

Diffusion bonding Tests

Anastasia Xydou
University of Patras

A. Introduction

- ✓ Aim of this study
- ✓ Configurations
- ✓ Pressure values
- ✓ Workflow
- ✓ Heating cycle
- ✓ Pictures of the assemblies

B. Theoretical Background

C. Results

- ✓ Comparison Between experimental and theoretical results: Simple disks
- ✓ Comparison Between experimental and theoretical results: RF disks
- ✓ Finite Element Model
- ✓ Ultra-sound results: Simple disks , RF disks

D. Conclusions

Aim of this study

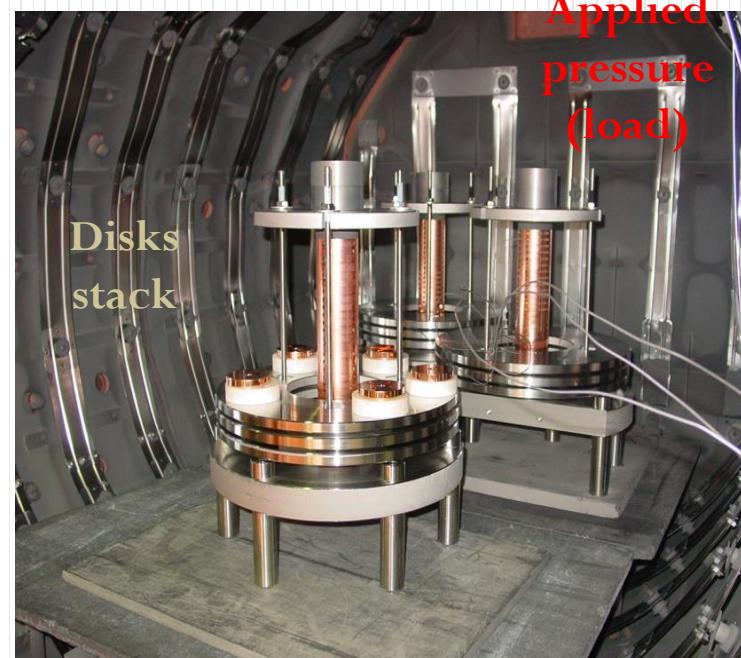
The aim of the experimental program on the diffusion bonding process is to study the influence of the applied pressure on:

- The **quality** of the final bonded joint
- The **residual deformations** at the end of the heating process

In parallel it is important to develop a theoretical model to predict the thermo-mechanical deformations.

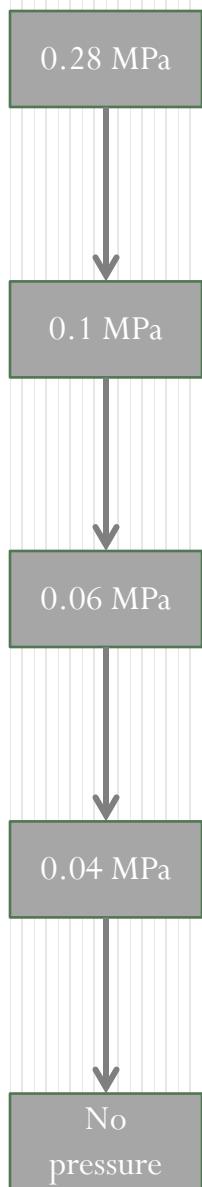
Diffusion Bonding

Diffusion bonding is a process that produces a solid-state coalescence when temperature is below the melting point (T_m) of the materials to be joined by applying a pressure. Such pressure could potentially cause macroscopic deformation of the parts to be joined.



Assembled disk stacks inside the oven ready
for the bonding procedure

Applied pressure - Configuration



SIMPLE DISKS: $\varnothing = 48$ mm



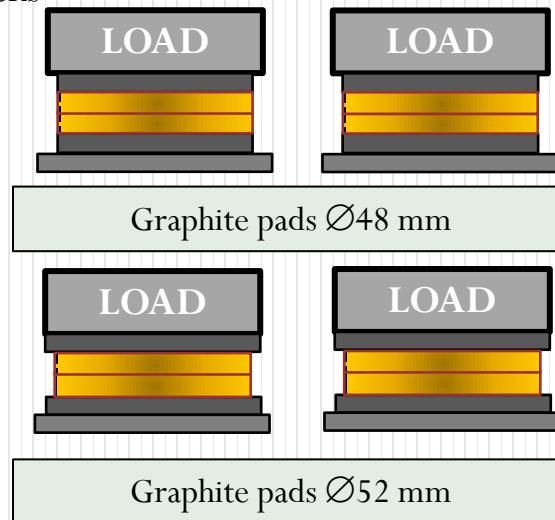
No drawing: [CLIATLAS0186](#)

Pads material: graphite;

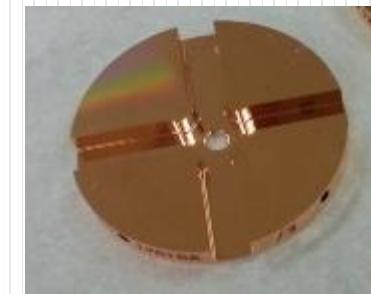
Pads diameter: $\varnothing 48$ mm and $\varnothing 52$ mm,

Quantity for each pressure: 8 copper disks:

4 stacks



RF DISKS: $\varnothing = 80$ mm



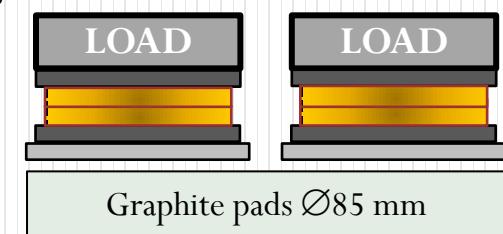
No drawing: [CLIAAS120108](#)

Pads material: graphite;

Pads diameter: $\varnothing 85$ mm,

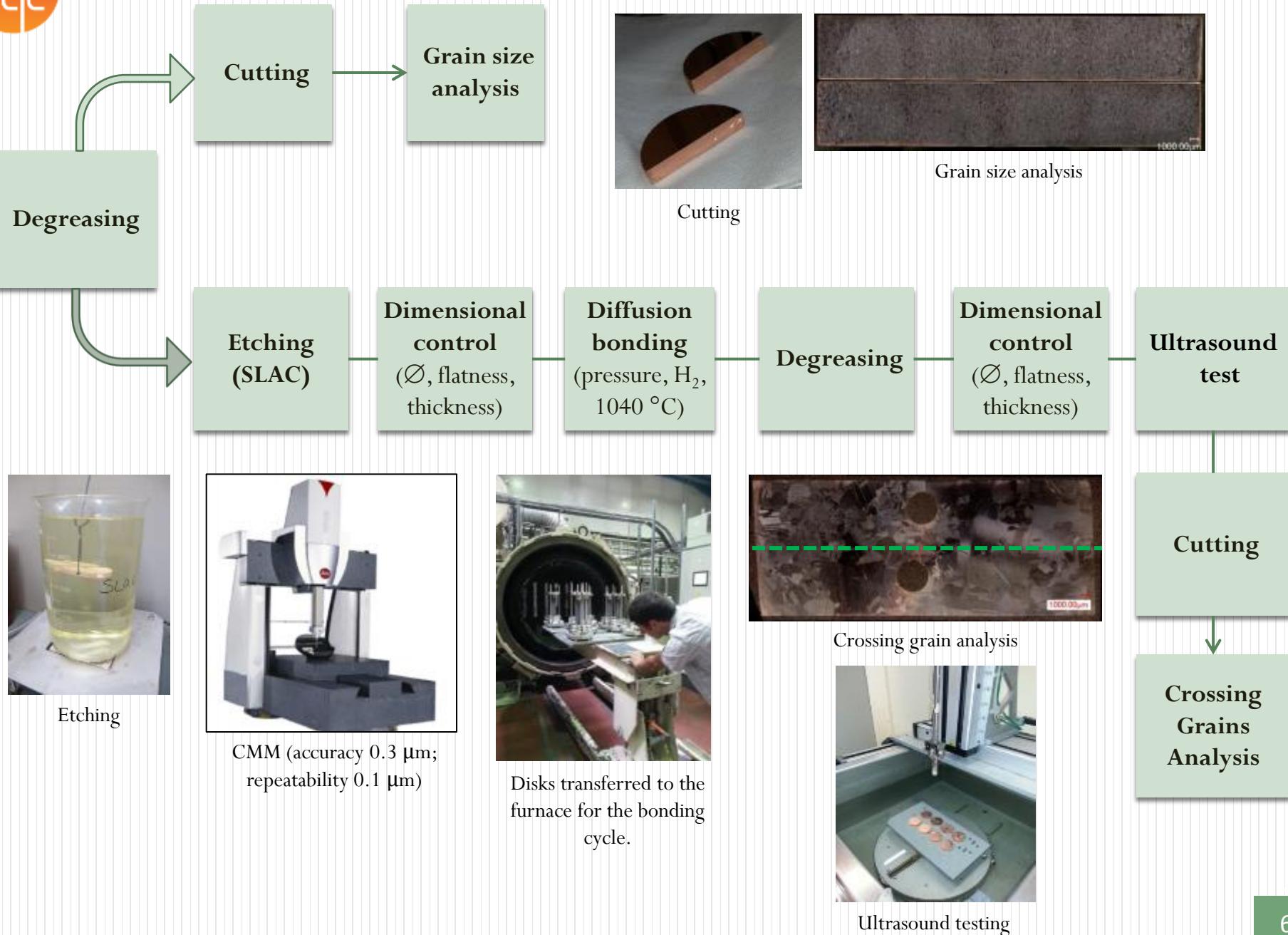
Quantity for each pressure: 4 copper disks :

2 stacks



Graphite 2191
 $T_m = 3650^\circ\text{C}$
 $\text{CTE} = 0.42 \times 10^{-5} / ^\circ\text{C}$

