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Laser-FALCONEYE digital-holographic gauge-camera

for
3D (surface shape change) DEFORMATION MEASUREMENT
(residual or full) STRESS FIELD DISTRIBUTION MEASUREMENT

MEASUREMENT PROTOCOL

5 July 2017

Measurement claimer
Sint Technology s.r.l.
Via delle Calandre, 63 - 50041 Calenzano (FI) ITALY

Measurement object
Shot-peened aluminum materials: 2 pcs (in block form)

Measurement purpose
Feasibility verification of surface or near-surface principal stresses and stress components with digital holographic blind-hole-drilling method in shot-peened material

Measurement result summary
Feasibility verification of stress measurement in shot-peened material with digital-holographic blind-hole-drilling method has been proved with success. It seems to be highly probable that the effectiveness of shot-peening techniques could be controlled *easily and fast* with this method…

Measurement details

1. Measurement conditions

The measurements have been made by the **Laser-FALCONEYE (LFE) digital-holographic gauge-camera** developed together by HOLOMETROX Holographic Metrology Co. Ltd. and by TECHNOORG-LINDA Scientific Technical Development Co. Ltd.

The LFE gauge-camera measures directly the surface deformation with 0.01 micrometer accuracy – on the whole surface examined, in 3D vector distribution. To achieve this, holographic, that is lensless "photographs" are taken from different directions (or with different illumination directions) and they are grouped in two: first the initial state of the object bevor the deformation is recorded, and then the final state of the object after deformation is recorded, as well. The so-called "holograms" are recorded by a digital camera and computer reconstructs numerically the so-called "phase sensitive" images and compares them with quarter wavelength accuracy. The result becomes a contour lines covered deformation map,
for each components separately.

In case of stress measurements, the surface deformation caused by a diagnostic borehole is measured in the direct neighborhood of the borehole by the gauge-camera and here the distortion of a concentric gauge-circle around the borehole can be recognized as going over into an ellipse. The principal axes show directly the direction of the principal stresses while their deviations from the gauge-circle radius depends on the stress values directly (the rescaling conversion can take place with finite element simulation or by empirical validation measurements).

The deformation of the gauge-circle take place even in the case when the borehole starts below the surface that is a deepening of the borehole is made – and thus in depth distribution of stresses can be measured, as well (with depth limitations depending on material properties and actual stress magnitude).

The holographic stress measurement technique is similar in its basics to the "classical" blind-hole drilling & strain-gauge-rosette stress measurement method used most often for stress measurements nowadays – however, it overcomes its classical counterpart with many better properties. **The holographic version can be applied much faster and more easily – it provides the real possibility of scanning a complete stress field in details during practically acceptable time. In addition, it is much undemanding regarding surface quality and because of its visual nature, its credibility is much reliable, too.**

Figure 1/a. illustrate the practical steps in the digital-holographic stress measurement based on blind-hole-drilling, while **Figure 1/b.** shows the main elements of rescaling the measured stress relief deformation into stress. In **Figure 1/c**., the LFE digital-holographic gauge-camera can be seen in operation – with the shot peened aluminum block to be measured beneath the black-silver-yellow camera body.

Figure 2. displays the two shot peened aluminum blocks: with distinction made as of fine (F) and rough (R) surface

In **Figure 3** the graphs of the deformation-stress conversion can be seen which were obtained by finite element simulation, with incremental deepening steps of 0.1 mm /Young's modulus 69 GPa, Poisson's ratio 0.33/.

2. Measurement results

According to the main purpose of our task, the measurements were performed as preliminary test measurement only, to verify the applicability of our **Laser-FALCONEYE (LFE) digital-holographic gauge-camera** for blind-hole-drilling based stress measurement – for prediction of shot peening quality. These measurements were performed on two unspecified objects with visibly different surface finishes: fine (F) and rough (R) surfaces.

The tables in **Figure 4/F and 4/R.** summarize the stress data obtained in the measurements named "**TEST MEASUREMENT I."** and "**TEST MEASUREMENT II."**, which were obtained on the two blocks separately, in both cases with two measurement points – and *with 3mm diameter boreholes, with 10 or 5 deepening steps: with 0.1 mm steps down to 1.0 or 0.5 mm. The stress in both blocks proved to be almost completely radial, direction independent – nevertheless the tables contain both principal stress components and the x&y stress components separately (as it used to be).*

In the case of the finer surface finish, in "TEST MEASUREMENT I."**,** the measured values are compressive (as expected) and:

start with -135 MPa in the uppermost 0.1 mm layer
and abrupt drop to almost zero already in the second 0.1 mm layer
– and remain there down to 1.0 mm depth.

In the case of the rougher surface finish, in "TEST MEASUREMENT II."**,** the measured values are compressive, as well, and:

start with little less, with -105 MPa, only, in the uppermost 0.1 mm layer
but *culminate with much higher, with -165(170) MPa in the second 0.1 mm layer*
and drop again abruptly, to less than half their maximum, to -65(60) MPa
in the third 0.1 mm layer
– and afterwards decrease down slowly still a little above zero
unto 1.0 mm depth.

In the case of both blocks, the measurements detailed above were repeated (to half depth) in another point, as well, to check repeatability – as much as possible in a different point. The results equaled almost completely at any depth at the finer block – and did the same at the rougher block, as well: with a moderate deviation, in the range of the double measurement error value, in the first layer. This moderate deviation, however, can be attributed quite probably to the uncertainties of drill bit positioning in our measurements – because of the lacking electronic null-position detection and because of the micrometer screw gauge based manual movement of the drilling. Naturally, both shortcomings could be fixed by commercially available hardware - if needed for higher accuracy.

Figure 5. shows the graphs of the measured stress distributions (by components) for better overview.

APPENDIX I. displays the false color holographic interferometric fringes of the stress released deformation as it can be seen within minutes on the computer screen by the operator of the measurement. One blue-red transition corresponds to 0.35 μm displacement difference between the end point and starting point of the read out and -0.35 μm displacement difference at opposite color transition (where positive and negative displacement difference direction are regarded with respect to the start-end direction).

For example, let us take the first interference picture in the first row on the left (in red frame)! As for the gauge circle diameter in horizontal direction, the displacement difference between its two endpoints is about ane and half times a complete colored fringe belt when going around the borehole from the left to the right side. This path starts in upper level red color, continues through a blue fringe to another red one and ends up in a second lower level blue fringe. This means that the length change of the gauge circle horizontal diameter is just about 1.5 x0.35 μm = 0.5 μm – and in negative direction: that is this is a compression of the gauge circle. Its radial change is the half of this: 0.25 μm – which gives you 466 MPa/μm x.0.25 μm = 116 MPa (where CE = 466 MPa/μm is the conversion factor from the FEM based graph in Figure 3.)

This calculation does not take a minute and gives a good approximation to the measured stress value. ***Thus just within twice of the drilling time, you can reach the required stress values – with a visual approximate evaluation! It can be ideal for fast surface stress mapping…***

APPENDIX II. refers to the naming code of the displacement field matrices – in components, /Naturally, the accuracy of the field values does not correspond to the given many number of digits because these values are the results of some mathematical filtering (averaging) in the last step – and the many digits come from there. To make further use of it, however, it seem s to be worth using more digits than the declared accuracy about 0.01 μm…/

APPENDIX III. visualizes gauge circle deformations into ellipsis – in the case of the uppermost drilling steps: just for better understanding the basis of the exact evaluation procedure…

Finally, **APPENDIX IV/A** and **B.** give an extra picturesque graphical representation of the numerical stress released deformation fields - in the case of the uppermost and next drilling steps. just to show the expected symmetry of the fields which come out really markedly in all cases.

3. Summary and further application suggestions

Feasibility verification of stress measurement in shot-peened material with digital-holographic blind-hole-drilling method has been proved with success. It seems to be highly probable that the effectiveness of shot-peening techniques could be controlled easily and fast with this method…

It may be worth emphasizing that just within twice of the drilling time, you can reach the required stress values – with a visual approximate evaluation! It can be ideal for fast surface stress mapping…

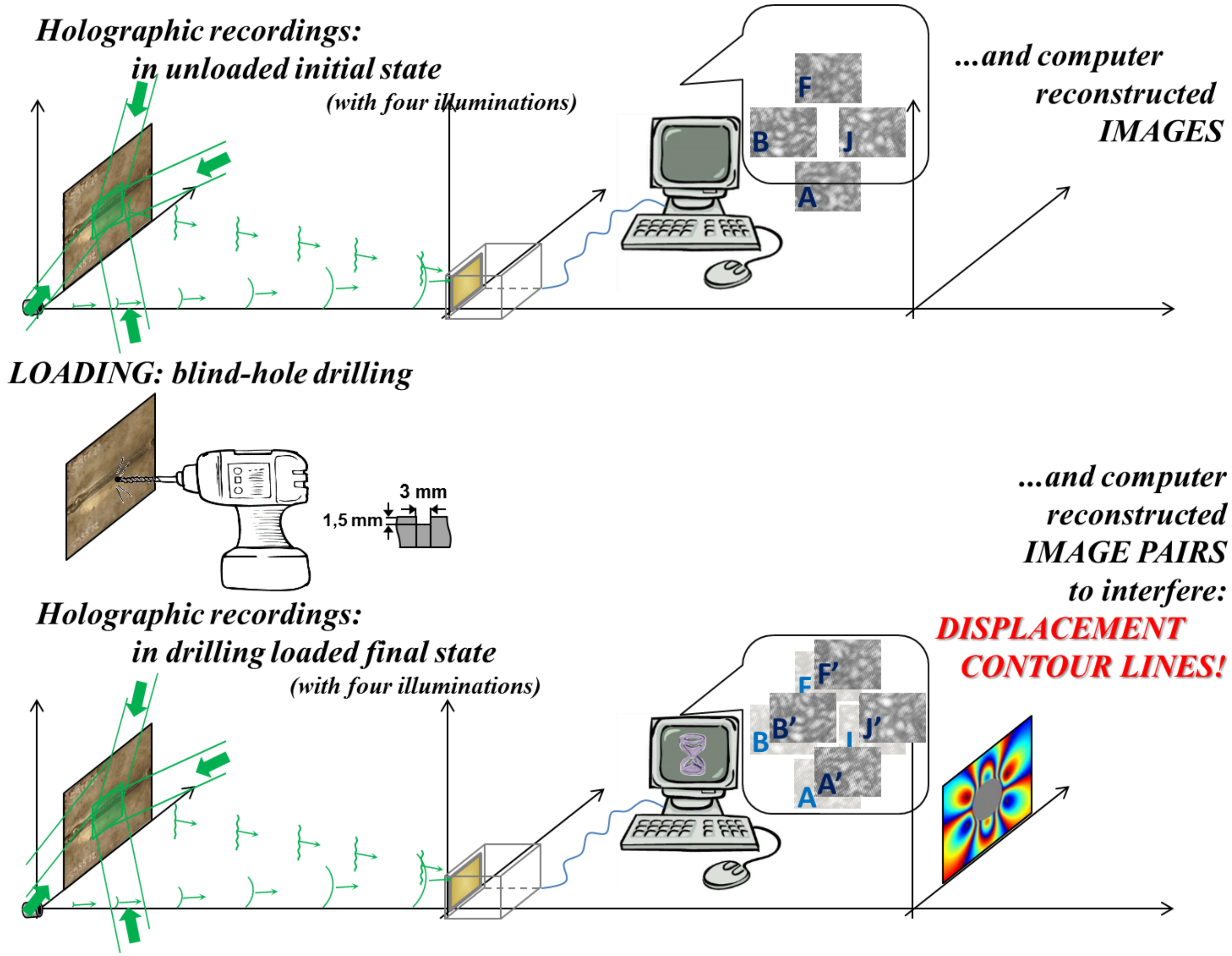


Figure 1/a.

The practical steps in digital-holographic stress measurement based on blind-hole-drilling.

