Effect of semi-product homogeneity and machining parameters on fatigue life of specimens from 42CrMo4+QT

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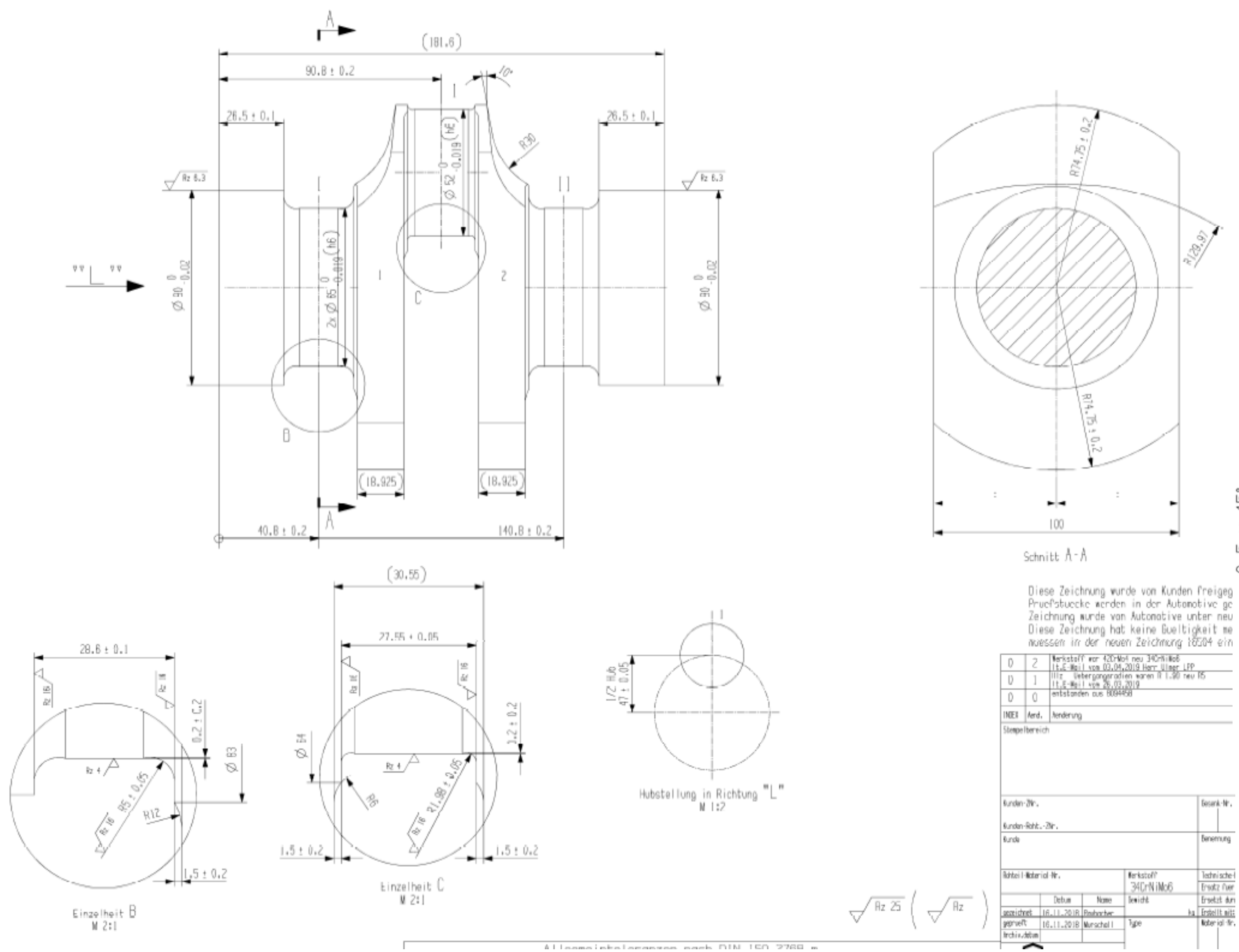
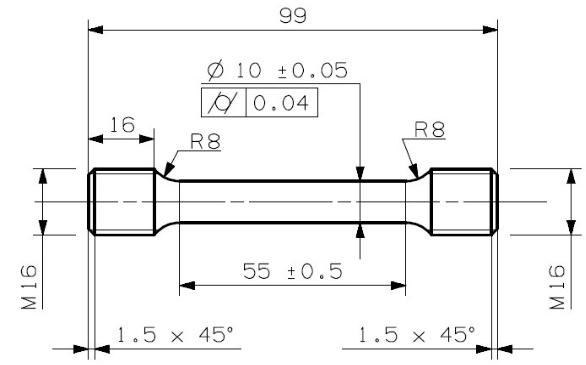
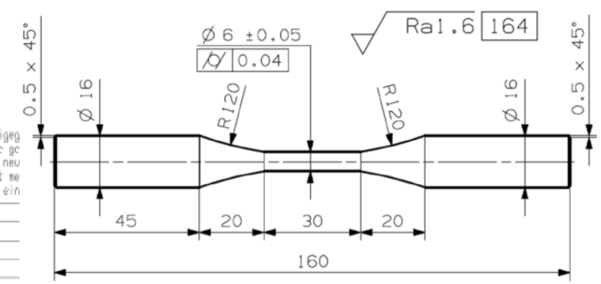
FABEST

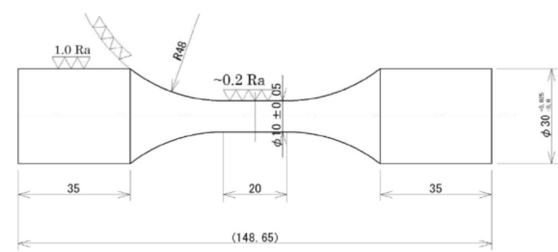
- Originally a subproject of the planned FABER project
  - challenge to reach the best fatigue life estimation to specific problems
- In the start of 2021, I bought 1.4 tons of 42CrMo4+QT (equivalent to 4140) from one heat, diameter 35mm, total length ~ 180 m
- I proposed FABER member to cooperate on its testing, and to build FABEST#0 on its results
  - 15 institutions joined this idea

The momentum – CIMAC challenge









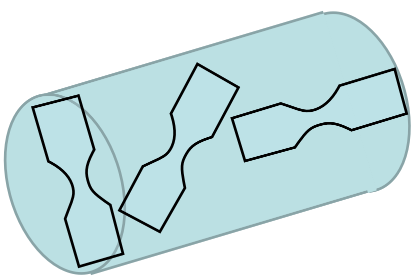
FABEST #0 Plan, Part I

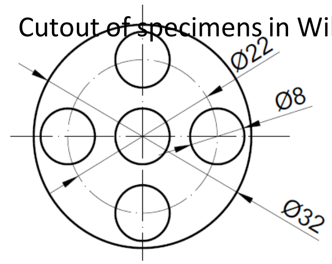
1. Size effect – tested push-pull and torsion, *R*=-1
    a. Full bars *D* = 1, 2, 4, 8, 12, 16 mm
    b. Hollow sections *D/d* = 1.8/1.5, 4/3.5, 8.1/7, 19.7/18, 26/23 mm
2. Frequency effect - Full bars *D*=4mm and hollow sections *D/d*=8.1/7 to be tested in push-pull and in torsion, *R*=-1, *f* = 5, 12, 25, 50, 100 Hz
3. Mean stress effect - Designs *D*=4mm and *D/d*=8.1/7 to be tested in push-pull and in torsion, *R*=-∞, -3, -1, 0, 0.33, 0.5, 0.7

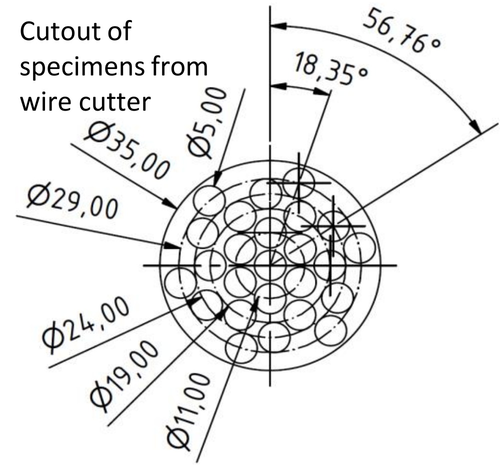
FABEST #0 Plan, Part II

4. Roughness effect - Designs D=4mm and D/d=8.1/7 to be tested in push-pull and in torsion, R_a= 0.1, 0.2, 0.4, 0.8, 1.6 μm
5. Bar homogeneity, anisotropy:

Different orientation

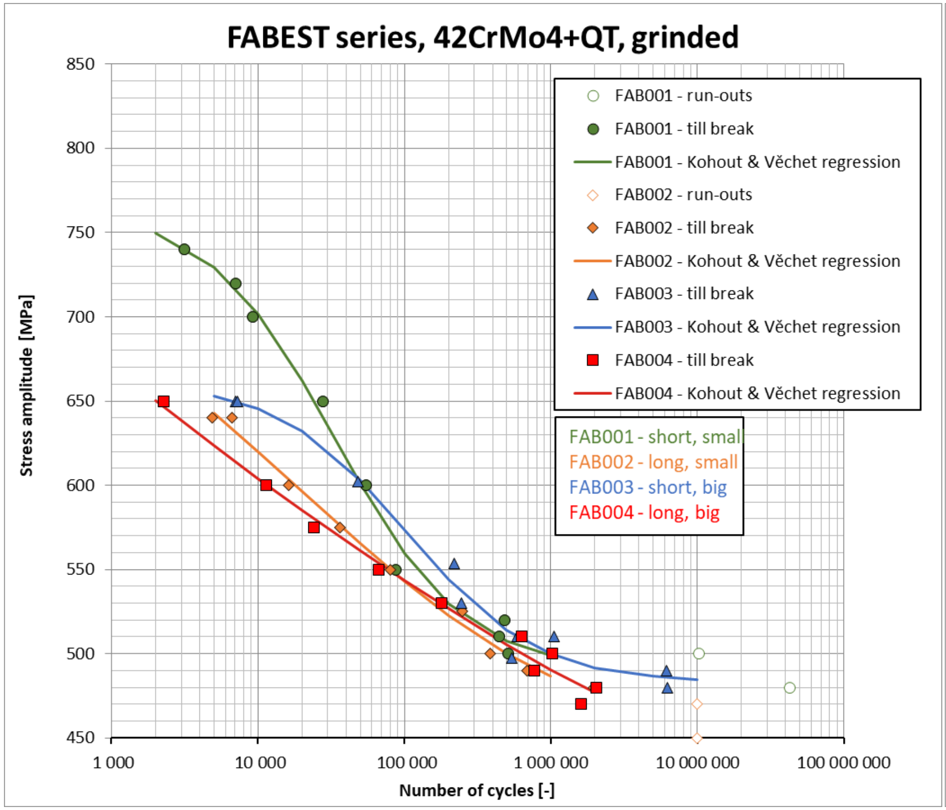


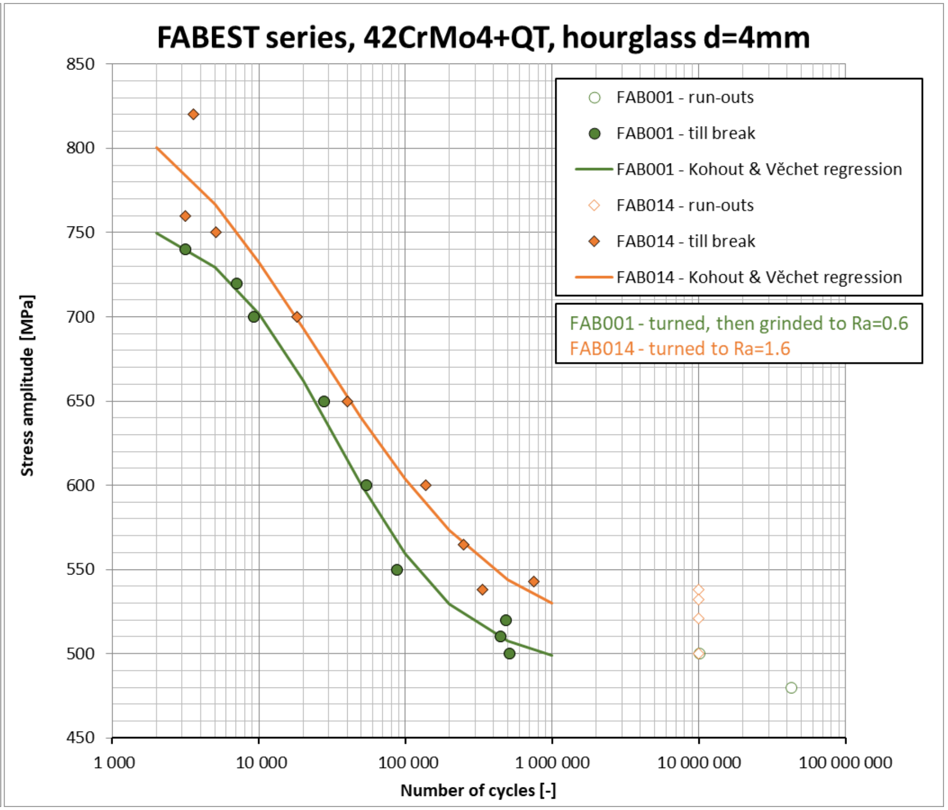




6. Notches – two diploma thesis of students from Padova, Italy,…
7. Multiaxial loading…
8. Fretting…

Reality? Size effect

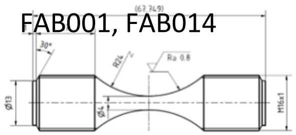


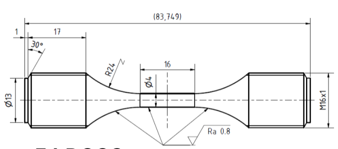


We would expect the same order of S-N curves positions from top to bottom, but this assumption does not fit

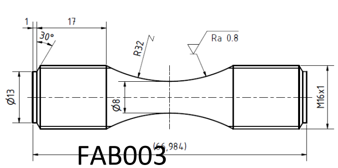
We would expect the grinded specimen to lie above the turned one

FAB001, FAB014

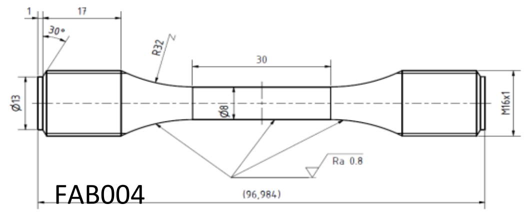




FAB002



FAB003

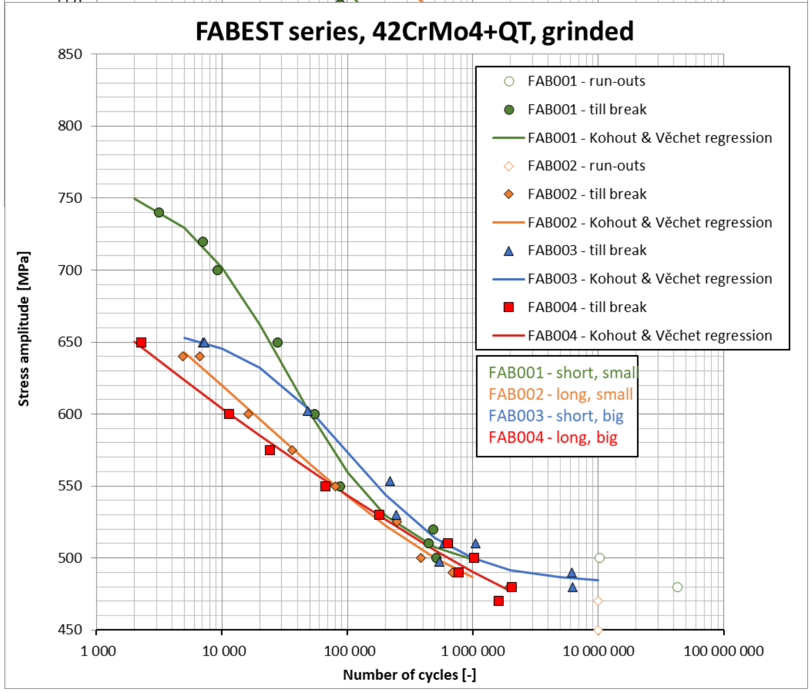


FAB004

Roughness

Series	Batch	Processes	Average Ra [µm]		
			All	CTU	Ostrava
A14	1	Turned	1.73		1.73
A01	2	Turned and ground	0.59	0.59	0.59
A02	1mod	Turned, later ground	0.37	0.37	
A03	1mod	Turned, later ground	0.64	0.61	0.65
A04	2	Turned and ground	0.44	0.25	0.64

- We still have doubts as regards the consistency of roughness measurements across whole batches (and more specimens are checked)
- This however cannot be the only reason of observed discrepancies – see the comparison in the upper graph



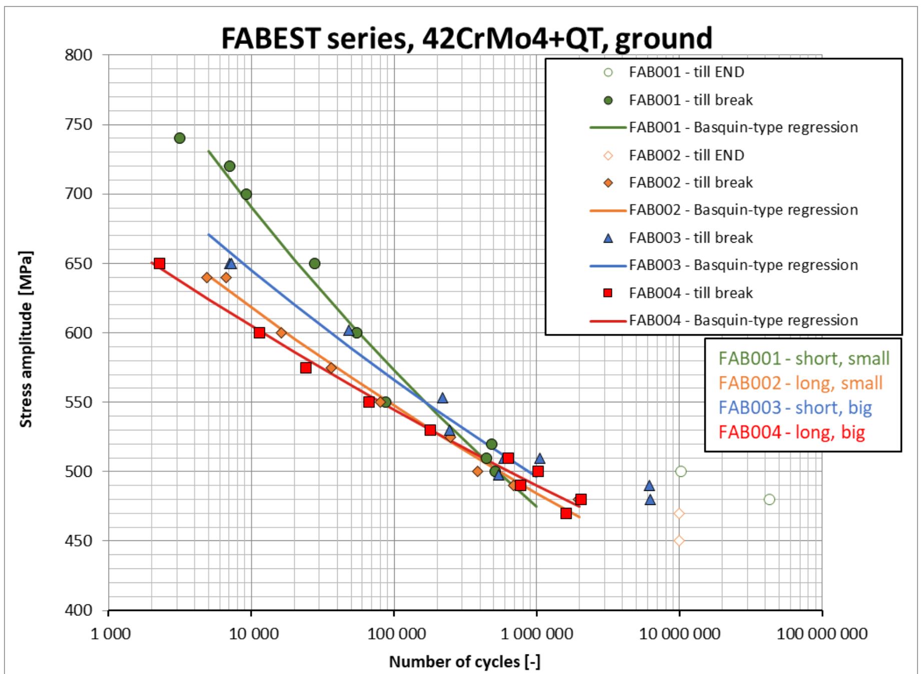
Processing the roughness issue

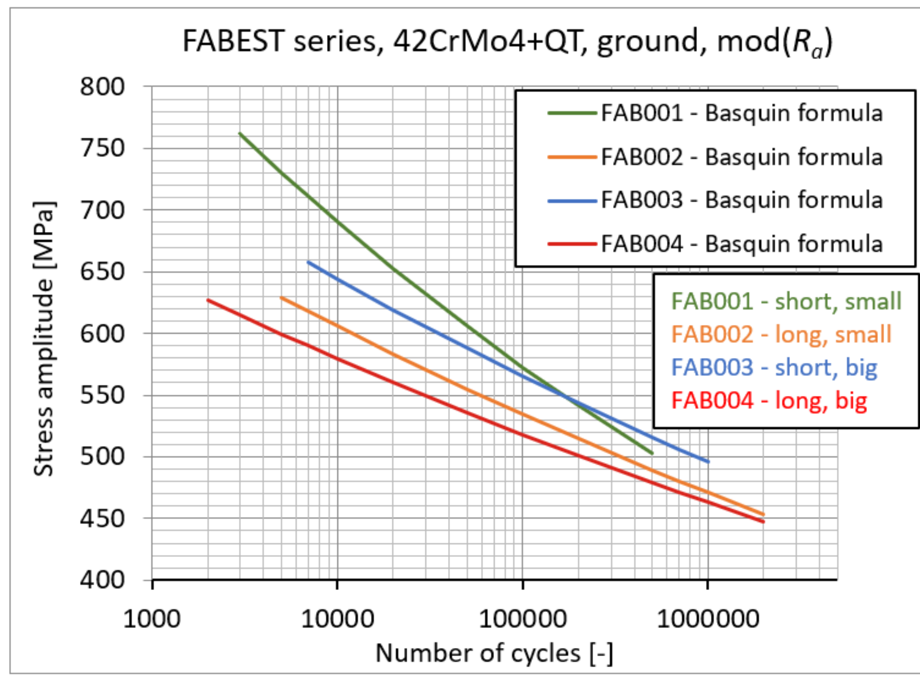
	FAB001	FAB002	FAB003	FAB004
R_a [µm]	0.59	0.37	0.61	0.25
R_z [µm]	4.66	3.26	4.56	2.23
$k_R / k_{R,A1}$[-]	1.000	0.972	0.998	0.944

FKM-Guideline:

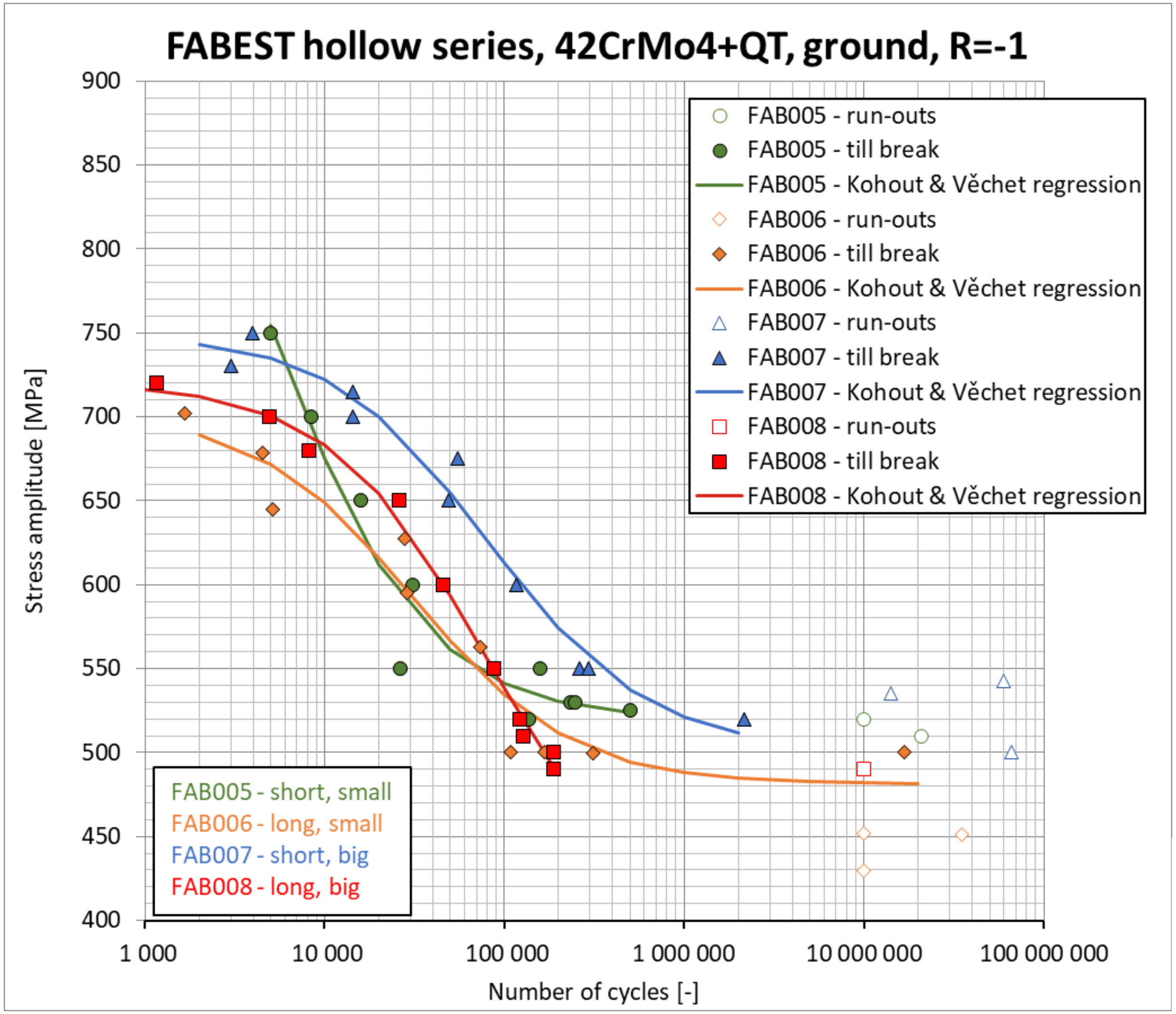
$$k_R = 1\text{-}0.22\log(R_z)\cdot\log(2R_m/400)$$

