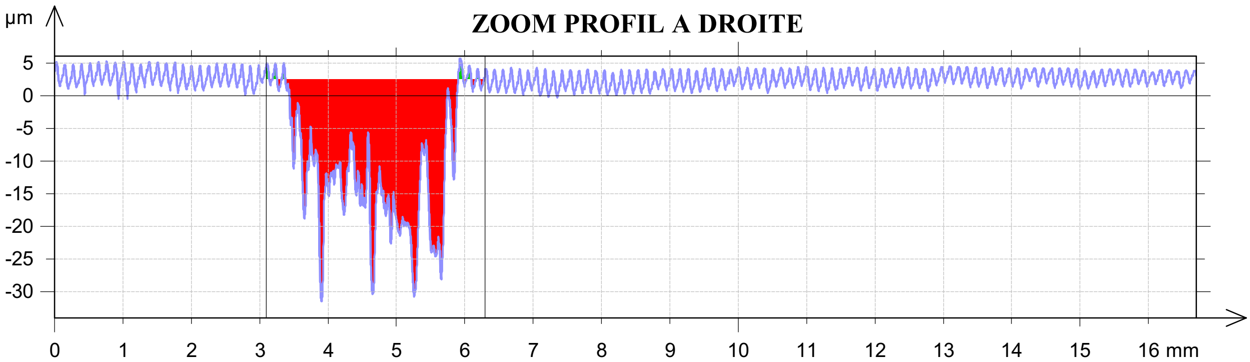
Profondeur maximum : 30.66 µm

Hauteur maximum : 2.595 µm

Surface du trou : 28029 µm2

Surface repoussée : 556.8 µm2

ZOOM PROFIL A DROITE



Profondeur maximum : 34.07 µm

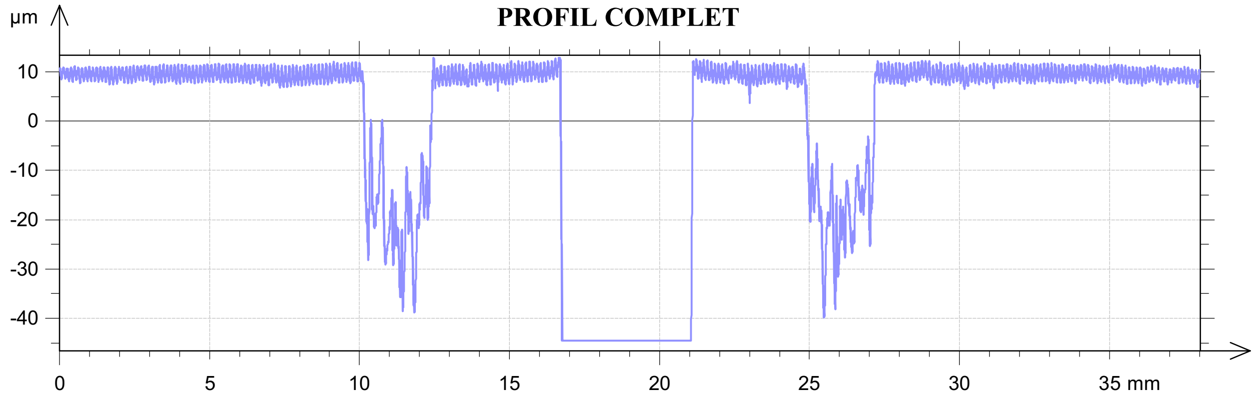
Hauteur maximum : 3.032 µm

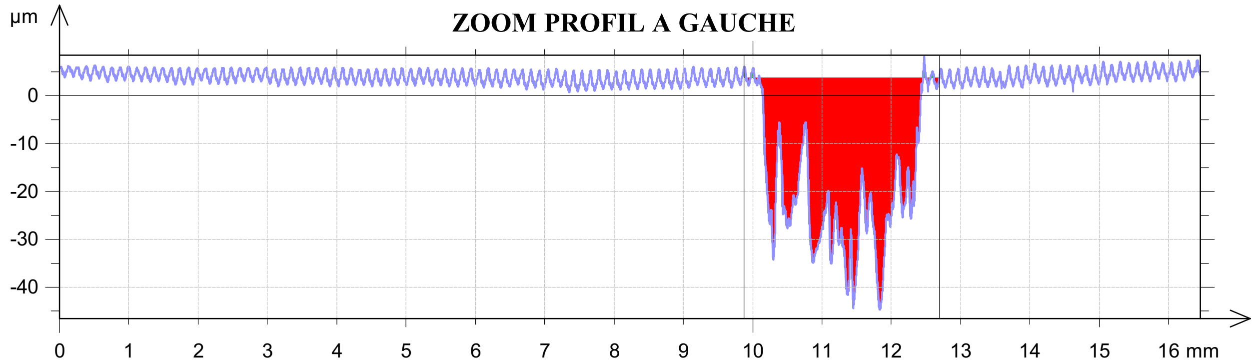
Surface du trou : 0.04342 mm2

Surface repoussée : 492.4 µm2

USURE A GAUCHE : **Largeur 2.416 mm**
USURE A DROITE : **Largeur 2.504 mm**
Usure sur diamètre int de **12.210 mm** et diamètre extérieure de **17.110 mm**

DISQUE REPERE 4
(PROFIL NUMERO 1)



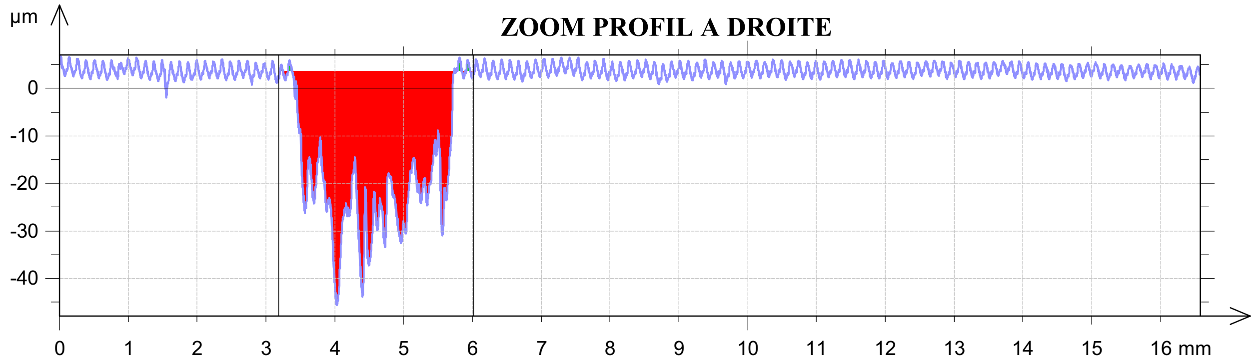


Profondeur maximum : 48.69 µm

Hauteur maximum : 4.147 µm

Surface du trou : 0.06574 mm2

Surface repoussée : 204.7 µm2



Profondeur maximum : 49.47 µm

Hauteur maximum : 2.682 µm

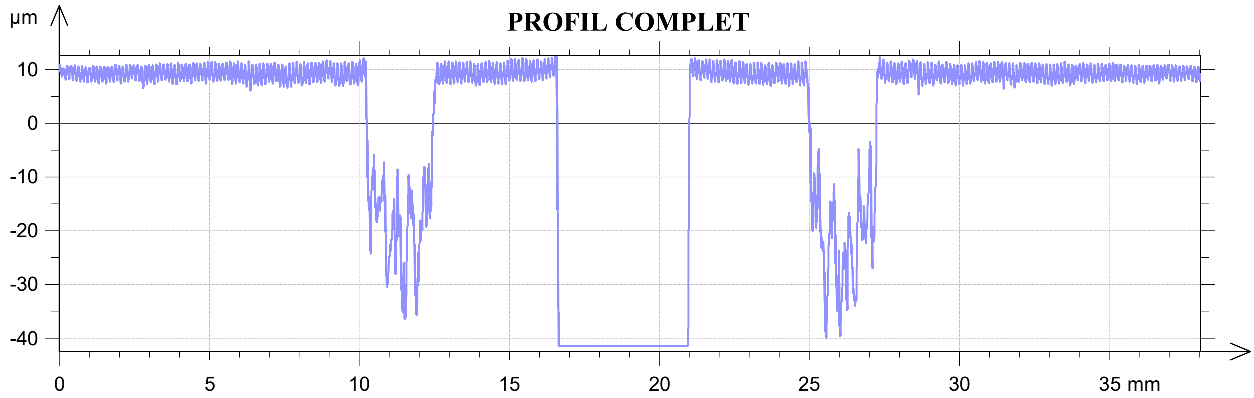
Surface du trou : 0.06274 mm2

Surface repoussée : 261.1 µm2

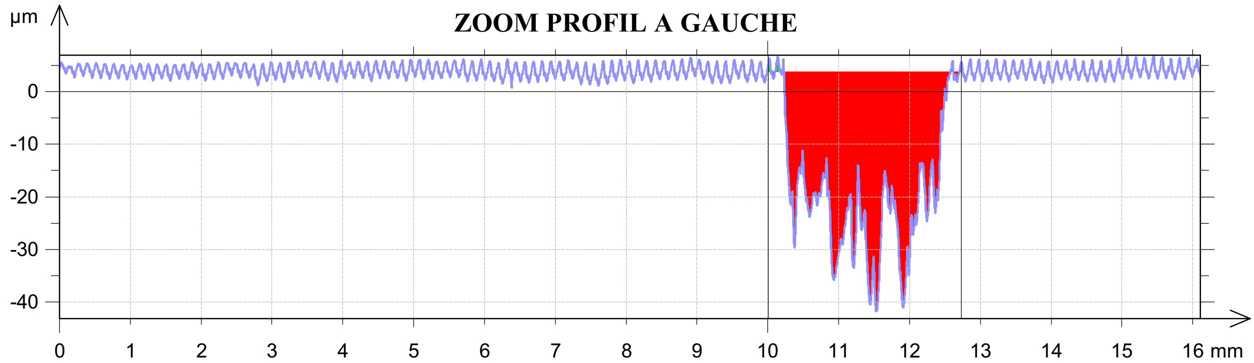
USURE A GAUCHE : **Largeur 2.349 mm**
USURE A DROITE : **Largeur 2.346 mm**
Usure sur diamètre int de **12.440 mm** et diamètre extérieure de **17.170 mm**

DISQUE REPERE 4
(PROFIL NUMERO 2)

