Digital Measurement of Cord Stresses in Container Glass

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Presentation Outline

- Company profile
- What is cord stress?
- Cord detection
- Manual assessment
- Digital measurement
- Performance comparison
- Gage R&R analysis

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ilis gmbh

- Founded 1998, based in Erlangen, Germany
- Competencies
  stress measurement, color measurement, batch calculation
- Target markets
  glass industry, optics & photonics, automotive, aerospace, pharma
- Application fields
  container glass, flat glass, tableware, tube and laboratory glass, pharmaceutical packaging, optical materials and components, transparent plastics
- Products and brands
  BatchMaker®, Chroma™, StrainScope®, StrainCam®, StrainScanner®, StrainMatic®

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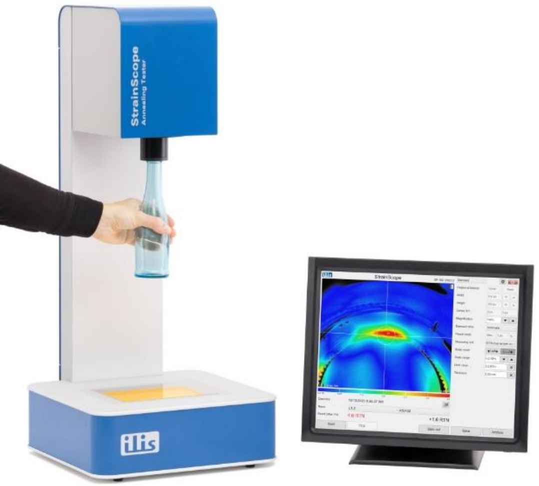
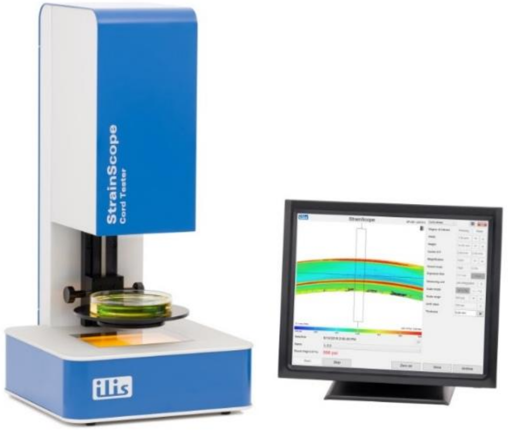
StrainScope®

imaging measurement of residual stresses in real time

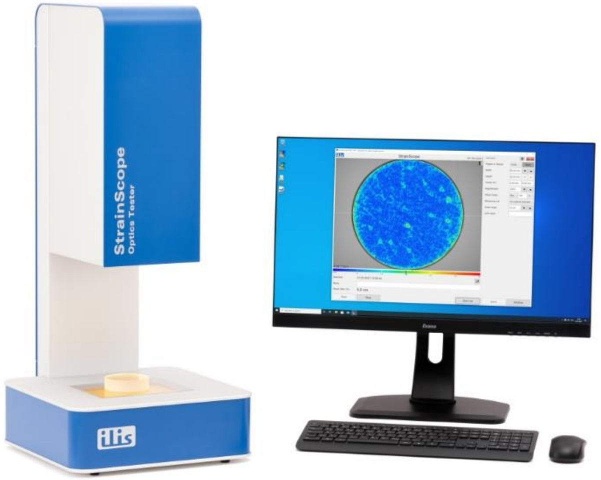
- Accurate and reproducible measurement of the stress distribution in real time
- Various variants, specially adapted to the respective measurement task



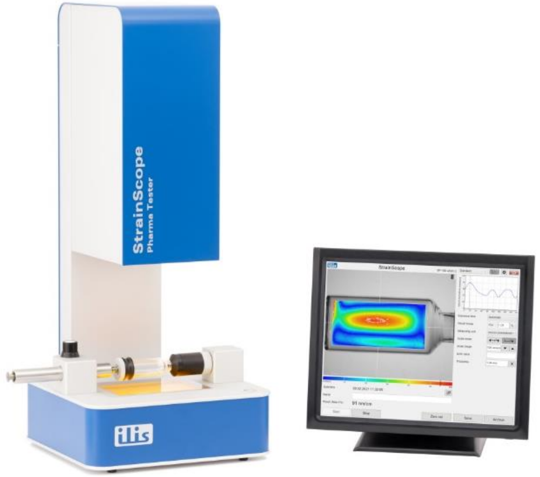
StrainScope® Annealing Tester
Residual stresses in container glass and tableware



StrainScope® Cord Tester
Cord stresses in container glass



StrainScope® Optics Tester
Stress birefringence in optical materials and components



StrainScope® Pharma Tester
Residual stresses in pharmaceutical packaging (syringes, vials, ampoules)

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What is Cord Stress?