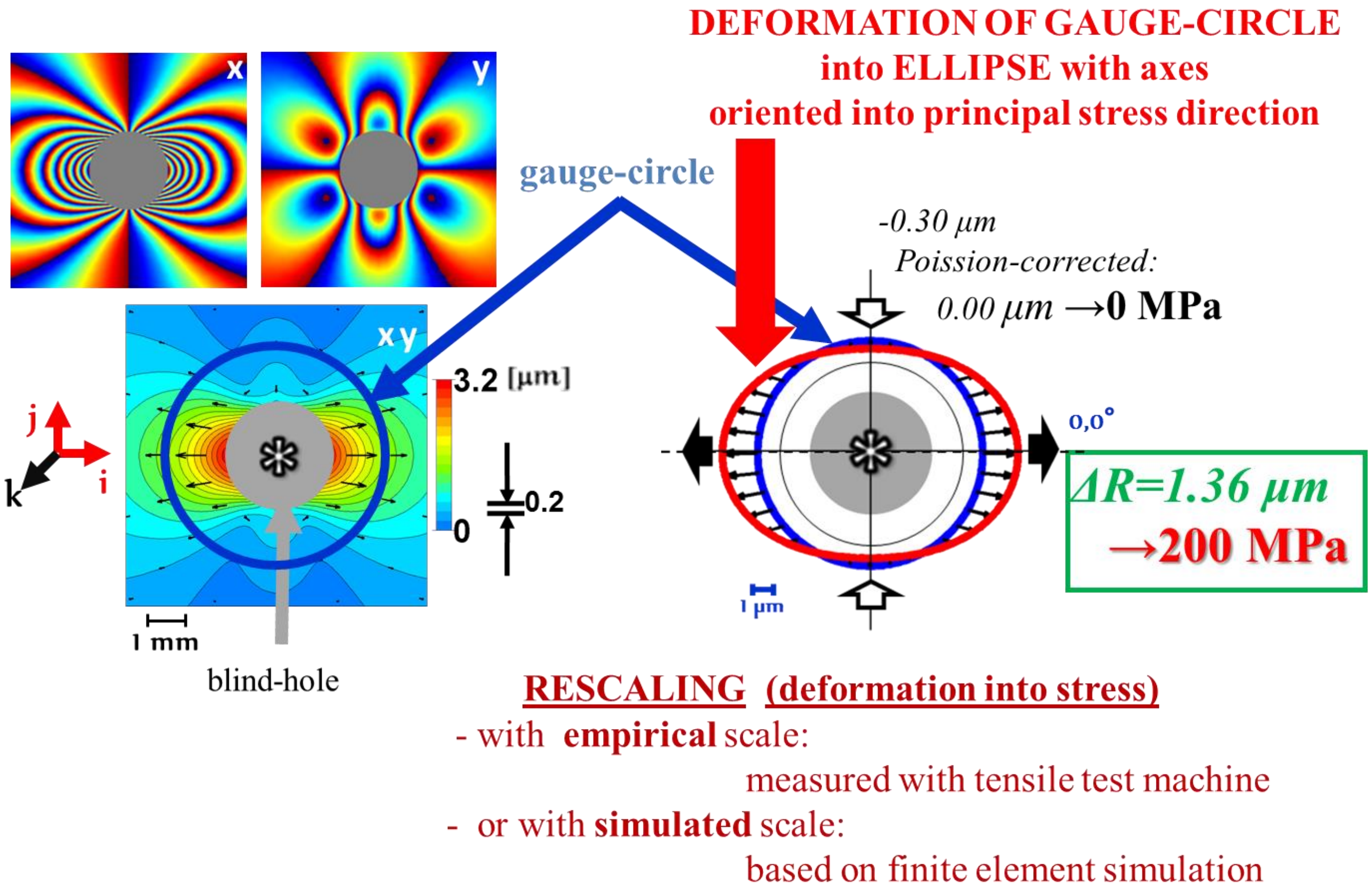


Figure 1/b.
The main elements of rescaling the measured stress relief deformation into stress.

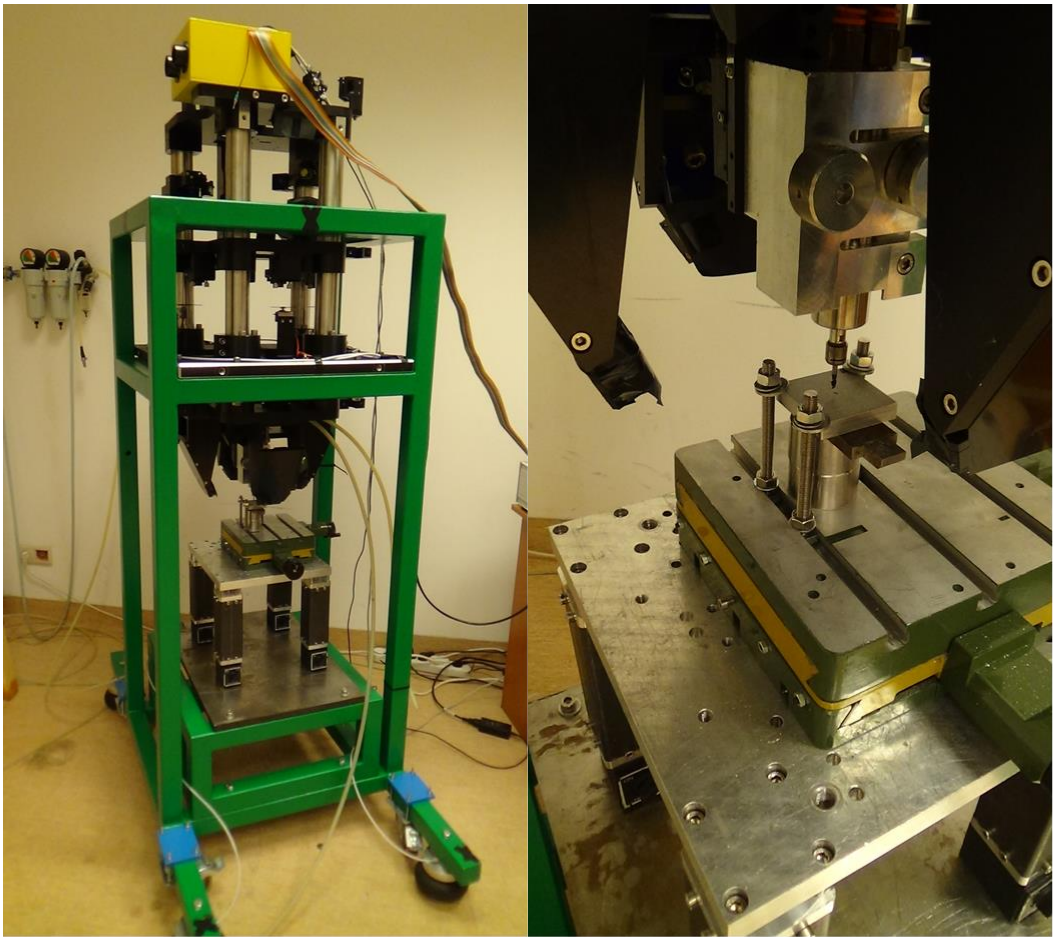


Figure 1/c.
The Laser-FALCONEYE digital-holographic gauge-camera in operation
- with the surface milled block (directly beneath the black-silver-yellow camera body),
in its two typical clamping positions.

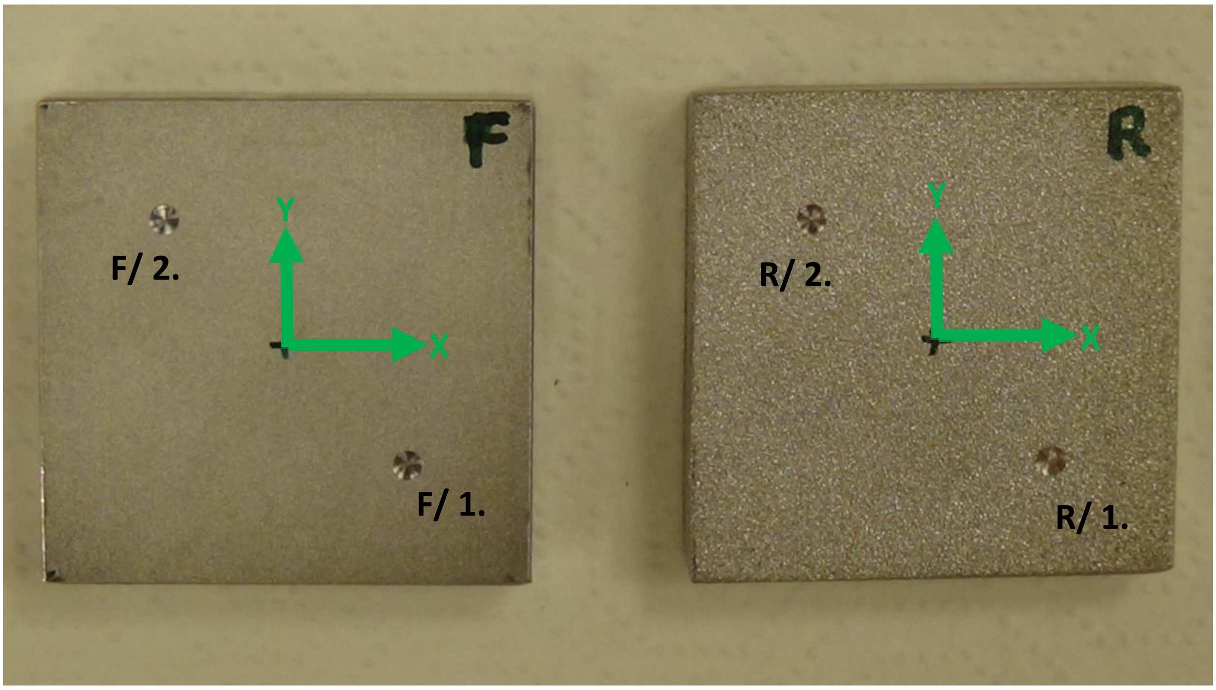
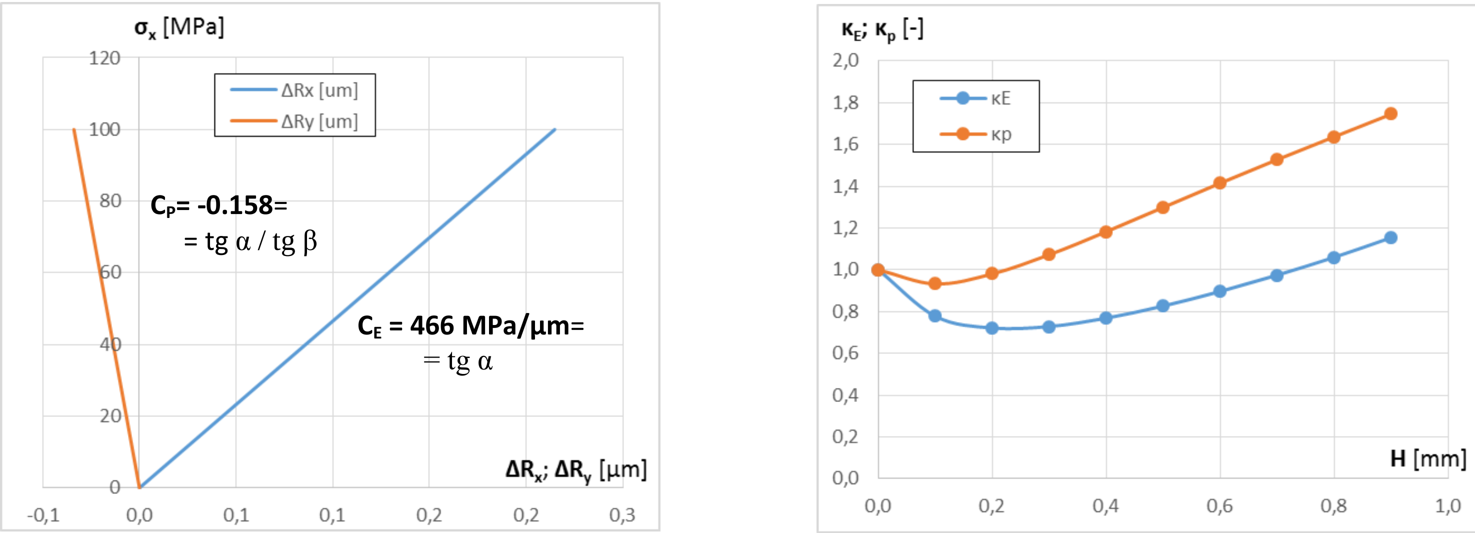


Figure 2.
The examined shot-peened aluminum blocks:
with distinction made as of fine (F) and rough (R) surface

Connection between gauge-circle deformation and stress
actual data from
finite element simulation

Material parameters:
E= 69 GPa   ν= 0.33

Measurement properties:
borehole diameter d= 3.0 mm,   gauge-circle diameter D= 4.5 mm
depth increment Δh= 0.1 mm,   *borehole initial level H= 0.0 – 1.0 mm*



DEFORMATION CONSTANTS (H= 0.0 mm):
borehole Young modulus: C_E
borehole Poisson ratio: C_P

DEPTHCORRECTION FACTORS in depth dependence:
at borehole Young modulus: $\kappa_E(H)$
at borehole Poisson ratio: $\kappa_P(H)$