- The fatigue strength at 1e6 cycles multiplied by the given ratio, the other S-N curve point, where the curve meets Rm is kept fixed.
- Logically, this solution affects (in a positive way) position of FAB002 and FAB004 curves above all, see below

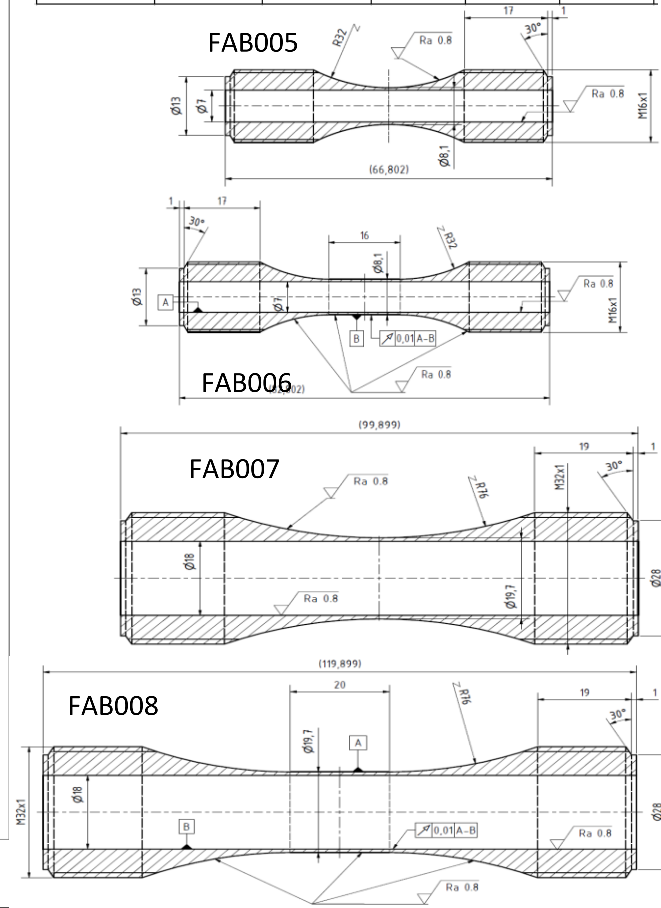




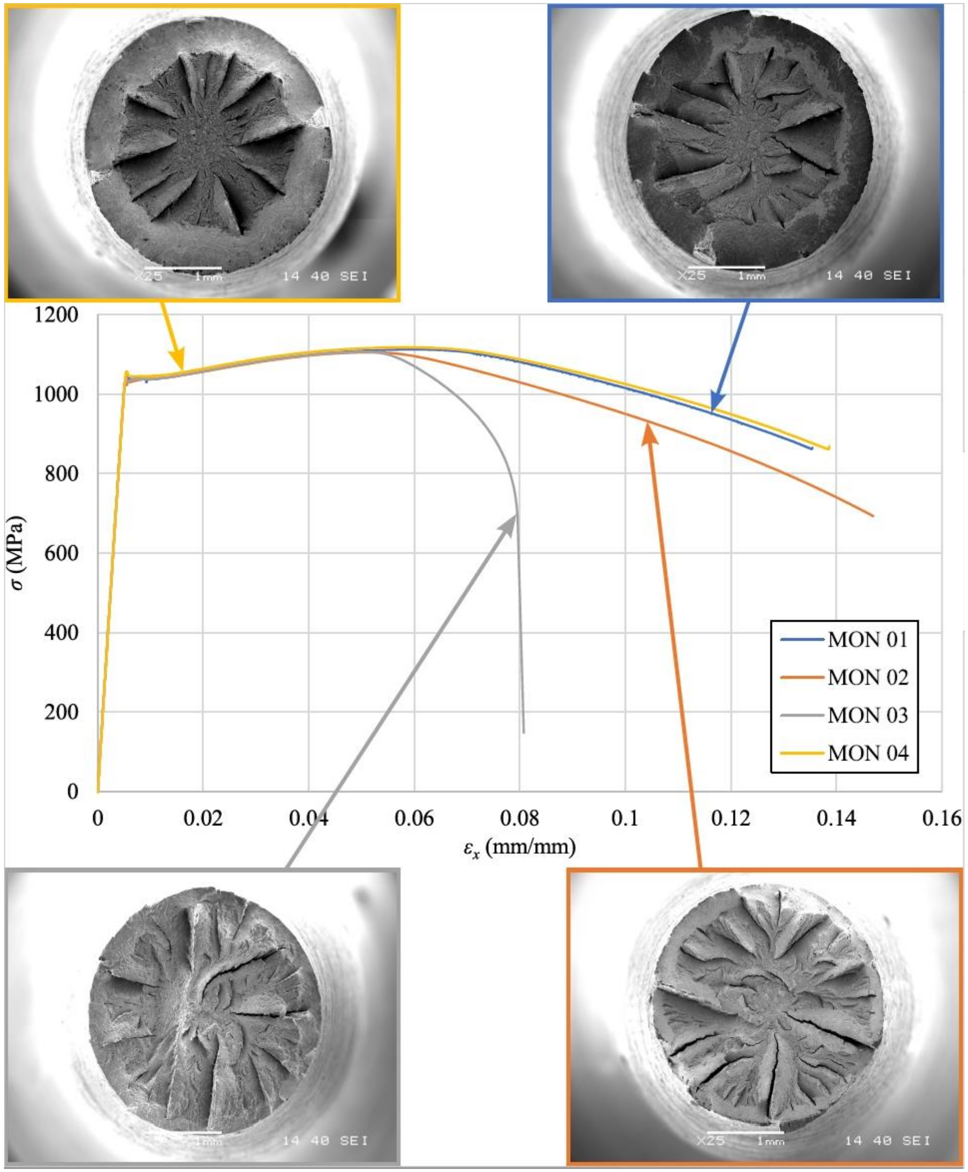
Size effect, Part II



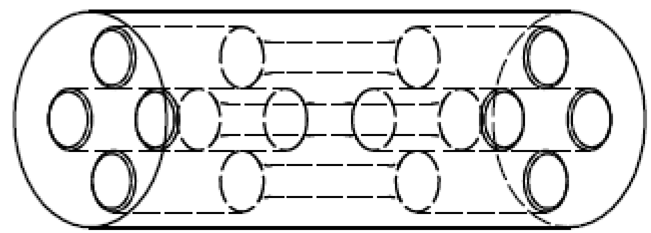
		FAB005	FAB006	FAB007	FAB008
Ra [mm]	Mean	0.58	1.05	1.04	0.91
	Max	0.646	1.148	1.304	0.948
Rz [mm]	Mean	4.21	6.74	6.31	5.46
	Max	4.776	7.043	8.07	5.904
k_R(FKM)	Mean	0.898	0.865	0.870	0.880
	Max	0.890	0.862	0.853	0.875
$k_R/k_{R,A1}$ [-]	Mean	0.992	1.030	1.025	1.013
	Max	0.981	1.012	1.023	0.997



Static tests

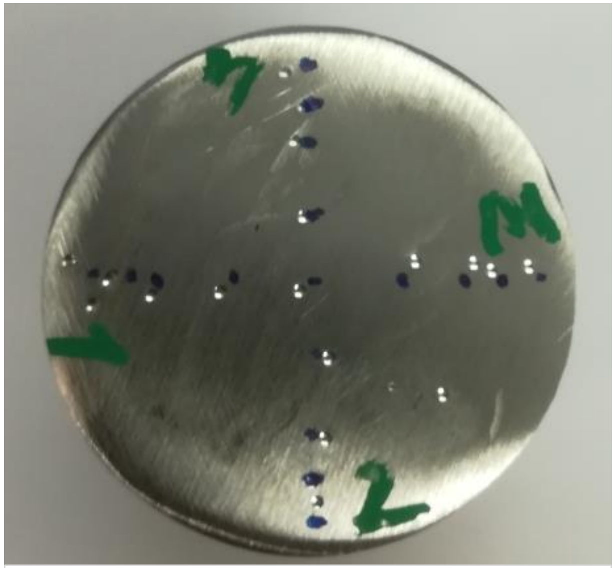


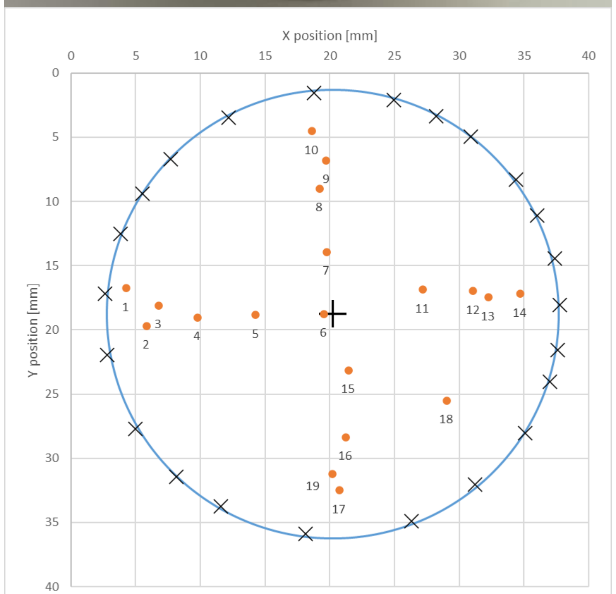
Lukasz Pejkowski, Jan Seyda, UTP Bydgoszcz, Poland

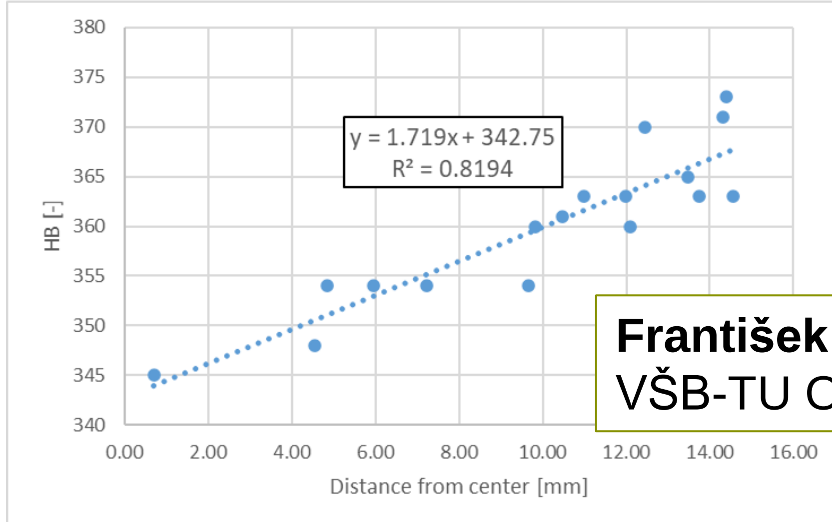


- The four specimens show different ductility
- Is the material homogenous across the cross-section?