- ‘Cord’ (aka ‘striae’ or ‘viscous knots’) are areas in the glass with a different chemical composition than the surrounding glass matrix
- Possible root causes: silo contamination, weighting errors, insufficient mixing, refractory corrosion, batch segregation, glass conditioning
- Cord can create high mechanical stresses, which are especially problematic in case of tensile stresses near the glass surface
- Mechanical stresses can lead to breakage when the glass container is being filled or used

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Cord Detection

- The polarization of light is influenced by mechanical stresses (photoelasticity, stress birefringence)
- Polariscopes and polarimeters can be used to only visualize or also quantify stresses in prepared ring sections of container glass
- High magnification is necessary to detect thin cord, so usually a polarization microscope is used for this purpose
- Cord can also be detected indirectly by closely monitoring the glass composition (density measurement or XRF) or by physical testing (e.g. abraded thermal shock)

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Sample Preparation

- Glass ring cut from the cylindrical part of the bottle or jar
- Tools: diamond saw or hot wire
- Notching the ring relaxes circumferential annealing stresses
- Thickness (i.e. cylinder height) must be uniform (approx. 10 mm for clear glass, 5 to 10 mm for colored glass); surfaces must be smooth
- Immersion in index-matching liquid (e.g. DMP, n≈1.51) compensates for uneven (hot wire) or rough (saw) surfaces

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Polarization Microscope with Berek Compensator

- Halogen light source
- Plan achromat 4x POL objective lens
- Wide-field 10x eye pieces
- FOV size approx. 5 x 5 mm²
- Full wave plate for scanning
- Berek tilting compensator for measuring
- Manual conversion of readings into PSI or MPa values using conversion tables

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Polarizing Microscope – Procedure

Step I (Scanning)

1. Remove Berek compensator and install FWP (full wave-plate)
2. Adjust table height, so that the top surface is in focus
3. Align the sample so that tension appears in yellow color
4. Rotate the Petri dish with the sample to find the point of maximum tension near the inner or outer glass surface
5. Remove FWP and install Berek compensator, set to neutral position

Step II (Measurement)

1. Rotate compensator dial clockwise until cord is compensated ⇨ value 1
2. Reset compensator to neutral position
3. Rotate dial counter-clockwise until cord is compensated ⇨ value 2
4. Calculate difference between value 1 and value 2, divide result by 2
5. Convert result to optical retardation using the Berek calibration chart
6. Convert optical retardation value to stress in PSI or MPa using the formula $S = R / (d \cdot C)$ with R = retardation, d = thickness, C = photoelastic constant

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Digital Measurement

- Polarization-sensitive matrix cameras make it possible to measure the optical retardation automatically and in real time
- Same physics, but image acquisition and result value calculation are automatic and instant
- Single-stage measurement process (no pre-scanning required)
- Results are objective (operator independent) and verifiably reproducible
- Digital measurement enables documentation of the measurement process and thus traceability of results