Figure 3.
GRAPHS OF THE DEFORMATION-STRESS CONVERSION
with incremental deepening steps of 0.1 mm
/Young's modulus 69 GPa, Poisson's ratio 0.33/

measured object	measurement character	measurement identifier	side	coordinates		h_0 [mm] borehole initial depth	h_1 [mm] borehole final depth	d [mm] borehole diameter	D [mm] gauge-circle diameter	C_P [-]	C_E [MPa/μm]	C_E [MPa /fringe (0.35μm)]	data of matched ellipses			Poisson-corrected data of matched ellipses		principal stresses (+/-15 MPa) /rounded to 5/		x&y stress components (+/-15 MPa) /rounded to 5/		
				x [mm]	**y** [mm]								α_1 [°]	ΔR_1 [μm]	ΔR_2 [μm]	$\Delta R'_1$ [μm]	$\Delta R'_2$ [μm]	σ_1 [MPa]	σ_2 [MPa]	σ_x [MPa]	σ_y [MPa]	τ_{xy} [MPa]
shot-peened aluminum block: *with fine surface* (F)	near surface measurement (0-1.0 mm)	F/1-0.0	top	12,5	-12,5	**0,0**	**0,1**	3	4,5	-0,158	466	**163**	44	-0,24	-0,26	**-0,29**	**-0,30**	-135	-140	**-135**	**-135**	**5**
		F/1-0.1				**0,1**	**0,2**	3	4,5	-0,147	362	**127**	16	-0,05	-0,08	**-0,06**	**-0,09**	-25	-30	**-25**	**-30**	**0**
		F/1-0.2				**0,2**	**0,3**	3	4,5	-0,155	336	**118**	14	-0,01	-0,06	**-0,02**	**-0,06**	-10	-20	**-10**	**-20**	**5**
		F/1-0.3				**0,3**	**0,4**	3	4,5	-0,169	339	**119**	15	-0,01	-0,05	**-0,02**	**-0,06**	-5	-20	**-5**	**-20**	**5**
		F/1-0.4				**0,4**	**0,5**	3	4,5	-0,187	358	**125**	10	-0,01	-0,05	**-0,02**	**-0,05**	-5	-20	**-5**	**-15**	**0**
		F/1-0.5				**0,5**	**0,6**	3	4,5	-0,205	385	**135**	16	0,00	-0,04	**-0,01**	**-0,04**	-5	-15	**-5**	**-15**	**5**
		F/1-0.6				**0,6**	**0,7**	3	4,5	-0,223	418	**146**	13	0,00	-0,03	**-0,01**	**-0,03**	-5	-15	**-5**	**-15**	**0**
		F/1-0.7				**0,7**	**0,8**	3	4,5	-0,241	454	**159**	8	0,01	-0,02	**0,01**	**-0,02**	5	-10	**5**	**-10**	**0**
		F/1-0.8				**0,8**	**0,9**	3	4,5	-0,258	494	**173**	17	0,00	-0,02	**-0,01**	**-0,02**	-5	-10	**-5**	**-10**	**5**
		F/1-0.9				**0,9**	**1,0**	3	4,5	-0,276	538	**188**	16	0,01	-0,02	**0,00**	**-0,02**	5	-10	**0**	**-5**	**5**
	<u>*repeated*</u> near surface measurement (0-0.5 mm)	F/2-0.0	top	-12,5	12,5	**0,0**	**0,1**	3	4,5	-0,158	466	**163**	19	-0,24	-0,27	**-0,29**	**-0,32**	-135	-150	**-135**	**-145**	**5**
		F/2-0.1				**0,1**	**0,2**	3	4,5	-0,147	362	**127**	11	-0,05	-0,08	**-0,06**	**-0,09**	-20	-35	**-20**	**-35**	**0**
		F/2-0.2				**0,2**	**0,3**	3	4,5	-0,155	336	**118**	9	-0,02	-0,07	**-0,03**	**-0,07**	-10	-25	**-10**	**-25**	**0**
		F/2-0.3				**0,3**	**0,4**	3	4,5	-0,169	339	**119**	16	-0,01	-0,05	**-0,02**	**-0,05**	-5	-15	**-5**	**-15**	**5**
		F/2-0.4				**0,4**	**0,5**	3	4,5	-0,187	358	**125**	15	0,00	-0,03	**0,00**	**-0,04**	0	-15	**0**	**-10**	**5**

Figure 4/F.

TEST MEASUREMENT I.: shot-peened aluminum block - with fine surface

/3mm diameter boreholes, with 10 or 5 deepening steps: with *0.1 mm steps down to 1.0 or 0.5 mm*/

where measured values

start with -135 MPa in the uppermost 0.1 mm layer

and abrupt drop to almost zero already in the second 0.1 mm layer

– and remain there down to 1.0 mm depth.

measured object	measurement character	measurement identifier	side	coordinates		h_0 [mm] borehole initial depth	h_1 [mm] borehole final depth	d [mm] borehole diameter	D [mm] gauge-circle diameter	C_p [-]	C_E [MPa/μm]	C_E [MPa /fringe (0.35μm)]	data of matched ellipses			Poisson-corrected data of matched ellipses		principal stresses (+/-15 MPa) /rounded to 5/		x&y stress components (+/-15 MPa) /rounded to 5/		
				x [mm]	y [mm]								α_1 [°]	ΔR_1 [μm]	ΔR_2 [μm]	$\Delta R'_1$ [μm]	$\Delta R'_2$ [μm]	σ_1 [MPa]	σ_2 [MPa]	σ_x [MPa]	σ_y [MPa]	τ_{xy} [MPa]
shot-peened aluminum block: with rough surface (R)	near surface measurement (0-1.0 mm)	R/1-0.0	top	12,5	-12,5	**0,0**	**0,1**	3	4,5	-0,158	466	**163**	-45	-0,19	-0,19	**-0,23**	**-0,22**	-105	-105	**-105**	**-105**	**0**
		R/1-0.1				**0,1**	**0,2**	3	4,5	-0,147	362	**127**	28	-0,39	-0,40	**-0,46**	**-0,47**	-165	-170	**-165**	**-170**	**0**
		R/1-0.2				**0,2**	**0,3**	3	4,5	-0,155	336	**118**	-44	-0,36	-0,33	**-0,42**	**-0,40**	-140	-135	**-135**	**-135**	**5**
		R/1-0.3				**0,3**	**0,4**	3	4,5	-0,169	339	**119**	-34	-0,17	-0,14	**-0,20**	**-0,17**	-65	-60	**-65**	**-60**	**5**
		R/1-0.4				**0,4**	**0,5**	3	4,5	-0,187	358	**125**	-22	-0,11	-0,08	**-0,13**	**-0,10**	-45	-35	**-45**	**-40**	**5**
		R/1-0.5				**0,5**	**0,6**	3	4,5	-0,205	385	**135**	-27	-0,07	-0,05	**-0,09**	**-0,07**	-35	-30	**-35**	**-30**	**0**
		R/1-0.6				**0,6**	**0,7**	3	4,5	-0,223	418	**146**	-27	-0,08	-0,04	**-0,10**	**-0,07**	-40	-25	**-40**	**-30**	**5**
		R/1-0.7				**0,7**	**0,8**	3	4,5	-0,241	454	**159**	-16	-0,05	-0,03	**-0,06**	**-0,04**	-30	-20	**-25**	**-20**	**0**
		R/1-0.8				**0,8**	**0,9**	3	4,5	-0,258	494	**173**	-17	-0,05	-0,03	**-0,06**	**-0,04**	-30	-20	**-30**	**-20**	**5**
		R/1-0.9				**0,9**	**1,0**	3	4,5	-0,276	538	**188**	-12	-0,03	-0,02	**-0,04**	**-0,03**	-20	-15	**-20**	**-15**	**0**
	repeated near surface measurement (0-0.5 mm)	R/2-0.0	top	-12,5	12,5	**0,0**	**0,1**	3	4,5	-0,158	466	**163**	-29	-0,15	-0,13	**-0,18**	**-0,16**	-80	-75	**-80**	**-75**	**5**
		R/2-0.1				**0,1**	**0,2**	3	4,5	-0,147	362	**127**	35	-0,39	-0,42	**-0,46**	**-0,49**	-170	-175	**-170**	**-175**	**5**
		R/2-0.2				**0,2**	**0,3**	3	4,5	-0,155	336	**118**	23	-0,37	-0,40	**-0,44**	**-0,47**	-150	-160	**-150**	**-155**	**5**
		R/2-0.3				**0,3**	**0,4**	3	4,5	-0,169	339	**119**	-29	-0,16	-0,13	**-0,18**	**-0,16**	-60	-55	**-60**	**-55**	**5**
		R/2-0.4				**0,4**	**0,5**	3	4,5	-0,187	358	**125**	-24	-0,11	-0,07	**-0,13**	**-0,10**	-45	-35	**-45**	**-35**	**5**

Figure 4/R.

TEST MEASUREMENT II.: shot-peened aluminum block - with rough surface

/3mm diameter boreholes, with 10 or 5 deepening steps: with *0.1 mm steps down to 1.0 or 0.5 mm*/

where measured values

start with little less, with -105 MPa, only, in the uppermost 0.1 mm layer

but *__culminate with much higher, with -165(170) MPa in the second 0.1 mm layer__*

and drop again abruptly, to less than half their maximum, to -65(60) MPa

in the third 0.1 mm layer

– and afterwards decrease down slowly still a little above zero

unto 1.0 mm depth.