Workflow



Pictures of the assemblies

Simple disks

Pressure [MPa]	Weight [kg]
0.28	51.6
0.1	18.4
0.06	11.1
0.04	7.4

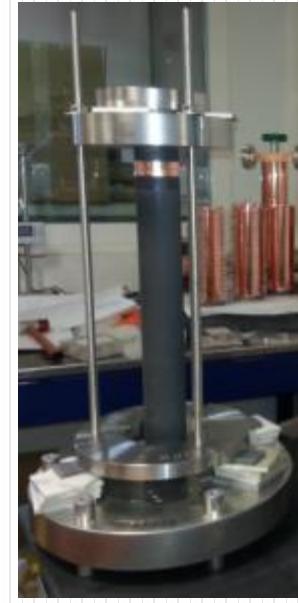
0.28 MPa



0.1 MPa



0.06 MPa

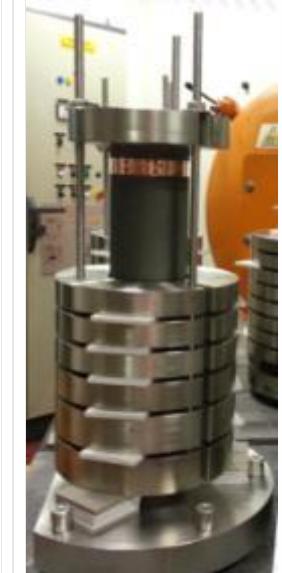


0.04 MPa

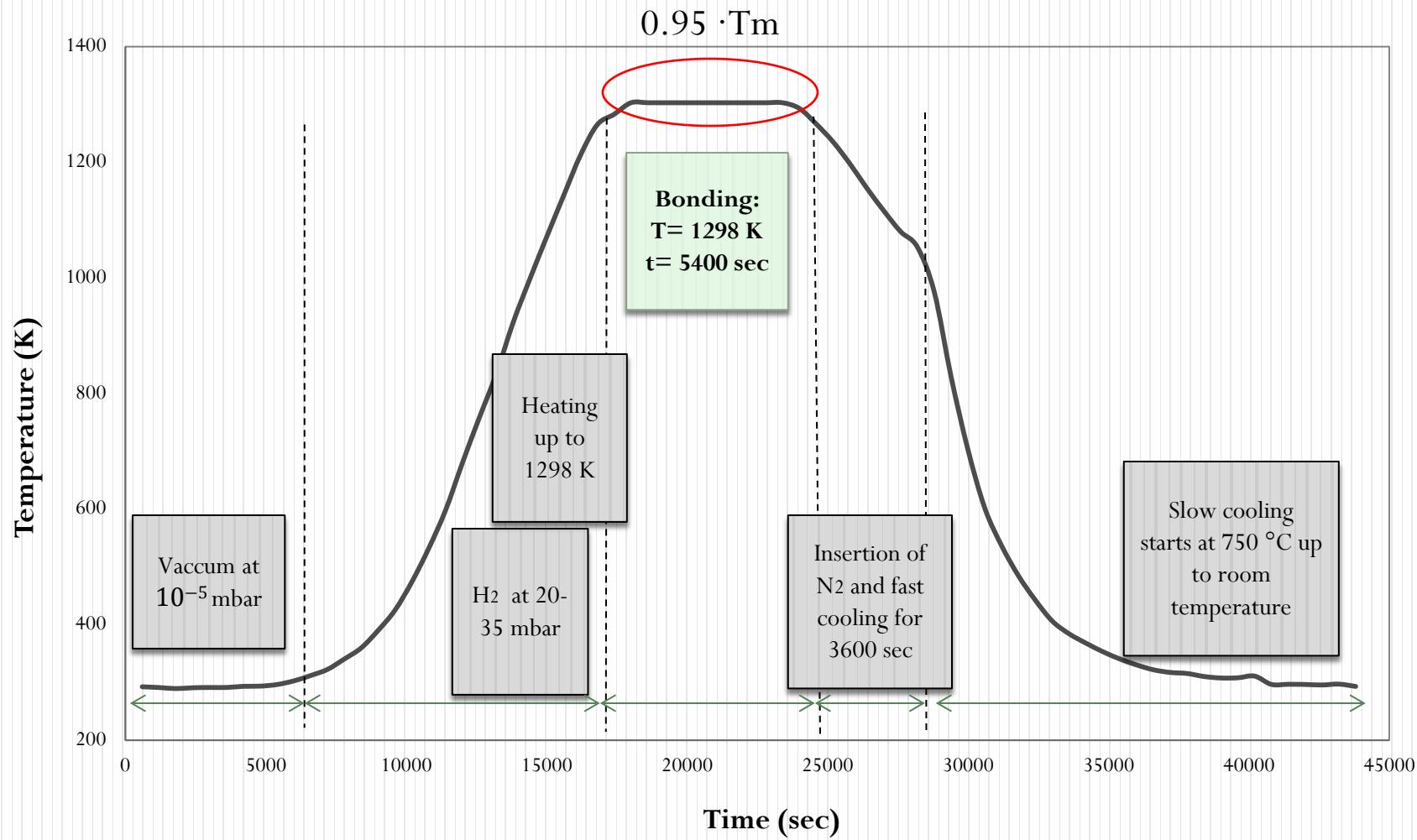


RF disks

Pressure [MPa]	Weight [kg]
0.28	114.2
0.1	40.8
0.06	24.5
0.04	16.3

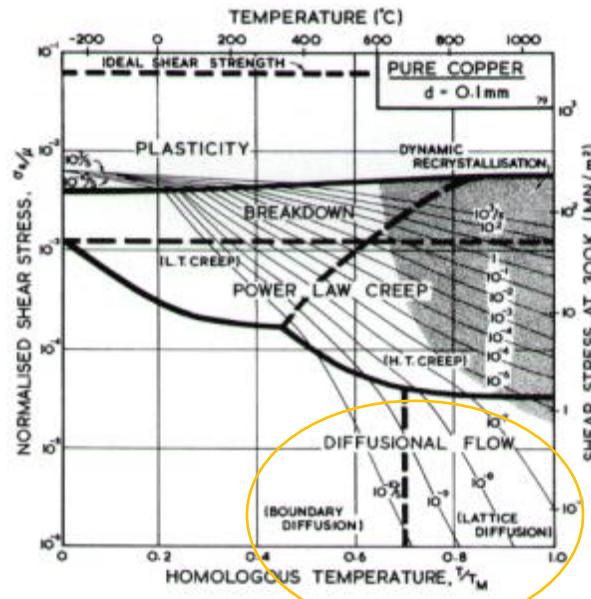


Heating cycle



Theoretical background: Diffusion Creep

Creep is a time dependent deformation of a material while it is subjected to a constant load and at a high temperature ($T > 0.4 T_m$). Depending on the range of temperature and stress different creep mechanism is activated:



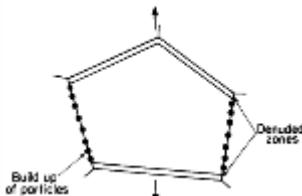
At high temperature and low stresses, deformation of fine-grained materials proceeds by:

- accommodating grain-boundary sliding
 - transport of matter, diffusion creep.
- a. Transport of matter occurs by lattice diffusion: **Nabarro- Herring creep**
 - b. Transport of matter occurs by grain-boundary diffusion: **Coble creep**

Theoretical background: Diffusion Creep

Grain boundary diffusion (Coble creep)

Coble creep ($T < 0.7 \cdot T_m$)



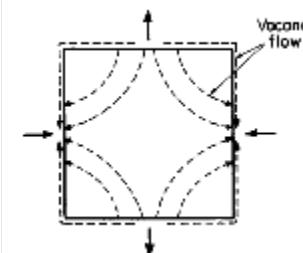
Vacancies flow along the grain boundaries

$$\dot{\varepsilon}_{Co} = A_{Co} \frac{\delta D_{gb} \Omega \sigma}{d^3 kT}$$

Parameter	Value	Units	Description
A_{Co}	$150/\pi$	-	Coble's constant
δD_{gb}	$D_b \cdot e^{(-\frac{Q_b}{R \cdot T})}$	m^3/s	Coefficient for grain boundary diffusion
D_b	$5e-15$	m^3/s	Pre-exponential
Q_b	$104e3$	J/mol	Activation energy
R	8.314	J/(K·mol)	Gas constant
Ω	$1.182e-29$	m^3	Atomic volume
d	...	m	Grain size
k	$1.3806505e-23$	J/K	Boltzmann's constant
T	...	K	Absolute temperature

Lattice diffusion (Nabarro-Herring creep)

Nabarro-Herring creep ($T > 0.7 \cdot T_m$)



Vacancies flow through the grains

$$\dot{\varepsilon}_{NH} = A_{NH} \frac{D_1 \Omega \sigma}{d^2 kT}$$

Parameter	Value	Units	Description
A_{NH}	[12-40]	-	Nabarro-Herring's constant
D_1	$D_o \cdot e^{(-\frac{Q}{R \cdot T})}$	m^2/s	Coefficient for lattice diffusion
D_0	$20e-6$	m^2/s	Pre-exponential
Q	$197e3$	J/mol	Activation energy
R	8.314	J/(K·mol)	Gas constant
Ω	$1.182e-29$	m^3	Atomic volume
d	...	m	Grain size
k	$1.3806505e-23$	J/K	Boltzmann's constant
T	...	K	Absolute temperature

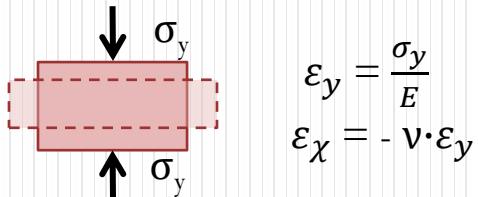
*Values taken from the **Deformation-Mechanism Maps, The Plasticity and Creep of Metals and Ceramics**, by Harold J Frost, Dartmouth College, USA, and Michael F Ashby, Cambridge University, UK.

Simple disks

[EDMS#1279671](#)

Analytical solution

Considering the uniaxial compression at the Generalised Hooke's law...



Deformation of external diameter

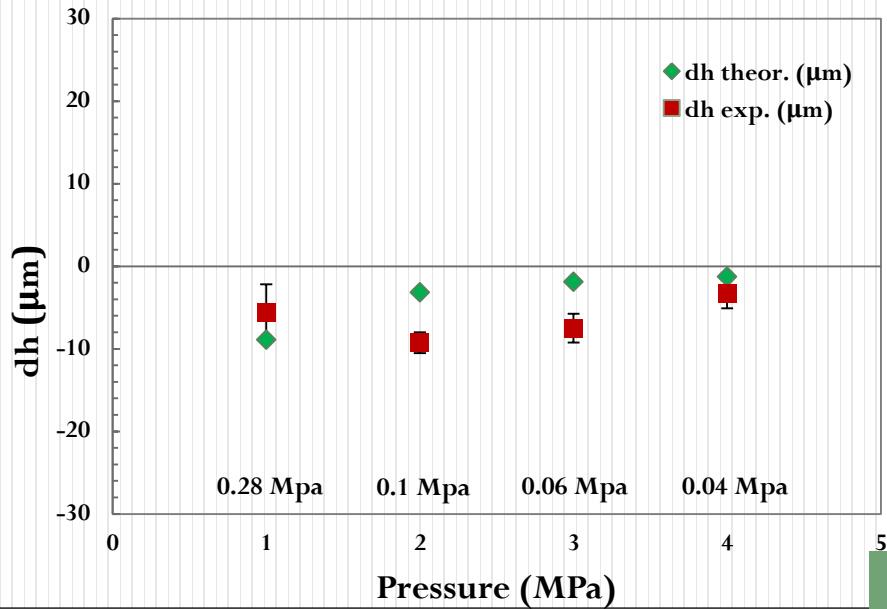
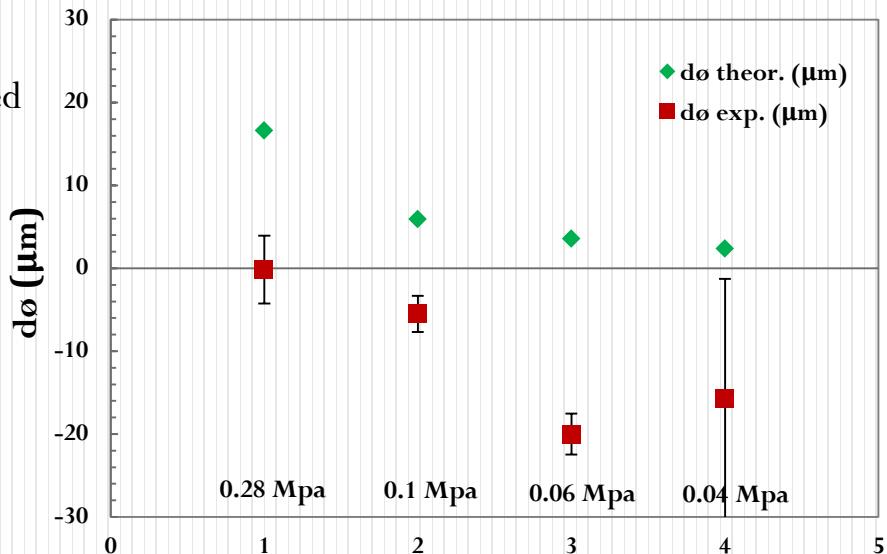
$$\Delta\phi = \phi \cdot v \cdot (\sum_0^{0.7 \cdot T_m} \dot{\varepsilon}_{Co} \cdot T \cdot \Delta t + \sum_{0.7 \cdot T_m}^{T_{max}} \dot{\varepsilon}_{NH} \cdot T \cdot \Delta t)$$

Deformation of thickness

$$\Delta h = (\sum_0^{0.7 \cdot T_m} \dot{\varepsilon}_{Co} \cdot T \cdot \Delta t + \sum_{0.7 \cdot T_m}^{T_{max}} \dot{\varepsilon}_{NH} \cdot T \cdot \Delta t) \cdot h$$

Where:

- T_{max} = bonding temperature
- T_m = melting temperature of copper (1356 K)
- $\Delta\phi$ and Δh is the variation of the diameter and of the thickness respectively
- ν is the Poisson ratio
- $\dot{\varepsilon}_{Co}$ and $\dot{\varepsilon}_{NH}$ are the strain rate predicted by Coble and Nabarro-Herring respectively.
- Δt is the time step used for the discretization of the curve.