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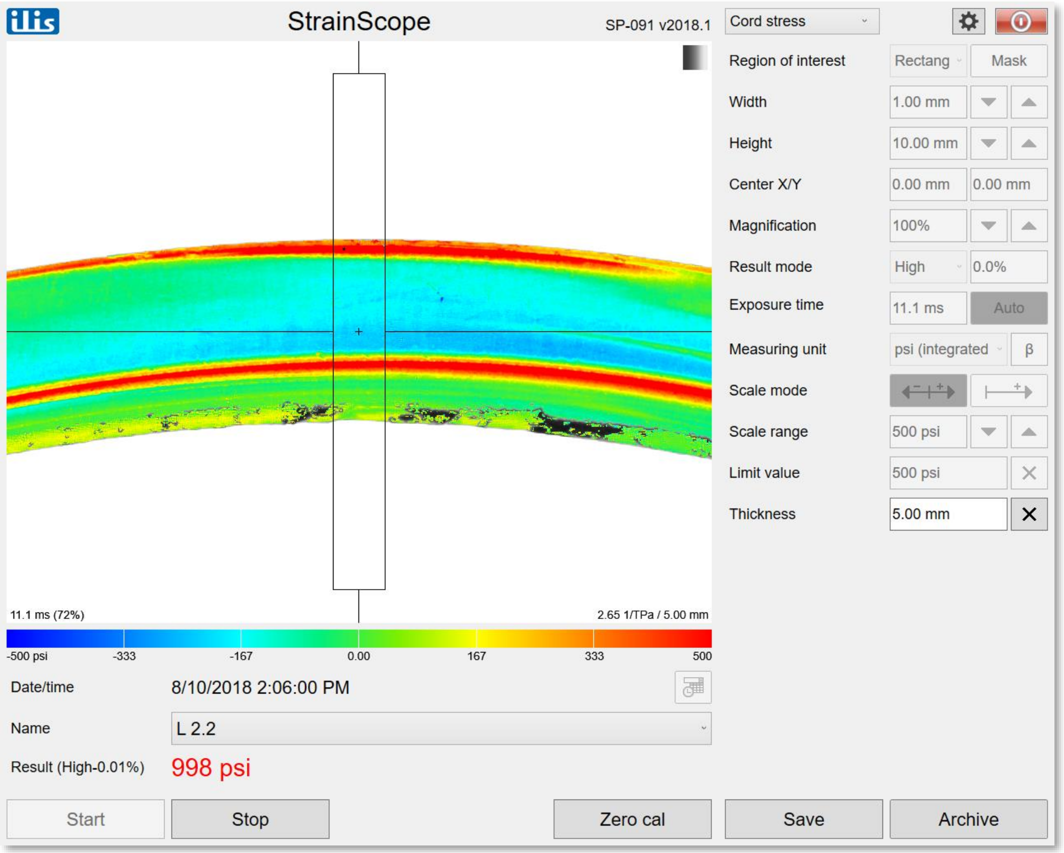
StrainScope Cord Tester

- FOV size 12 x 10 mm²
- Resolution 14 microns
- Monochromatic light source



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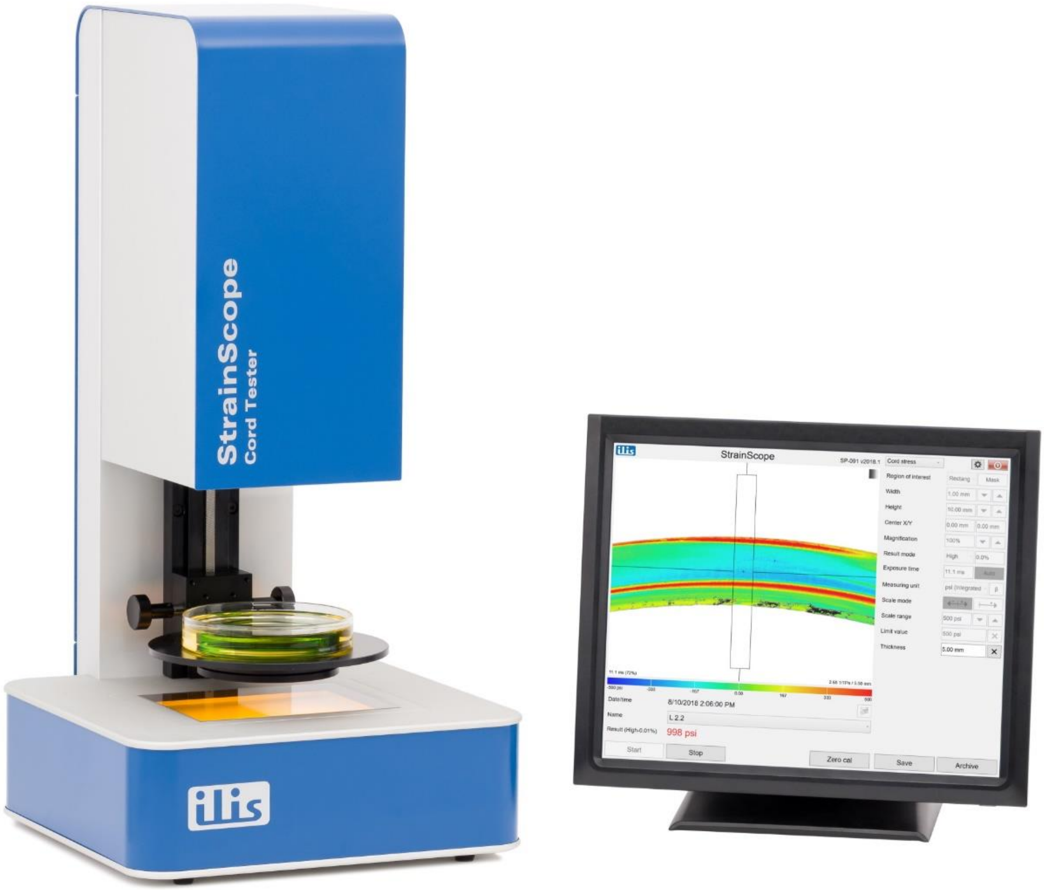
StrainScope Cord Tester – Procedure