PROFIL COMPLET



ZOOM PROFIL A GAUCHE



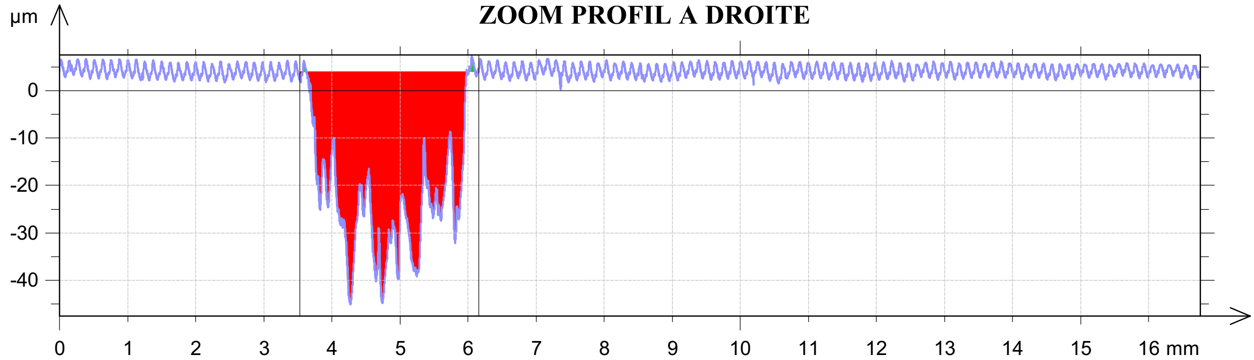
Profondeur maximum : 45.69 µm

Hauteur maximum : 2.774 µm

Surface du trou : 0.06242 mm2

Surface repoussée : 235.2 µm2

ZOOM PROFIL A DROITE



Profondeur maximum : 49.21 µm

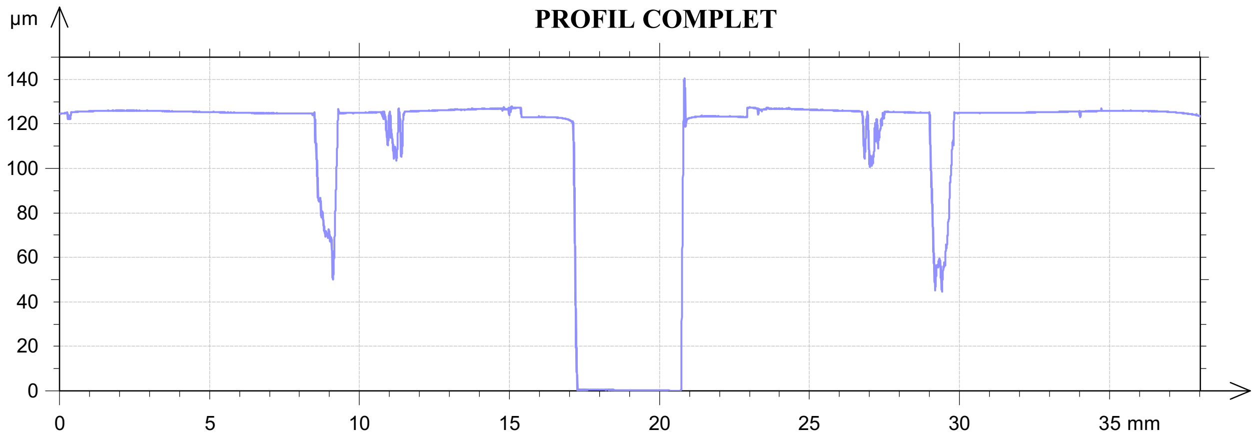
Hauteur maximum : 3.042 µm

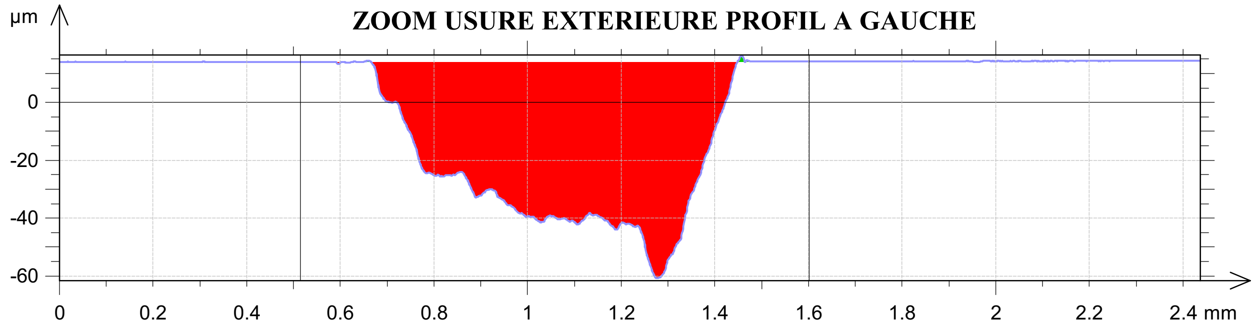
Surface du trou : 0.06842 mm2

Surface repoussée : 182.8 µm2

USURE A GAUCHE : **Largeur 2.363 mm**
USURE A DROITE : **Largeur 2.354 mm**
Usure sur diamètre int de **12.350 mm** et diamètre extérieure de **17.090mm**

DISQUE REPERE 11
(FACE 2 PISTES - PROFIL NUMERO 1)



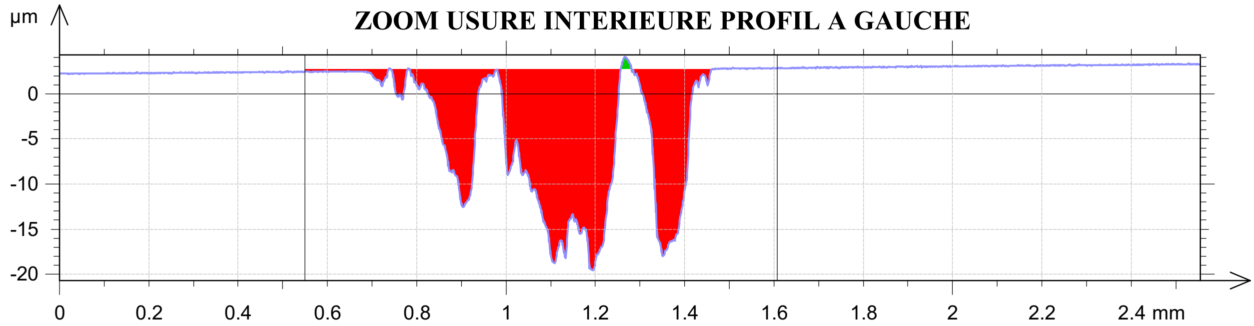


Profondeur maximum : 75 µm

Hauteur maximum : 1.978 µm

Surface du trou : 34655 µm2

Surface repoussée : 23.37 µm2

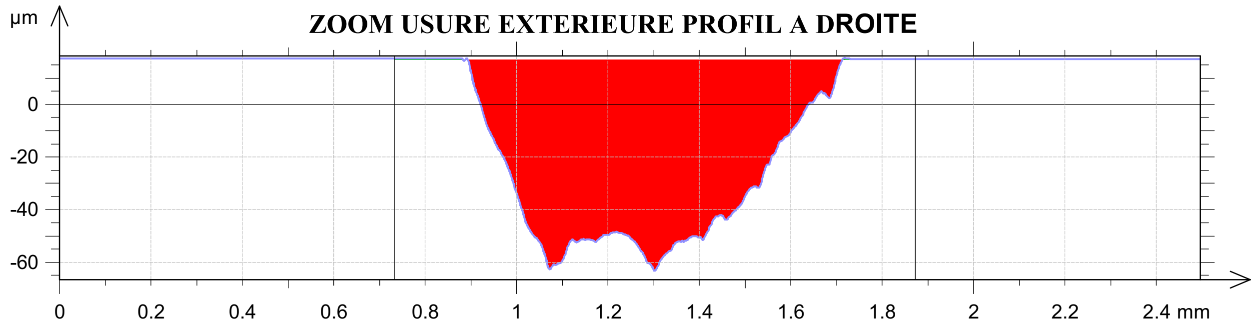


Profondeur maximum : 22.39 µm

Hauteur maximum : 1.318 µm

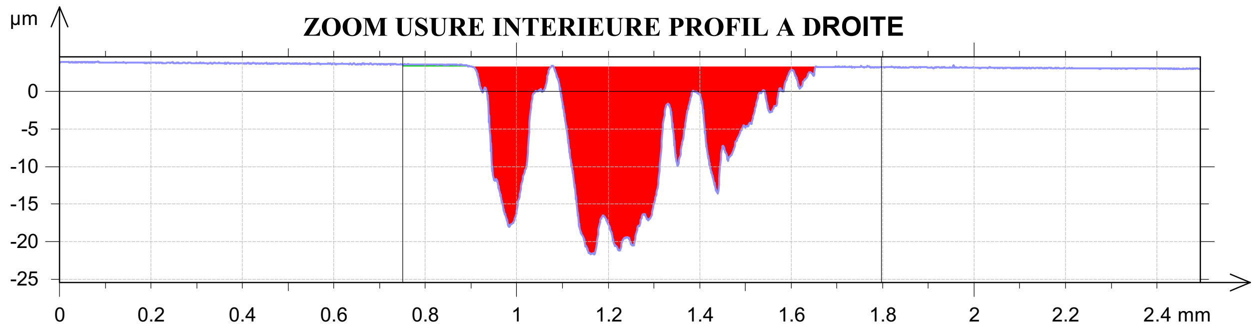
Surface du trou : 7100 µm2

Surface repoussée : 22.39 µm2



Profondeur maximum : 80.57 µm
Hauteur maximum : 0.32 µm

Surface du trou : 0.04294 mm2
Surface repoussée : 9.971 µm2



Profondeur maximum : 25.09 µm
Hauteur maximum : 192 nm

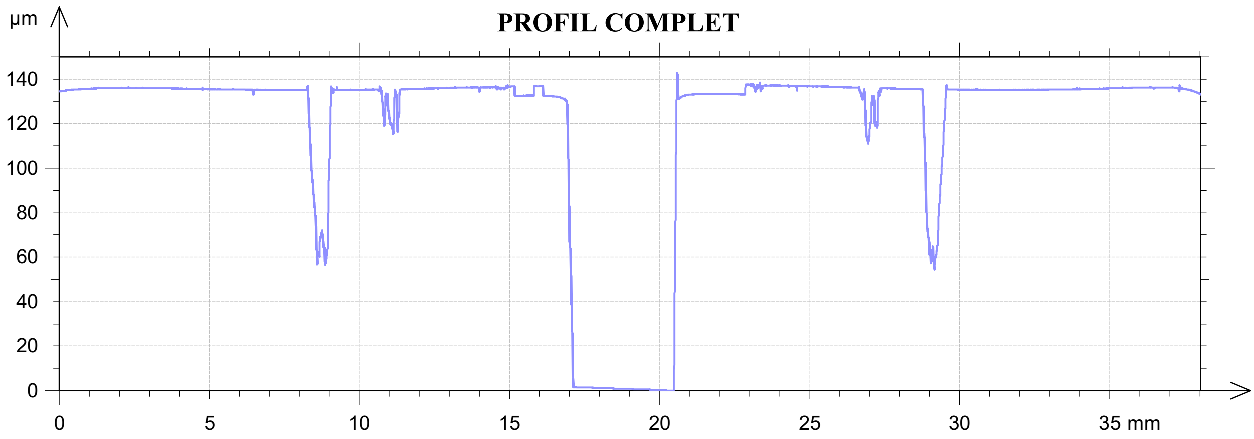
Surface du trou : 8450 µm2
Surface repoussée : 16.41 µm2

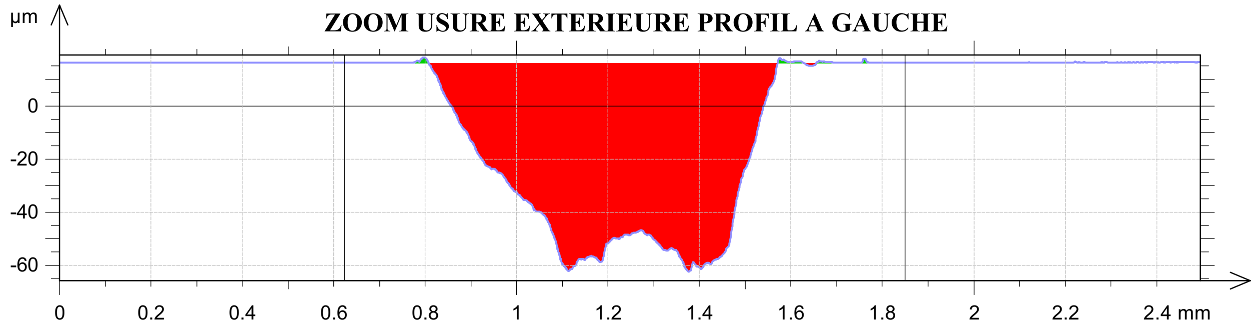
USURE A GAUCHE	Usure extérieure: **Largeur 0.809 mm**	Usure intérieure: **Largeur 0.765 mm**
USURE A DROITE	Usure extérieure: **Largeur 0.822 mm**	Usure intérieure: **Largeur 0.759 mm**

Usure extérieure sur diamètre int de **19.710 mm** et diamètre extérieure de **21.350 mm**

Usure intérieure sur diamètre int de **15.220 mm** et diamètre extérieure de **16.760 mm**

DISQUE REPERE 11
(FACE 2 PISTES - PROFIL NUMERO 2)