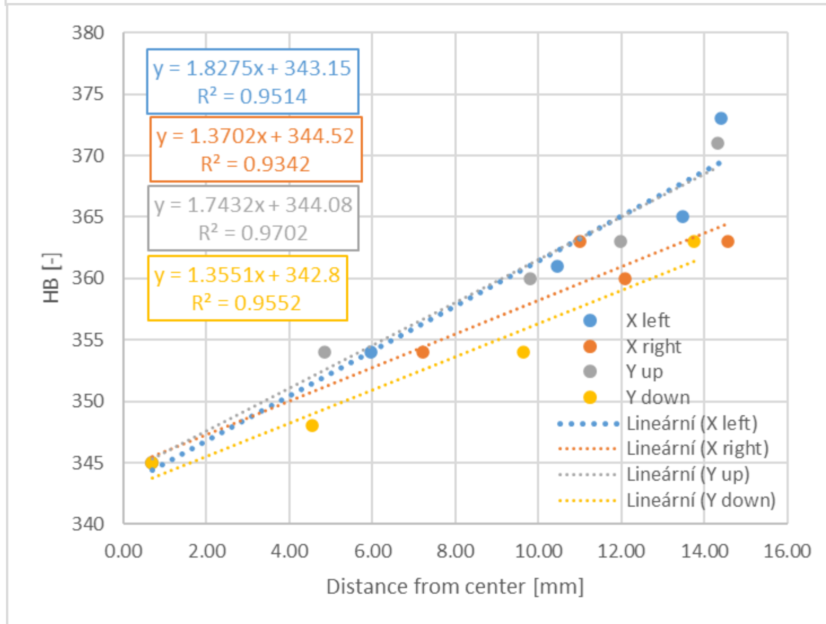
Hardness tests, vol. 1





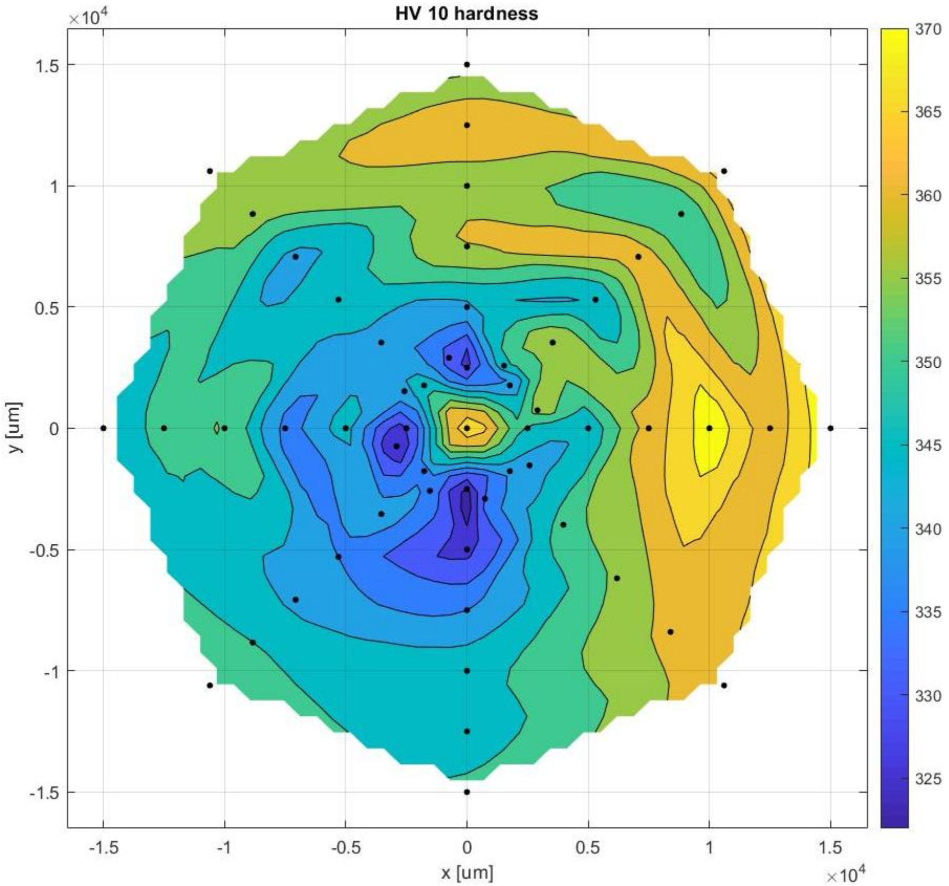


František Fojtík,
VŠB-TU Ostrava, Czechia



Not only radial change observed

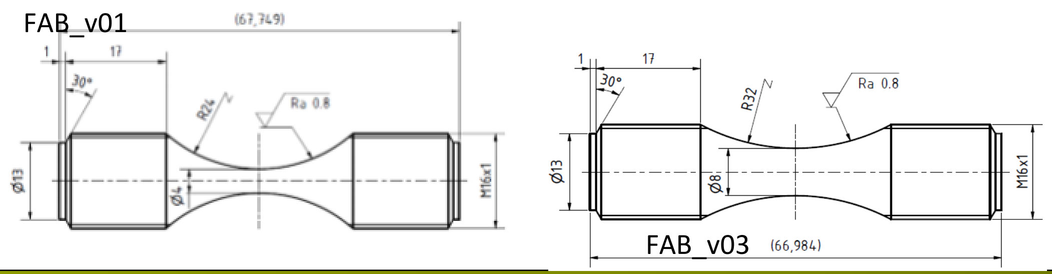
Hardness tests, vol. 2



František Fojtík, VŠB-TU Ostrava, Czechia

Questionable (and sole) value measured in the centre

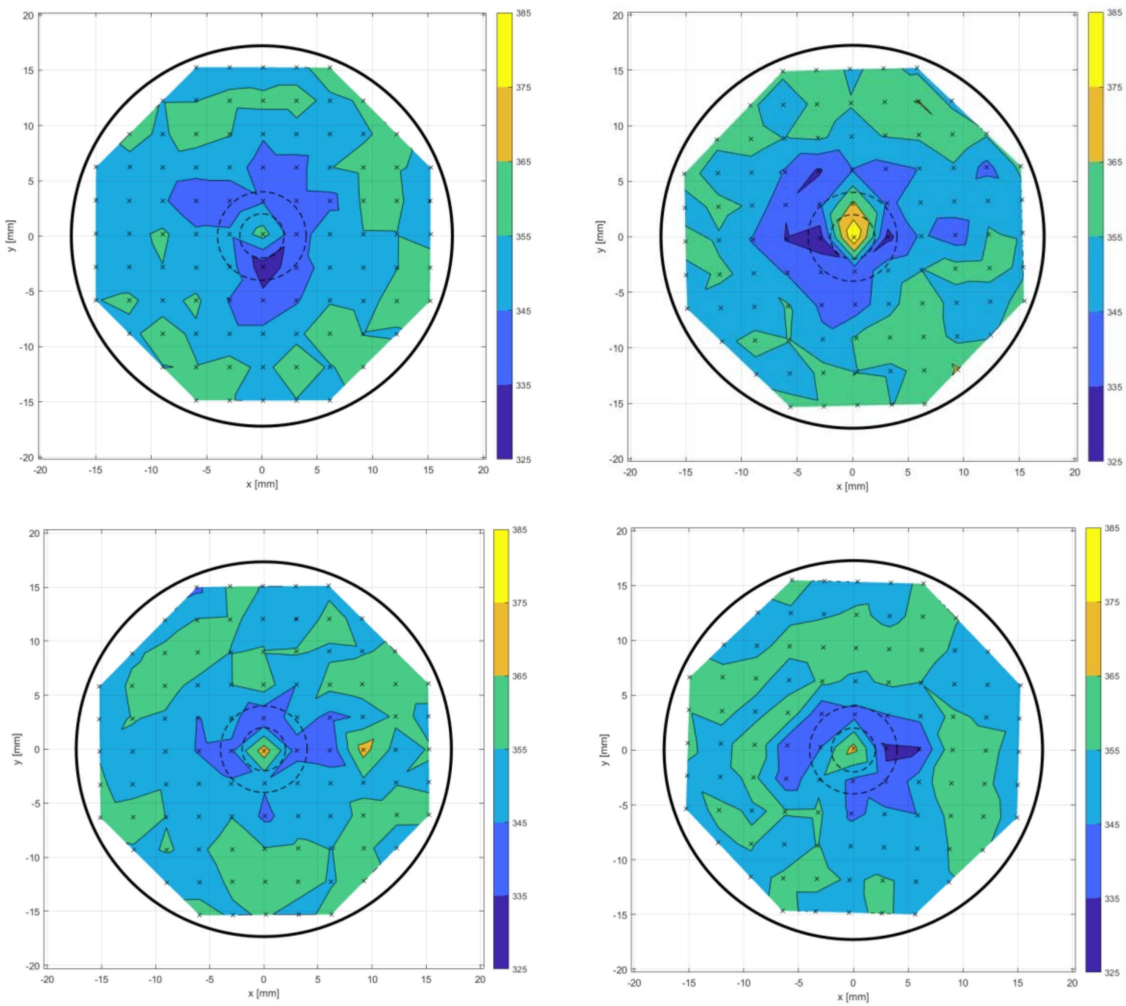
Relatively low measurement density



Hardness tests, vol. 3

Vladimír Mára,
CTU in Prague, Czechia

- Four sections from different positions of the total bar content chosen, their cross-sections analyzed by HV10 measurements



Note the dashed lines showing the critical cross-sections of A1-A4 specimen types

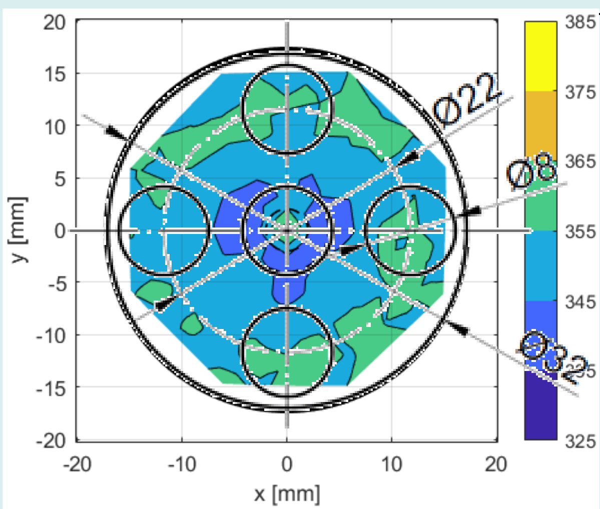
Vladimír Mára: „*Higher hardness values in the center are probably the result of manufacture process of the 42CrMo4+QT steel bar. Continuous casting tends to form the centerline shrinkage. It is subsequently removed by the rolling process resulting in increased hardness. The areas of lower hardness around the center are associated with the original microstructure and deformation during the rolling process of the billet.*“