1. Click ‘zero cal’ to compensate for any stress offsets
2. Enter thickness value (ring cylinder height)
3. Adjust table height, so that the top surface is in focus
4. Align the sample so that the surface is aligned horizontally in the image
5. Rotate the Petri dish with the sample to find the point of maximum tension near the inner or outer glass surface
6. Save the measurement



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Manual vs. Digital Measurement – Challenges

Polarizing Microscope

- Requires highly qualified, experienced operation personnel
- Difficult to use especially with colored glass (distorted polarization colors)
- Offset errors due to residual stresses in microscope optics and Petri dish
- Small field of view and depth of field; easy to miss the highest tension value
- Results difficult to document and audit
- Work is tiring and time-consuming

StrainScope Cord Tester

- Fixed optical resolution; cord thinner than the pixel pitch cannot be detected
- Limited measuring range (ca. 14 MPa or 2000 PSI at 8 mm thickness) can lead to confusion of tension and compression for stress values of higher order
- Higher investment costs

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Performance Comparison

- Whether it is possible to completely replace conventional polarization microscopes with digital measurement technologies has recently been a subject of some controversy
- To put this discussion on a data-driven foundation, a comprehensive Gage R&R study was conducted
- A set of representative samples (bottle rings) were examined multiple times by different operators using a conventional polarization microscope and the StrainScope Cord Tester

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Measurement System Analysis with the Gage R&R ANOVA Method

- Gage Repeatability & Reproducibility Studies (Gage R&R) are well suited to assess the suitability of a measurement system for a specific measurement task
- Gage R&R provides information on the practically achievable reproducibility under real operating conditions
- A representative set of samples, covering the entire process spread, is measured multiple times by multiple operators
- The suitability of a measurement system can be described with only one number, which simplifies use and continuous monitoring

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Gage R&R Outcome

- The overall result of a Gage R&R study is the **Gage R&R % Study Var**

Criterion	Meaning
Gage R&R % Study Var < **10%**	Measurement system is acceptable
10% ≤ Gage R&R % Study Var ≤ **30%**	Measurement system may be acceptable for some applications
Gage R&R % Study Var > **30%**	Measurement system is not acceptable

- The second class (10% .. 30%) is often further subdivided as many difficult measuring tasks fall into this category
- The **Number of Distinct Categories (NDC)** represents the ability of a measurement system to distinguish between different parts
- The NDC value should be 5 or larger

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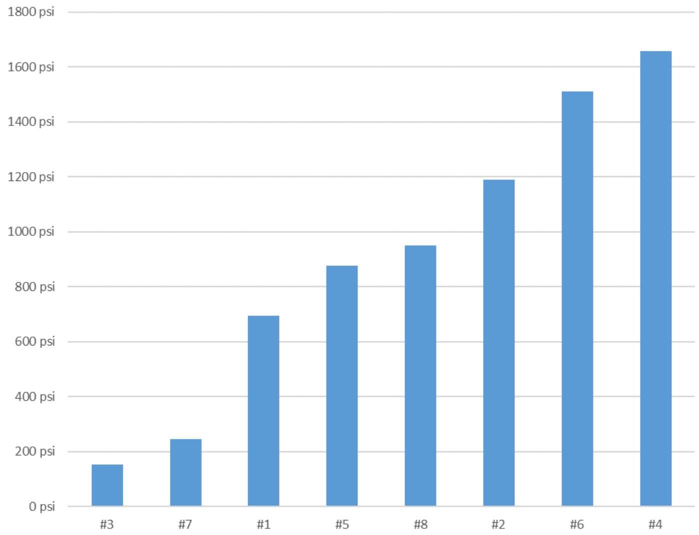
Samples