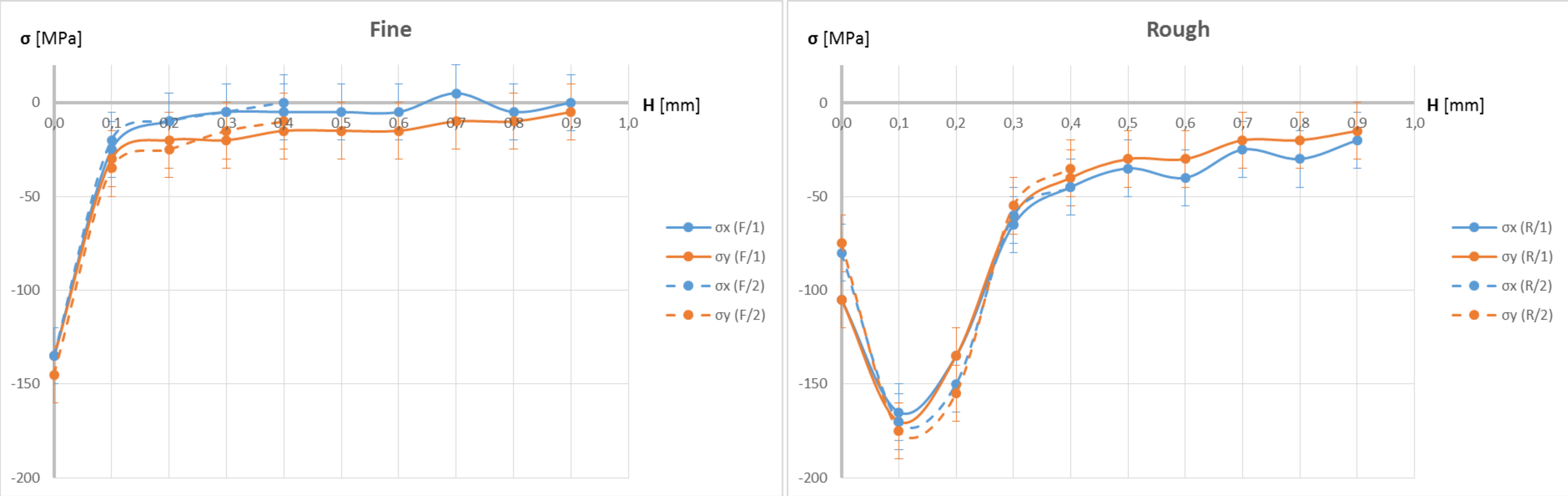
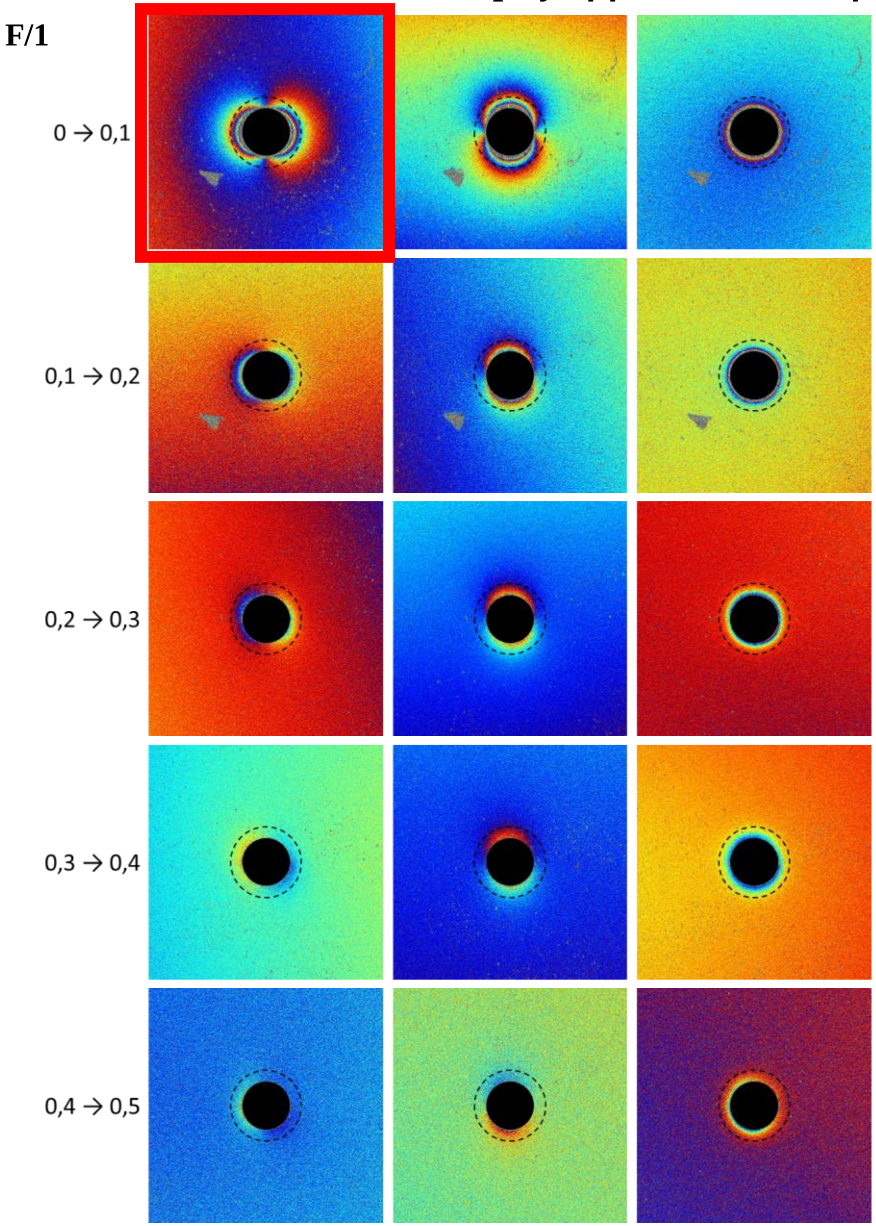
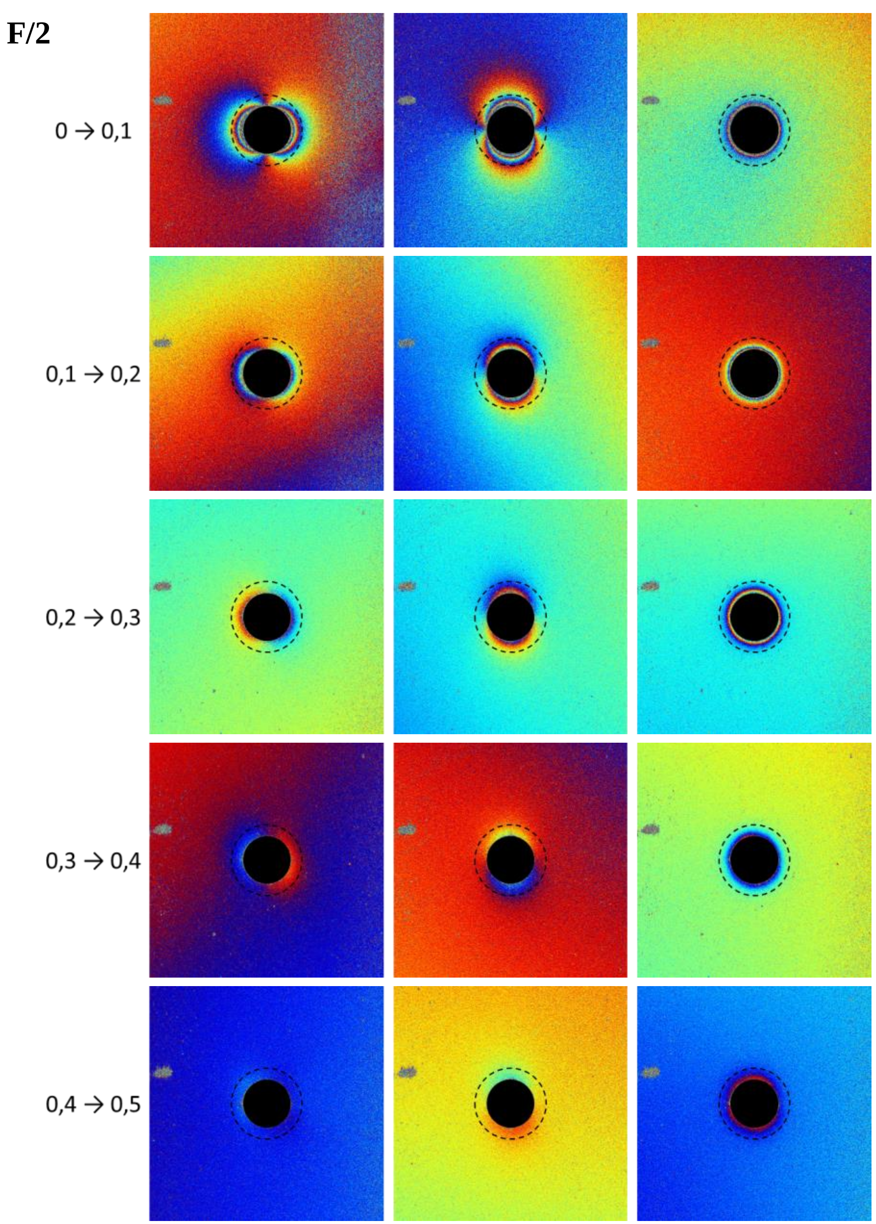


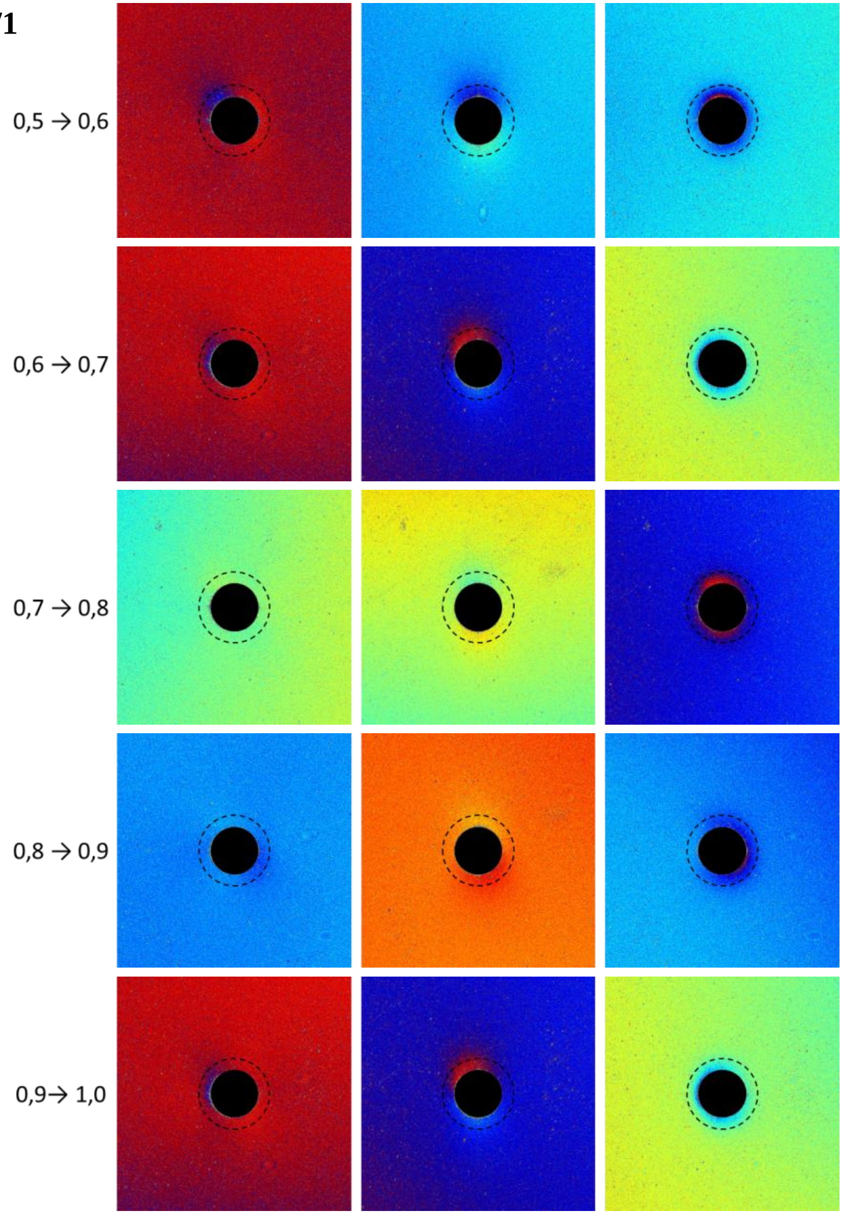
Figure 5.
Graphs of the measured stress distributions (by components)
for fine and rough surfaces

APPENDIX I.: ***Display of false color interferometric fringes of the stress released deformation***