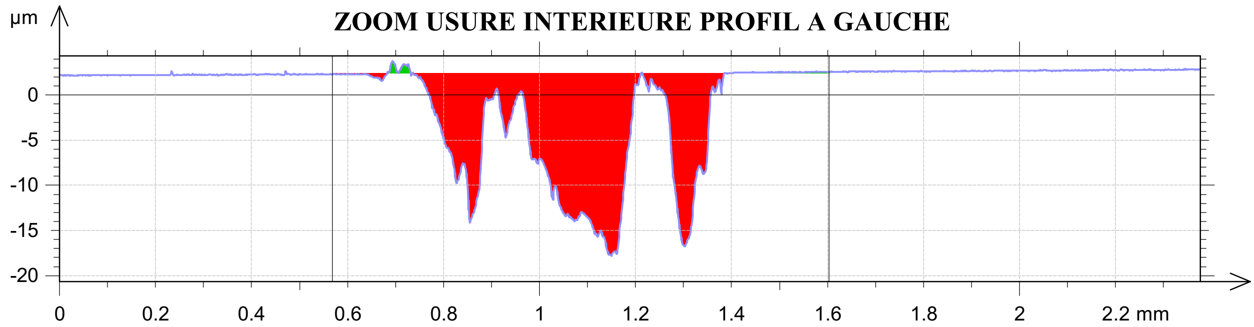


Profondeur maximum : 78.75 µm

Hauteur maximum : 1.984 µm

Surface du trou : 0.04068 mm2

Surface repoussée : 83.15 µm2

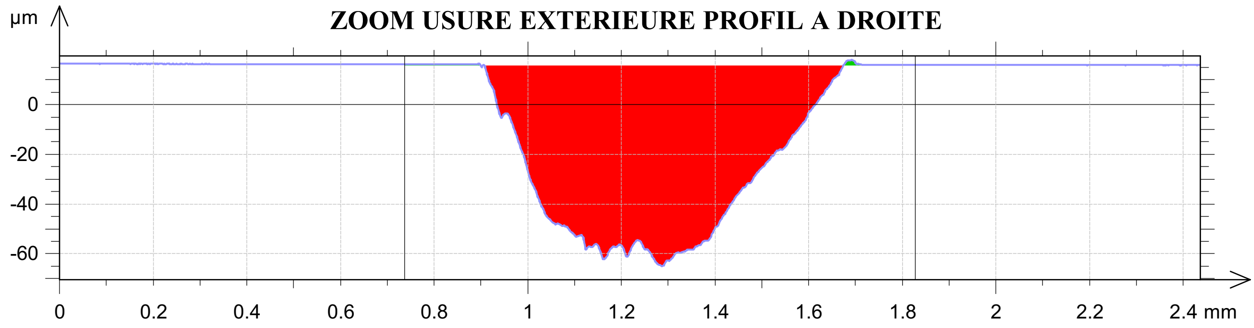


Profondeur maximum : 20.34 µm

Hauteur maximum : 1.229 µm

Surface du trou : 6021 µm2

Surface repoussée : 33.48 µm2

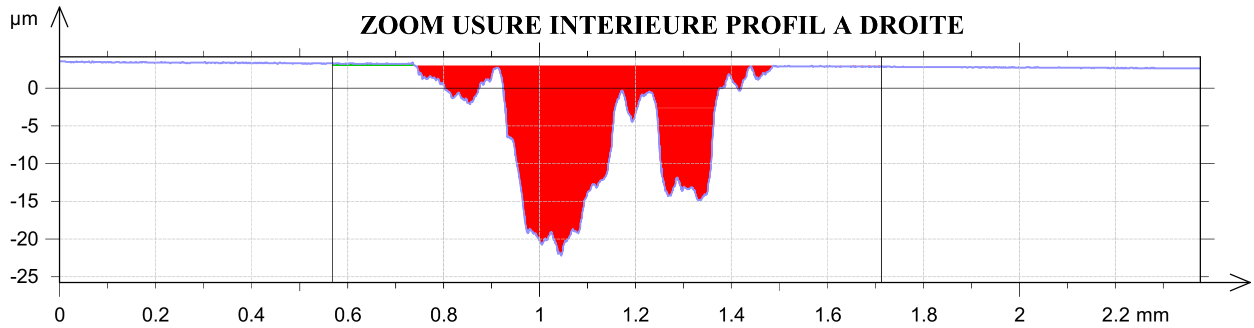


Profondeur maximum : 81.15 µm

Hauteur maximum : 1.85 µm

Surface du trou : 39505 µm2

Surface repoussée : 51.97 µm2



Profondeur maximum : 25.29 µm

Hauteur maximum : 0.3392 µm

Surface du trou : 7328 µm2

Surface repoussée : 37.81 µm2

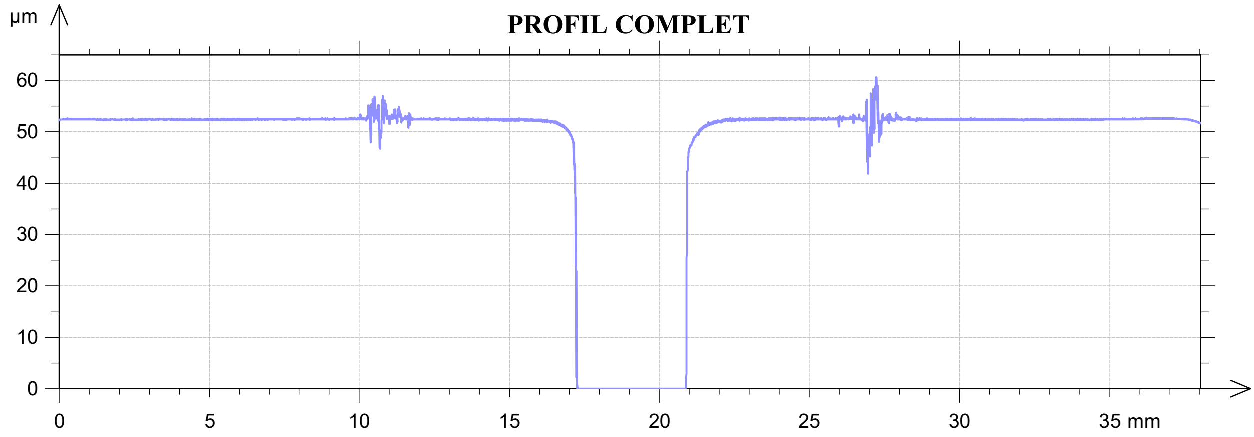
USURE A GAUCHE Usure extérieure: **Largeur 0.863 mm** Usure intérieure: **Largeur 0.764 mm**

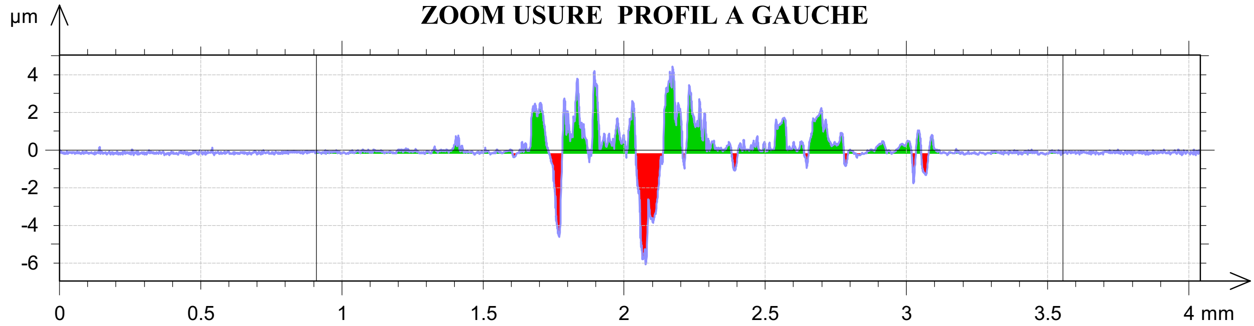
USURE A DROITE Usure extérieure: **Largeur 0.794 mm** Usure intérieure: **Largeur 0.755 mm**

Usure extérieure sur diamètre int de **19.650 mm** et diamètre extérieure de **21.320 mm**

Usure intérieure sur diamètre int de **15.180 mm** et diamètre extérieure de **16.700 mm**

DISQUE REPERE 11
(FACE 1 PISTE - PROFIL NUMERO 1)



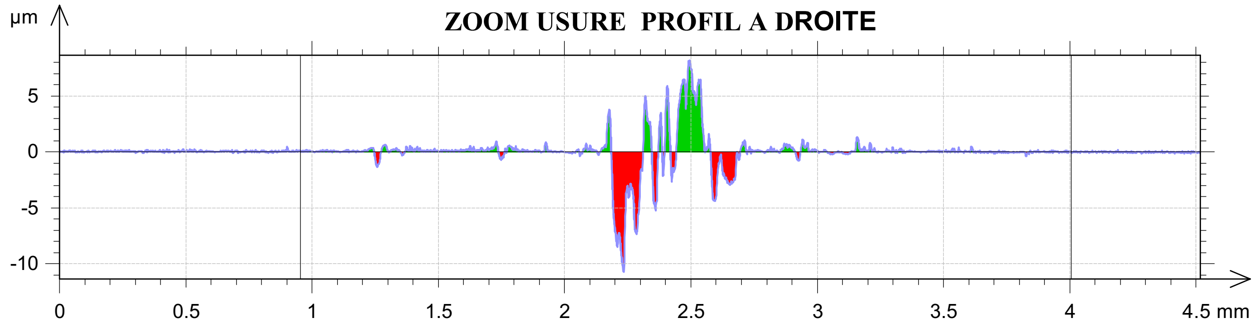


Profondeur maximum : 5.917 µm

Hauteur maximum : 4.598 µm

Surface du trou : 490.5 µm2

Surface repoussée : 1239 µm2



Profondeur maximum : 10.76 µm

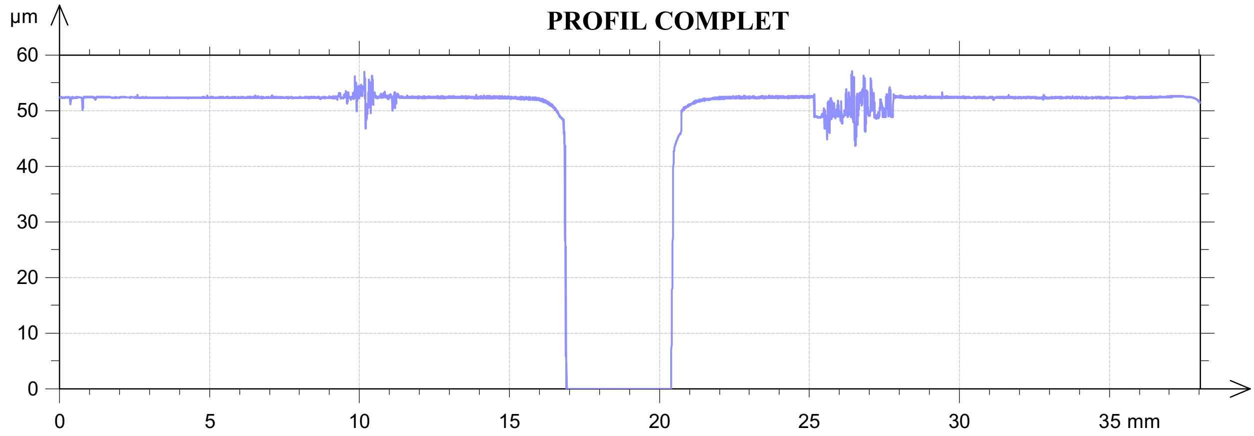
Hauteur maximum : 8.154 µm

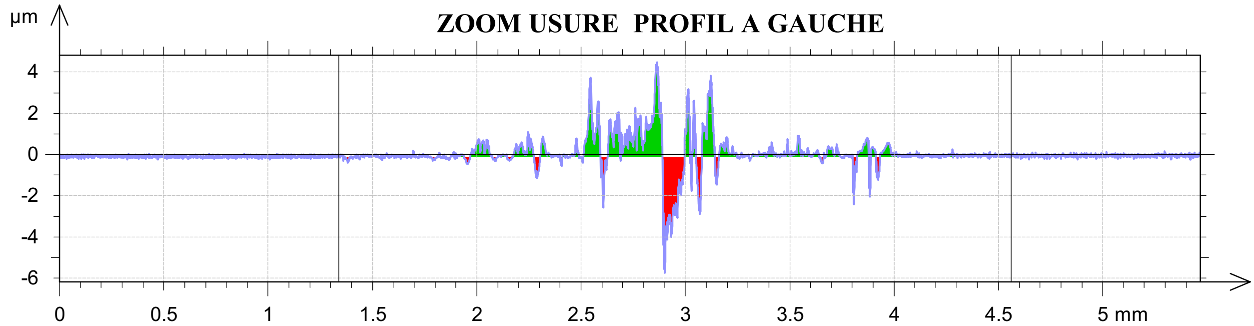
Surface du trou : 1216 µm2

Surface repoussée : 1150 µm2

USURE A GAUCHE : **Largeur 1.753 mm**
USURE A DROITE : **Largeur 2.109 mm**
Usure sur diamètre int de **14.320 mm** et diamètre extérieure de **18.010 mm**

DISQUE REPERE 11
(FACE 1 PISTE - PROFIL NUMERO 2)