- 8 ring samples of different glass color, wall thickness, ring diameter and ring thickness have been selected for this Gage R&R study, designated with #1 to #8
- A measuring range of approx. 150 to 1600 psi (1 to 11 MPa) is evenly covered

Sample number	Glass color	Ring thickness
#1	green	5.0 mm
#2	clear	10.8 mm
#3	amber	12.5 mm
#4	clear	6.7 mm
#5	olive green	7.4 mm
#6	clear	9.9 mm
#7	amber green	10.5 mm
#8	light blue	9.2 mm



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Operators

- Four operators participated in the Gage R&R study (designated as A, B, C, D)
- Three of the operators (A, B, C) have a technical background, but little or no previous experience in measuring cord stress
- One operator (D) is experienced in both measurement methods, including the theoretical background
- The three novice operators were briefly trained on both measurement methods and supervised by the experienced operator during the first test run
- This selection represents a situation that is often found in a manufacturing environment (one supervisor and three operators working in shifts)

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Test Planning and Execution

- The 8 samples were each measured 3 times by the 4 operators on each of the 2 measuring devices
  ⇨ 8 x 3 x 4 x 2 = 192 measurements
- Testing was randomized (order of samples changed in each test run)
- The measurement task was to find and measure the highest tension (in PSI) for each sample
- In addition to the measurement results, the time required for each test run was recorded

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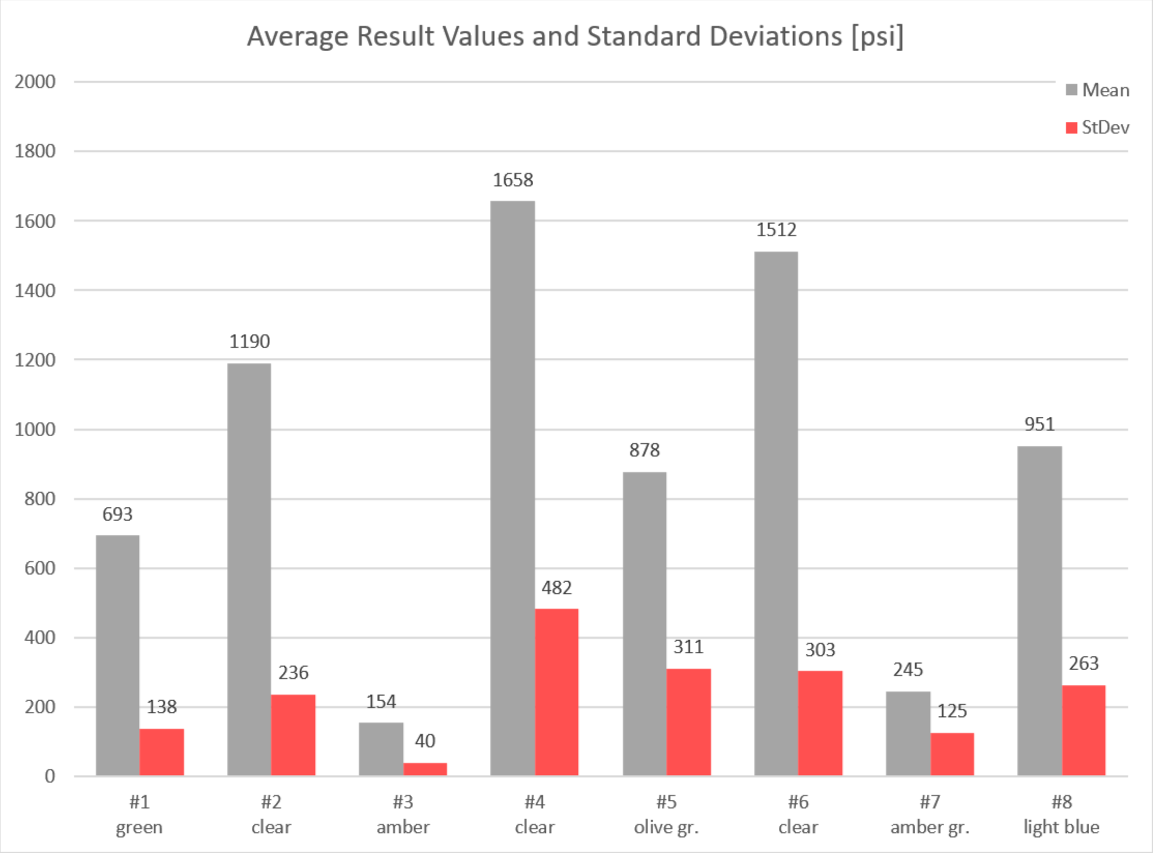
All Measurement Results