Comparison Between experimental and theoretical results

RF disks

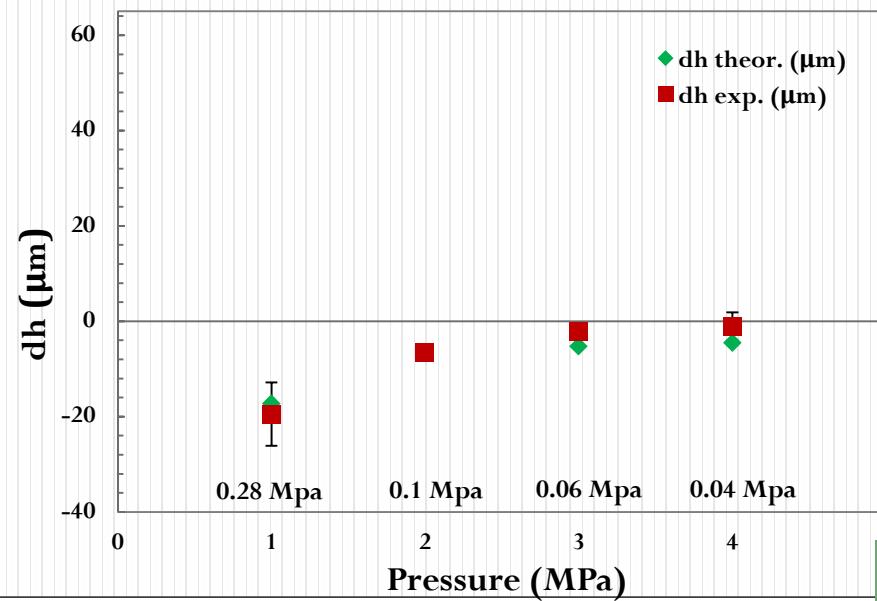
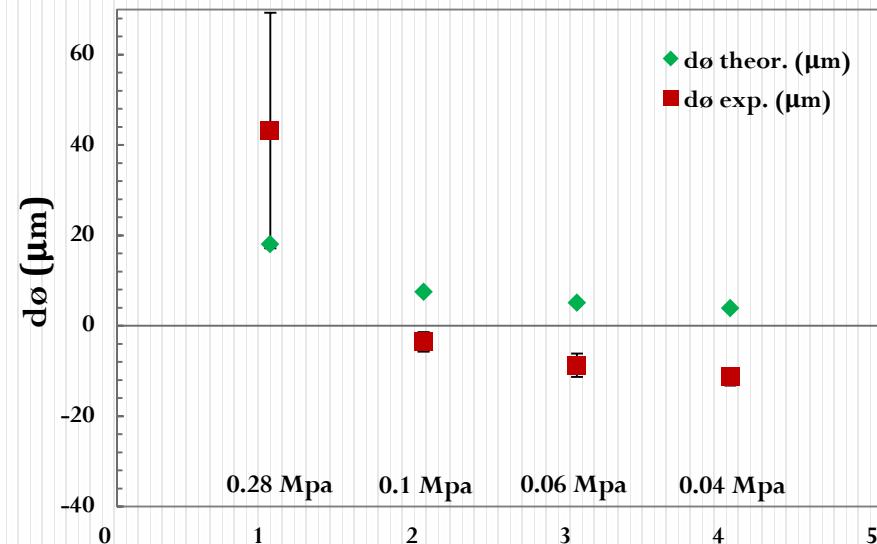
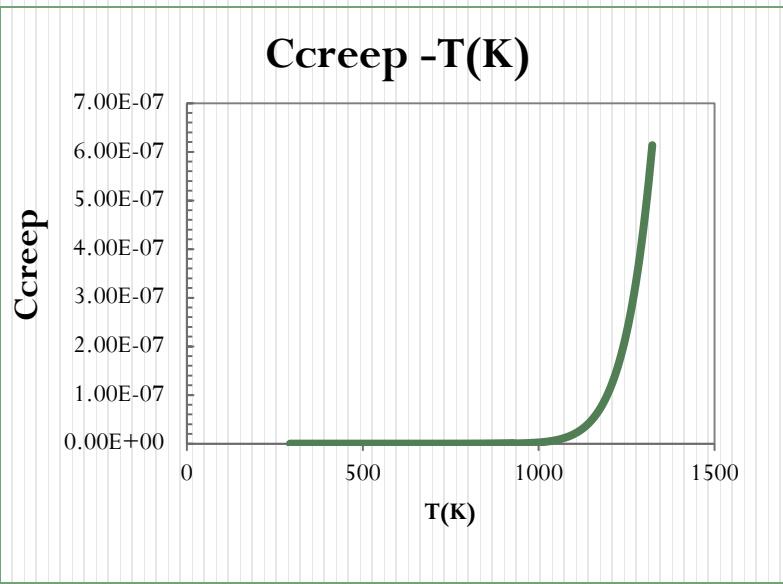
[EDMS#1391276](#)
[EDMS#1409813](#)

Finite Element Analysis

Using both formulas from Coble and Nabarro-Herring the *creep constant for the full Heating cycle* is calculated:

$$C_{creep} = \frac{A \cdot D \cdot \Omega}{d^n \cdot k \cdot T}$$

* where $n=2$ or 3

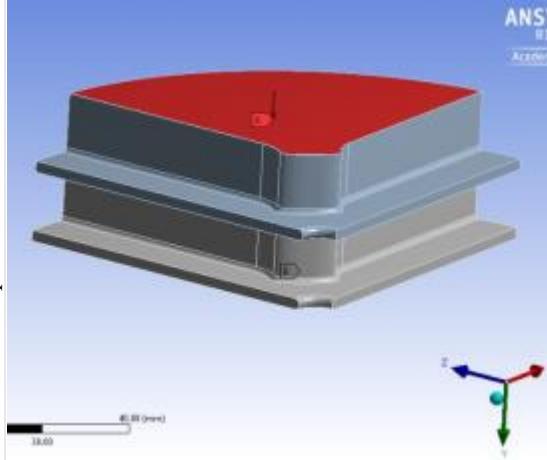


Finite Element Model

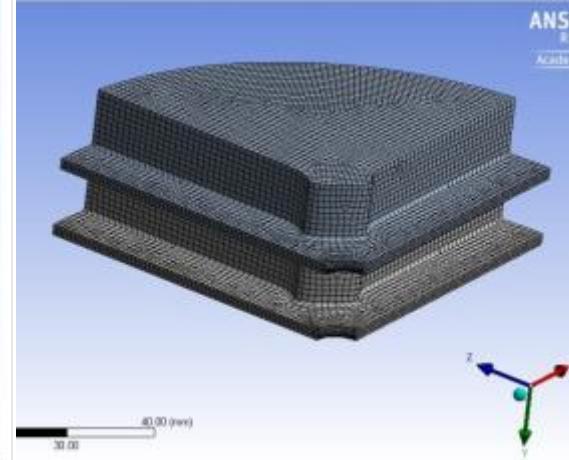
27-Jan-15

Aim: the aim of the development of the FEA model is to compare the outcome of the simulations with the experiments.

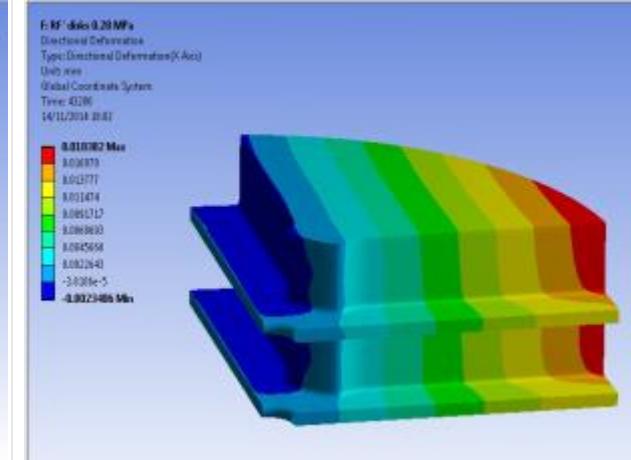
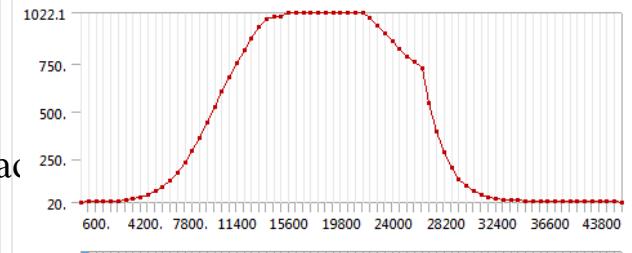
- **Nonlinear material model**
- **Material properties as function of the temperature** (20 - 1040 °C): Density, Isotropic Elasticity (Young's Modulus), Isotropic Thermal Conductivity, Specific Heat, Thermal expansion
- **Symmetry:** Symmetric to both lateral faces
- **Contacts:** Frictional contacts in the interface of the disks
- **Boundary conditions:** Simply supported on the lower face
- **Loads:** Pressure value on the upper face
- **Thermal condition:** thermal cycle



A: applied pressure, **B:** zero displacement on the z axis.



Element size 0.8 mm
Nodes: 249.247, Elements :64979



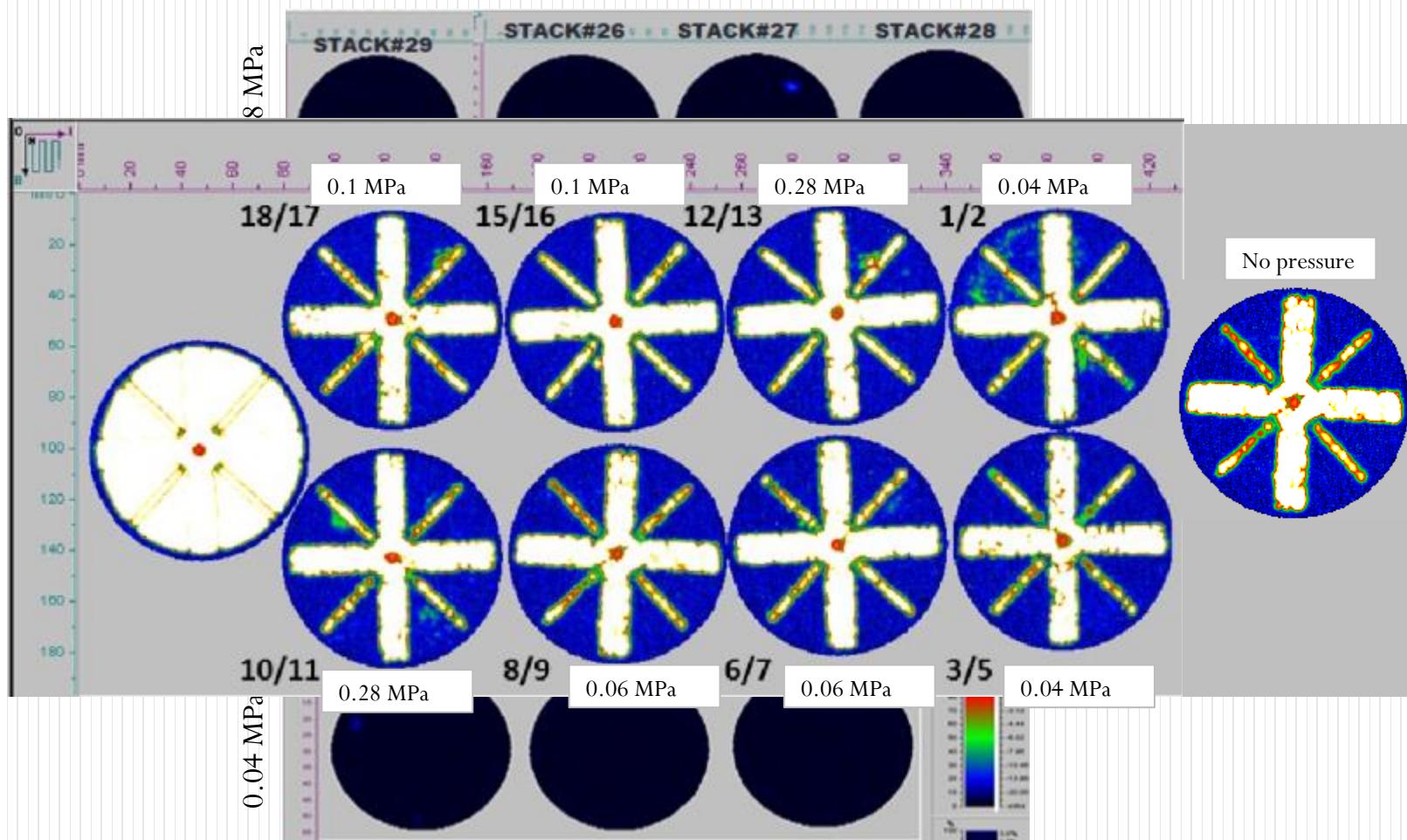
Displacement result of the x axis

Ultra-sound results

[EDMS #1459904](#)

[EDMS #1414269](#)

Simplesisks

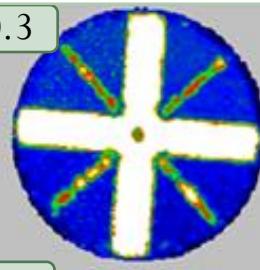


- Only small imperfections were observed.
- The pressure doesn't seem to affect the final result of the bonded joint. → The only variable that may affect is the flatness in the interface → A targeted test was performed afterwards.

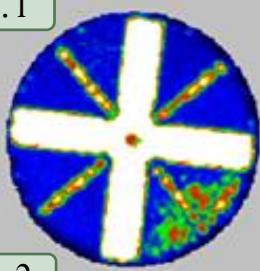
Additional test

Flatness dif. (μm) in the interface

0.3



0.1



6.2

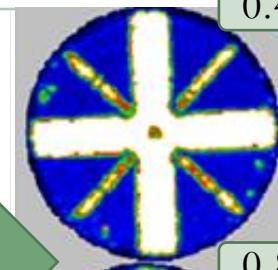


7.2



Flatness dif. (μm) in the interface

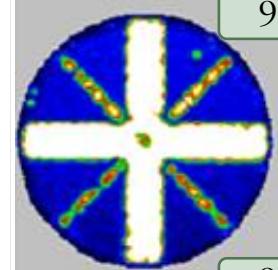
0.4



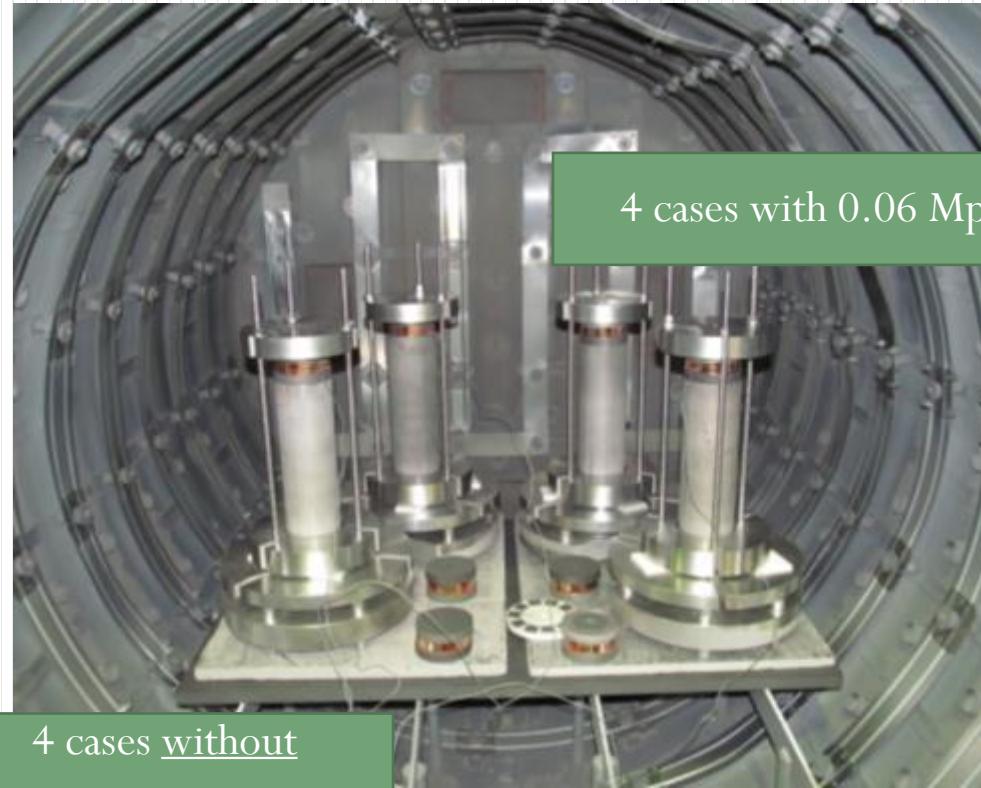
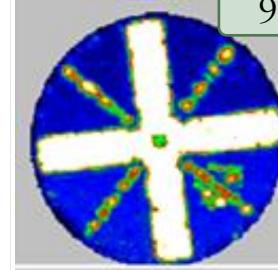
0.8



9



9



Cutting is needed to:

- Quantify the indicated imperfections
- Verify the crossing grains in the interface.