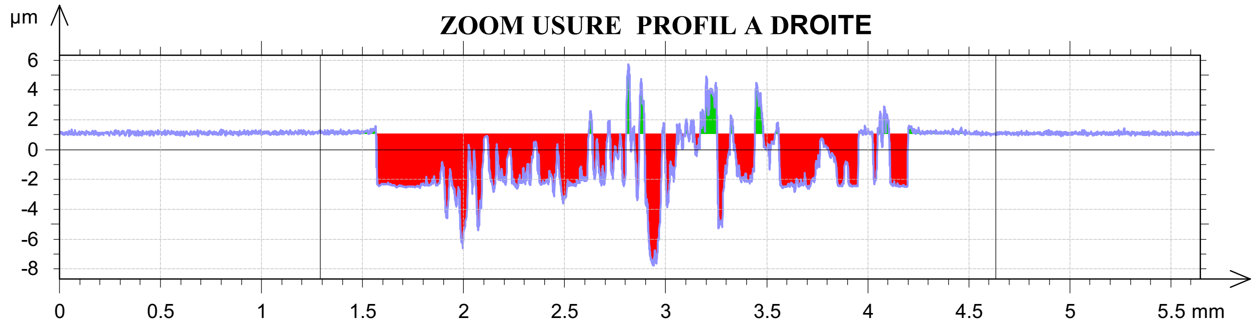


Profondeur maximum : 5.653 µm

Hauteur maximum : 4.581 µm

Surface du trou : 511.3 µm2

Surface repoussée : 1045 µm2



Profondeur maximum : 8.907 µm

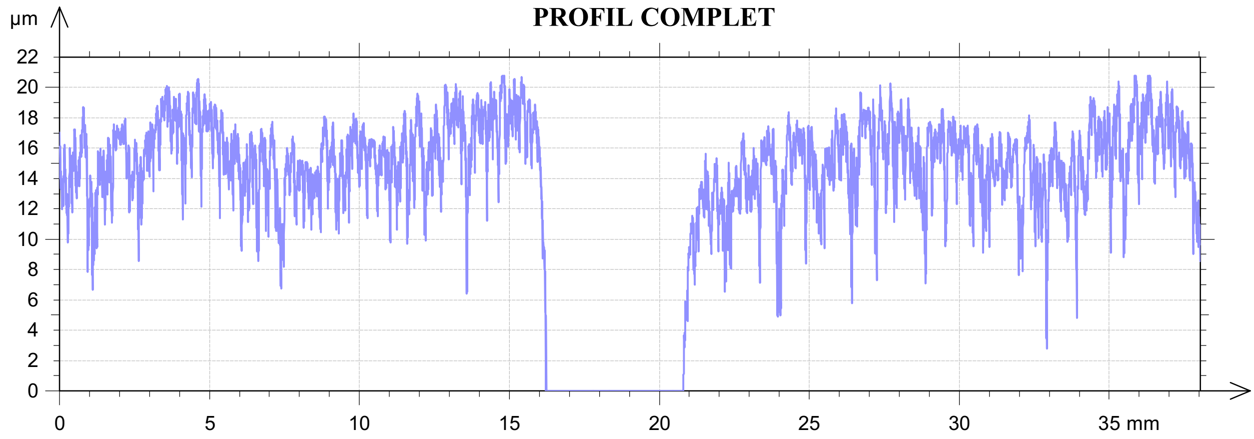
Hauteur maximum : 4.621 µm

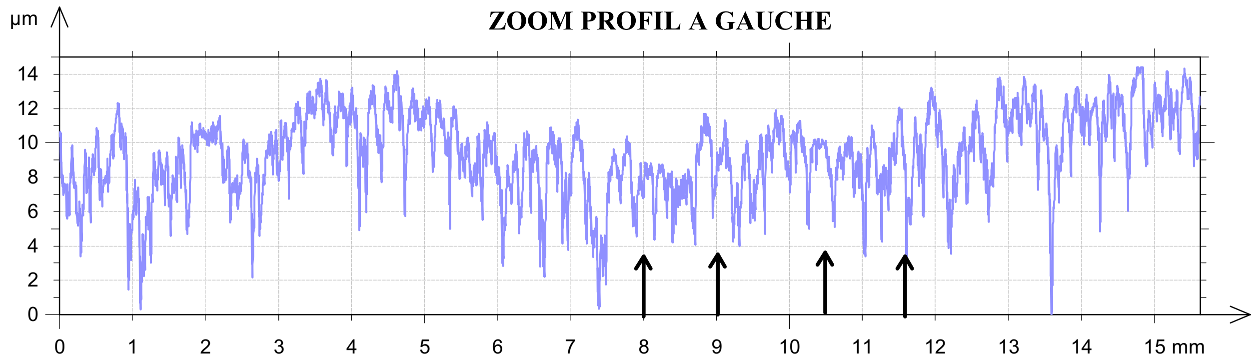
Surface du trou : 6719 µm2

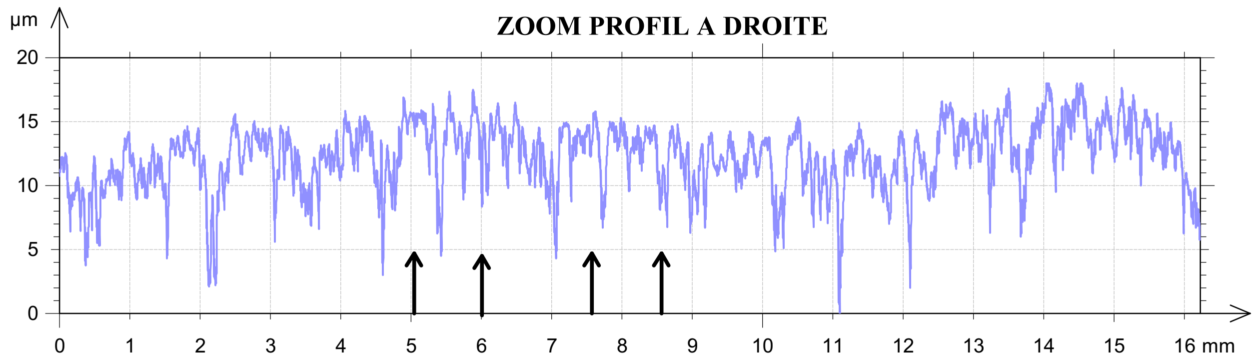
Surface repoussée : 546.7 µm2

USURE A GAUCHE : **Largeur 2.073 mm**
USURE A DROITE : **Largeur 2.646 mm**
Usure sur diamètre int de **13.790 mm** et diamètre extérieure de **18.510 mm**

DISQUE REPERE 12
(PROFIL NUMERO 1)



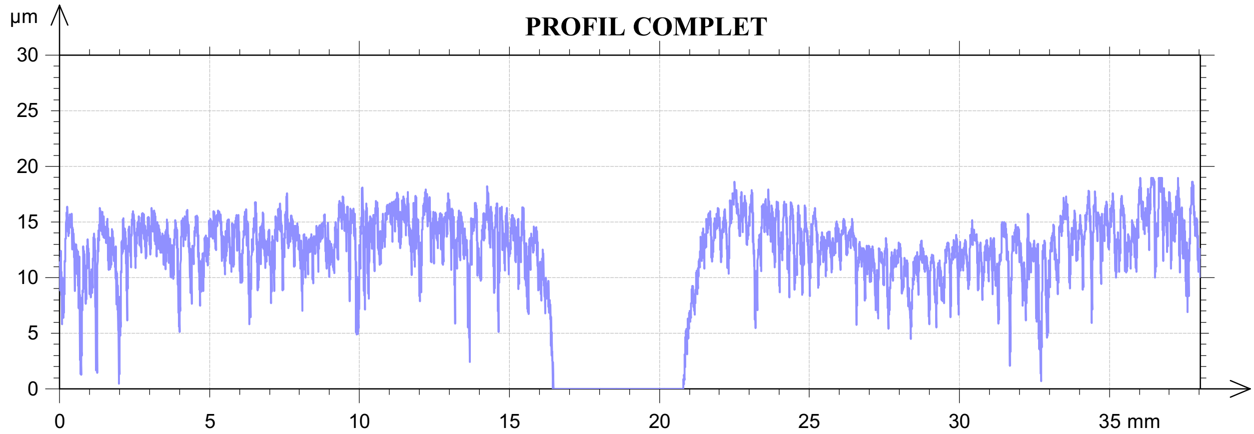


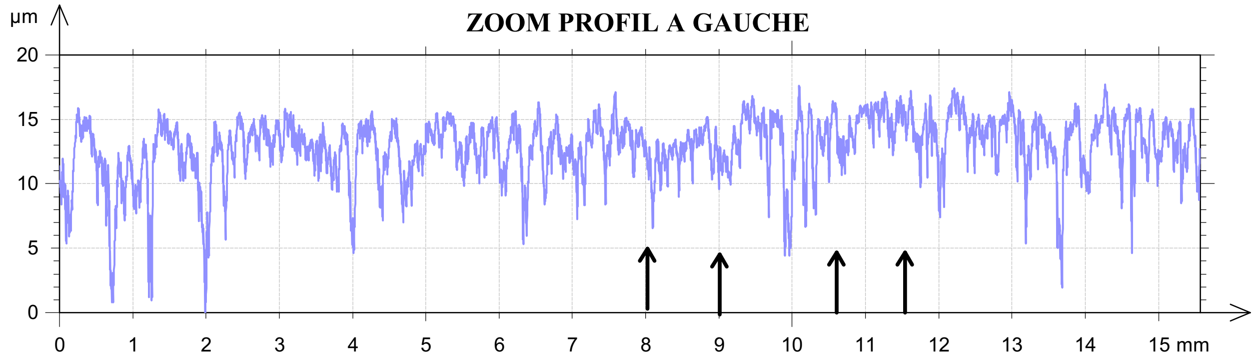


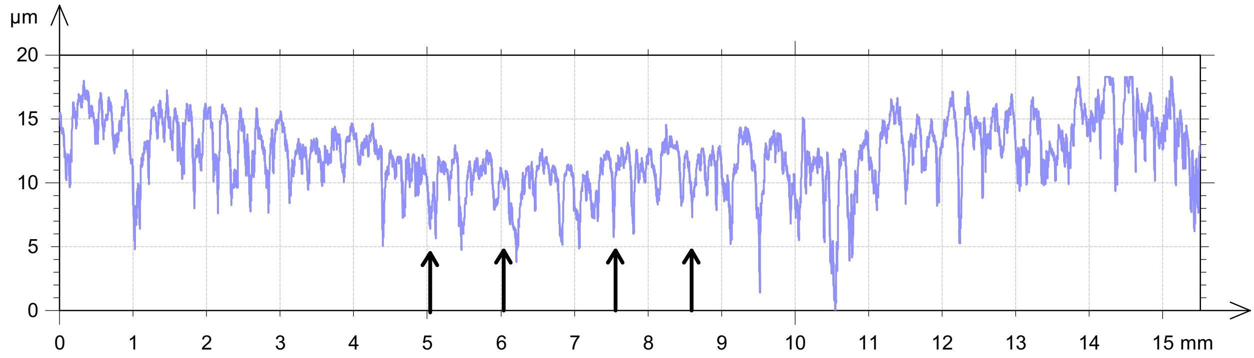
USURE A GAUCHE Usure extérieure: **Largeur 0.820 mm** Usure intérieure: **Largeur 0.741 mm**
USURE A DROITE Usure extérieure: **Largeur 0.772 mm** Usure intérieure: **Largeur 0.800 mm**
Usure extérieure sur diamètre int de **19.884mm** et diamètre extérieure de **21.476 mm**
Usure intérieure sur diamètre int de **15.380 mm** et diamètre extérieure de **16.921mm**

L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 12
(PROFIL NUMERO 2)





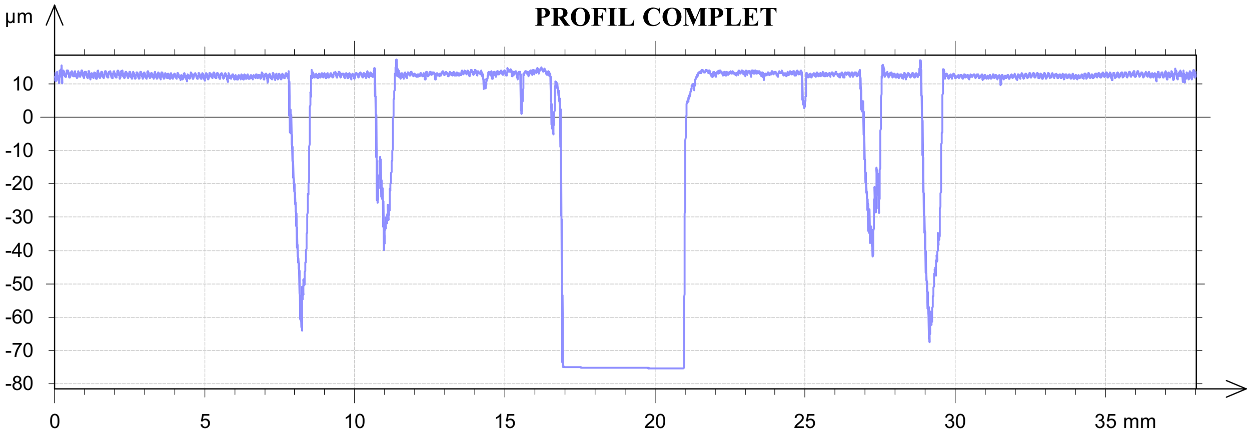


USURE A GAUCHE Usure extérieure: **Largeur 0.804 mm** Usure intérieure: **Largeur 0.677 mm**
USURE A DROITE Usure extérieure: **Largeur 0.778 mm** Usure intérieure: **Largeur 0.722 mm**
Usure extérieure sur diamètre int de **19.907mm** et diamètre extérieure de **21.489 mm**
Usure intérieure sur diamètre int de **15.343 mm** et diamètre extérieure de **16.742mm**

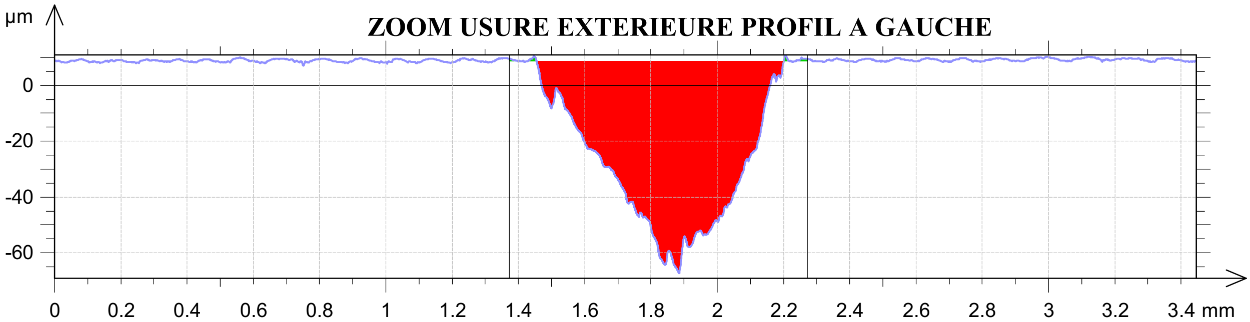
L'usure n'est pas assez importante pour une détermination valable de la zone à contrôler.
(entre les flèches, zones usées)