All Measurements				Sample Number / Color / Thickness [mm]							
Gage	Operator	Run	Time	#1 green 5,0	#2 clear 10,8	#3 amber 12,5	#4 clear 6,7	#5 olive gr. 7,4	#6 clear 9,9	#7 amber gr. 10,5	#8 light blue 9,2
StrainScope Cord Tester	Opr. A	1	0:37	732	1456	131	2075	831	1635	252	952
		2	0:38	719	1414	130	2067	823	1631	277	905
		3	0:31	697	1434	132	1974	842	1622	243	889
	Opr. B	1	1:15	704	1427	152	2044	1336	1618	192	855
		2	0:35	706	1482	175	1652	1298	1608	142	841
		3	0:35	722	1472	155	2164	1081	1631	193	855
	Opr. C	1	1:45	729	1442	166	1704	1118	1627	207	854
		2	0:37	710	1324	159	1055	1152	1593	206	852
		3	0:35	724	1209	164	1162	1172	1630	198	851
	Opr. D	1	0:25	710	1451	147	1839	963	1624	223	944
		2	0:35	720	1435	165	1633	1240	1611	196	948
		3	0:20	722	1373	166	1714	1230	1620	202	953
Polarizing Microscope	Opr. A	1	1:05	789	962	226	1965	437	1991	507	872
		2	0:45	660	844	264	1666	996	1770	478	852
		3	0:45	576	1034	217	1583	1191	1116	667	904
	Opr. B	1	1:35	576	962	113	2172	875	530	198	958
		2	1:25	635	912	113	1315	658	1162	222	958
		3	0:55	369	863	83	1550	763	1049	198	852
	Opr. C	1	1:40	477	902	126	629	351	1245	146	752
		2	1:20	611	1185	199	372	421	1257	274	474
		3	0:55	542	1108	144	1141	225	1536	146	733
	Opr. D	1	1:02	843	922	133	2192	709	1828	116	1653
		2	0:55	1113	1023	113	2021	598	1590	189	1624
		3	0:45	857	932	133	2096	752	1770	208	1499
Both Gages	All Opr.	Mean	0:53	693	1190	154	1658	878	1512	245	951
		StDev	0:23	138	236	40	482	311	303	125	263
		SD/Mean	44%	20%	20%	26%	29%	35%	20%	51%	28%



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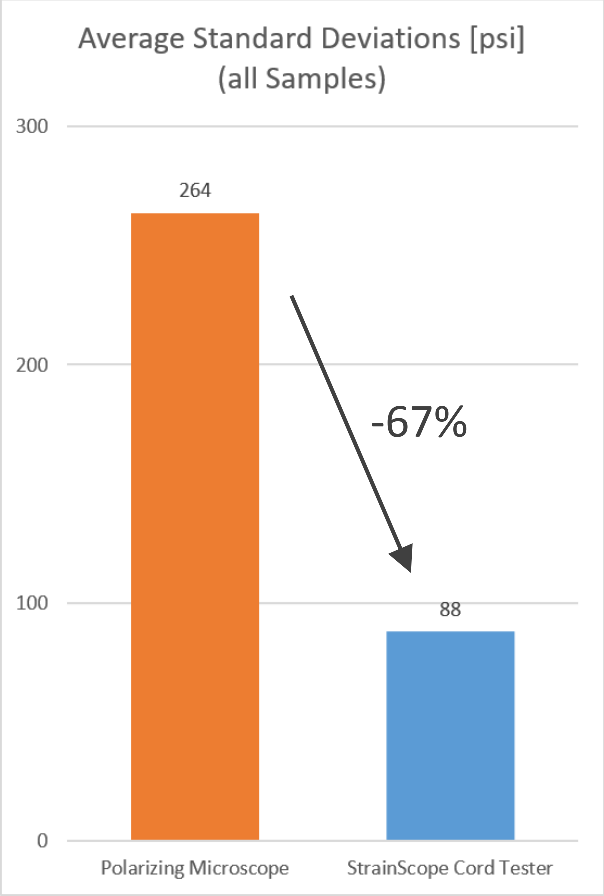
Measurement Results (by Gage & Operator)