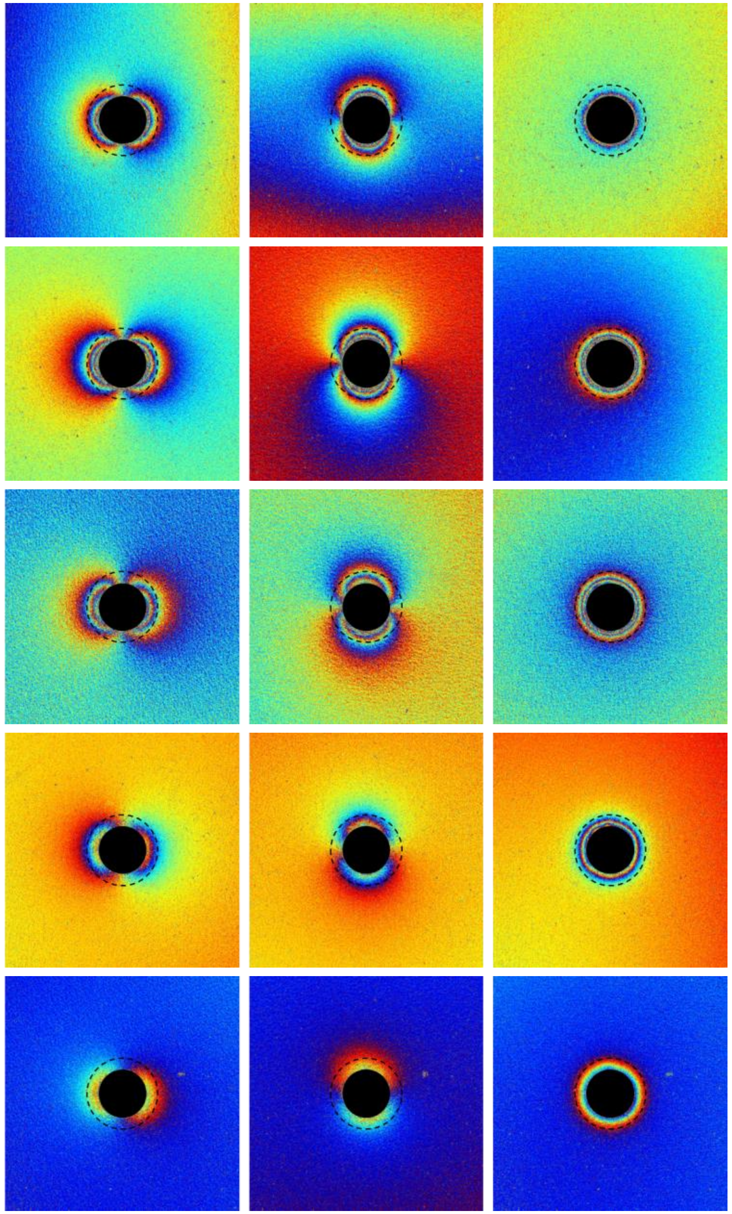




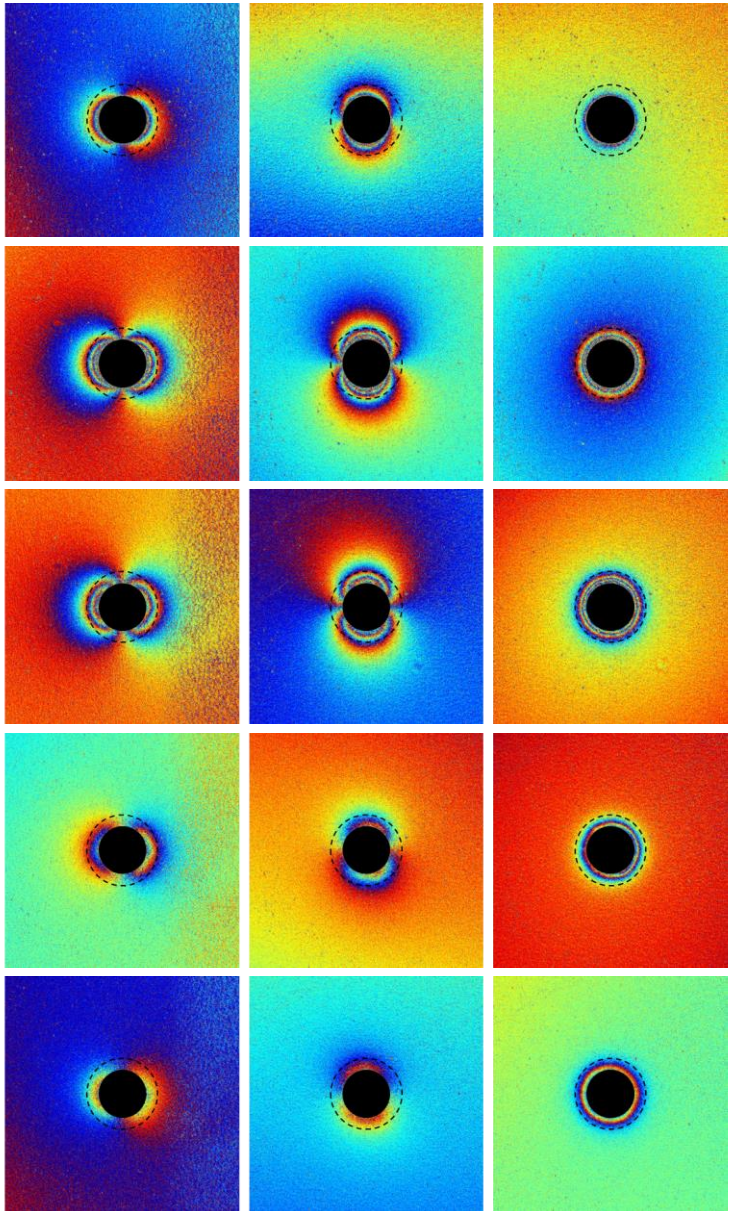
F/1

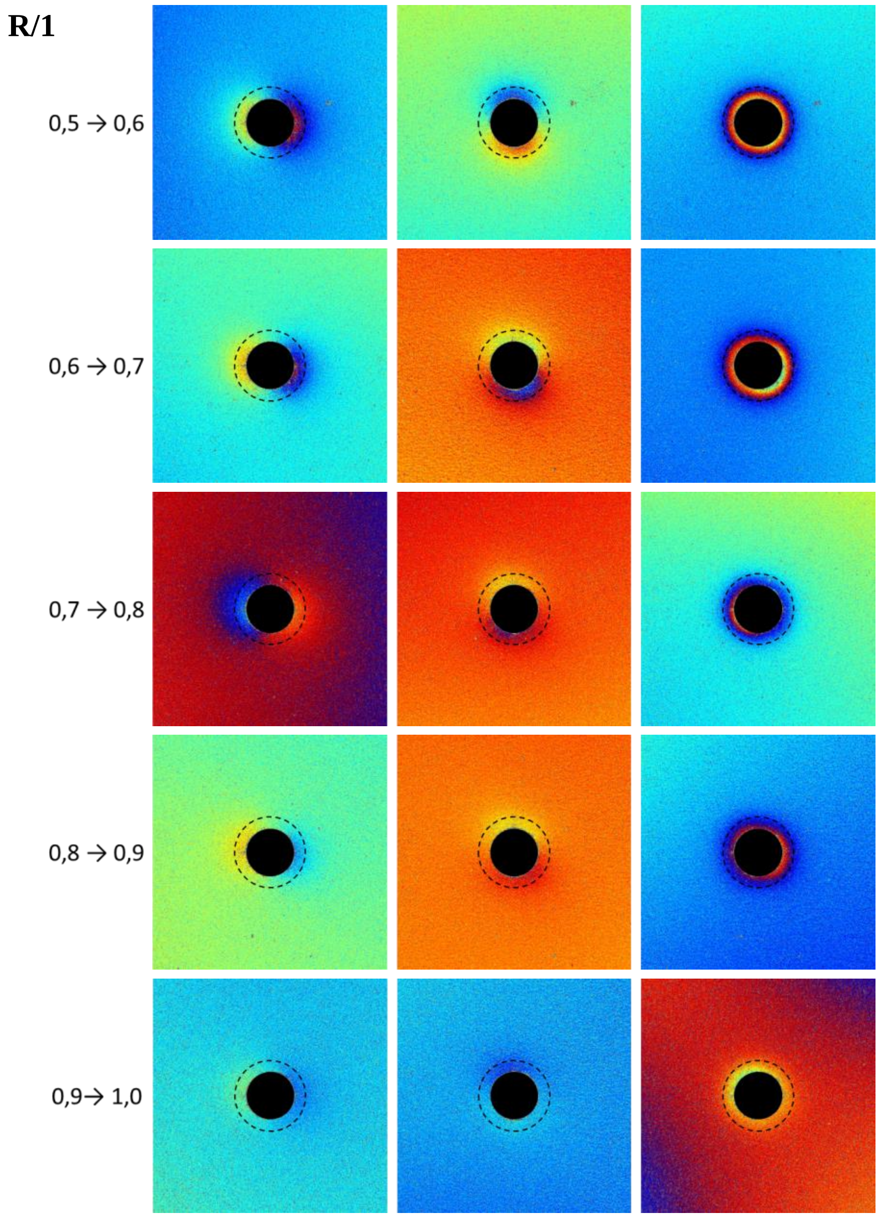


R/1



R/2




R/1
0,5 → 0,6
0,6 → 0,7
0,7 → 0,8
0,8 → 0,9
0,9→ 1,0

APPENDIX II.:

Numerical description of the stress released deformation fields at incremental hole drilling – in 3D coordinates representation

See attached Excel files named as below:

F/1

F1_0.0_xy-component(um)_850x850(px)_pxsize14,49(um).xlsx

and F/2

F2_0.0_xy-component(um)_850x850(px)_pxsize14,49(um).xlsx

R/1

R1_0.0_xy-component(um)_850x850(px)_pxsize14,49(um).xlsx

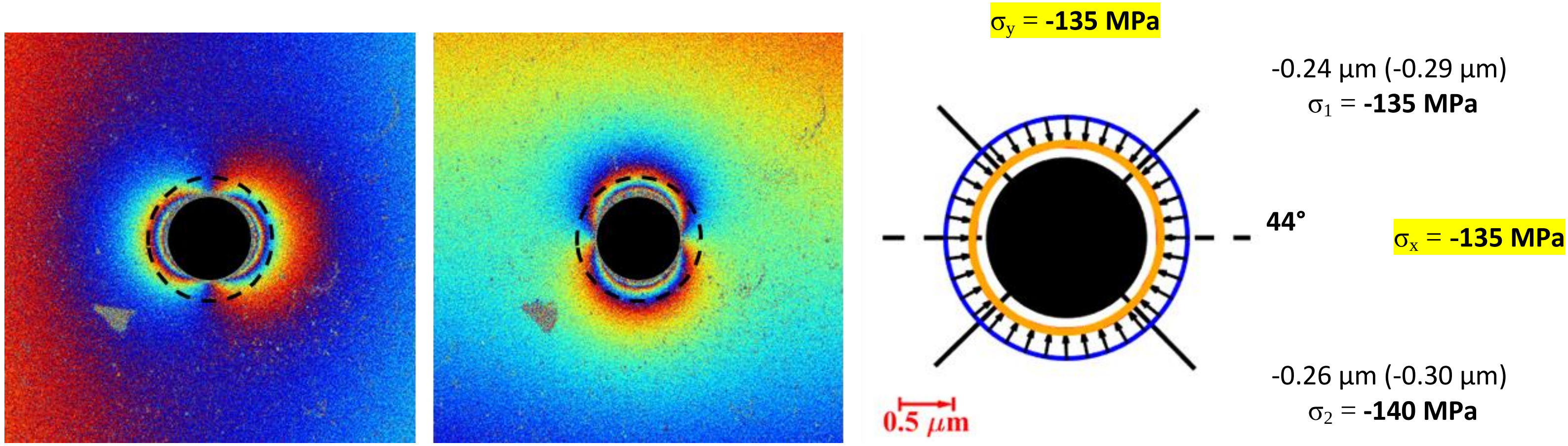
and R/2

R2_0.0_xy-component(um)_850x850(px)_pxsize14,49(um).xlsx

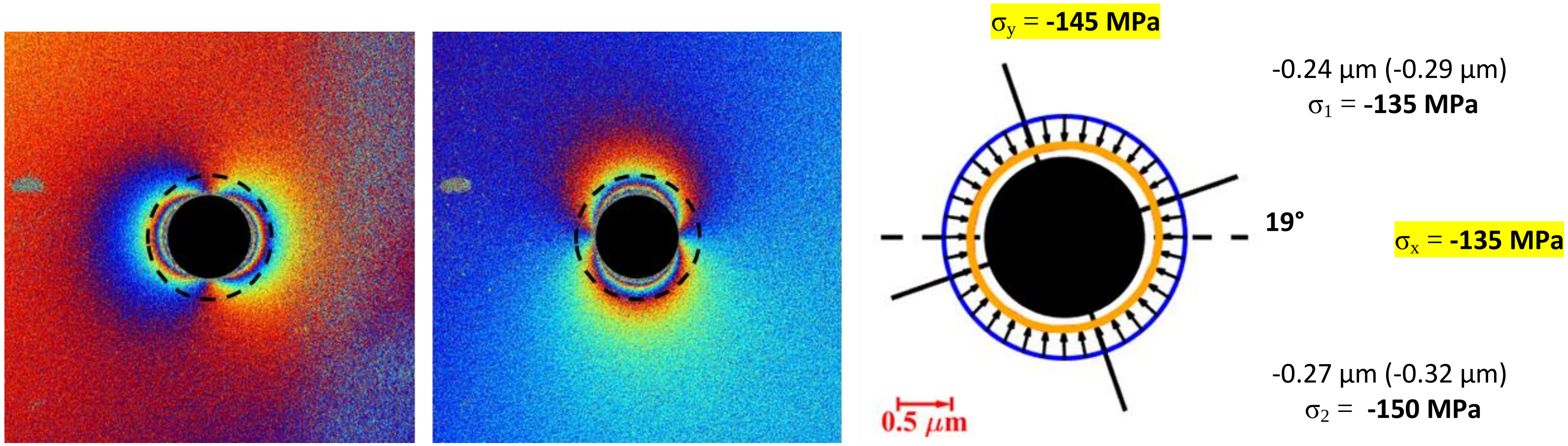
APPENDIX III.:

Display of gauge circle deformations into ellipsis – in the case of the uppermost drilling steps