DISQUE REPERE 13
(FACE 2 PISTES - PROFIL NUMERO 1)

PROFIL COMPLET



ZOOM USURE EXTERIEURE PROFIL A GAUCHE



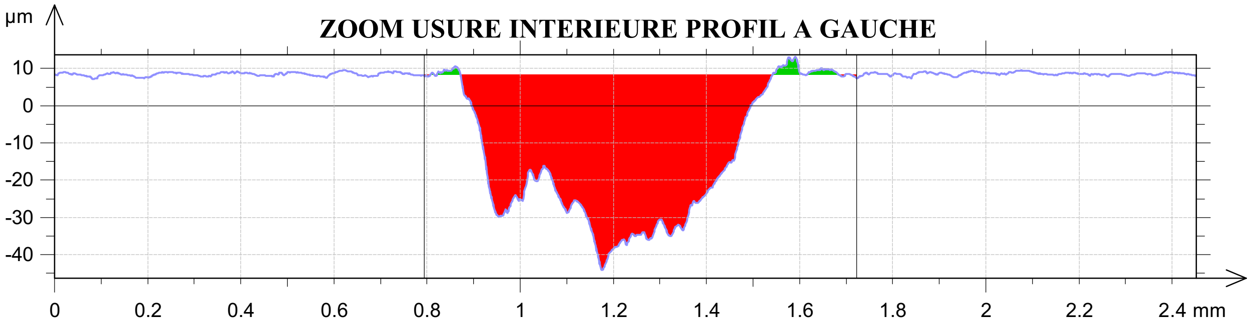
Profondeur maximum : 76.33 µm

Hauteur maximum : 1.731 µm

Surface du trou : 30769 µm2

Surface repoussée : 46.96 µm2

ZOOM USURE INTERIEURE PROFIL A GAUCHE

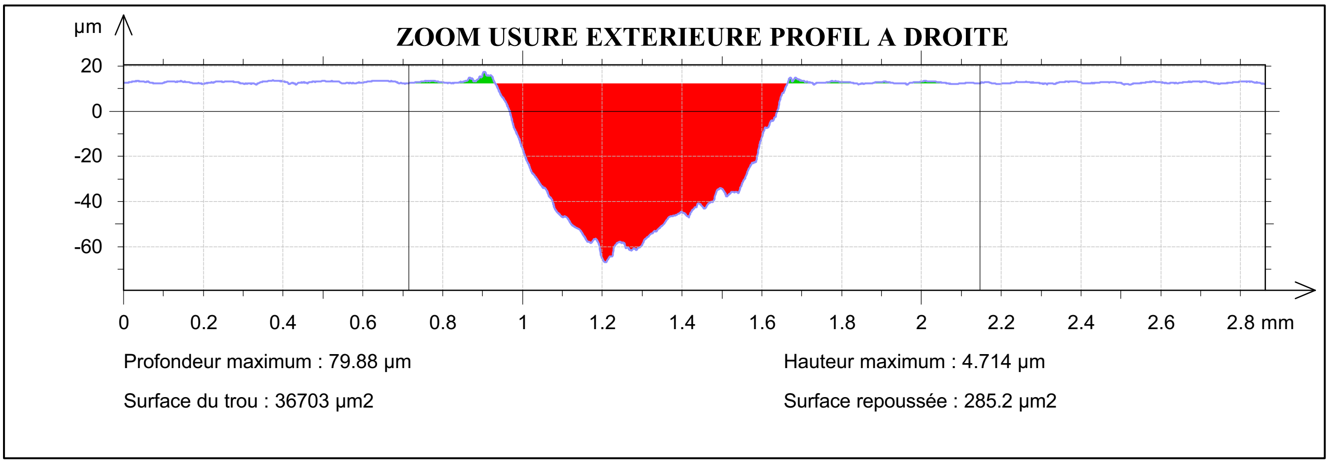


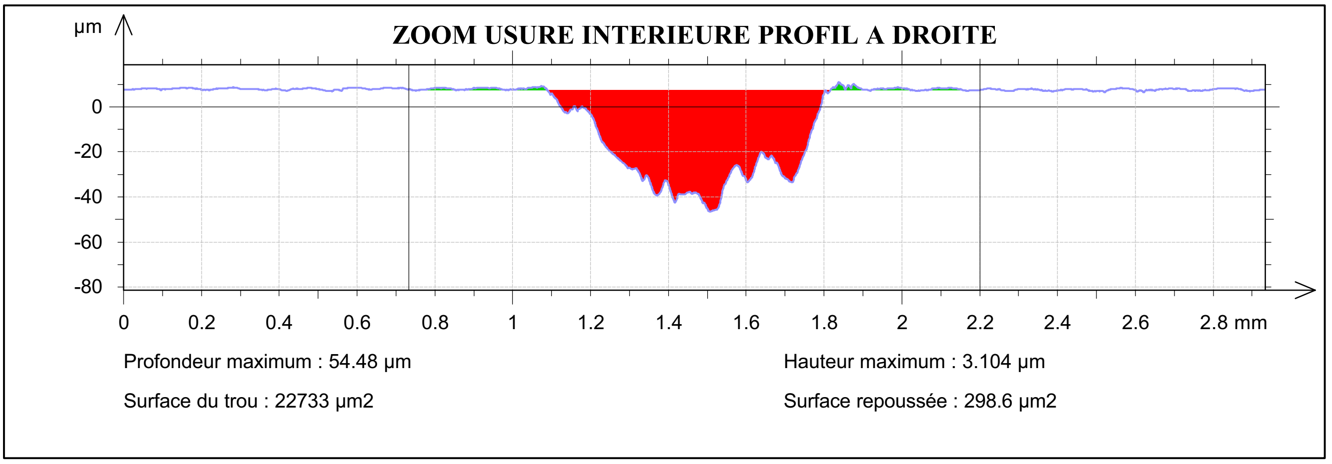
Profondeur maximum : 52.67 µm

Hauteur maximum : 4.611 µm

Surface du trou : 20988 µm2

Surface repoussée : 262.2 µm2





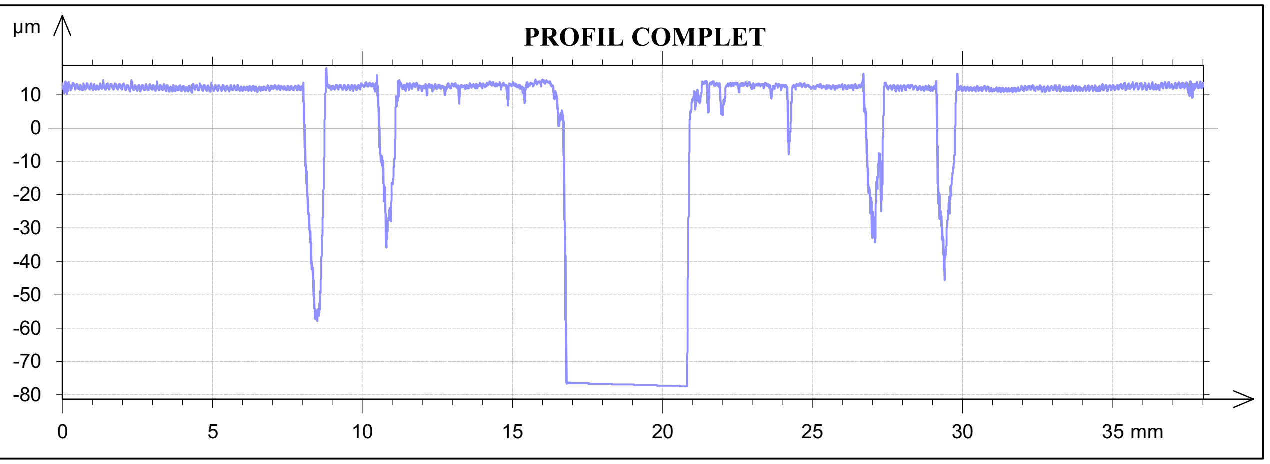
USURE A GAUCHE Usure extérieure: **Largeur 0.756 mm** Usure intérieure: **Largeur 0.725 mm**

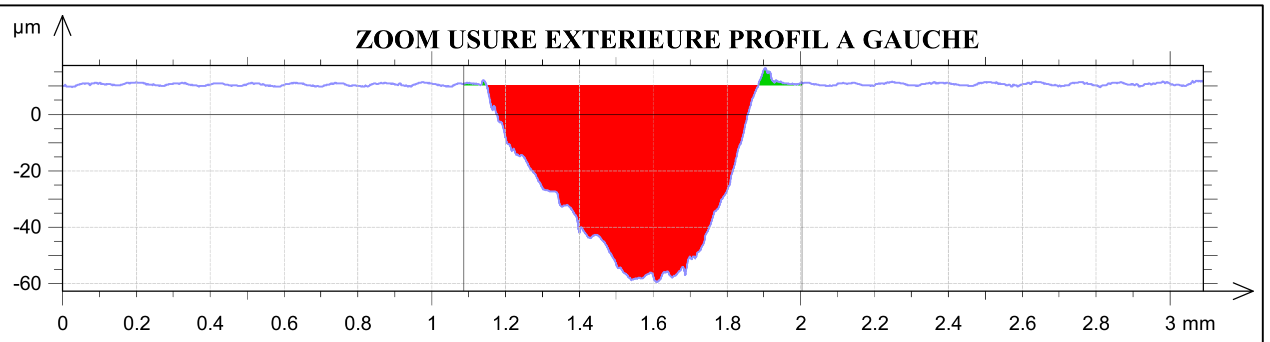
USURE A DROITE Usure extérieure: **Largeur 0.763 mm** Usure intérieure: **Largeur 0.755 mm**

Usure extérieure sur diamètre int de **20.270 mm** et diamètre extérieure de **21.820 mm**

Usure intérieure sur diamètre int de **15.470 mm** et diamètre extérieure de **16.920 mm**

DISQUE REPERE 13
(FACE 2 PISTES - PROFIL NUMERO 2)