By Gage & Operator (all Runs)			Run Time	#1 green	#2 clear	#3 amber	#4 clear	#5 olive gr.	#6 clear	#7 amber gr.	#8 light blue	Avg StDev
StrainScope Cord Tester	All Opr.	Mean	0:42	716	1410	154	1757	1091	1621	211	892	
		StDev	0:22	10	73	15	339	176	11	33	44	88
	Opr. A	Mean	0:35	716	1435	131	2039	832	1629	257	915	
		StDev	0:03	14	17	1	46	8	5	14	27	17
	Opr. B	Mean	0:48	711	1460	161	1953	1238	1619	176	850	
		StDev	0:18	8	24	10	219	112	9	24	7	52
	Opr. C	Mean	0:59	721	1325	163	1307	1147	1617	204	852	
		StDev	0:32	8	95	3	284	22	17	4	1	54
	Opr. D	Mean	0:26	717	1420	159	1729	1144	1618	207	948	
		StDev	0:06	5	34	9	85	128	5	12	4	35
Polarizing Microscope	All Opr.	Mean	1:05	671	971	155	1559	665	1404	279	1011	
		StDev	0:18	192	96	54	575	267	400	167	359	264
	Opr. A	Mean	0:51	675	947	236	1738	875	1626	551	876	
		StDev	0:09	88	78	20	164	320	372	83	21	143
	Opr. B	Mean	1:18	527	912	103	1679	765	914	206	923	
		StDev	0:17	114	40	14	362	89	275	11	50	119
	Opr. C	Mean	1:18	543	1065	156	714	332	1346	189	653	
		StDev	0:18	55	119	31	320	81	134	60	127	116
	Opr. D	Mean	0:54	938	959	126	2103	686	1729	171	1592	
		StDev	0:06	124	45	9	70	65	101	40	67	65