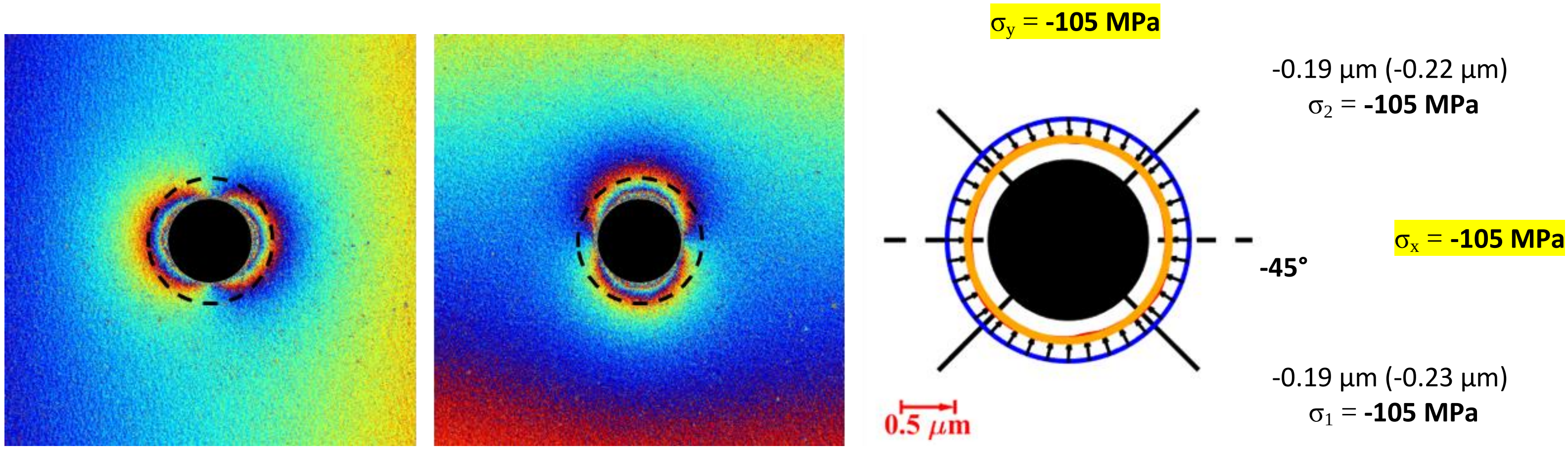
F/1-0.0



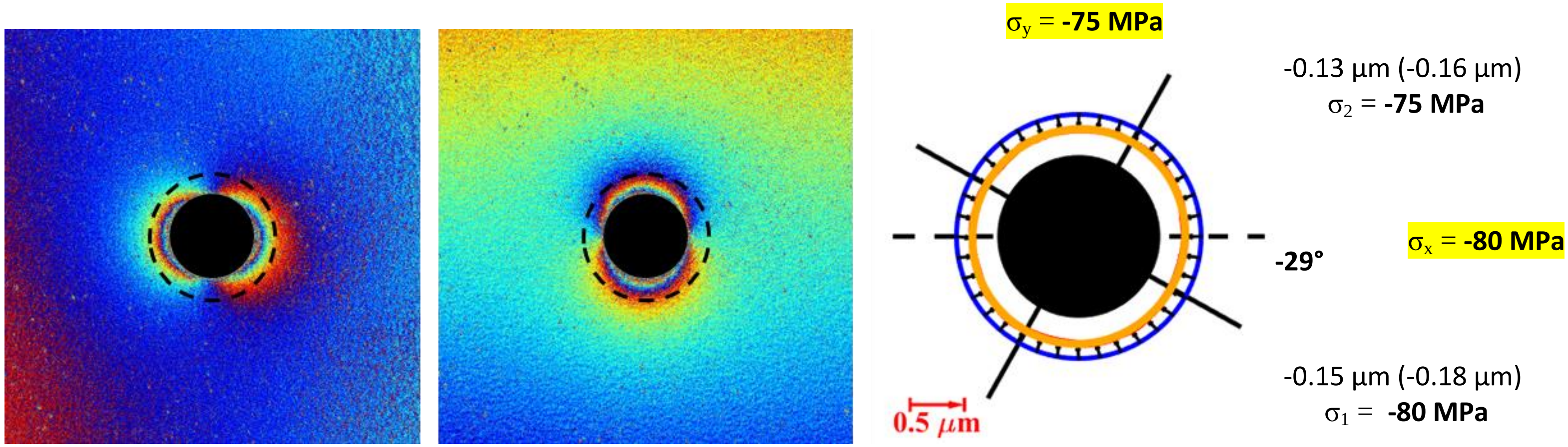
F/2-0.0



R/1-0.0


σy = -105 MPa
-0.19 µm (-0.22 µm)
σ2 = -105 MPa
σx = -105 MPa
-45°
-0.19 µm (-0.23 µm)
σ1 = -105 MPa
0.5 µm

R/2-0.0


σy = -75 MPa
-0.13 µm (-0.16 µm)
σ2 = -75 MPa
σx = -80 MPa
-29°
-0.15 µm (-0.18 µm)
σ1 = -80 MPa
0.5 µm

APPENDIX IV/A:

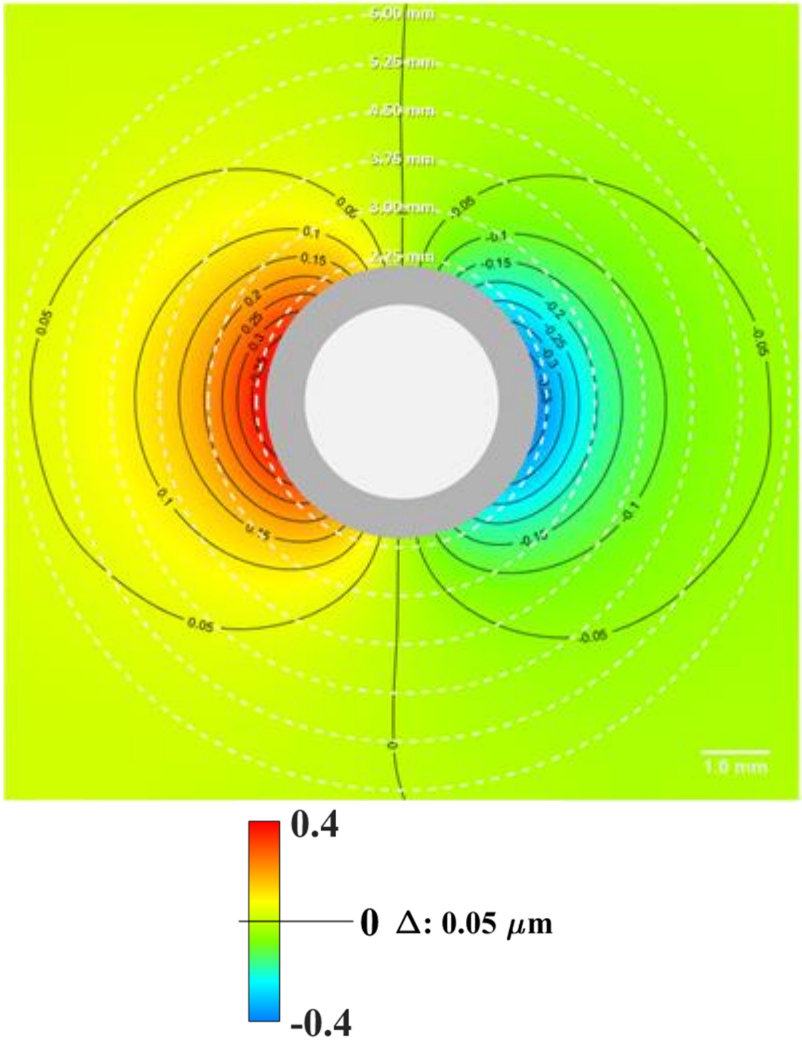
DEFORMATION CONTOUR LINES

GRAPHICAL REPRESENTATION of the numerical stress released deformation fields
- in the case of the uppermost and next drilling steps