Conclusions

Deformations

- The model developed in ANSYS is able to predict the permanent deformations
- The behavior of the deformations verifies the two creep laws of Nabarro-Herring and Coble.
- The higher the pressure the bigger the absolute deformations on the external diameter and the thickness.
- A shrinkage is observed in most of the cases which can be explained at some point by the sublimation due to the high temperature. Where another explanation could be the rearrangement of the microstructure.

Bonded joint

- The bonded joint doesn't seem to depend on the pressure or the flatness in the interface, at the tested temperature. Further verification is needed by cutting and observe the crossing grains.

Thank you for your attention!

Many thanks for their valuable contribution to: S. Lebet, A. Perez
Fontenla, D. Glaude.



EXTRA



Graphite pad drawing

IND.	DATE	NOM/NAME	MODIFICATION
A	2013-01-25	A. Xydotu	delete note

DESSIN RÉGULIÈREMENT SELON LES STANDARDS
DRAUGHTING REGULARLY ACCORDING TO STANDARDS
DRAWING REGULARMENTE SECONDES STANDARDS
ACCORDING TO STANDARDS

PROJECTION

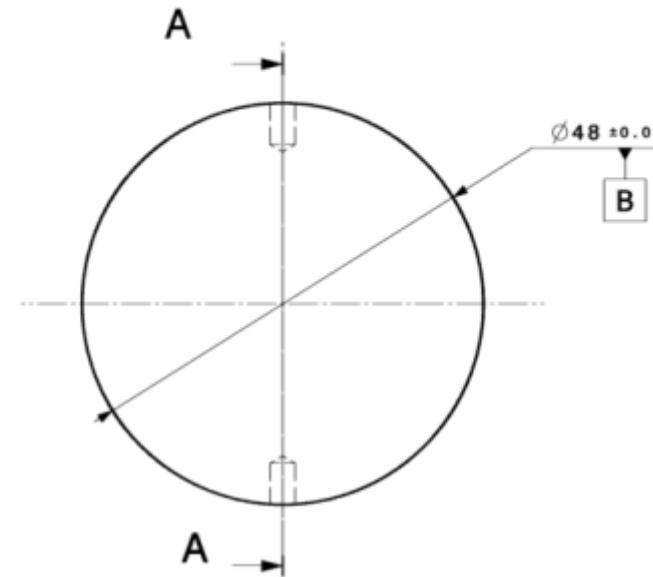
N	a (mm)
1	48
2	52
3	85

CLIC INSTITUTE FOR HIGH ENERGY PHYSICS
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN
THIS DRAWING IS THE PROPERTY OF CERN
IT MUST NOT BE COPIED OR USED FOR COMMERCIAL PURPOSE WITHOUT WRITTEN AUTHORIZATION

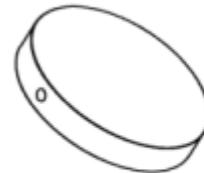
QUANT.	DESCRIPTION	POS.	MAT.	OBSERVATIONS	REF. CERN
1	2191PT				
1	CLIC tools for assembly and production GRAPHITE PAD FOR BONDING	ECH. SCAL.	DES./DRA.	A. XYDOTU	2013-01-10
		1:1	CONTROLLED	A. SOLIBKO	2013-01-25
			RELEASED	A. SAMOSHIN	2013-01-25
			APPROVED	CLI\ATOOL\CLIATOOL0230	
			REPLACE/REPLACES		

RELEASED BY: PROJECT ENGINEER: FOR INFORMATION: DATE: CLIATOOL0230 SIZE: IND: 4 A

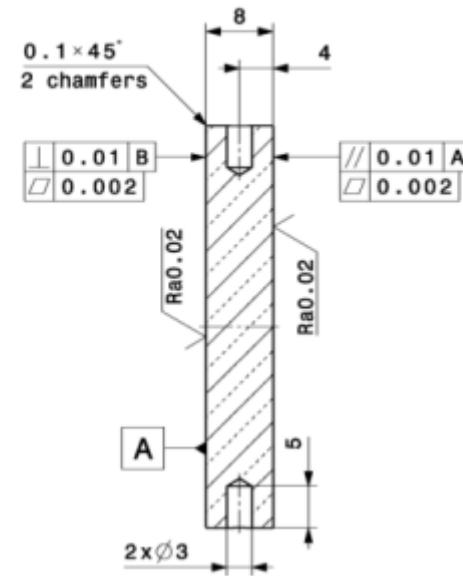
Simple disk drawing



Front view
Scale: 2:1



Isometric view
Scale: 1:1



NOTES:

- Dimensions in this drawing are at 20°C in free state.
- Lubricant based on Chlorine or Sulfur should be avoided.
- No polishing is allowed.
- No deformations admissible due to stress release or shocks during and after machining.
- Each disk must be marked as showed below
S(No. 00, 01...06)
ex. First disk - S00, second disk - S01 etc.
- The product must be individually packed inside a main delivery box.

ROUND BARS	1	CU-OFE	44.09.47
			550.5
QUA	DESCRIPTION	POS. MAT.	OBSERVATIONS
ENS/ASS			6.ENS/6.ASS

ISO 2768-fH	$\sqrt{Ra\ 1.6}$ (✓)	ISO 13715 $[-0.3\ +0.3]$ (L)
-------------	----------------------	------------------------------

CLIC Test (Lab.) - Accelerating Structure		DES/DRA.	A. SOLONKO	2012-07-17
BONDING TESTS		SCALE	F. ROSSI	2012-07-19
SAMPLE DISK			G. RIZZONE	2012-07-19
2:1		APPROVED		
CAD Document Number: ST0435356_02		REPLACES		

RELEASED BY 	FOR INFORMATION	DATE	SIZE
PROJECT ENGINEER	-	CLIATLAS0186	3

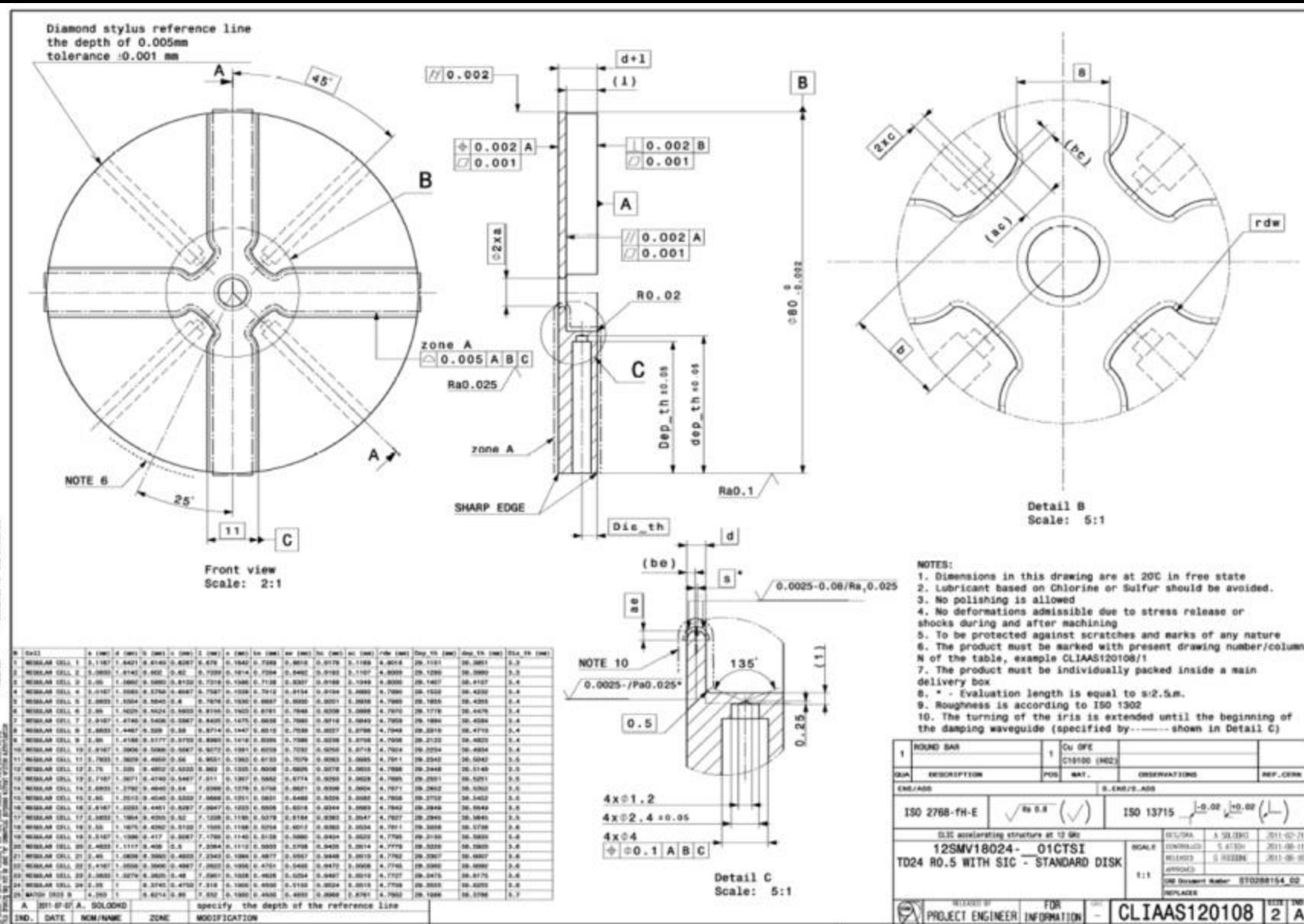
DESIGN, MACHINERY, TOLERANCES
DRAWINGS, MACHINERY, TOLERANCES
ACCORDING TO ISO STANDARDS

PROJECTION
PROJECT

CLIC ASSOCIATION, EUROPEAN LEAD
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
GENEVA
This drawing is part of CLIC Project. It is the property of CLIC Project.
It is not to be reproduced without written authorisation.