The non-homogeneity along the angle direction of the cylindrical coordinate system is not confirmed (it is not enough pronounced to be observed given the common scatter in HV10 measurements)

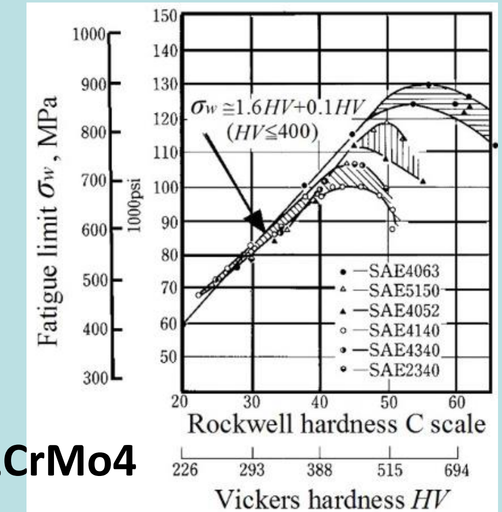
Hardness tests, vol. 4

- Vickers hardness seems to be related to the fatigue response, see right
- Typical initiation hot-spot in our cases is surface – it is a question whether the bigger hardness in the center of specimens affects the fatigue response (but it could for D=2 mm)
- The hardness decrease in the region close to the center could impact the output

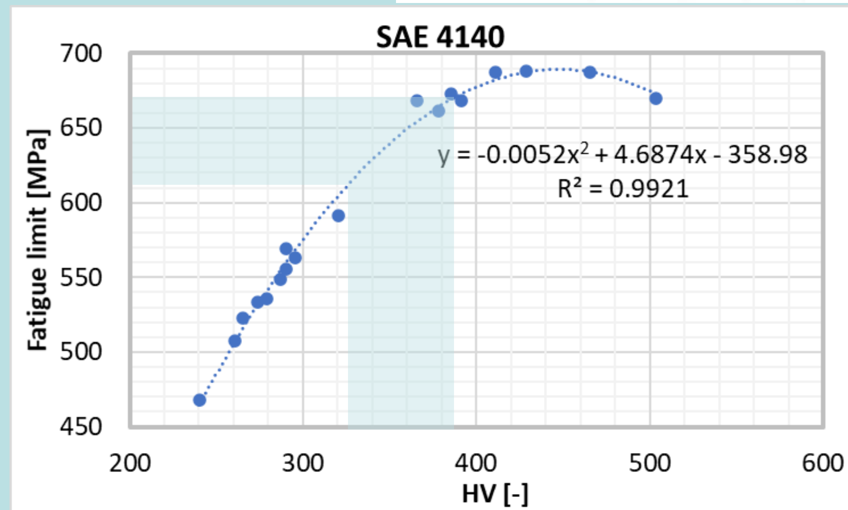
Composite figure from all 4 tests averaged + the cut-out proposed by Alek Karolczuk:



Garwood, M.F., Zurburg, H. H., Erickson, M. A., 1951, Correlation of Laboratory Tests and Service Performance, Interpretation of Tests and Correlation with Service, ASM, Philadelphia, PA, pp. 1-77.



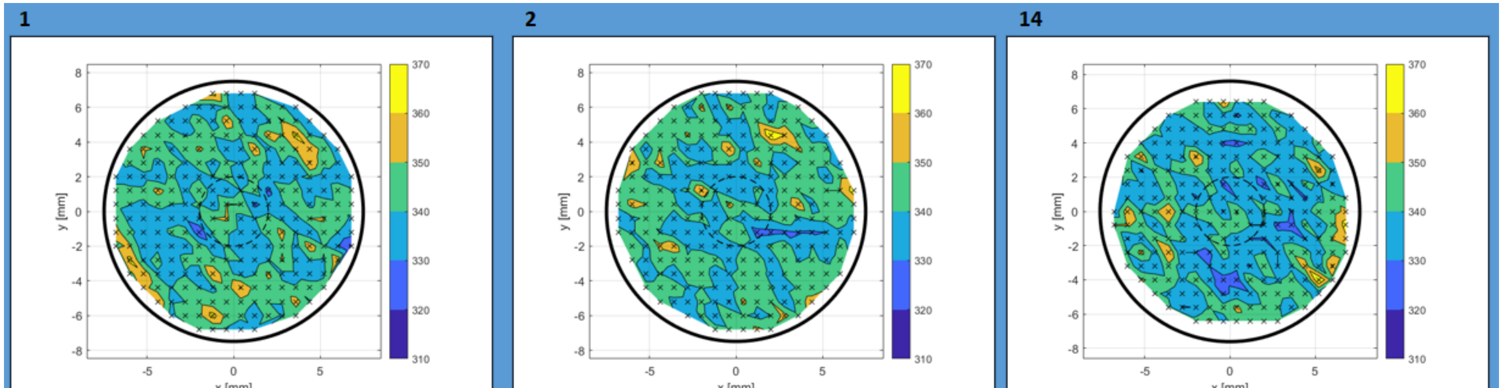
SAE4140 ~ 42CrMo4



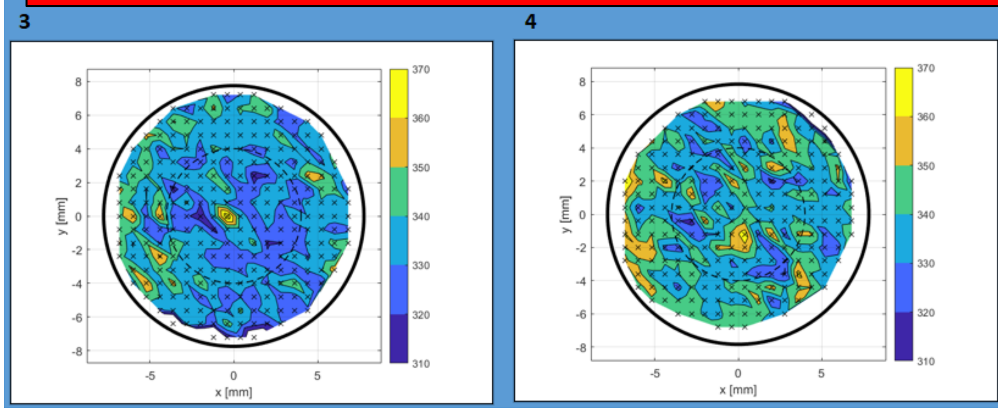
Hardness tests, vol. 5

Vladimír Mára,
CTU in Prague, Czechia

- HV10 on the cross-section of the head of one specimen from each test series examined



The central shrinkage is not visible for specimen A14, the weaker area around it is not visible for A01 and A02!!!



HV10	sig_FL
365	654
355	645
345	634
335	623
325	611
315	598

Santus, C., Taylor, D., Benedetti, M.: Sensibility analysis of the fatigue critical distance values assessed by combining plain and notched cylindrical specimens. Procedia Structural Integrity 8, 67-74 (2018).

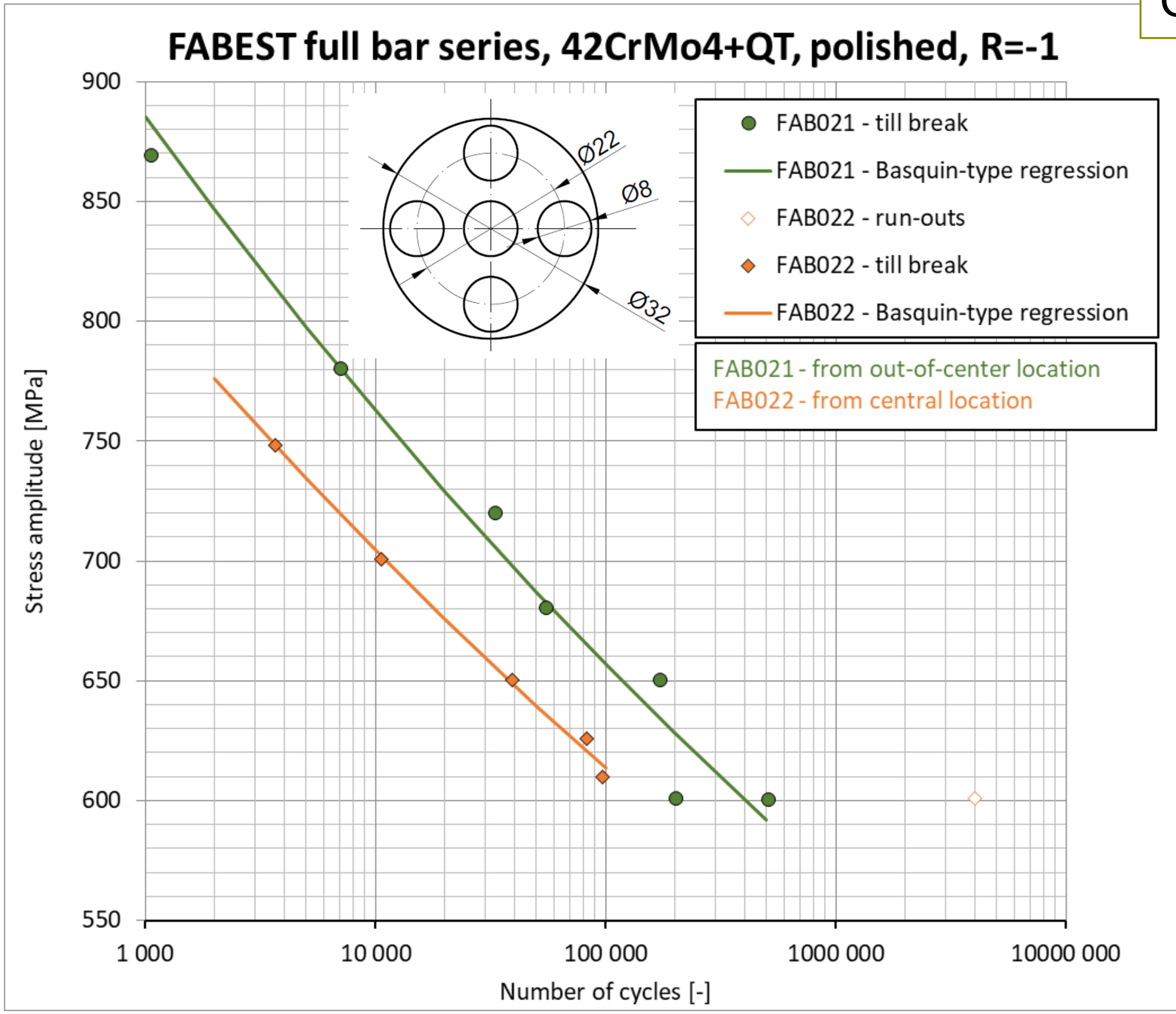
Only volume close to the surface decides the fatigue life
L_{CD}=0.15 mm chosen

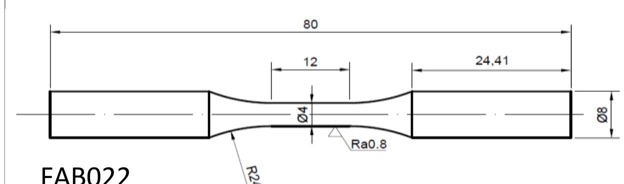
		HV10 at full cross-section			HV10 within the critical distance		
Specimen type	D [mm]	Max	Min	Mean	Max	Min	Mean
A001, A002	4	353	327	339	349	328	338
A001, A002, A014	4	352	327	339	348	329	338
A001, A002, A014, A004	4, 8	356	324	339	349	327	337
A003, A004	8	373	314	334	349	318	334