DEFORMATION

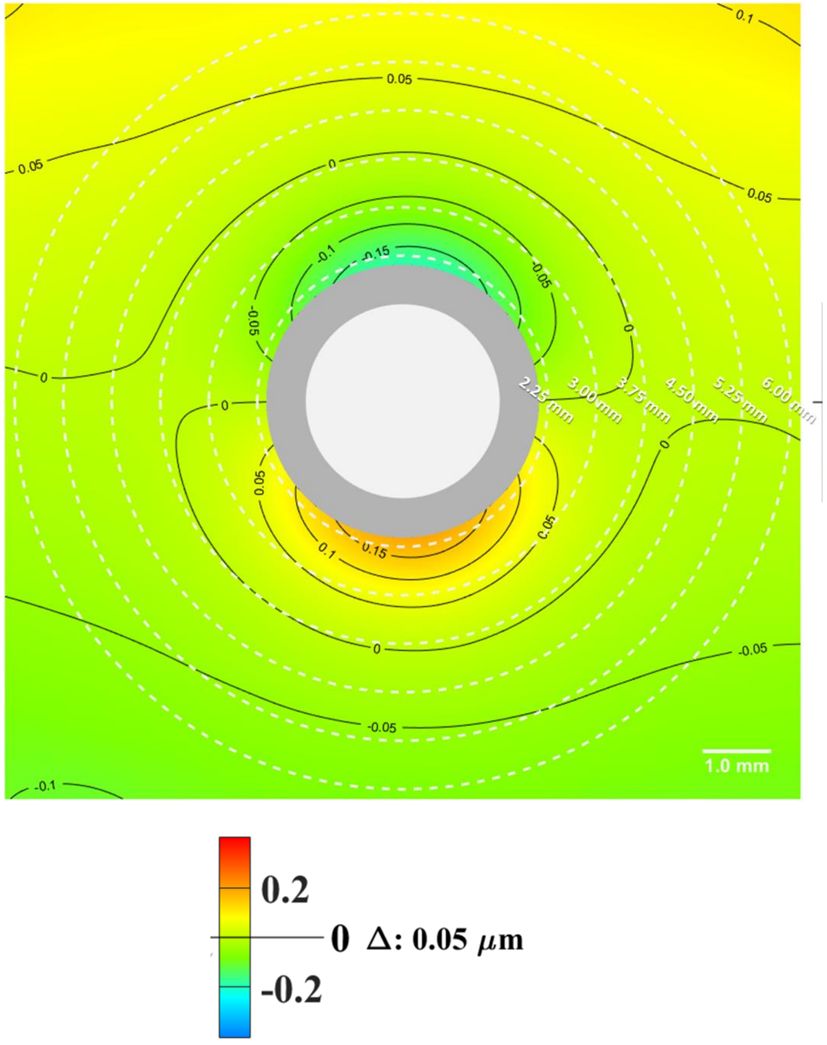
R/1-0.0: u_x

R/1-0.1: u_x

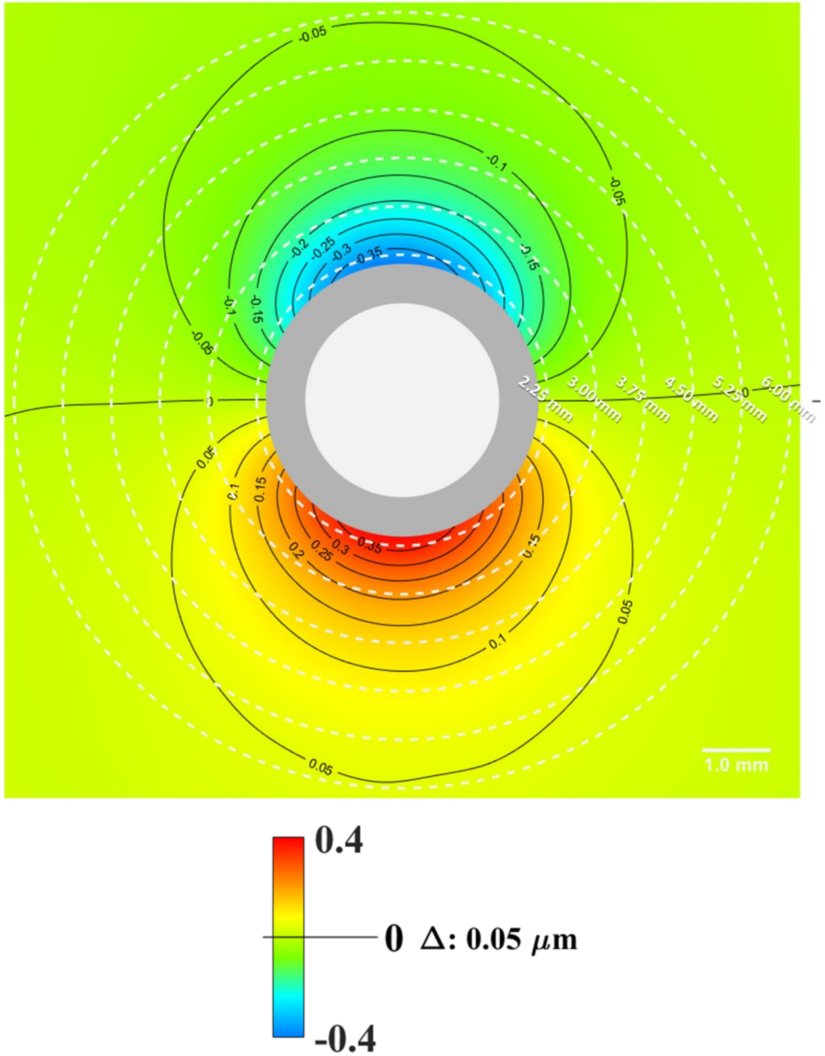


DEFORMATION

R/1-0.0: u_y

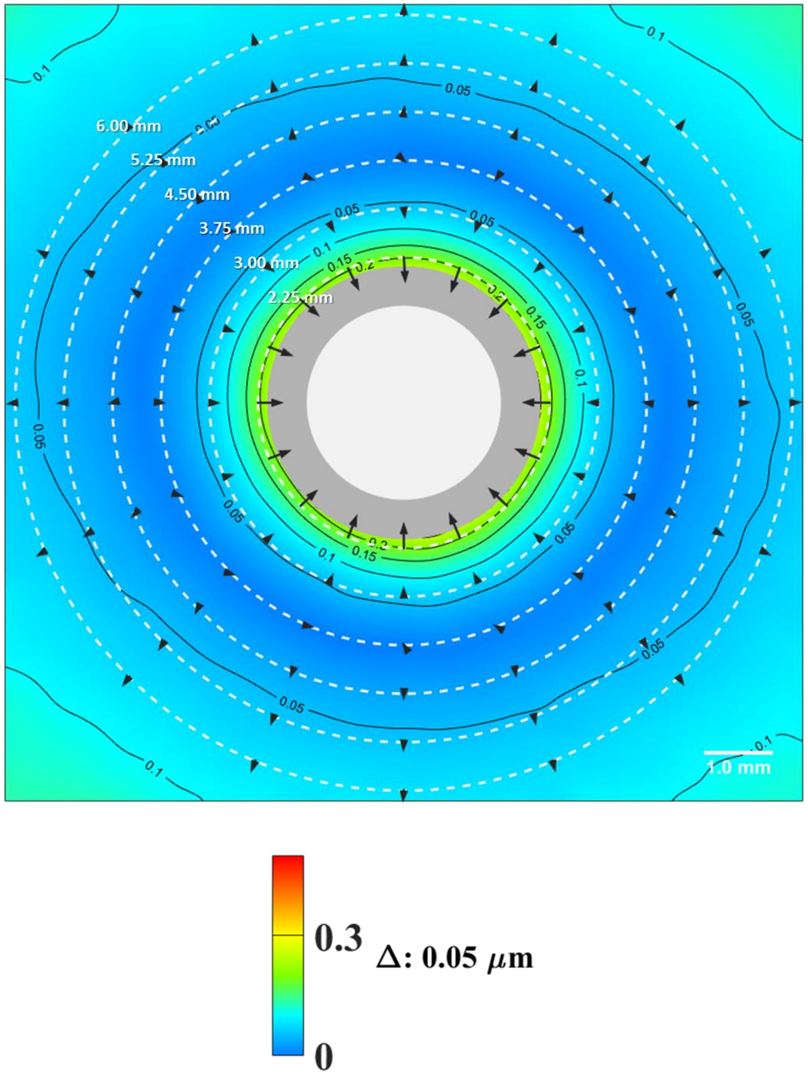


R/1-0.1: u_y

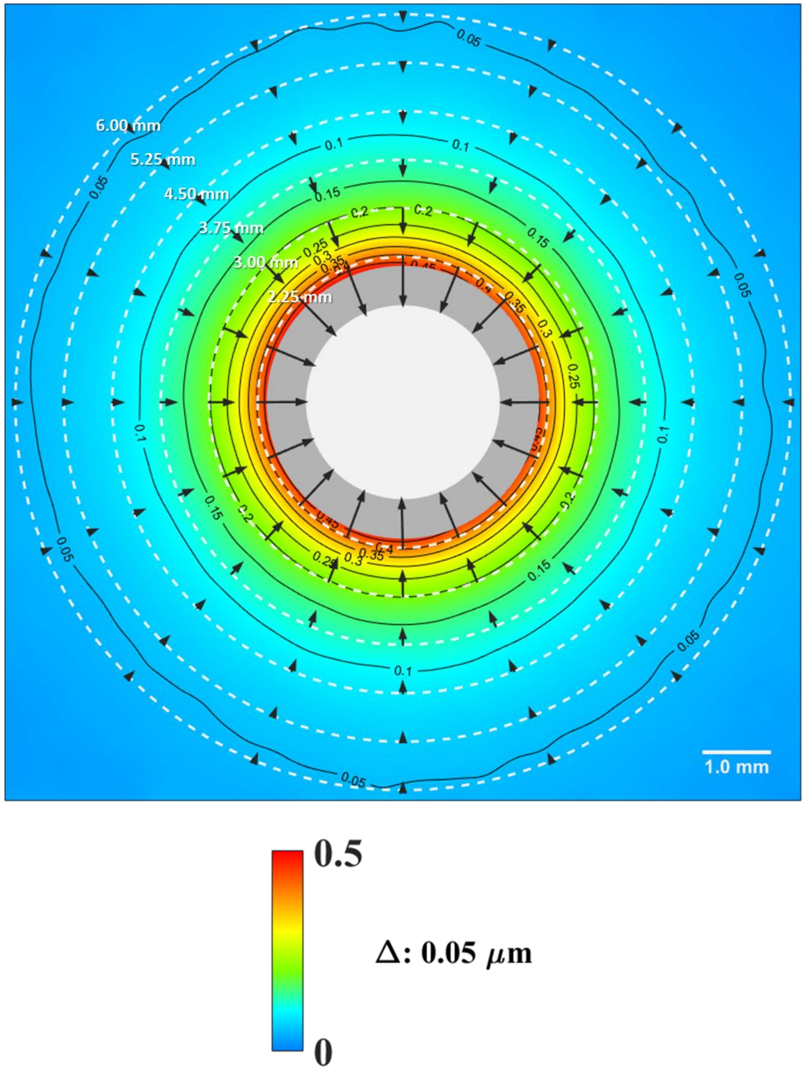


DEFORMATION

R/1-0.0: u_{xy}

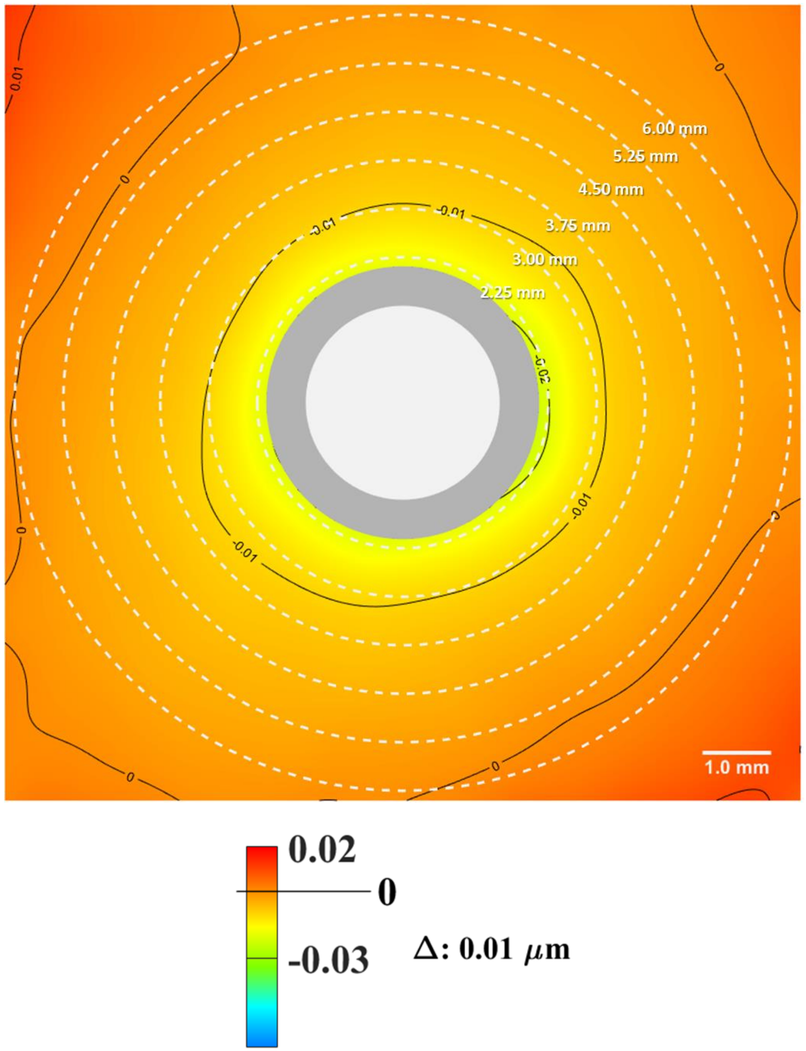


R/1-0.1: u_{xy}

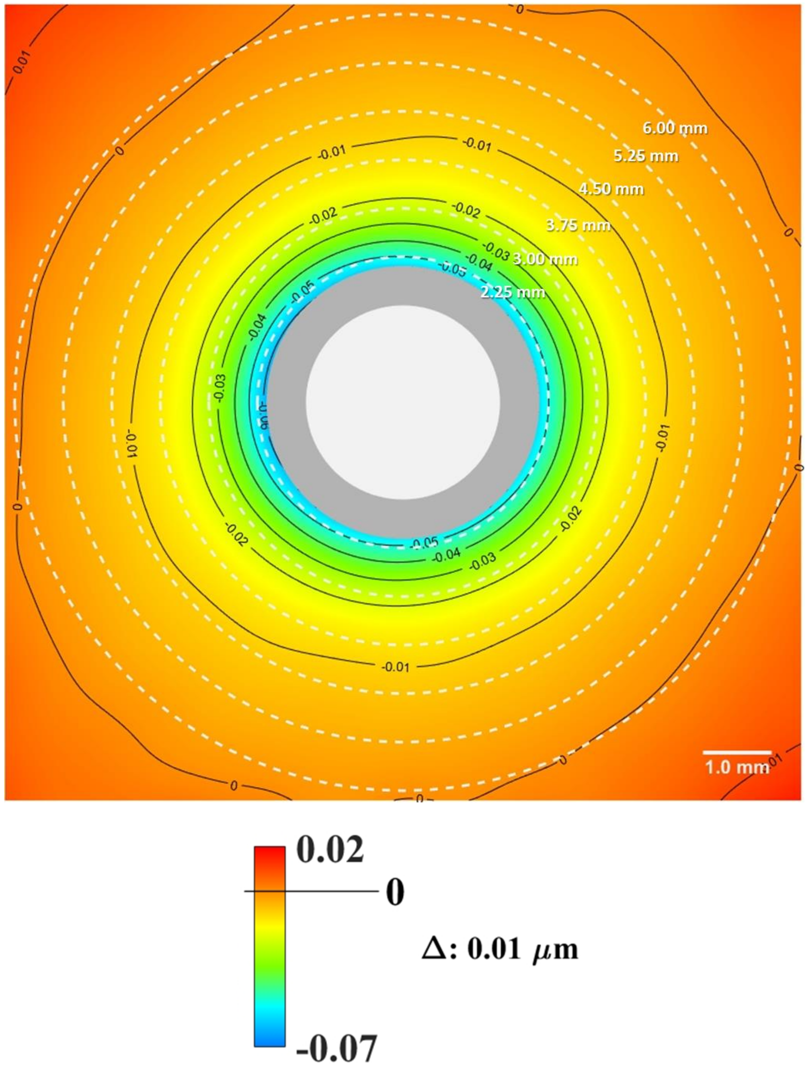


DEFORMATION

R/1-0.0: $\boldsymbol{u_z}$



R/1-0.1: $\boldsymbol{u_z}$



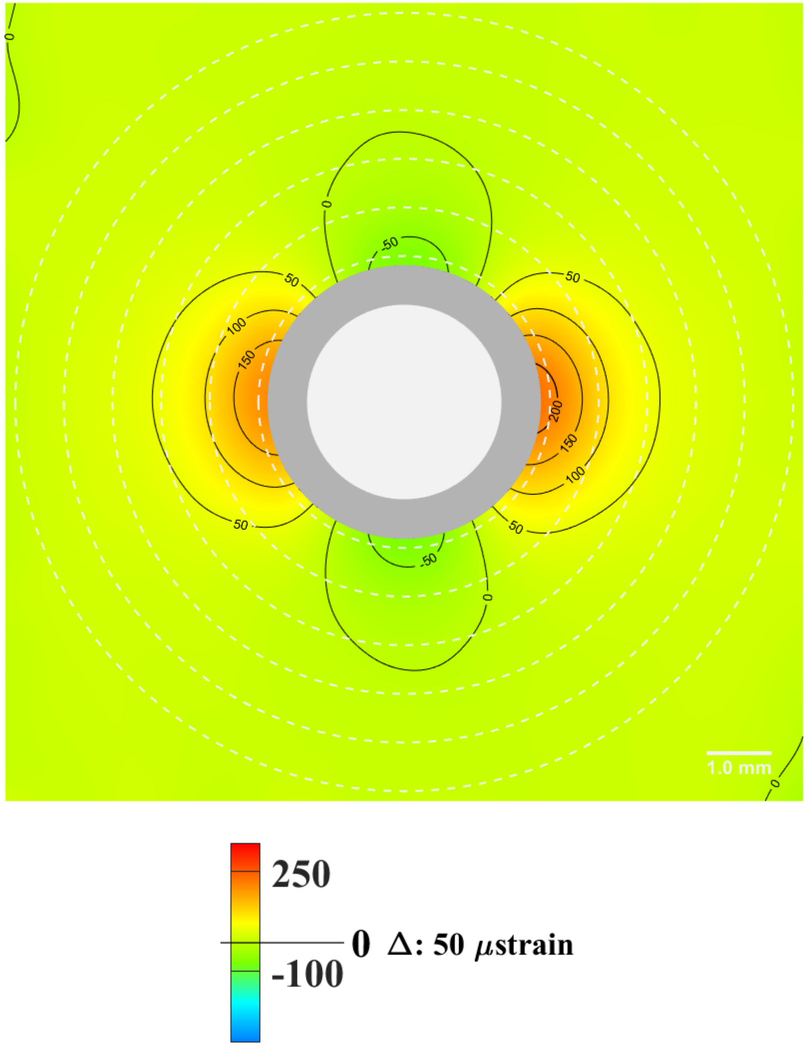
APPENDIX IV/B:

STRAIN CONTOUR LINES

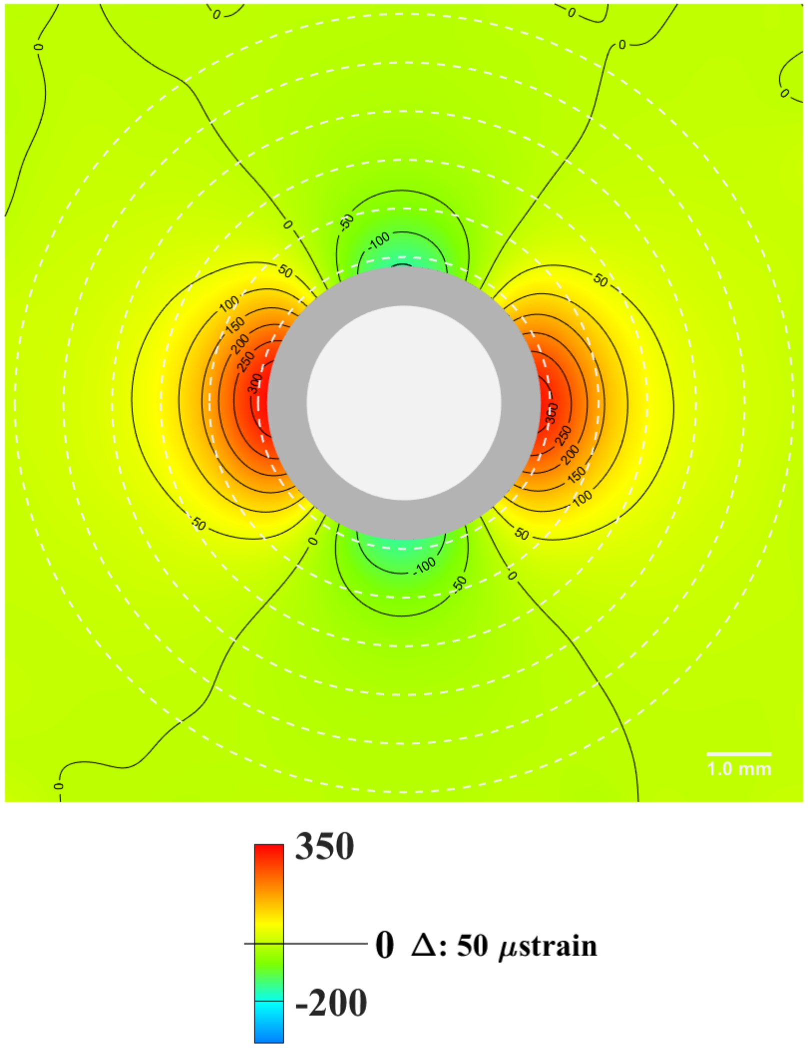
GRAPHICAL REPRESENTATION of the numerical stress released strain fields
- in the case of the uppermost and next drilling steps

STRAIN

R/1-0.0: ε_{xx}

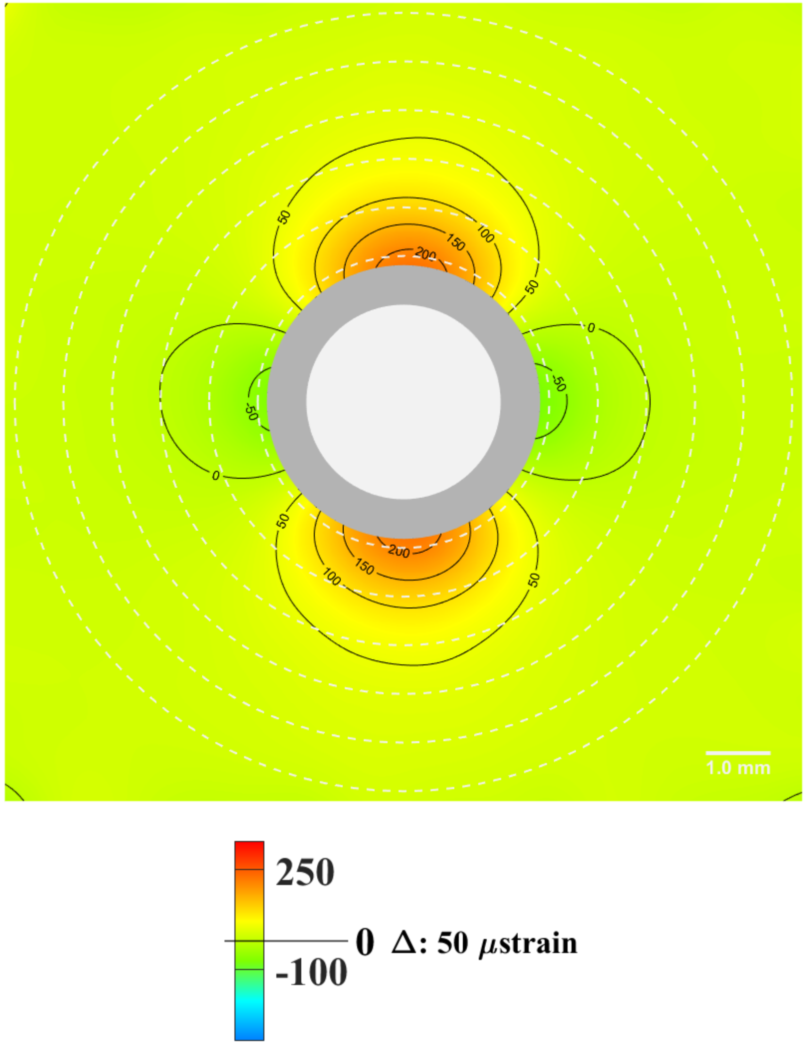


R/1-0.1: ε_{xx}

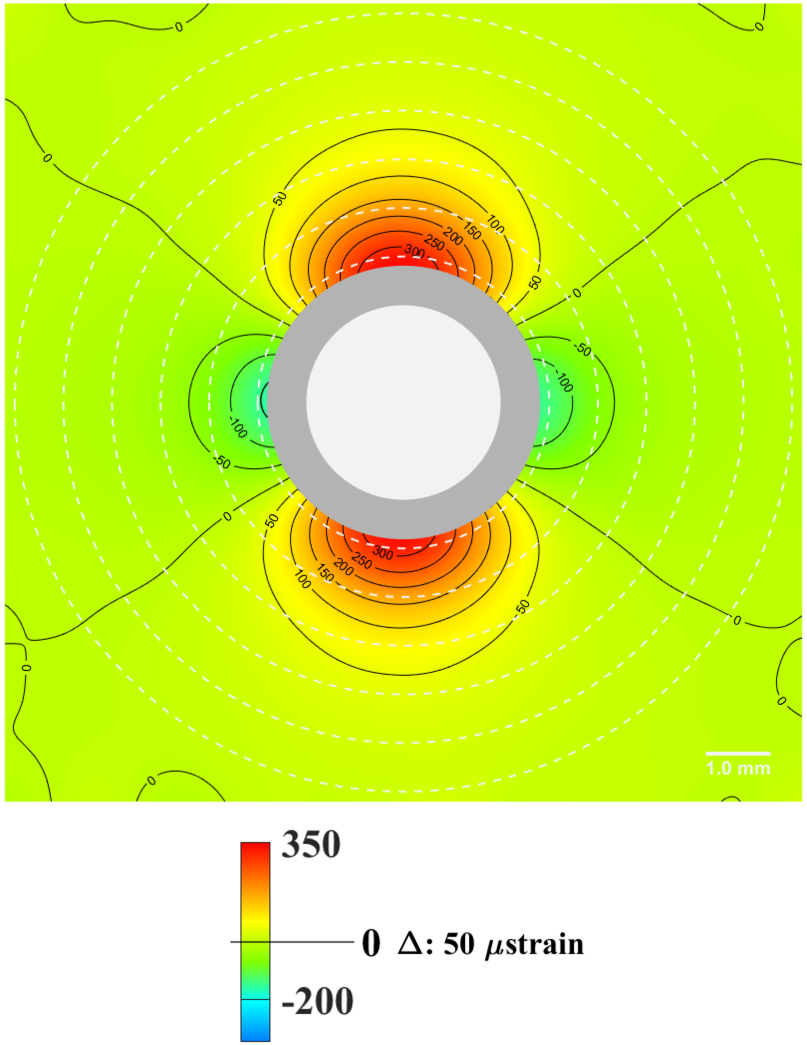


STRAIN

R/1-0.0: ε_{yy}

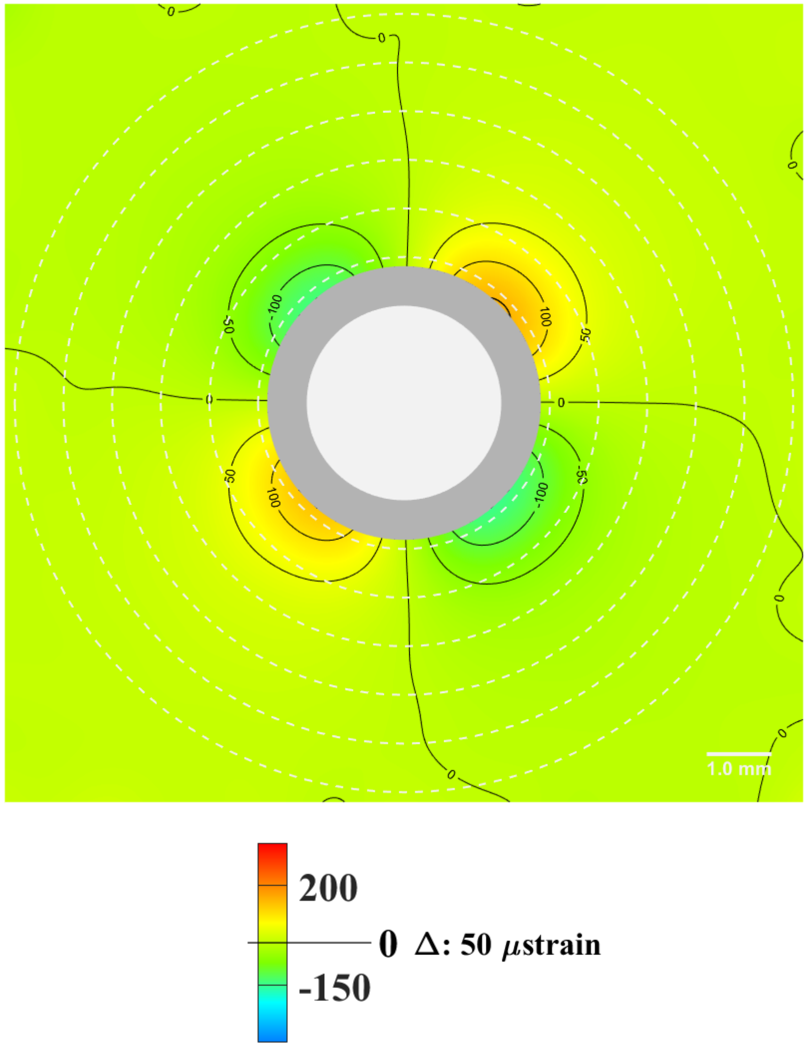


R/1-0.1: ε_{yy}



STRAIN

R/1-0.0: $\varepsilon_{xy} = \varepsilon_{yx}$



R/1-0.1: $\varepsilon_{xy} = \varepsilon_{yx}$