RF disk drawing

CLIAAS120108
REVISION: A DRAFT DATE: 01/01/2011
DRAWER: CLIAAS120108 DRAWER NUMBER: 0001
PROJECT: PROJECT NUMBER: TD24 R0.5 WITH SIC - STANDARD DISK

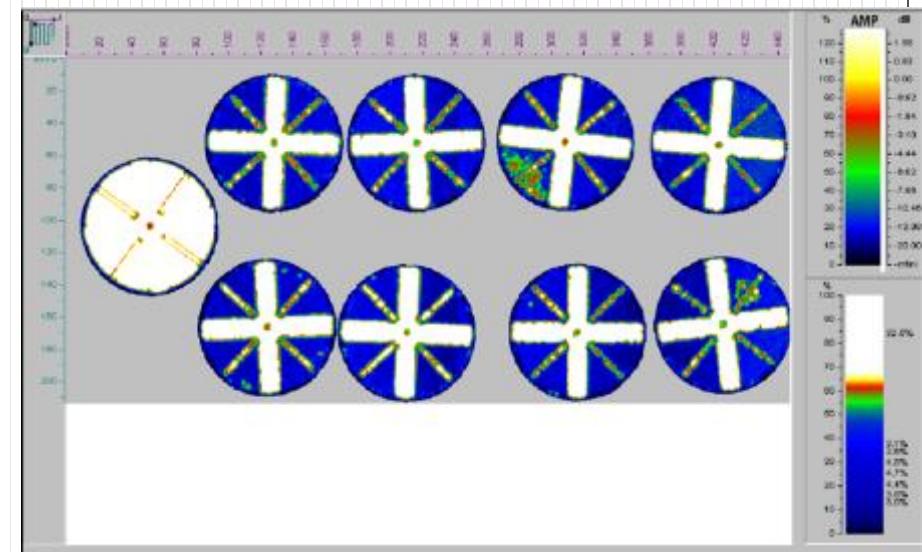




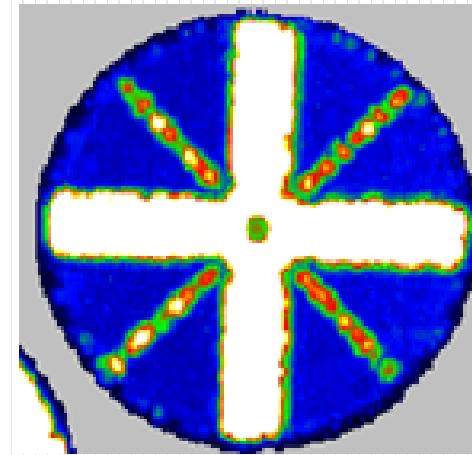
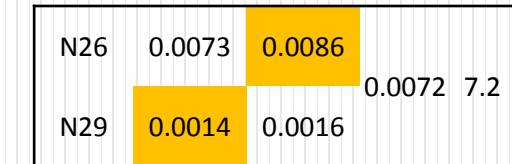
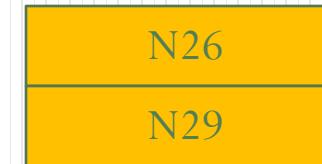
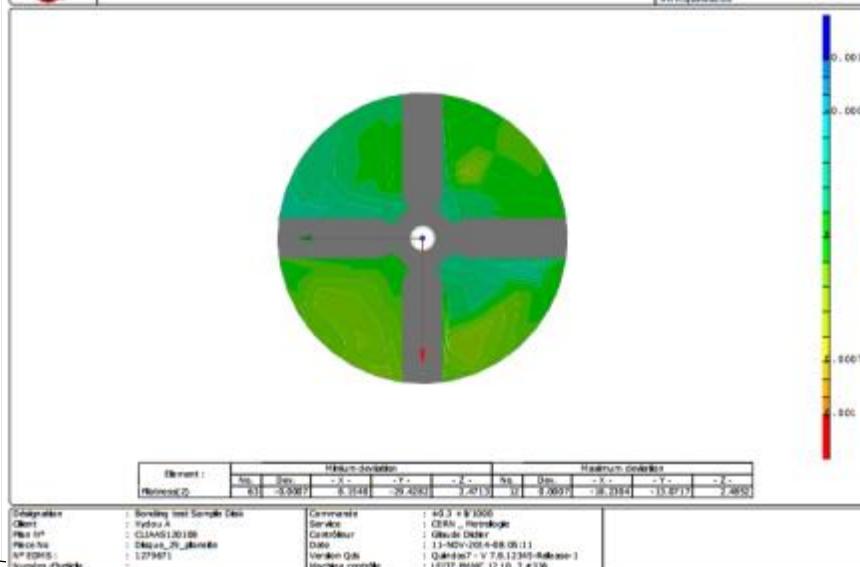
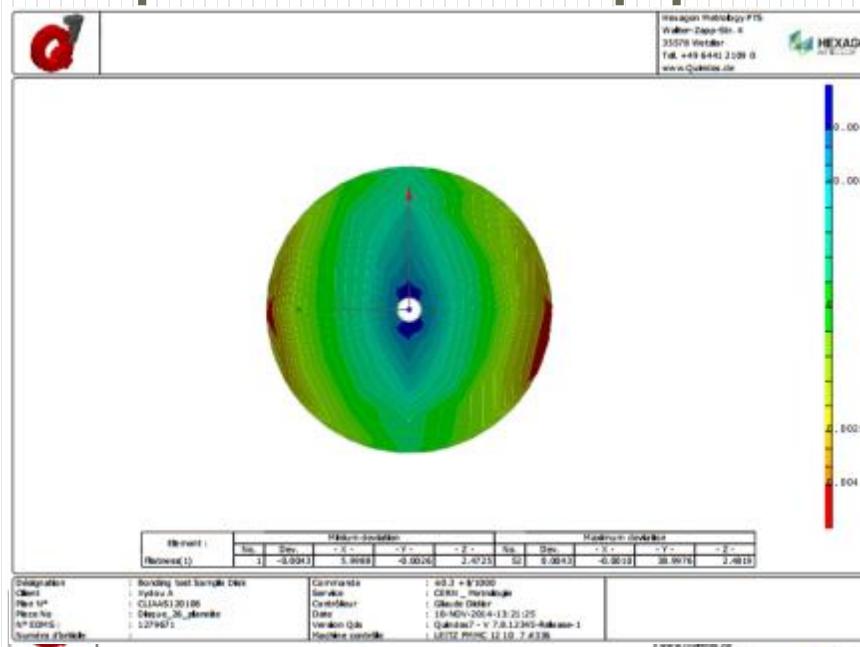
With pressure 0.06 Mpa

Without pressure

	TOP PLANE	BOTTOM PLANE			TOP PLANE	BOTTOM PLANE		
N19	0.011	0.014		0.009	9	N26	0.0073	0.0086
N34	0.005	0.0066				N29	0.0014	0.0016
N36	0.0103	0.0131		0.009	9	N21	0.0037	0.0075
N31	0.0041	0.0069				N32	0.0013	0.0013
N28	0.002	0.0034		0.0008	0.8	N33	0.0022	0.0036
N24	0.0026	0.003				N22	0.0035	0.0035
N23	0.0015	0.0024		0.0004	0.4	N25	0.0029	0.0048
N27	0.002	0.0039				N35	0.0045	0.0027
								0.0003
								0.3

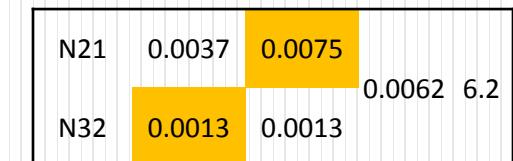
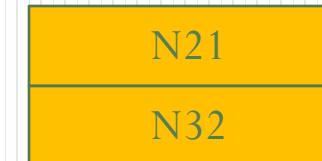
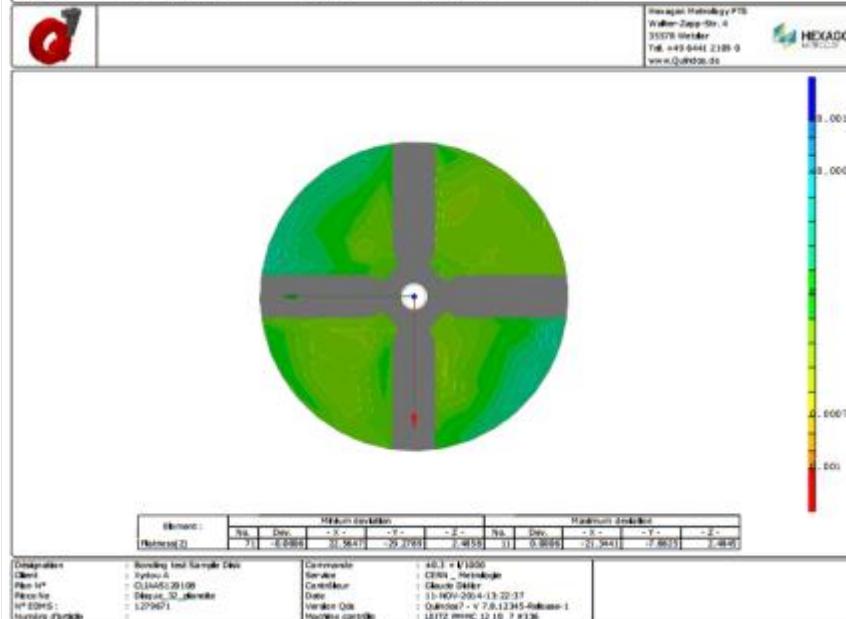
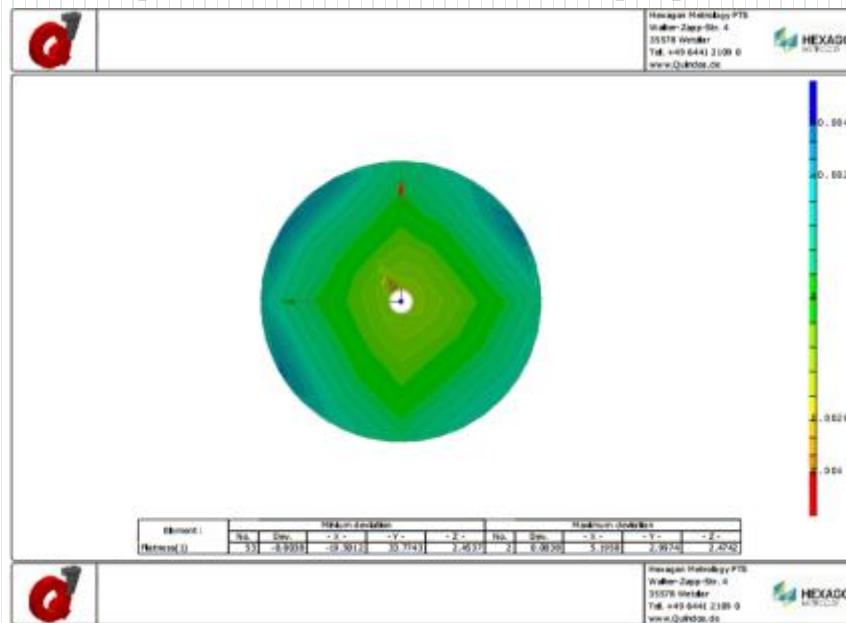


No pressure applied



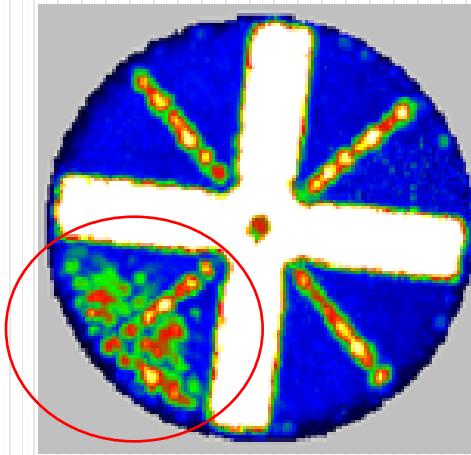
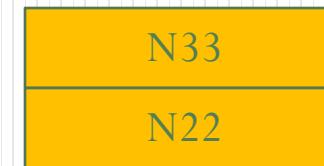
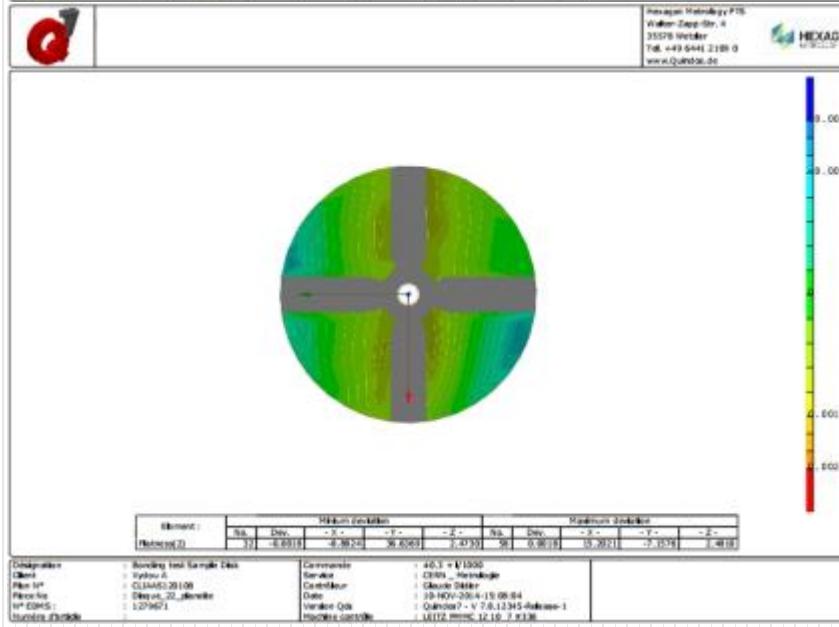
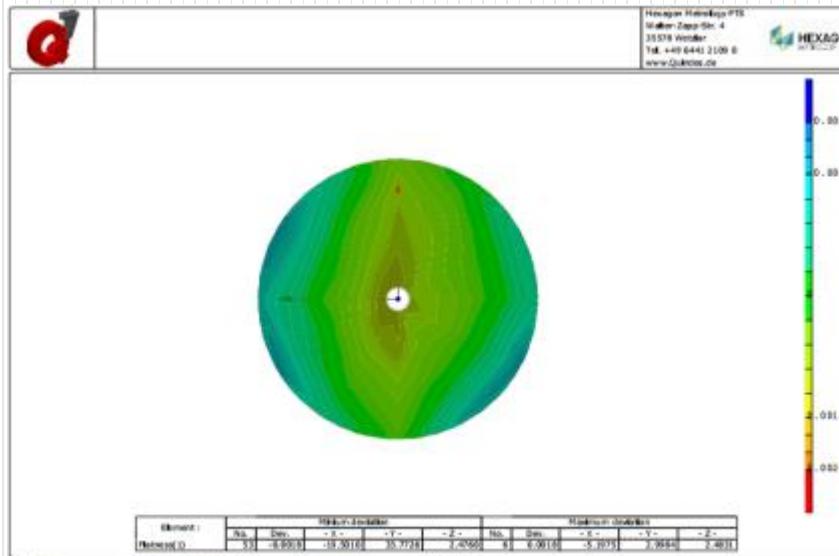