Only A3 specimen shows significant difference
This is the only curve showing higher scatter
Two more specimens will be checked

Bar homogeneity

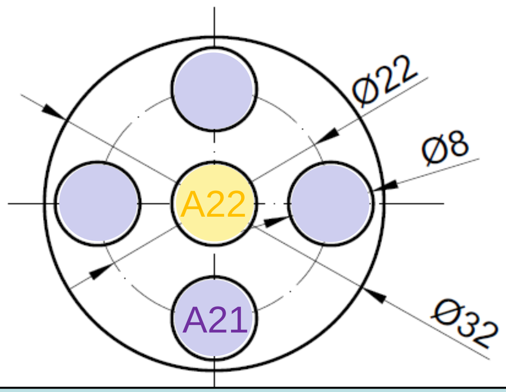
Aleksander Karolczuk,
Opole Polytechnics, Poland

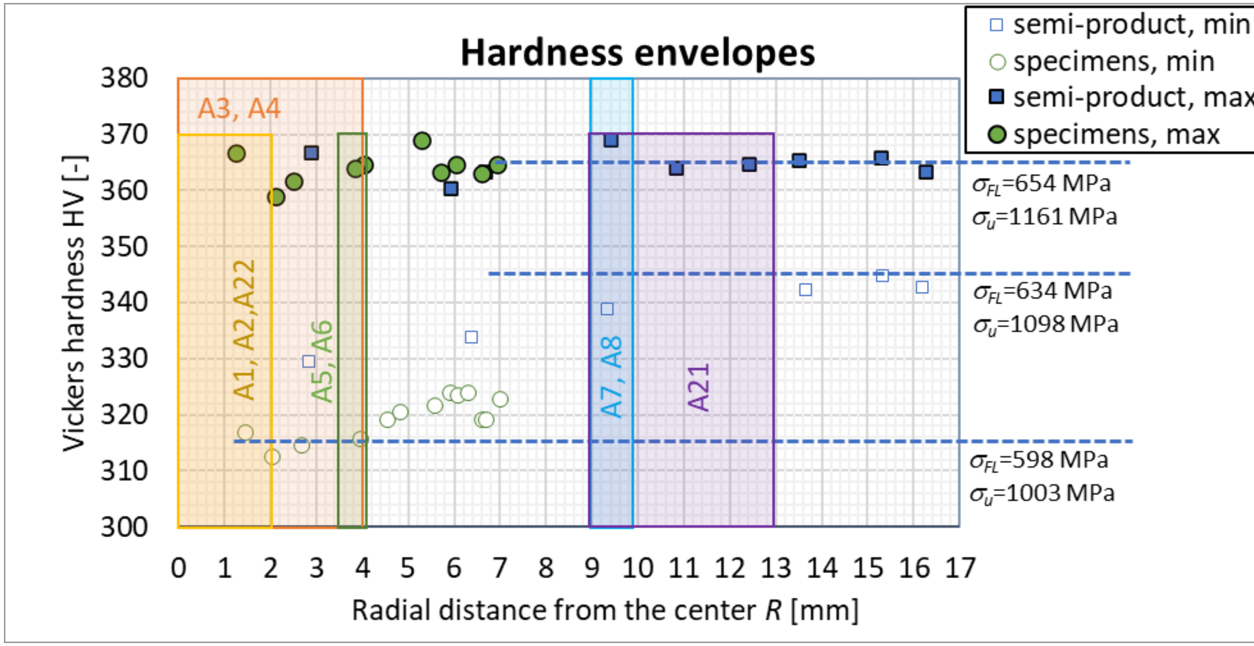




FAB022

Bar homogeneity, vol. 2

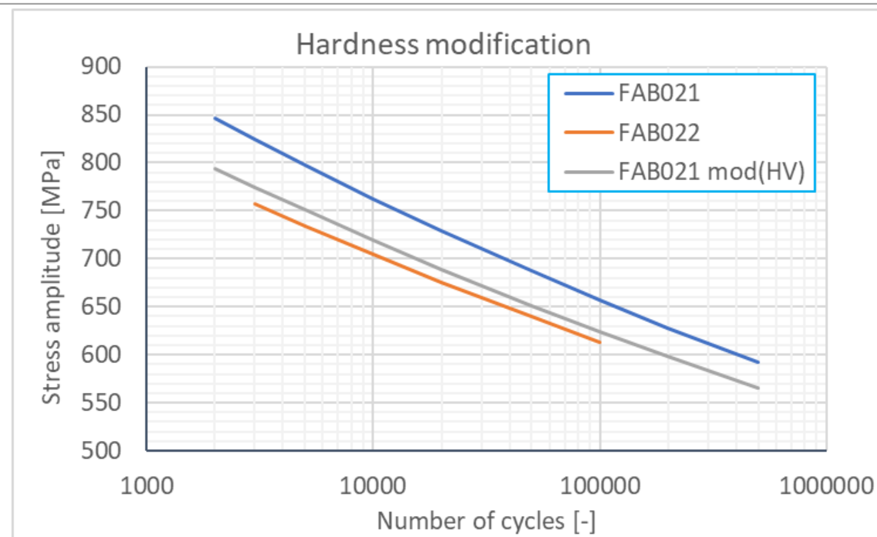




sig_Y: Pavlina EJ, Van Tyne CJ. Correlation of Yield Strength and Tensile Strength with Hardness for Steels. Journal of Materials Engineering and Performance 2008;17:888-93.

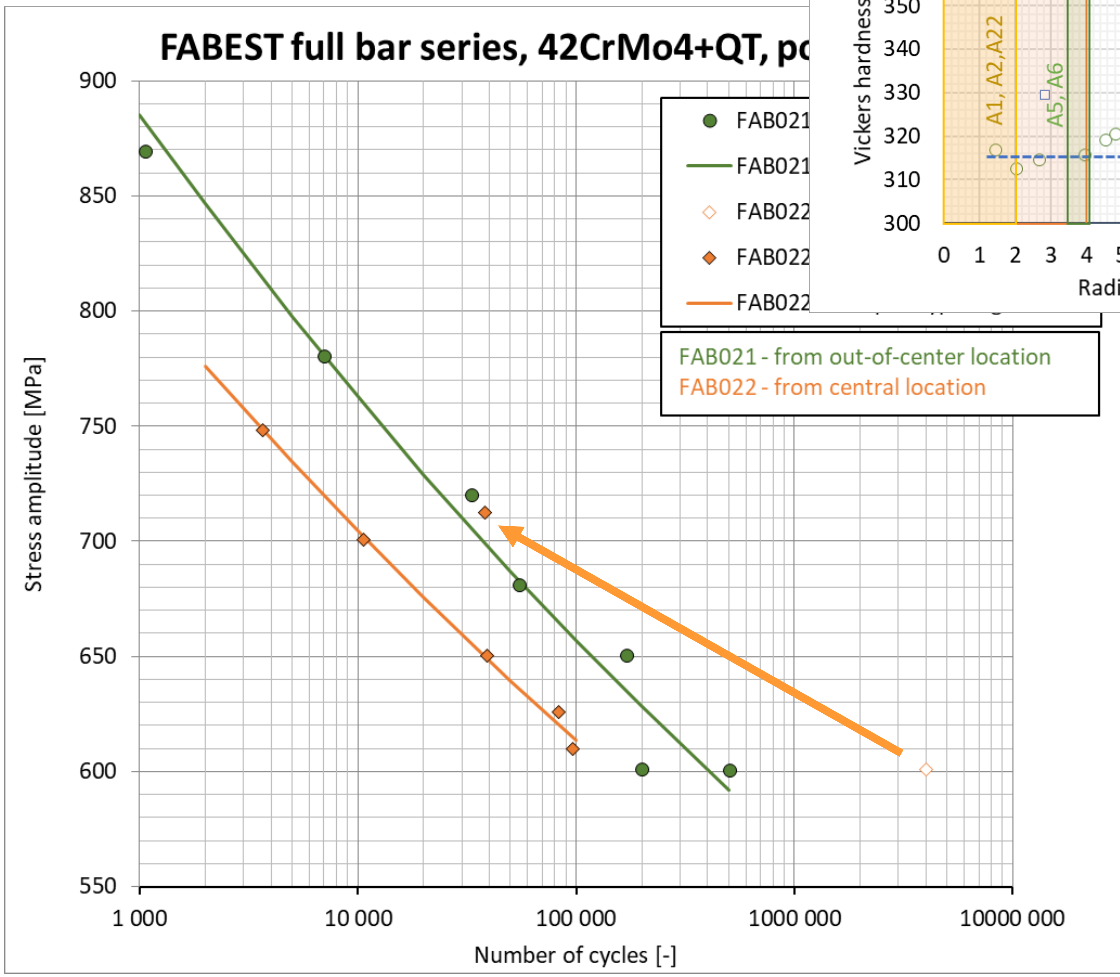
sig_U: Garwood, M.F., Zurburg, H. H., Erickson, M. A., 1951, Correlation of Laboratory Tests and Service Performance, Interpretation of Tests and Correlation with Service, ASM, Philadelphia, PA, pp. 1-77.

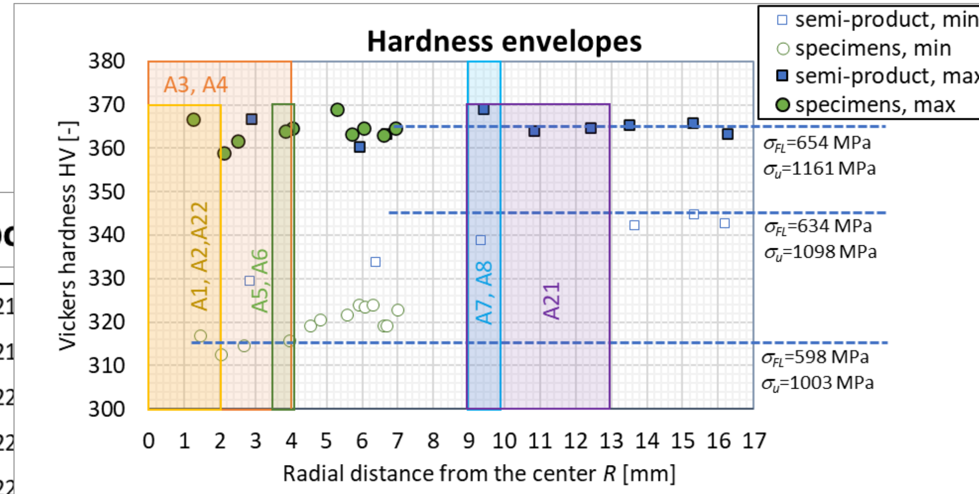
HV10	sig_FL	sig_U	sig_Y
365	653.8	1160.75	1058.9
355	644.7	1129.25	1030.3
345	634.5	1097.75	1001.7
335	623.2	1066.25	973.1
325	611.0	1034.75	944.5
315	597.6	1003.25	915.9