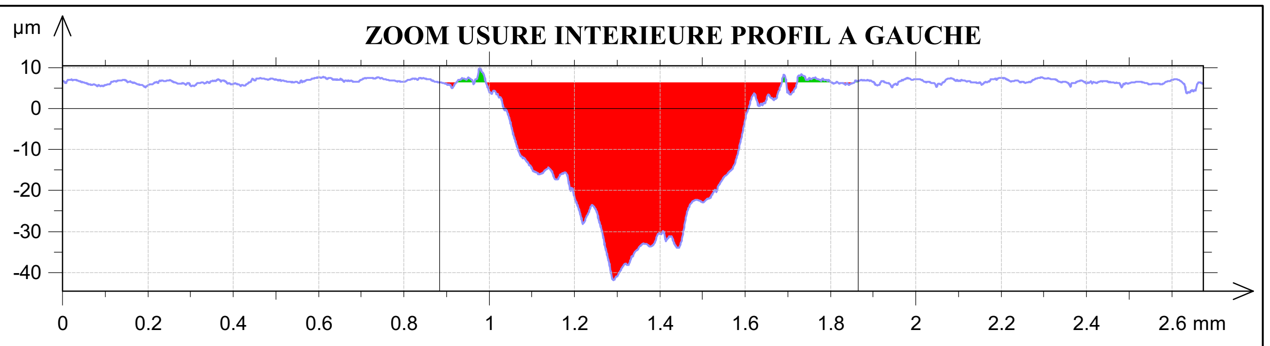


Profondeur maximum : 70.17 µm

Hauteur maximum : 5.834 µm

Surface du trou : 33133 µm2

Surface repoussée : 196.9 µm2

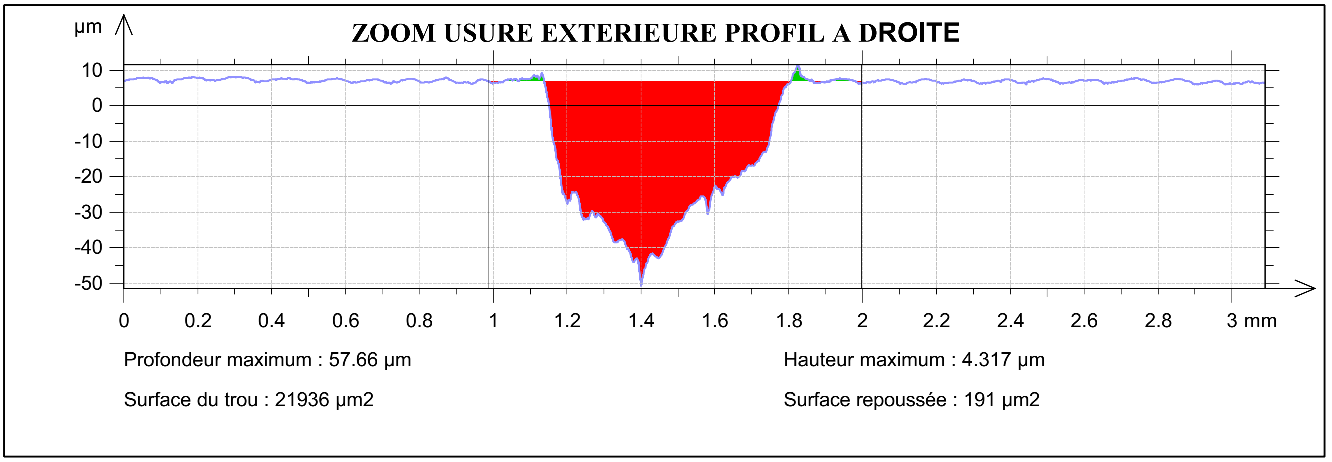


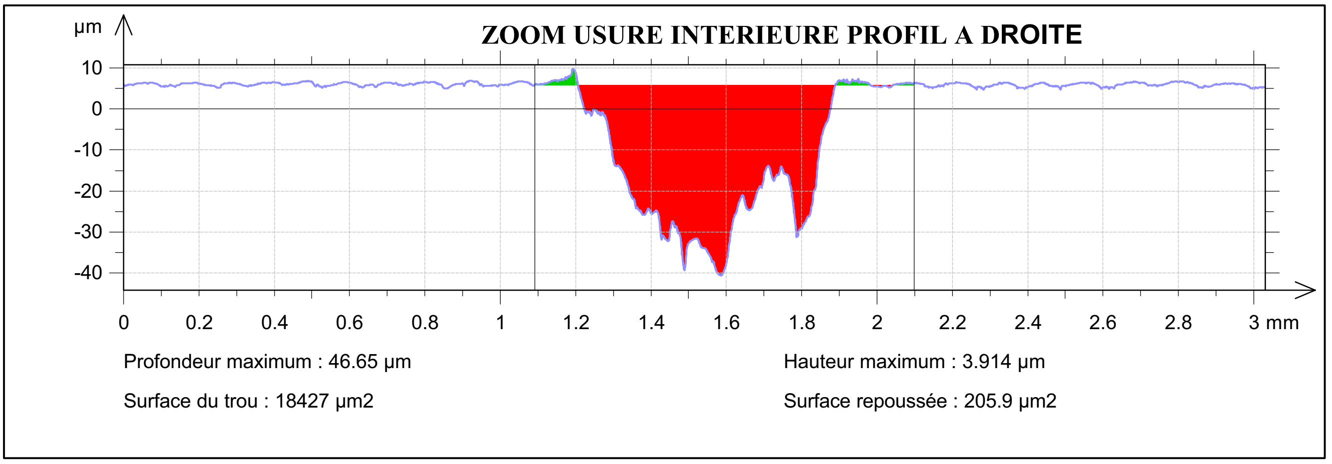
Profondeur maximum : 48.47 µm

Hauteur maximum : 3.338 µm

Surface du trou : 17500 µm2

Surface repoussée : 136.7 µm2



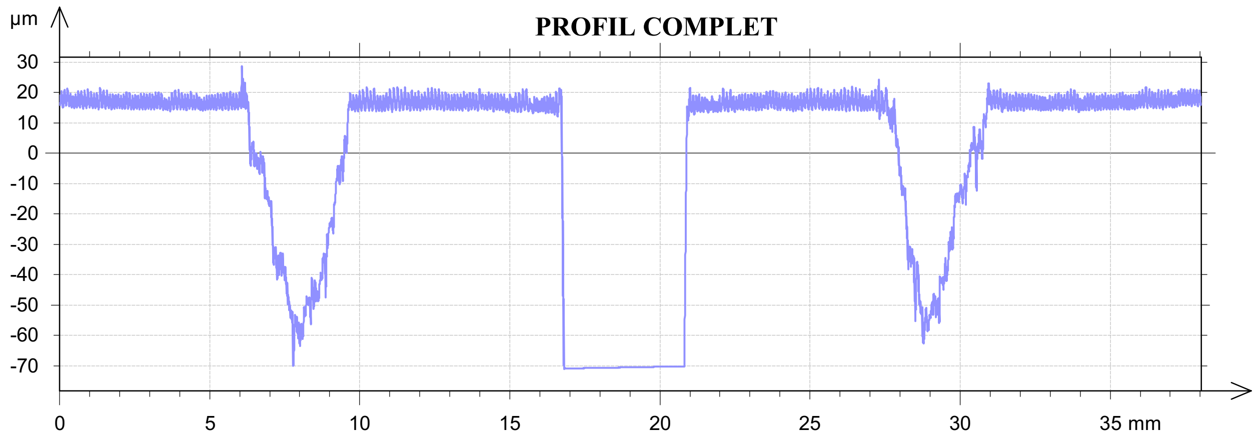


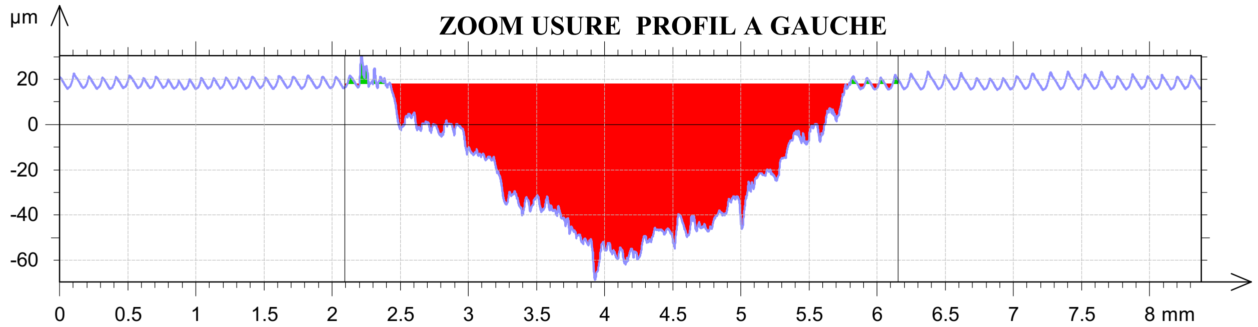
USURE A GAUCHE	Usure extérieure: **Largeur 0.757 mm**	Usure intérieure: **Largeur 0.746 mm**
USURE A DROITE	Usure extérieure: **Largeur 0.693 mm**	Usure intérieure: **Largeur 0.697 mm**

Usure extérieure sur diamètre int de **20.350 mm** et diamètre extérieure de **21.870 mm**

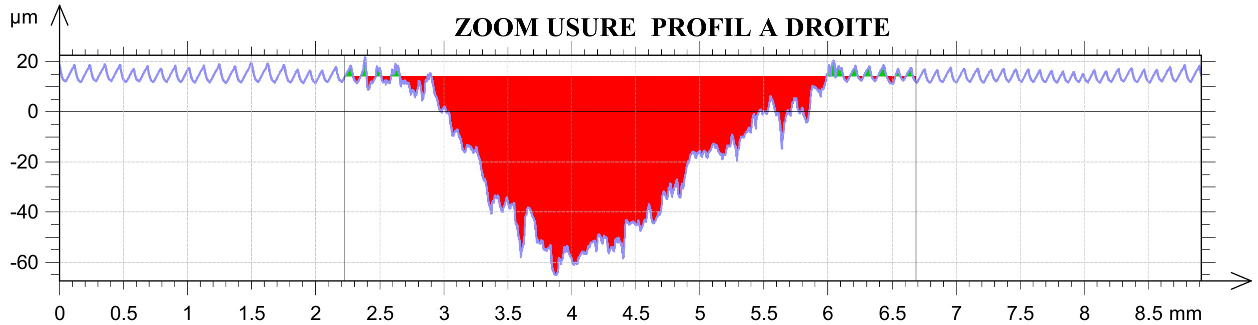
Usure intérieure sur diamètre int de **15.490 mm** et diamètre extérieure de **16.900 mm**

DISQUE REPERE 13
(FACE 1 PISTE - PROFIL NUMERO 1)





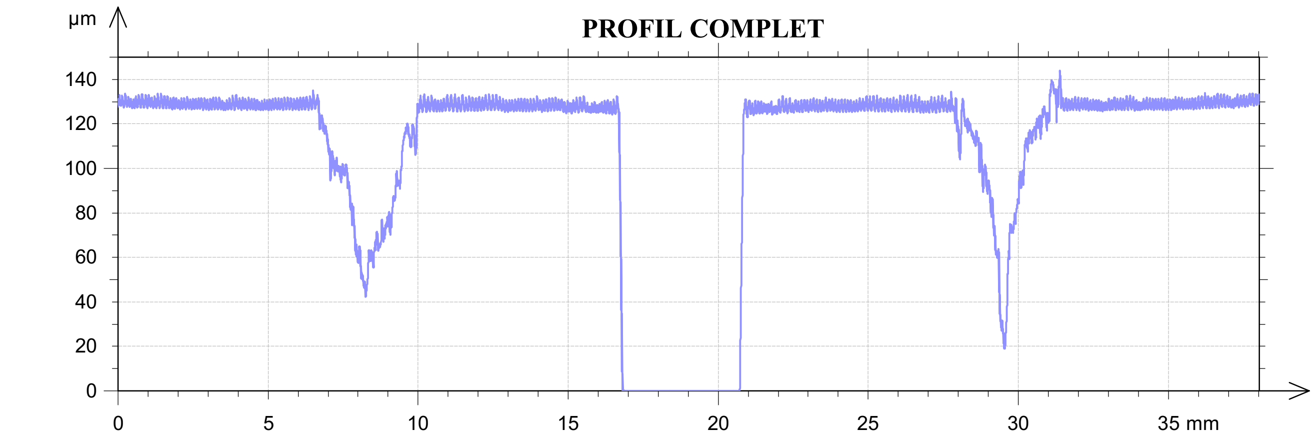
Profondeur maximum : 86.92 µm
Hauteur maximum : 12.03 µm
Surface du trou : 0.1528 mm2
Surface repoussée : 966.5 µm2

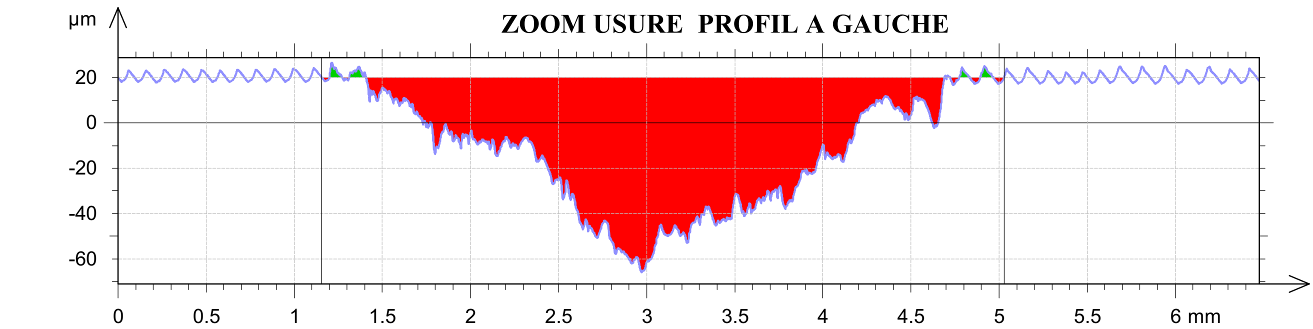


Profondeur maximum : 79.54 µm
Hauteur maximum : 7.552 µm
Surface du trou : 0.1287 mm2
Surface repoussée : 1427 µm2

USURE A GAUCHE : **Largeur 3.580 mm**
USURE A DROITE : **Largeur 3.424 mm**
Usure sur diamètre int de **17.830 mm** et diamètre extérieure de **24.830 mm**

DISQUE REPERE 13
(FACE 1 PISTE - PROFIL NUMERO 2)