No pressure applied

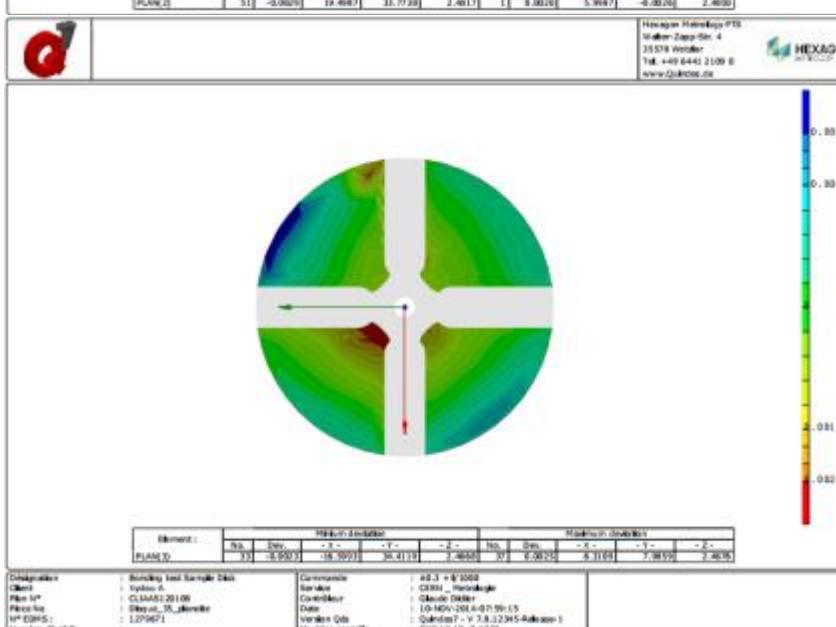
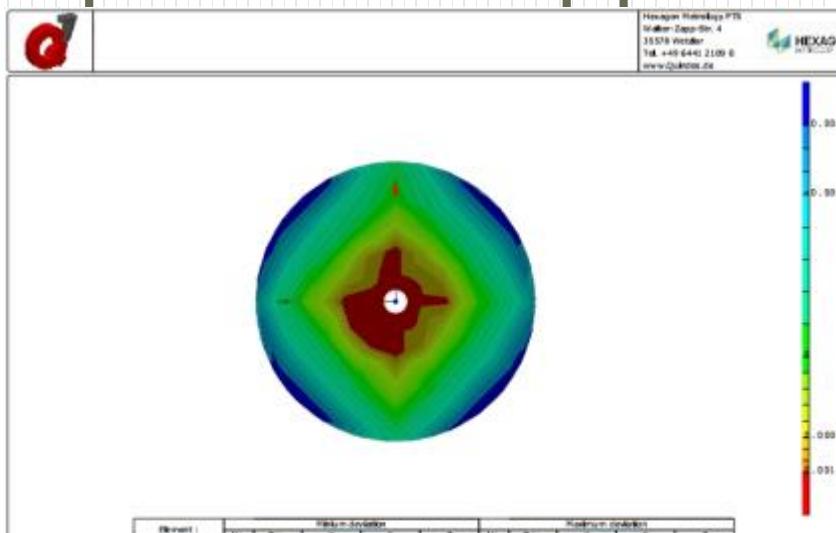




No pressure applied



No pressure applied

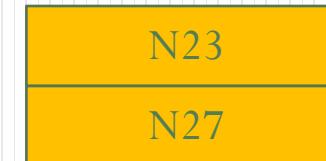
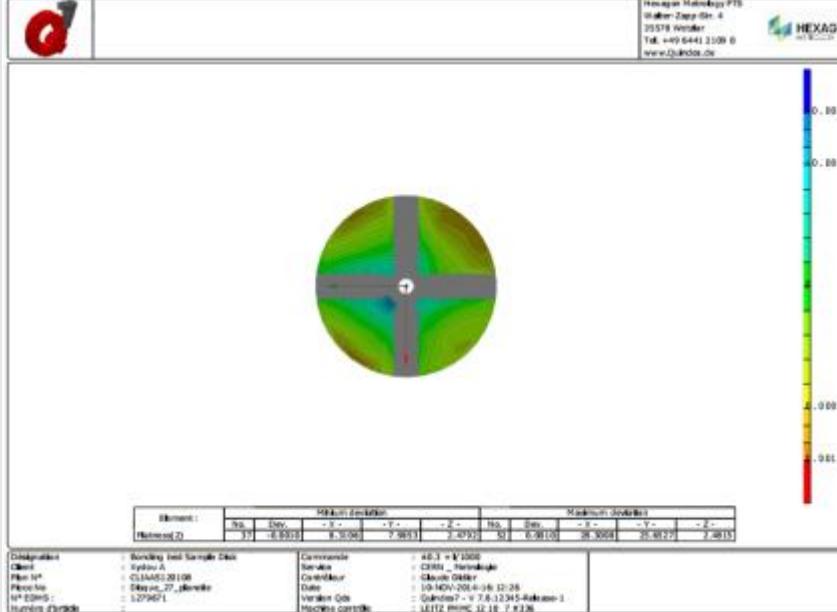
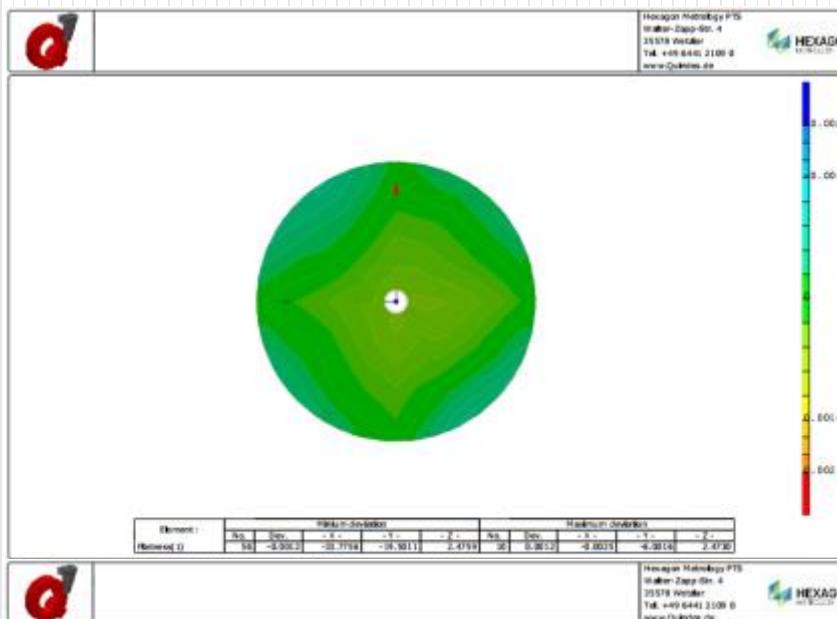


N25
N35

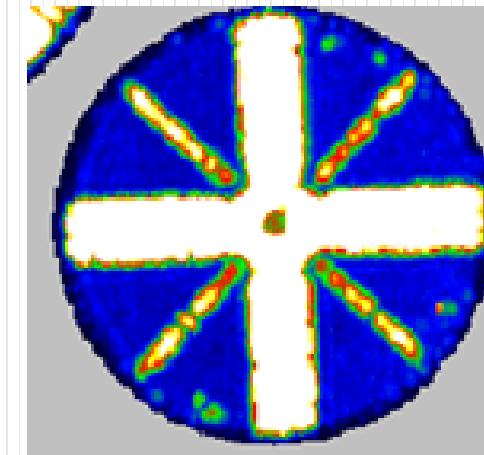
N25	0.0029	0.0048	0.0003	0.3
N35	0.0045	0.0027		



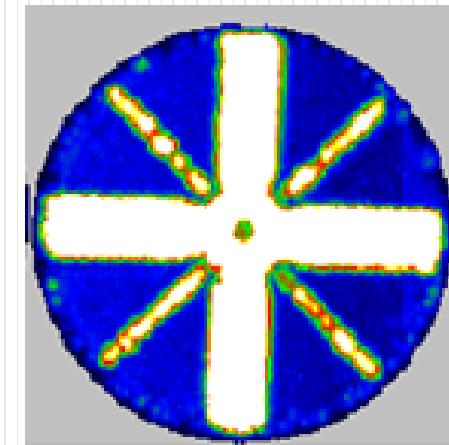
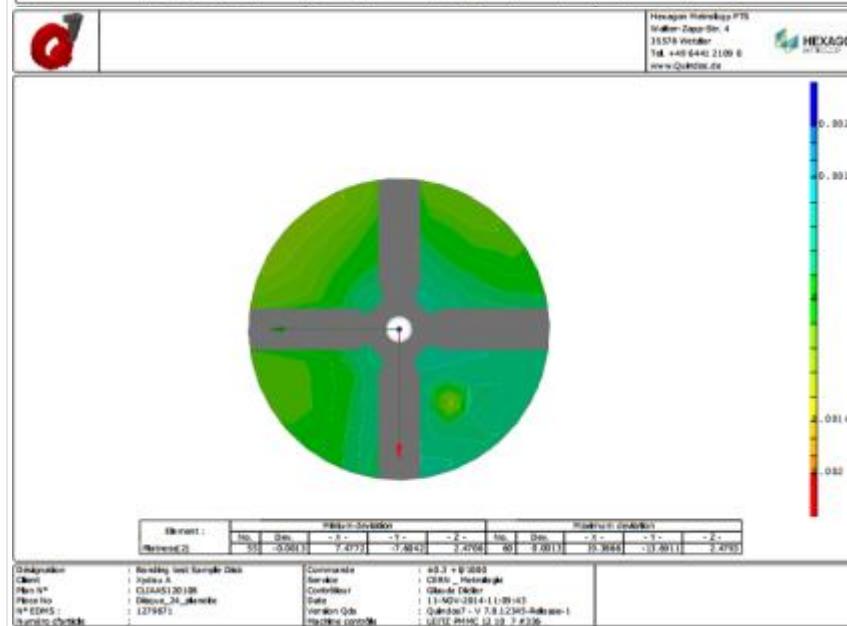
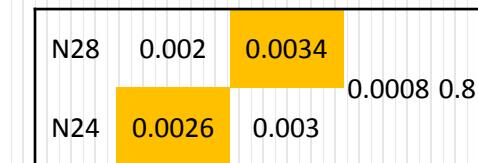
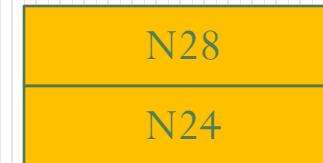
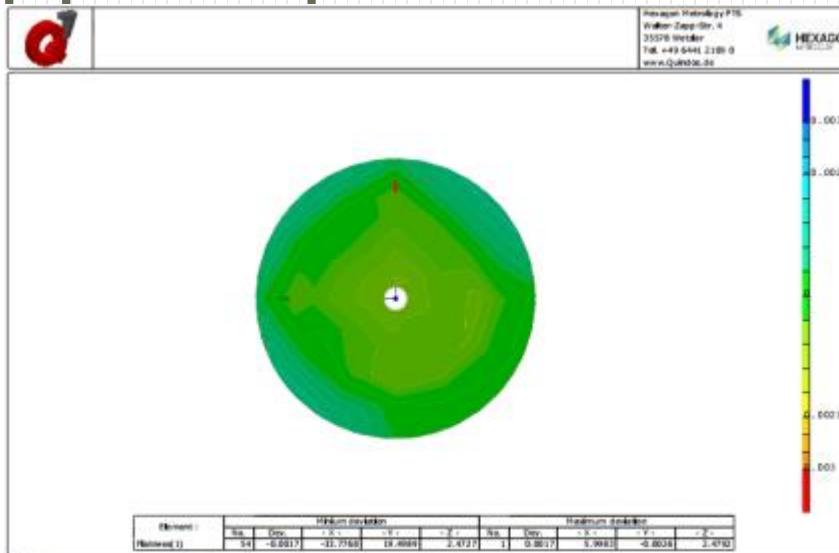
Applied pressure: 0.06 Mpa



N23	0.0015	0.0024	
N27	0.002	0.0039	0.0004 0.4

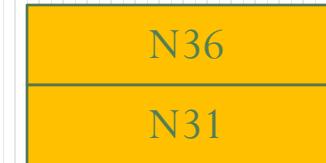
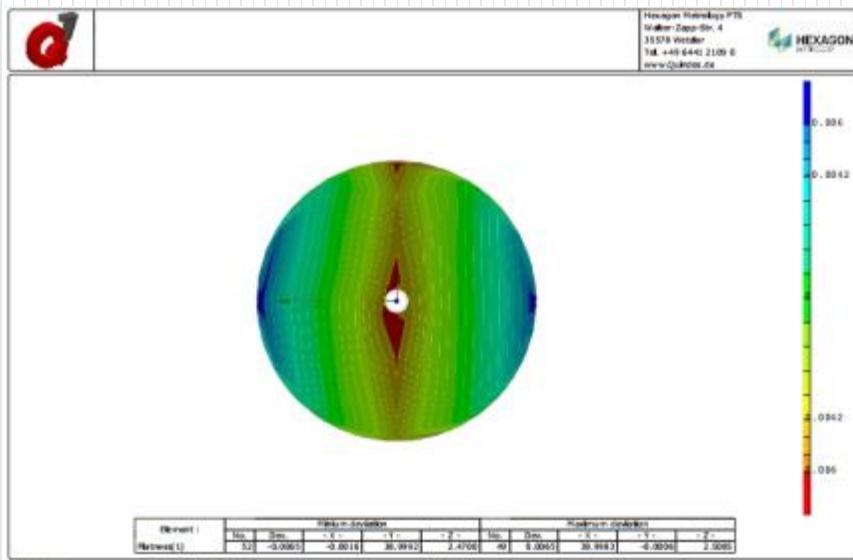