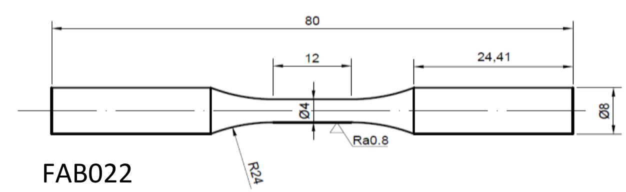
Bar homogeneity, vol. 3

- The run-out specimen from the central position was retested





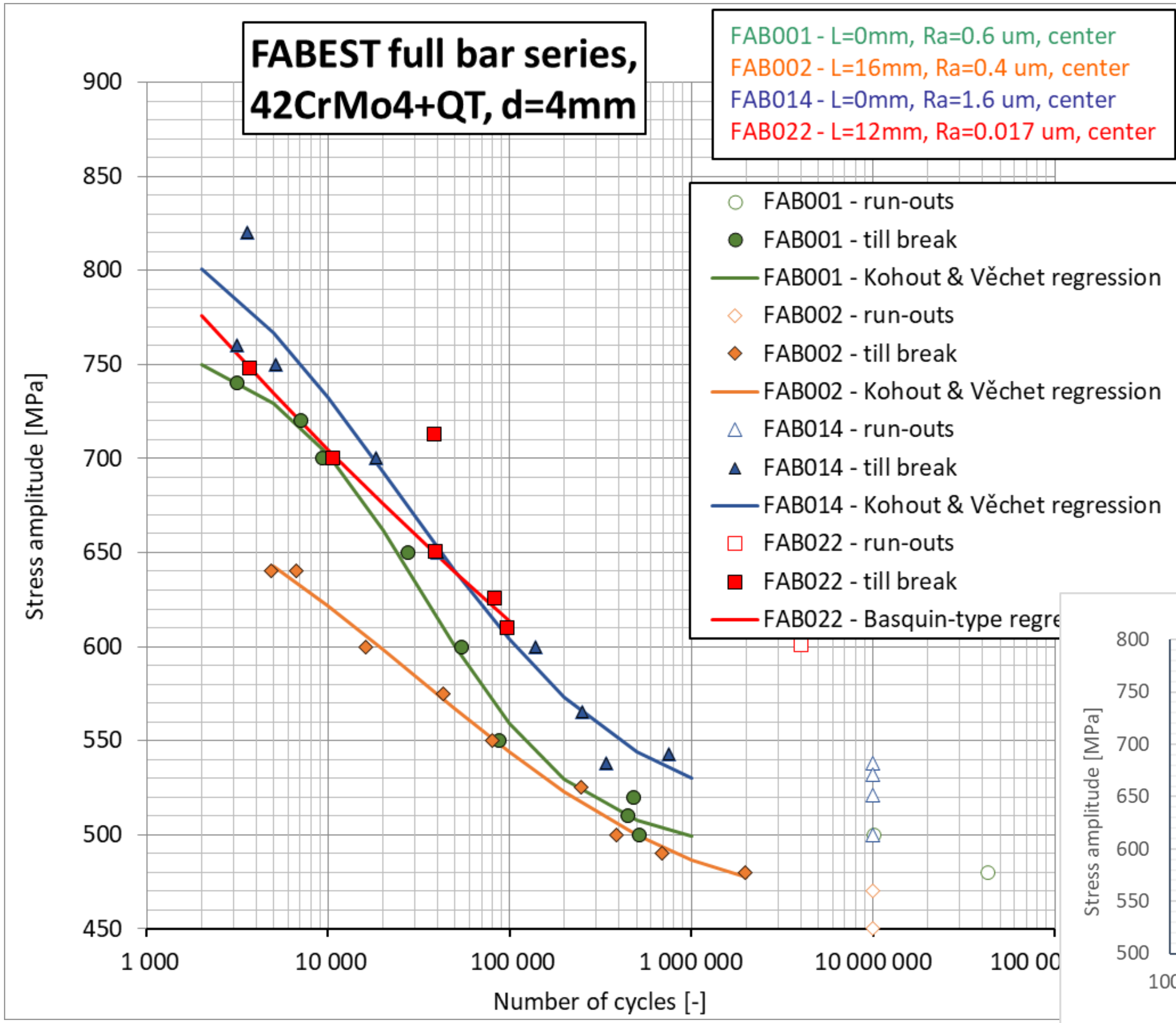
- More specimens from the central position will be tested in Opole

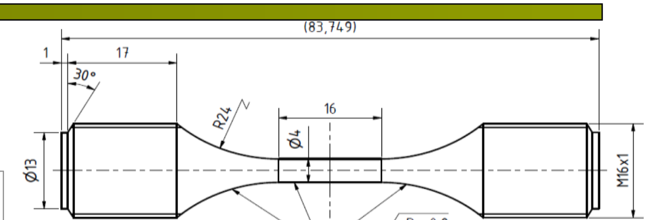


FAB022

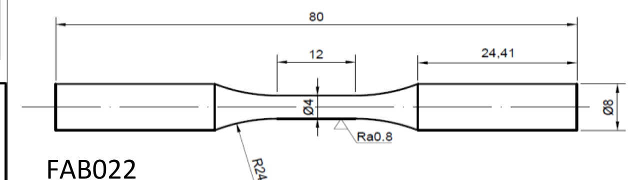
Back to surface roughness

$$k_R = 1 - 0.22\log(Rz)\cdot\log(2R_m/400)$$

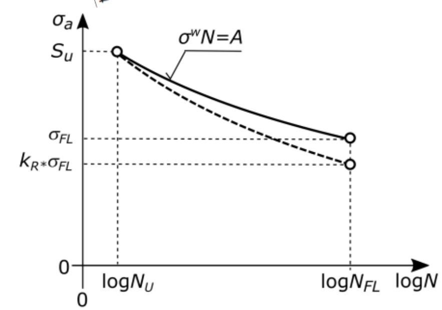


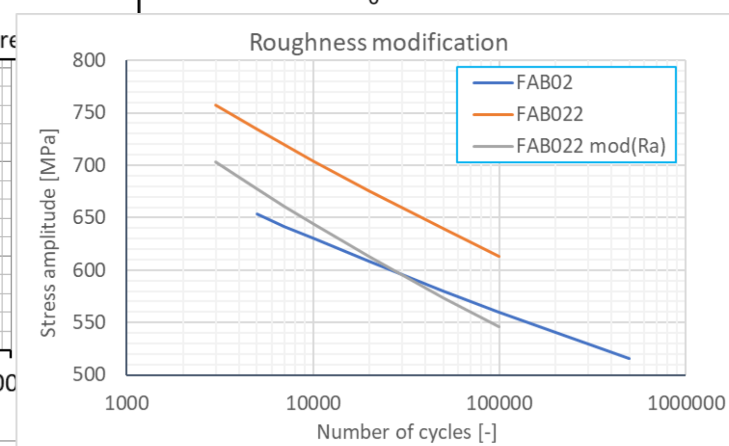


FAB002



FAB022





On manufacturing parameters

Zielinski, T.; Vovk, A.; Riemer, O.; Karpuschewski, B.: An Investigation on Internal Material Loads and Modifications in Precision Turning of Steel 42CrMo4. Micromachines 2021, 12, 526.

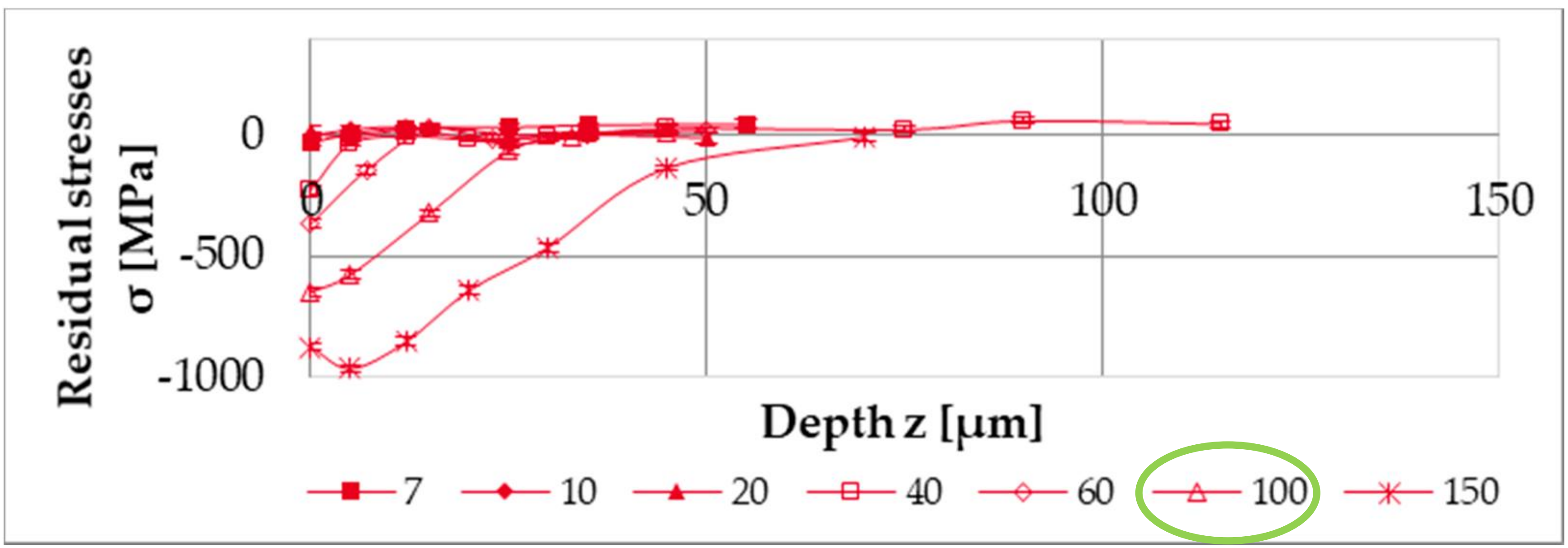
Table 1. The chemical composition of the AISI 4140 steel (in wt. %).

Material	C	Si	Mn	P	S	Cr	Mo
wt. %	0.44	0.26	0.73	0.012	0.002	1.08	0.24

C	Mn	Si	P	S	Cu	Cr	Ni	Al	H
0.42	0.64	0.21	0.013	0.009	0.02	1.04	0.06	0.026	1.30 ppm
N	Mo	V	Ti	Sn					
0.0086	0.185	0.006	0.0013	0.003					

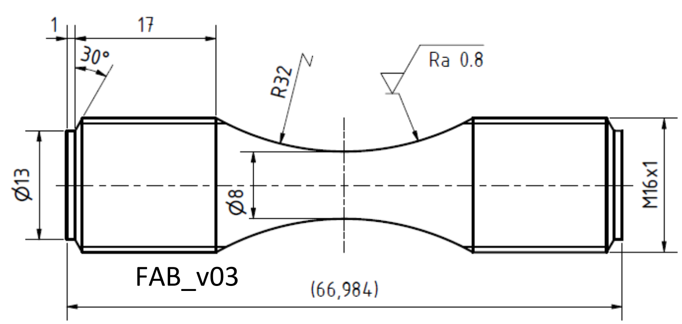
Table 2. The machining parameters.