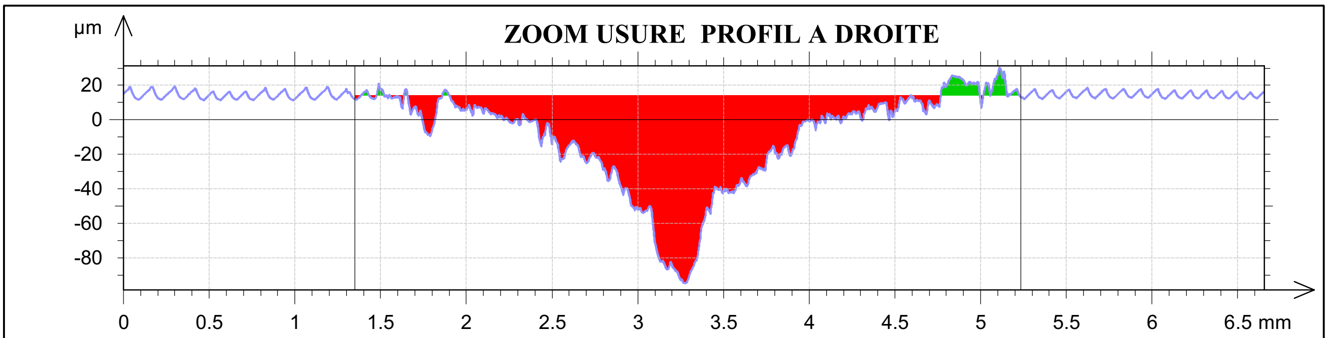


Profondeur maximum : 86.41 µm

Hauteur maximum : 6.246 µm

Surface du trou : 0.1334 mm2

Surface repoussée : 664 µm2



Profondeur maximum : 109.4 µm

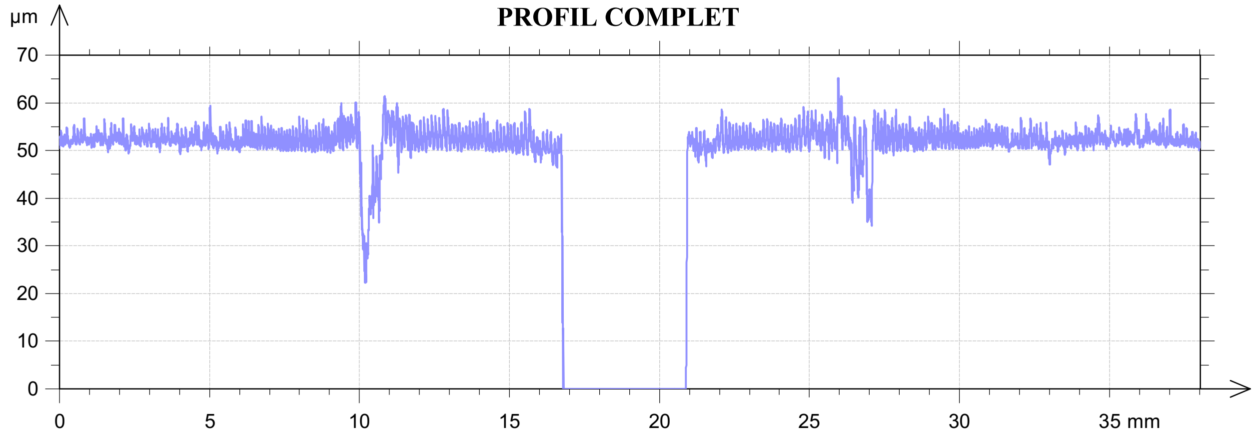
Hauteur maximum : 15.56 µm

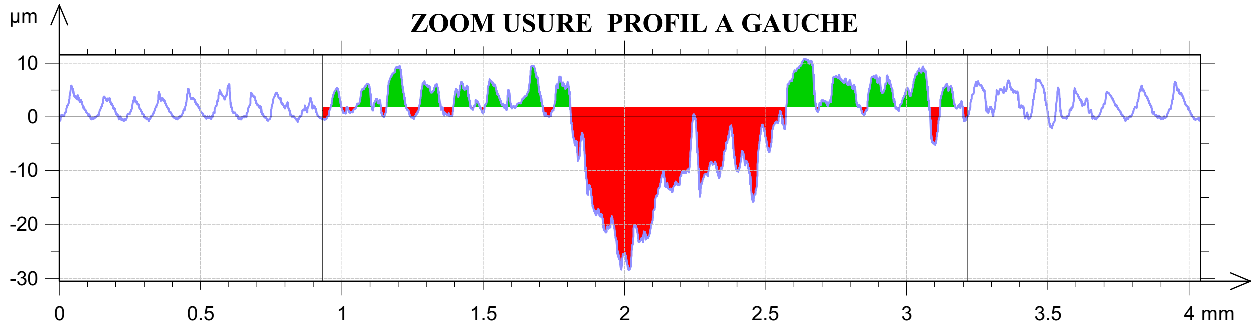
Surface du trou : 0.1001 mm2

Surface repoussée : 3191 µm2

USURE A GAUCHE : **Largeur 3.379 mm**
USURE A DROITE : **Largeur 3.626 mm**
Usure sur diamètre int de **17.880 mm** et diamètre extérieure de **24.820 mm**

DISQUE REPERE 14
(FACE USURE DIAMETRE LE PLUS PETIT - PROFIL NUMERO 1)



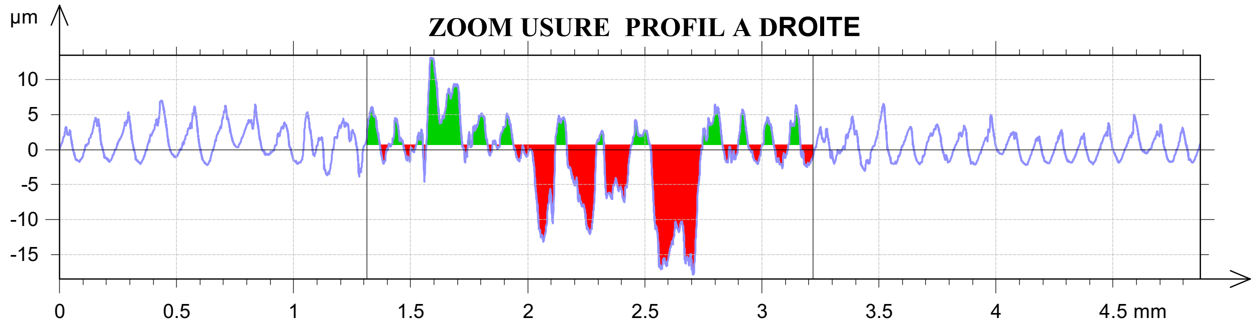


Profondeur maximum : 30.34 µm

Hauteur maximum : 8.872 µm

Surface du trou : 11316 µm2

Surface repoussée : 3801 µm2



Profondeur maximum : 18.69 µm

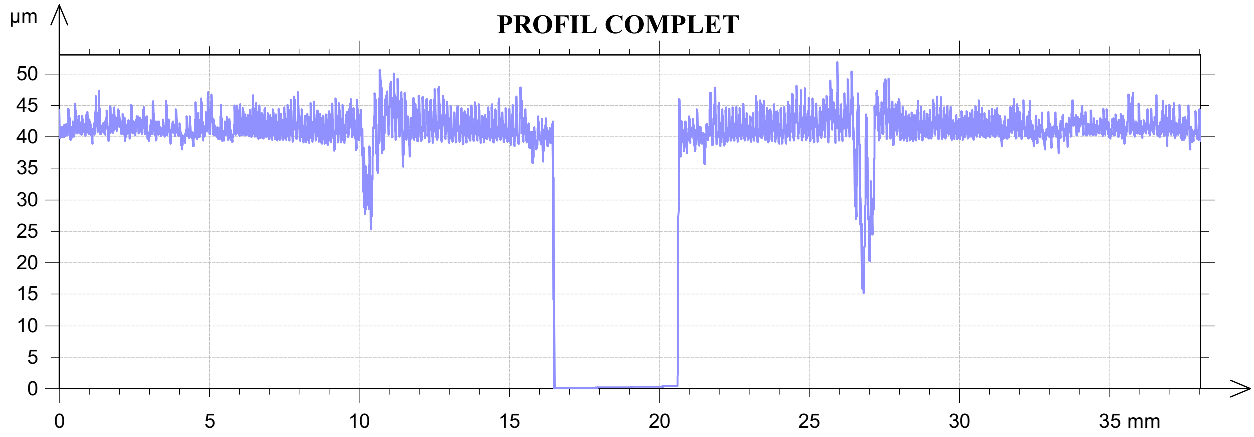
Hauteur maximum : 12.37 µm

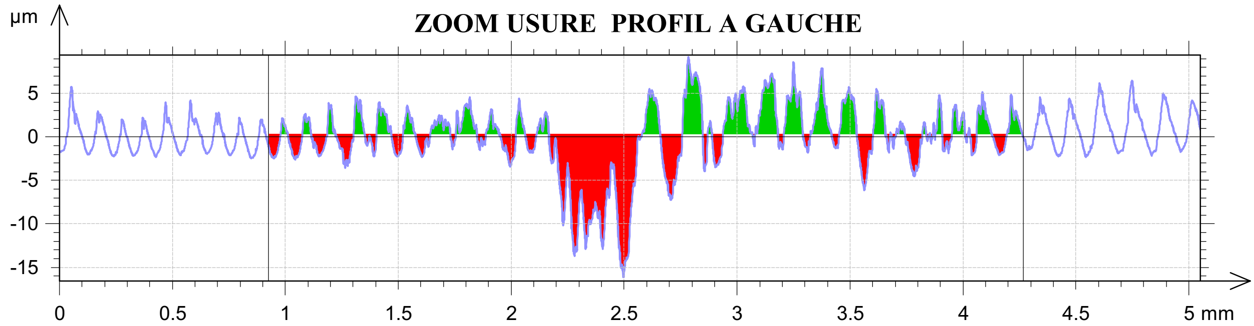
Surface du trou : 6235 µm2

Surface repoussée : 2654 µm2

USURE A GAUCHE : **Largeur 1.969 mm**
USURE A DROITE : **Largeur 1.265 mm**
Usure sur diamètre int de **14.170 mm** et diamètre extérieure de **17.290 mm**

DISQUE REPERE 14
(FACE USURE DIAMETRE LE PLUS PETIT - PROFIL NUMERO 2)



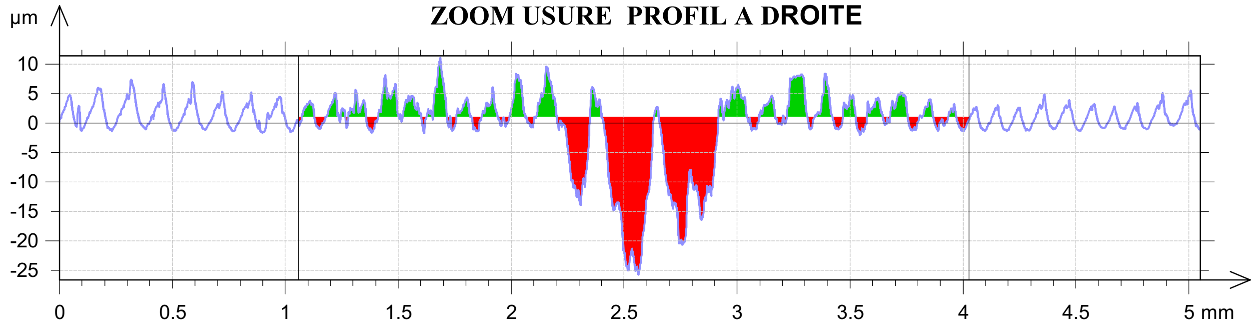


Profondeur maximum : 16.59 µm

Hauteur maximum : 8.802 µm

Surface du trou : 6108 µm2

Surface repoussée : 4072 µm2



Profondeur maximum : 26.89 µm

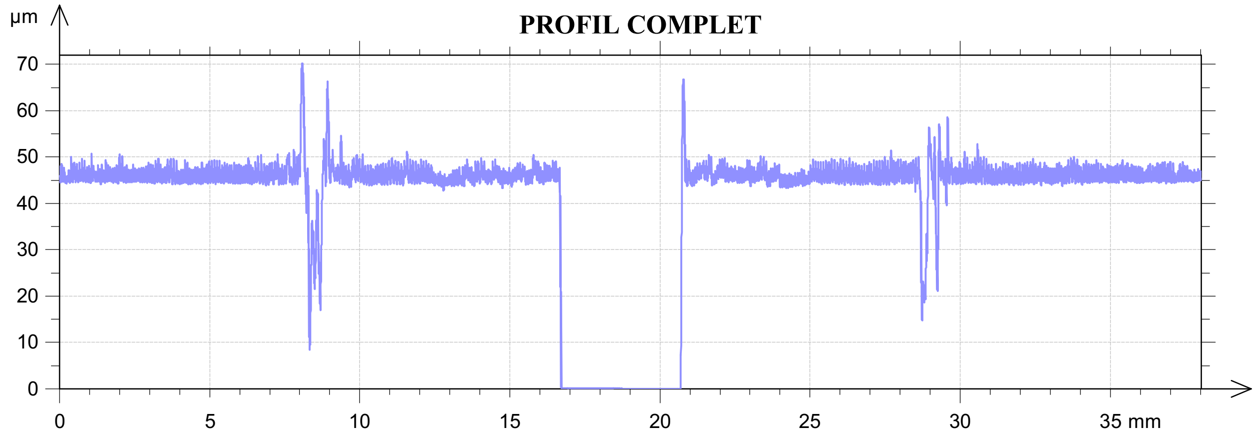
Hauteur maximum : 9.893 µm

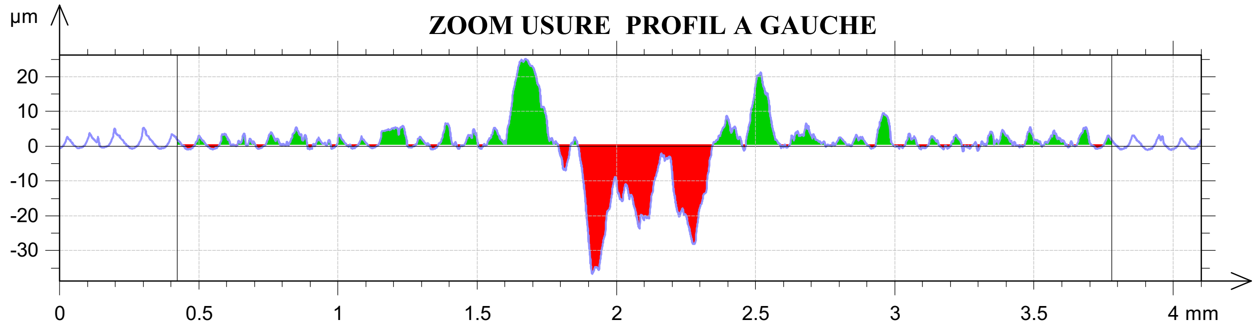
Surface du trou : 9574 µm2

Surface repoussée : 3934 µm2

USURE A GAUCHE : **Largeur 1.957 mm**
USURE A DROITE : **Largeur 1.798 mm**
Usure sur diamètre int de **13.910 mm** et diamètre extérieure de **17.510 mm**