Applied pressure: 0.06 Mpa

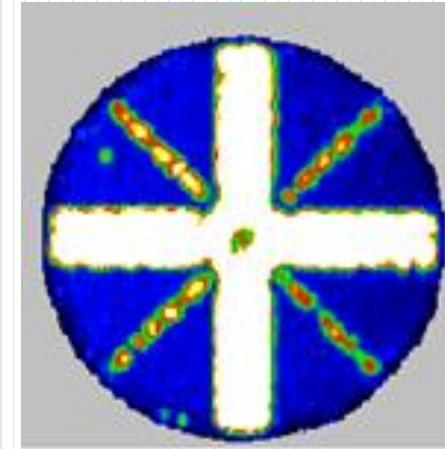
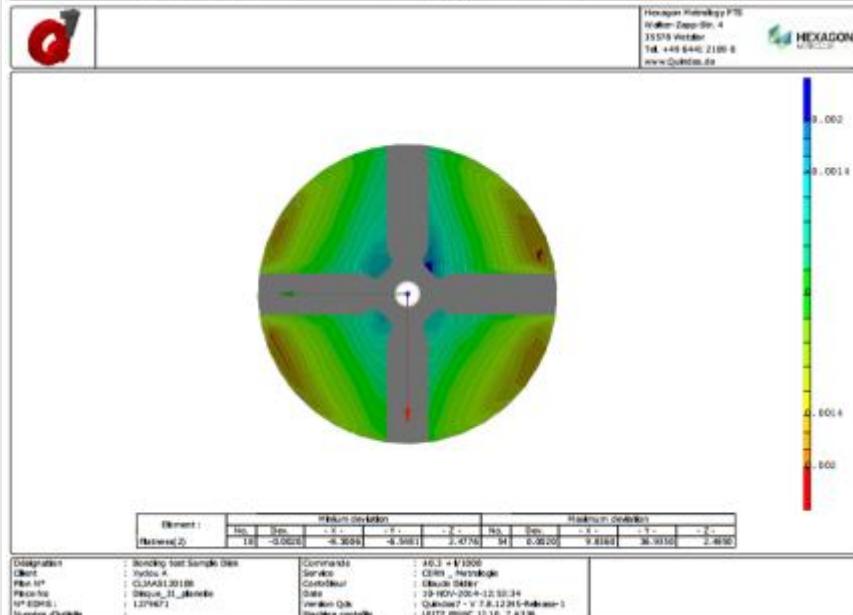




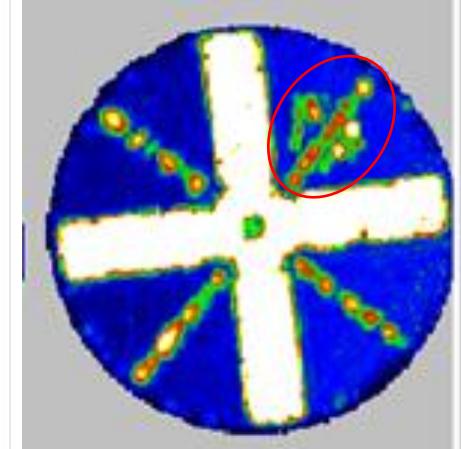
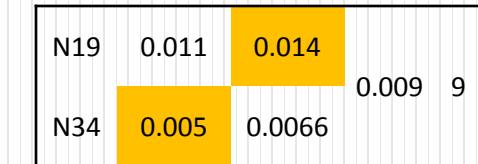
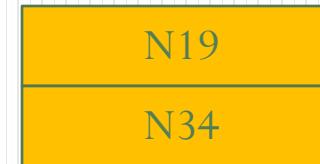
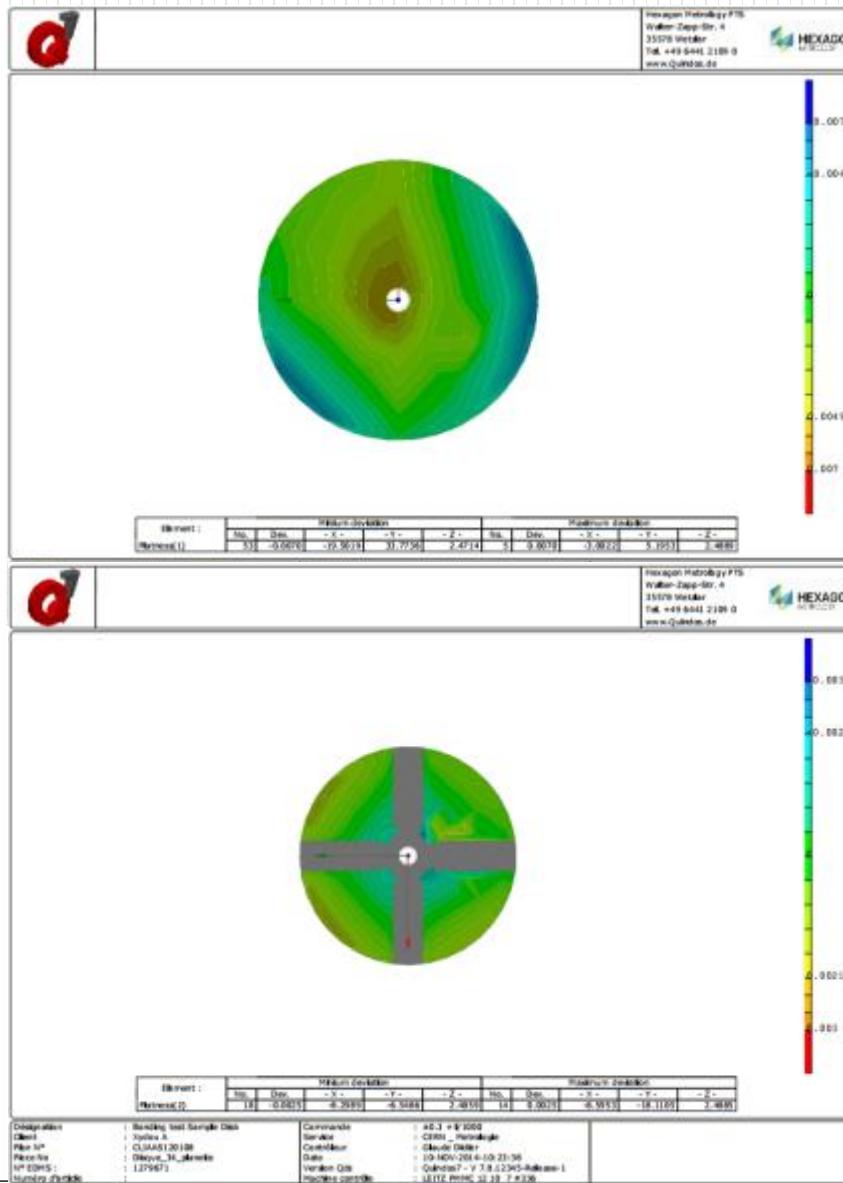
Applied pressure: 0.06 Mpa



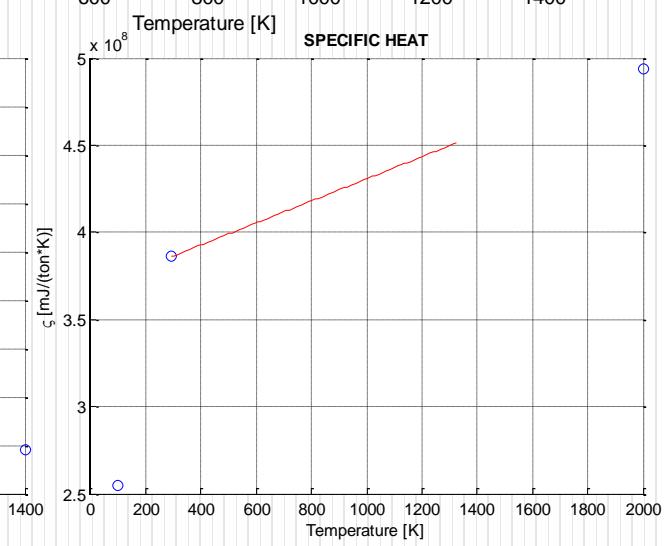
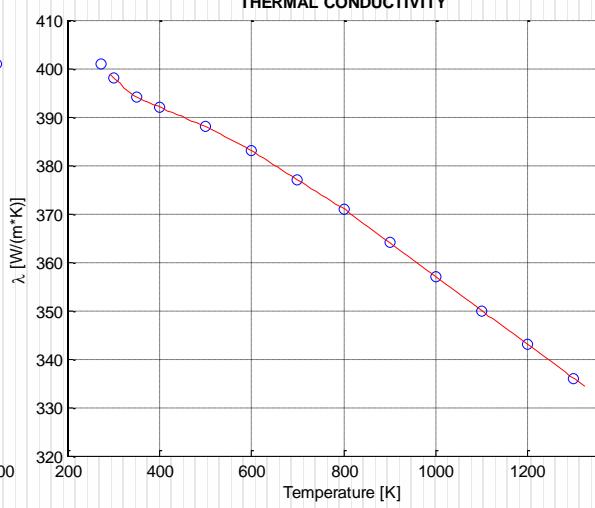
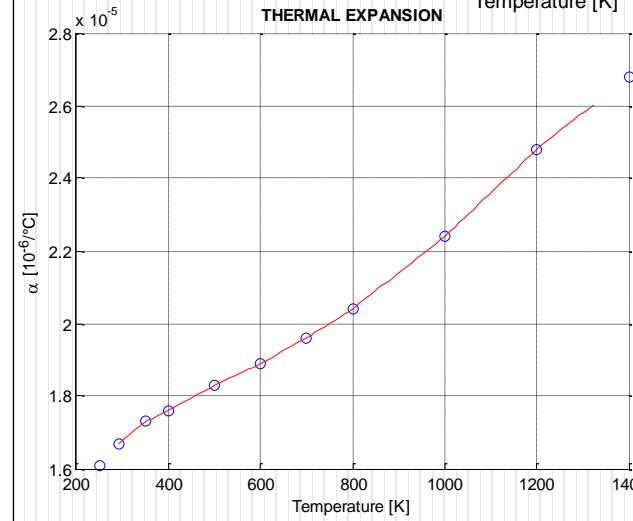
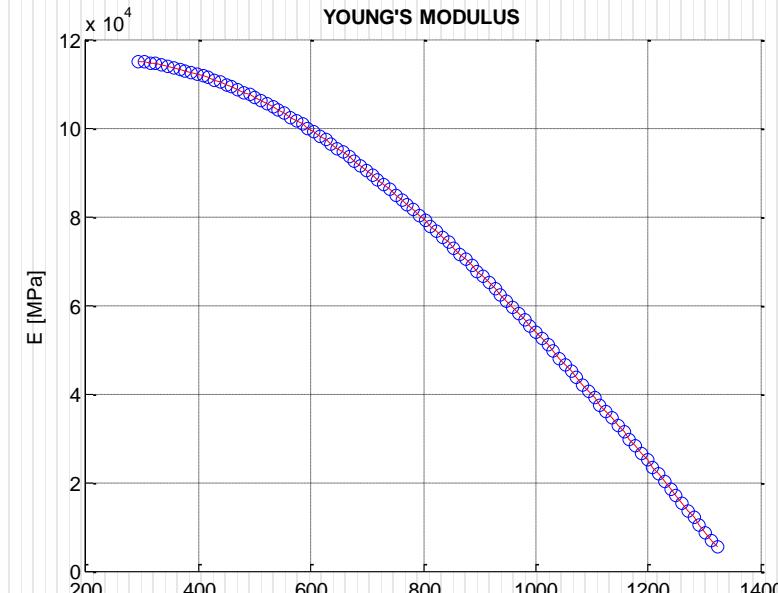
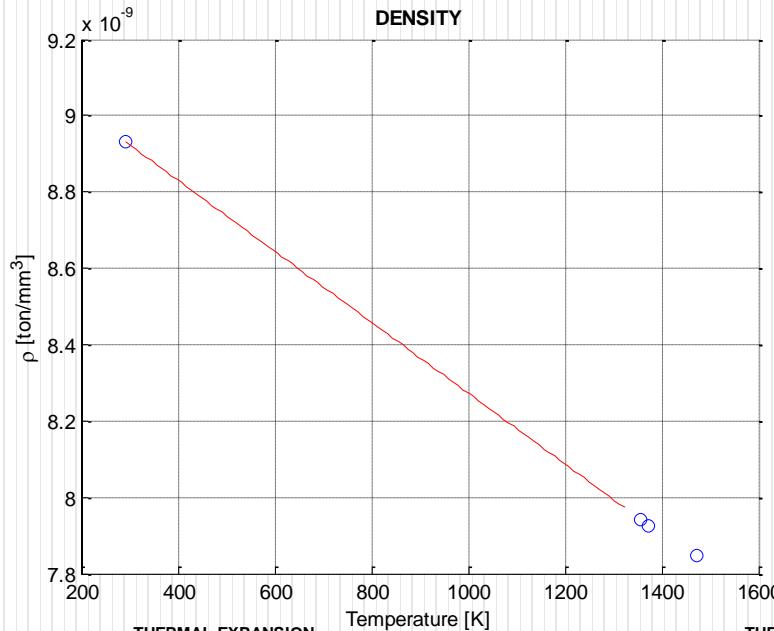
N36	0.0103	0.0131		
N31	0.0041	0.0069	0.009	9