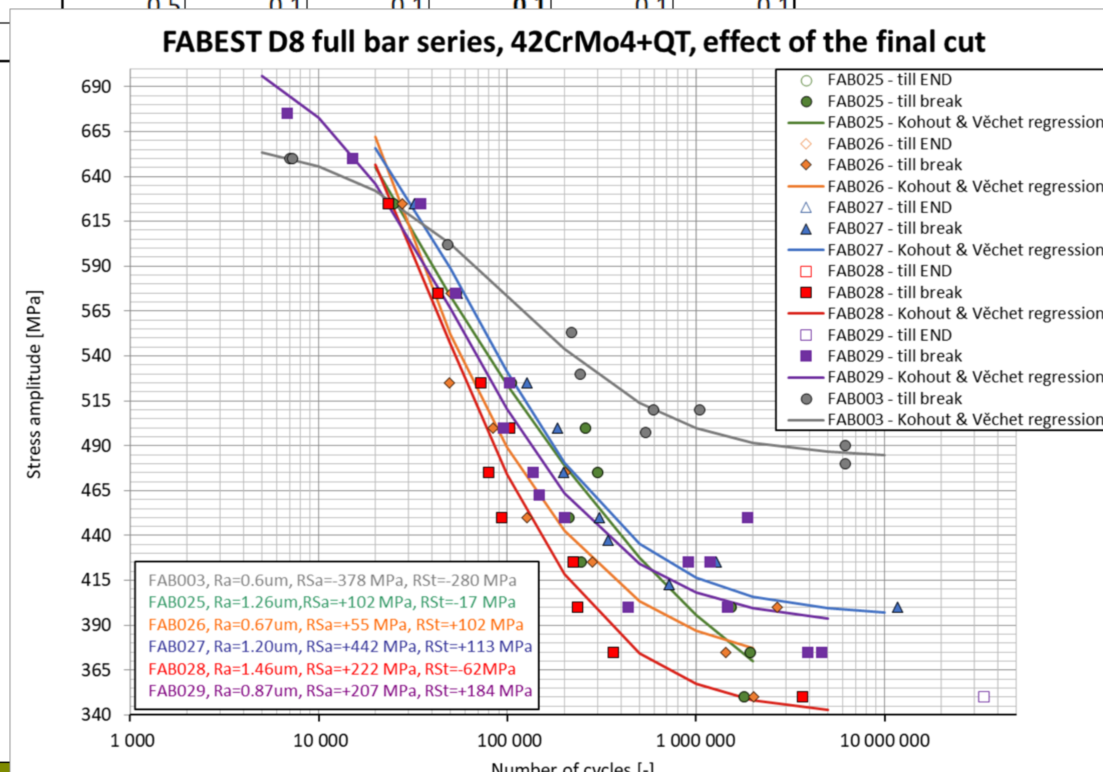
Parameter	Value	
Depth of cut a_p (μm)	7, 10, 20, 40, 60, 100, 150	100
Cutting speed v_c (m/min)	100	100
Feed f_r (mm/rev)	2.5	0.1
Coolant	Dry	dry



Technology tests, vol. 1

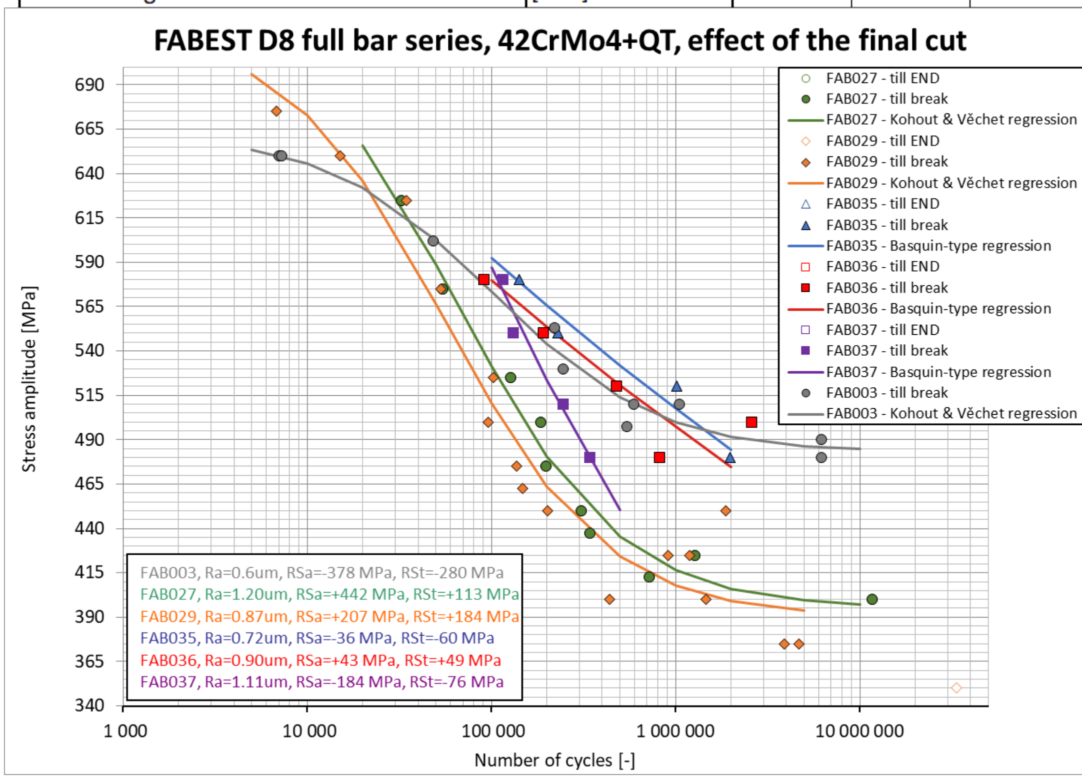
		A03	A25	A26	A27	A28	A29
Cutting speed	Vc [m/min]		75		**100**		
Cutting speed	[rot/min]	4000	2984	3000	**3979**	2500	3000
at D=8mm	Vc [m/min]	100.5	75	75.4	**100**	62.8	75.4
at D=4mm	Vc [m/min]			37.7		31.4	37.7
at D=2mm	Vc [m/min]			18.8		15.7	18.8
Feed rate	F [mm/rev]	0.1	0.05	0.05	**0.1**	0.1	0.1
Process fluid (Decocut 1040 during roughing)	Y/N	Y	Y	Y	**Y**	Y	Y
Cooling fluid during last cuts	Y/N	Y	Y	N	**Y**	N	N
Cutter nose radius [mm]	R [mm]	0.4	0.4	0.4	**0.4**	0.4	0.4
Last cut height	[mm]	0.1	0.05	0.1	**0.1**	0.05	0.1
Second-last cut height	[mm]	0.5	0.1	0.1	**0.1**	0.1	0.1
Third-last cut height	[mm]						

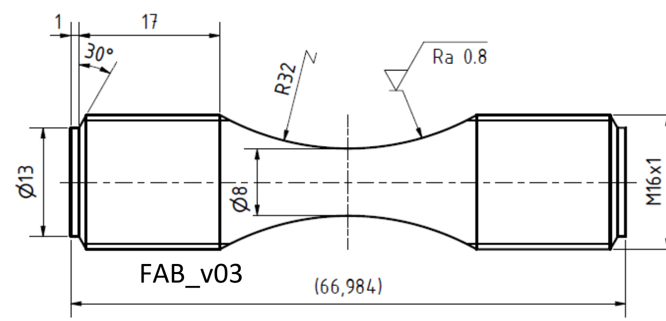




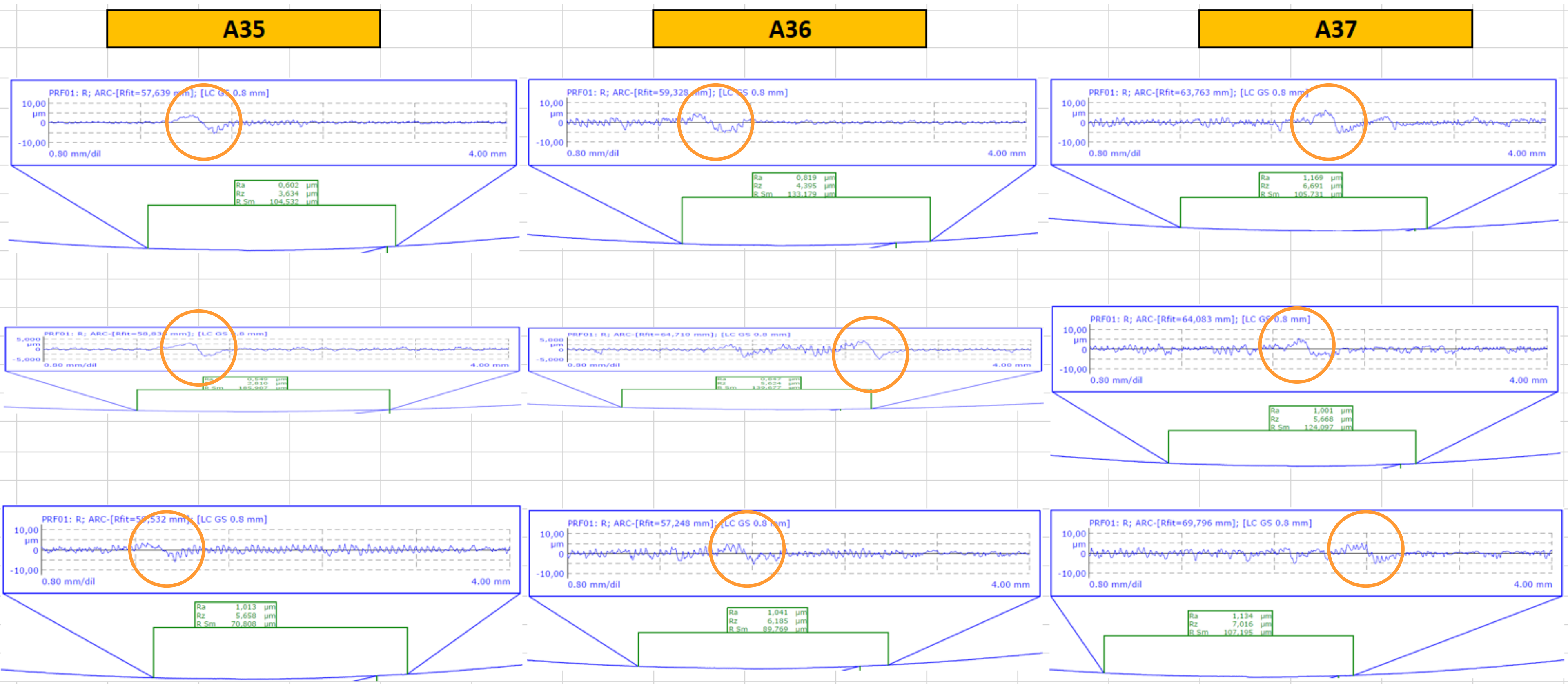
Technology tests, vol. 2

		A03	A25	A26	A27	A28	A29	A35	A36	A37
Cutting speed	Vc [m/min]		75		**100**			100	100	100
Cutting speed	[rot/min]	4000	2984	3000	**3979**	2500	3000	3979	3979	3979
at D=8mm	Vc [m/min]	100.5	75	75.4	**100**	62.8	75.4	100.0	100	100.0
at D=4mm	Vc [m/min]			37.7		31.4	37.7	50.0	50	50.0
at D=2mm	Vc [m/min]			18.8		15.7	18.8			
Feed rate	F [mm/rev]	0.1	0.05	0.05	**0.1**	0.1	0.1	0.05	0.05	0.05
Process fluid (Decocut 1040 during roughing)	Y/N	Y	Y	Y	**Y**	Y	Y	Y	Y	Y
Cooling fluid during last cuts	Y/N	Y	Y	N	**Y**	N	N	Y	Y	Y
Cutter nose radius [mm]	R [mm]	0.4	0.4	0.4	**0.4**	0.4	0.4	0.8	0.4	0.4
Last cut height	[mm]	0.1	0.05	0.1	**0.1**	0.05	0.1	0.1	0.05	0.1
					0.1	0.1	0.1	0.2	0.15	0.2
					0.1	0.15	0.1	0.2	0.3	0.2





Surface roughness closer



- *Ra* vs *Rz* vs other parameters?
- Is this step of about 10μm crucial? It's much less steep than it seems…

Technology tests, vol. 3 (tbd)

Input Factors

- Feed rate (mm/rev) from 0.05 to 0.25
- Cutting speed (m/min) from 80 to 225
- Radius of the cutting tool (mm) 0.4 and 0.8
- Depth of last 3 cuts (mm) from 0.05 to 0.5

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- **Production tests (D=28 mm)**
  - Check of residual stress on the surface and of the surface roughness parameters – 68 combinations
- **Specimens D=12 mm**
  - Fatigue tests – four test series

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