DISQUE REPERE 14
(FACE USURE DIAMETRE LE PLUS GRAND - PROFIL NUMERO 1)



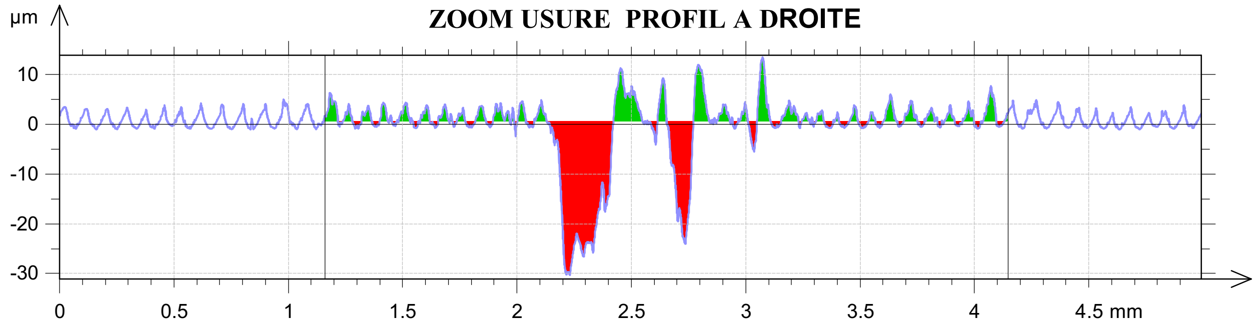


Profondeur maximum : 37.59 µm

Hauteur maximum : 24.28 µm

Surface du trou : 9679 µm2

Surface repoussée : 6821 µm2



Profondeur maximum : 31.23 µm

Hauteur maximum : 12.71 µm

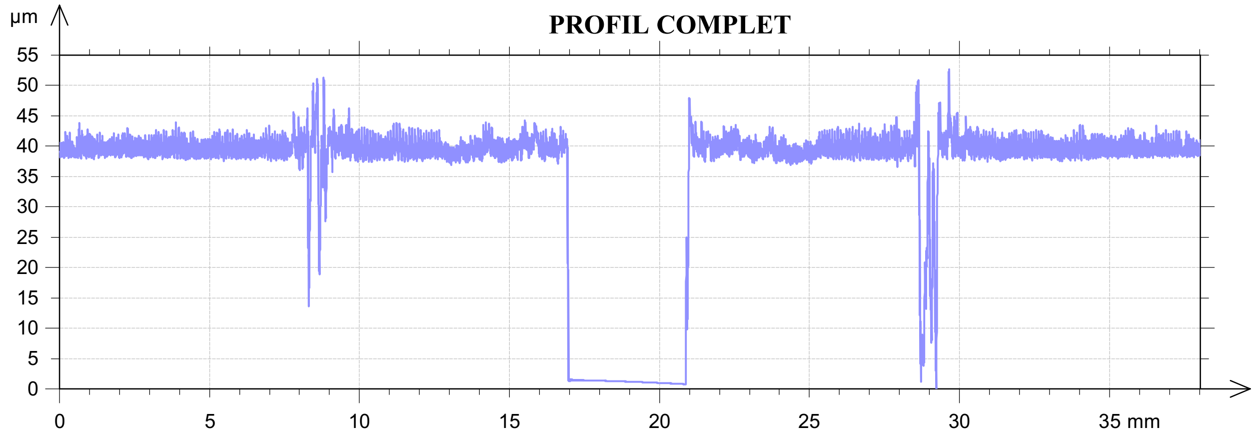
Surface du trou : 8116 µm2

Surface repoussée : 3834 µm2

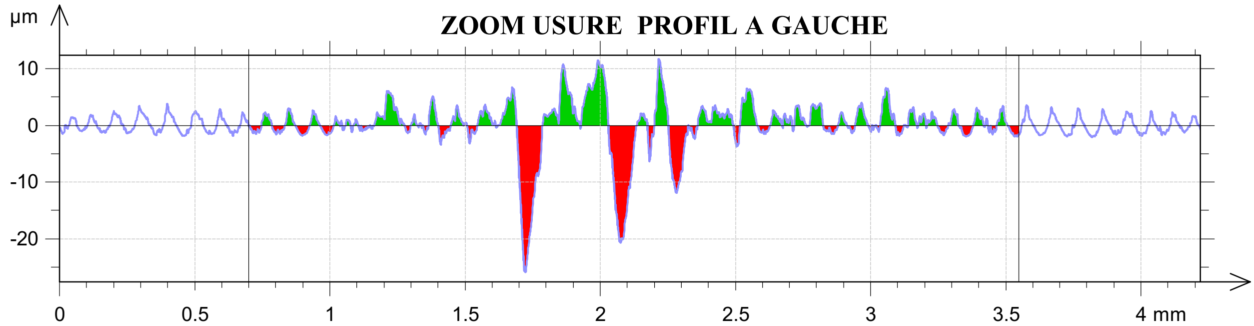
USURE A GAUCHE : **Largeur 1.126 mm**
USURE A DROITE : **Largeur 1.214 mm**
Usure sur diamètre int de **19.460 mm** et diamètre extérieure de **21.860 mm**

DISQUE REPERE 14
(FACE USURE DIAMETRE LE PLUS GRAND - PROFIL NUMERO 2)

PROFIL COMPLET



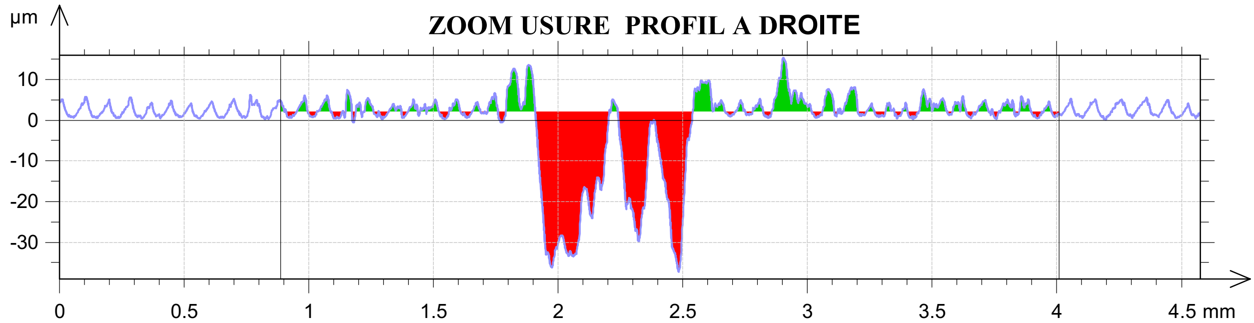
ZOOM USURE PROFIL A GAUCHE



Profondeur maximum : 26.04 µm | Hauteur maximum : 11.66 µm

Surface du trou : 4210 µm2 | Surface repoussée : 4136 µm2

ZOOM USURE PROFIL A DROITE



Profondeur maximum : 39.69 µm | Hauteur maximum : 12.96 µm

Surface du trou : 14531 µm2 | Surface repoussée : 3885 µm2

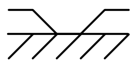
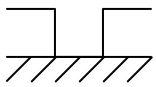
USURE A GAUCHE : **Largeur 1.502 mm**
USURE A DROITE : **Largeur 1.249 mm**
Usure sur diamètre int de **19.400 mm** et diamètre extérieure de **21.990 mm**

APPENDIX 2: NNC comments FRA ANP SAS analysis

The analysis of the NNC comments will be inserted in D42 (compendium of recommendations).

NNC comments	FRA ANP analysis
Specific comments on the tests	
Why was the HR230 vs HR230 test done at 450°C and not 500°C? This combination gave the severe wear (galling) and high friction that would be expected.	CEA test was realized at 450°C, before FRA ANP test. So for this reference test, we decided to keep the same parameters as CEA. The explanations are mentioned in D41-a, issued by CEA
ZrO_2 looks promising: the disc wear rate (~$3x10^{-13}$ m^3/Nm) suggested by the Test 5 result is low in helium. Mild (low) wear in oxidizing environments corresponds to a wear rate of ~10^{-14} m^3/Nm.	Correct. The wear coefficient (or wear rate) are given in table 3.
In the ZrO_2/CaF_2 tests the CaF_2 seems to have transferred to the pin. It appears therefore that the load was too high.	The transfer to the pin is very low. Maybe this coating is not adapted to this required load level.
The WC/Ni-Cr coating looks good at 250°C as NNC would have expected. We would like to see a like-on-like test.	This configuration could be realized in RAPHAEL SP-CT WP3.
TiC clearly needs a supporting (under) coat to help it function.	Due to thermal expansion differences, this type of coating needs further developments.
Some remarks on the test results	
HR230, like-on-like - 450°C -Framatome As expected, the tests on HR230 vs HR230 at 450°C gave rise to severe adhesive wear (galling), with a friction coefficient of up to 0.8. In a like-on-like configuration, HR230 is clearly unsuitable for rubbing applications at 450°C, and most probably at all temperatures in the range of interest.	Agreement on this comment
HR230 + NiCrAlY + ZrO_2-Y_2O_3, like-on-like - 450°C, Framatome HR230 with a coating of yttria-stabilised zirconia on a NiCrAlY undercoat was shown to wear	

NNC comments	FRA ANP analysis
moderately in the Framatome test in a like-on-like configuration at 450°C, with a wear rate of ~3x10^{13} m^3/Nm. The friction coefficient remained high, at ~0.8, throughout the test. The intrinsically high friction coefficient of the coating will preclude its use in some situations.	Agreement on this comment
HR230 + NiCrAlY + ZrO_2-Y_2O_3/CaF_2, like-on-like - 450°C, Framatome With the solid lubricant CaF_2 incorporated into the ZrO_2-Y_2O_3 coating, wear was greatly reduced at 450°C. During the test, the solid lubricant was gradually removed from the wear track on the disc, the friction coefficient building from 0.35 to 0.7.	This is the test result.
Z10CDVNb91, like-on-like - 250°C & 450°C - Framatome This combination wears severely at both temperatures and gave rise to high values of friction coefficient. The Z10CDVNb91 alloy clearly has no potential for use in rubbing situations without a coating.	Agreement on this comment
Z10CDVNb91 vs Z10CDVNb91 + WC/Ni-Cr - 250°C, Framatome In this test, the uncoated pin wore severely, while the coated disc remained hardly worn. As expected the WC/Ni-Cr coating has provided excellent wear resistance at 250°C. There is now a clear need to perform tests in a like-on-like configuration at temperatures up to 450°C.	Agreement on this comment
Z10CDVNb91 vs Z10CDVNb91 + TiC - 250 & 450°C, Framatome Again, a test on a very thin coating has produced early penetration. Like SiC, this coating requires a hard undercoat, capable of supporting the thin coating under the test load.	Agreement on this comment
<u>Some general comments</u> The measurements of wear during testing refer principally to pin wear. This should be discussed.	The measurements include the global wear depth (pin + disk)

NNC comments	FRA ANP analysis
Although these measurements are useful it would be good to see also disc wear results (from profilometry) and pin wear (from weight loss) tabulated for each test. If no wear is seen then a limit can be put on the wear rate. The disc wear rates calculated from the profilometer traces are best calculated in m^3/Nm (i.e. volume of material lost per N of load per m of sliding) for comparison with other data. Pin wear rates can also be calculated as m^3/Nm.	These results are in tables 3 and 4 See tables
We would like to see some profilometer traces included. Also please confirm whether the geometry of the pin is flat or rounded as in Figure 1.	See appendix 1 The pin is flat (due to the low contact pressure required).
The load is important in the test and should be quoted as well as the initial pressure. The pressure will change as you are probably aware. Note that load and pressure have been confused in some places.	In the first test series, the pin has a conical shape under the flat surface. So, effectively, the mentioned pressure is the initial pressure.  For the second series of test, the pin is cylindrical (with a flat surface), so the contact pressure is constant during the test. 
The report would benefit greatly from a results summary table including disc and pin wear rates and disc wear depths.	See tables 3 and 4