Applied pressure: 0.06 Mpa

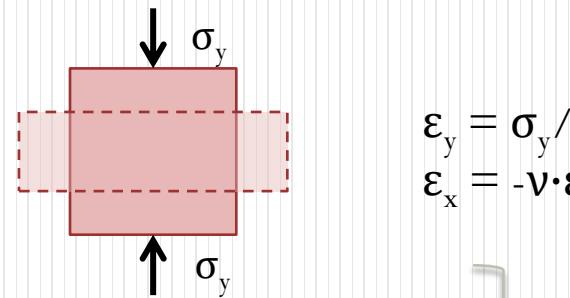


Material properties as function of temperature: OFE copper





Calculations



$$\varepsilon_y = \sigma_y/E$$
$$\varepsilon_x = -v \cdot \varepsilon_y$$

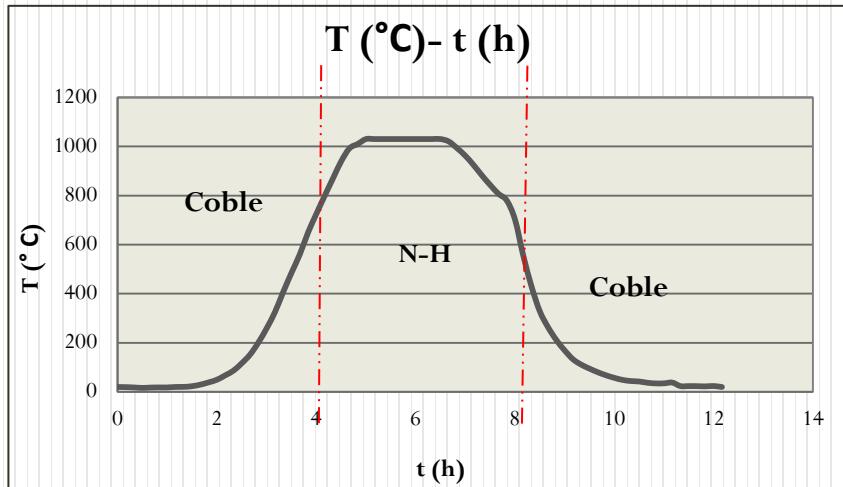
Where $\varepsilon_x = \Delta L/L = \Delta \phi/\phi$

$$\dot{\varepsilon}_{y,Co} = A_{Co} \frac{\delta D_{gb} \Omega \sigma_L}{d^3 k T}$$

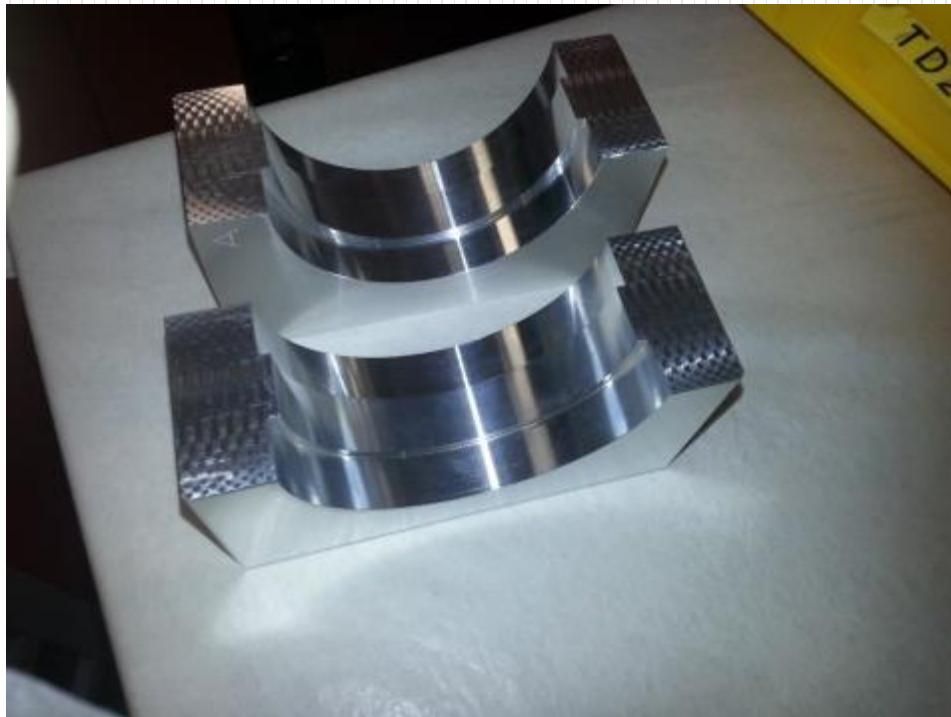
Where $\varepsilon_y = \dot{\varepsilon}_y / \Delta t$

$$\dot{\varepsilon}_{y,NH} = A_{NH} \frac{D_1 \Omega \sigma_L}{d^2 k T}$$

$$\Delta \phi = \phi \cdot v \cdot \left(\sum_{T < 0.7 \cdot T_m} \dot{\varepsilon}_{Co}(T) \cdot \Delta t + \sum_{T > 0.7 \cdot T_m} \dot{\varepsilon}_{NH}(T) \cdot \Delta t \right)$$



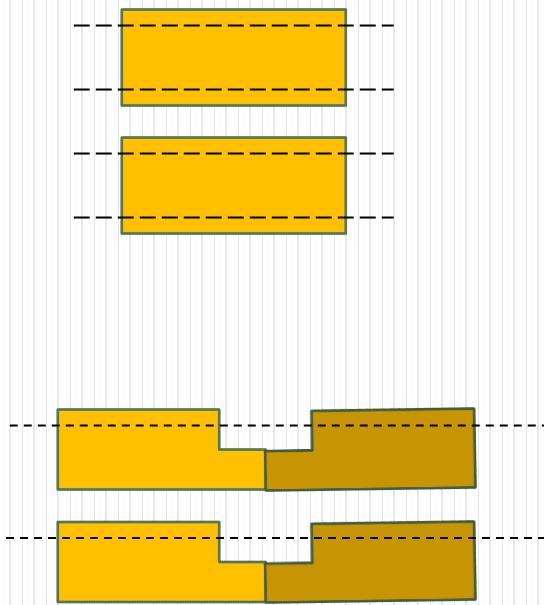
Tooling for alignment



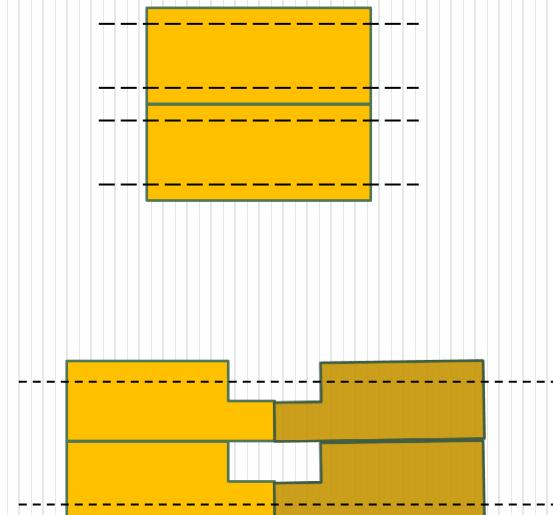


Dimensional Control

Before Bonding



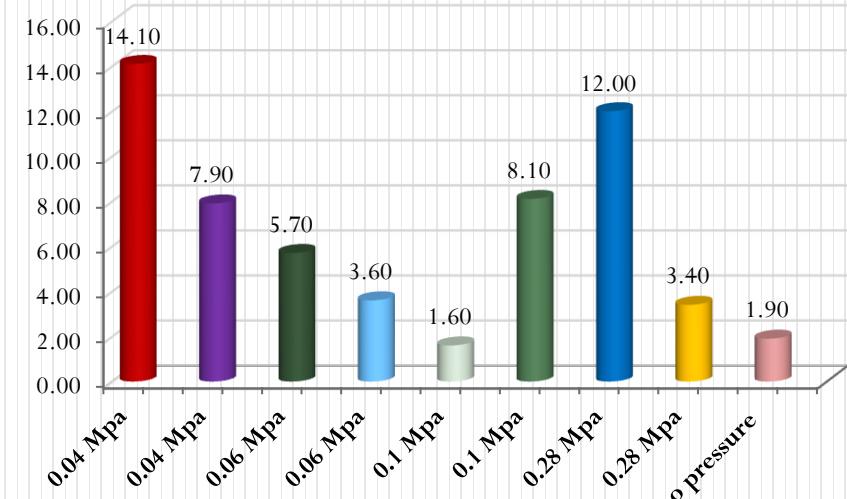
After Bonding



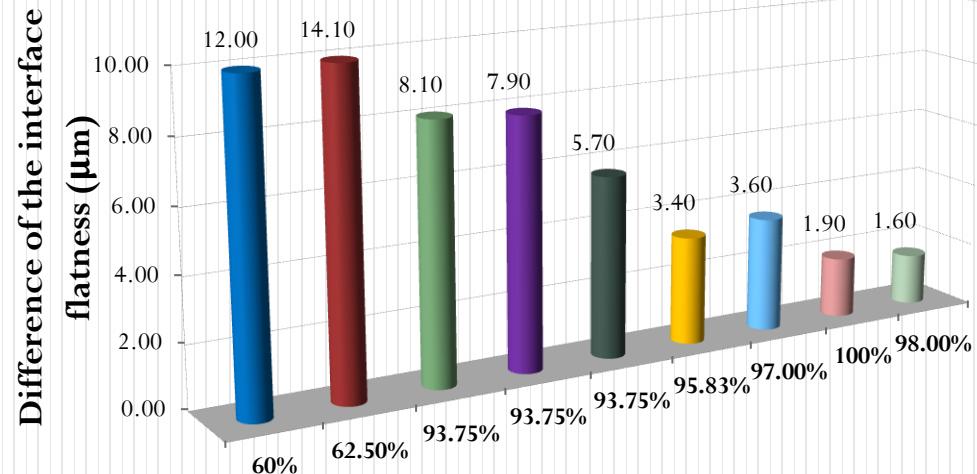
	FLATNESS		FLATNESS		dif(mm)	dif(um)
	top (plane A)	bottom (plane B)	top (plane A)	bottom (plane B)		
0.04 Mpa	N1 0.0129	0.0149	12.900 0	14.900 0	0.0141	14.10
	N2 0.0008	0.0006	0.8000 0	0.6000 0	0	
0.04 Mpa	N3 0.0128	0.0138	12.800 0	13.800 0	0.0079	7.90
	N5 0.0059	0.0066	5.9000 1.5000	6.6000 1.3000	0.0057	
0.06 Mpa	N6 0.0015	0.0013	1.5000 7.0000	1.3000 7.1000	0.0057	5.70
	N7 0.007	0.0071	7.0000 9.1000	7.1000 9.4000	0.0036	
0.06 Mpa	N8 0.0091	0.0094	9.1000 5.8000	9.4000 4.5000	0.0036	3.60
	N9 0.0058	0.0045	5.8000 5.9000	4.5000 6.1000	0.0016	
0.1 Mpa	N15 0.0059	0.0061	5.9000 4.5000	6.1000 4.7000	0.0016	1.60
	N16 0.0045	0.0047	4.5000 14.600	4.7000 15.100	0	
0.1 Mpa	N17 0.0146	0.0151	14.600 0	15.100 0	0.0081	8.10
	N18 0.007	0.0074	7.0000 12.900	7.4000 13.500	0	
0.28 Mpa	N12 0.0129	0.0135	12.900 0	13.500 0	0.0120	12.00
	N13 0.0015	0.0012	1.5000 3.2000	1.2000 2.4000	0	
0.28 Mpa	N10 0.0059	0.0066	5.9000 3.2000	6.6000 2.4000	0.0034	3.40
	N11 0.0032	0.0024	3.2000 8.3000	2.4000 5.0000	0	
no pressure	N4 0.0083	0.0050	8.3000 6.9000	5.0000 6.8000	0.0019	1.90
	N14 0.0069	0.0068				

Difference of the interface flatness (μm)

Difference of the interface Flatness- Applied pressure



Difference of the interface flatness - Percentage of the bonded joint





Copper properties

Property	Value	Unit
Density	8960	kg / m ³
Coefficient of thermal expansion	$1.7 * 10^{-5}$	1 / °C
Thermal conductivity	401	W / m °C
Specific heat	385	J / kg °C
Poisson's ratio	0.30447	-