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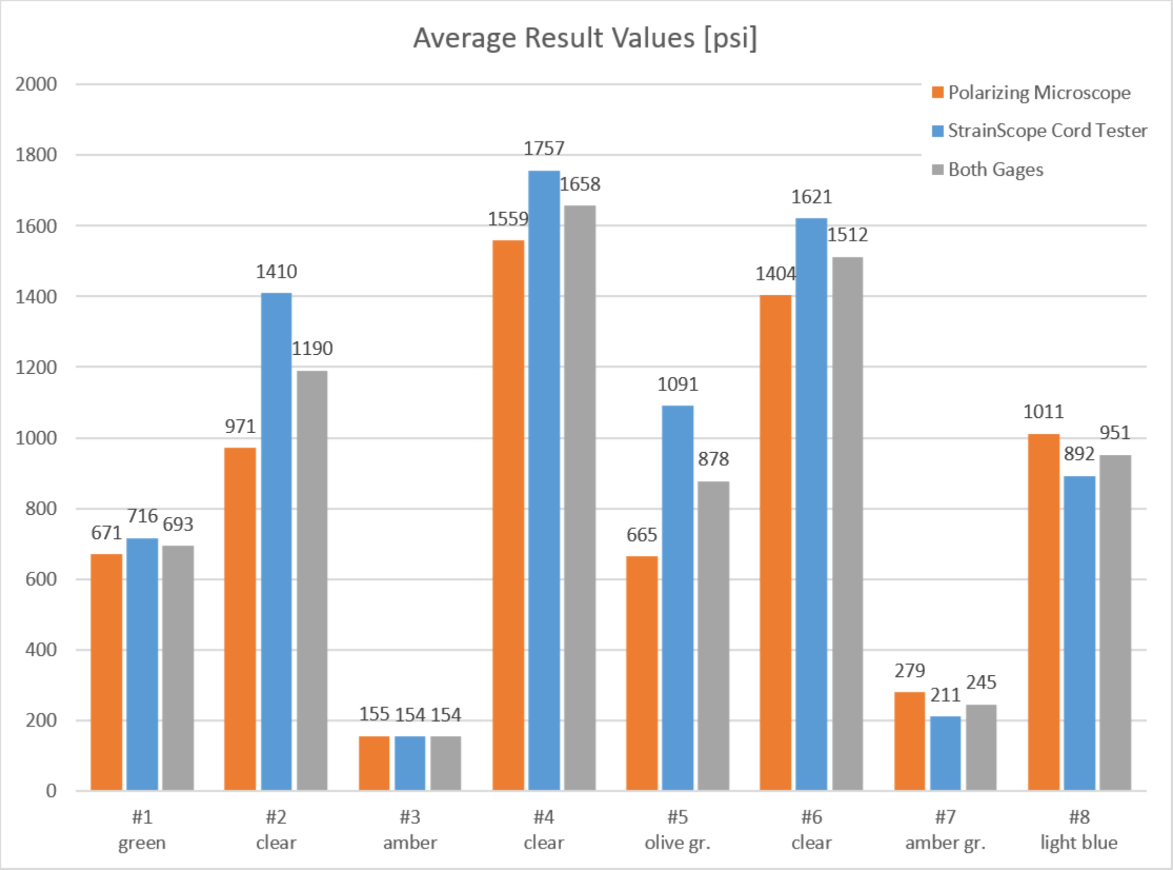
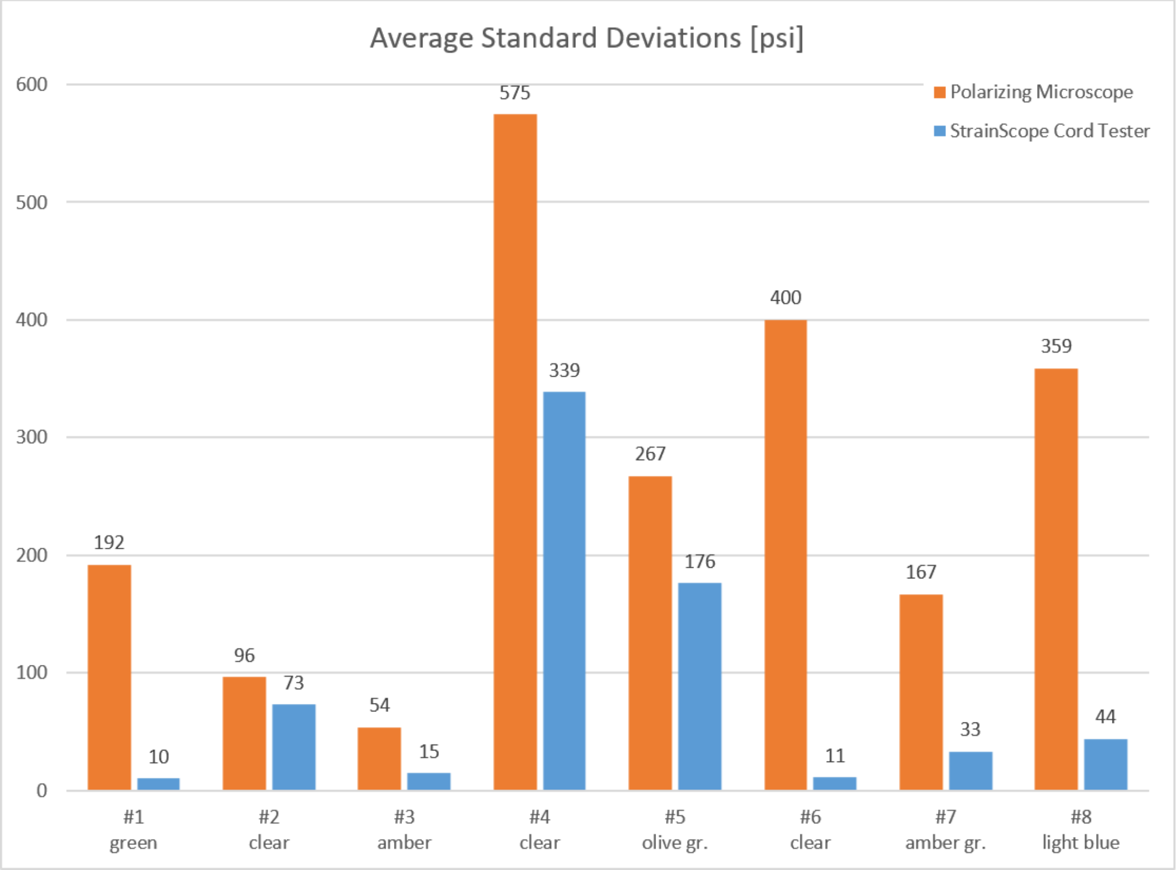
Measurement Results (Gage Averages)





-95% -24% -72% -41% -34% -97% -80% -88%

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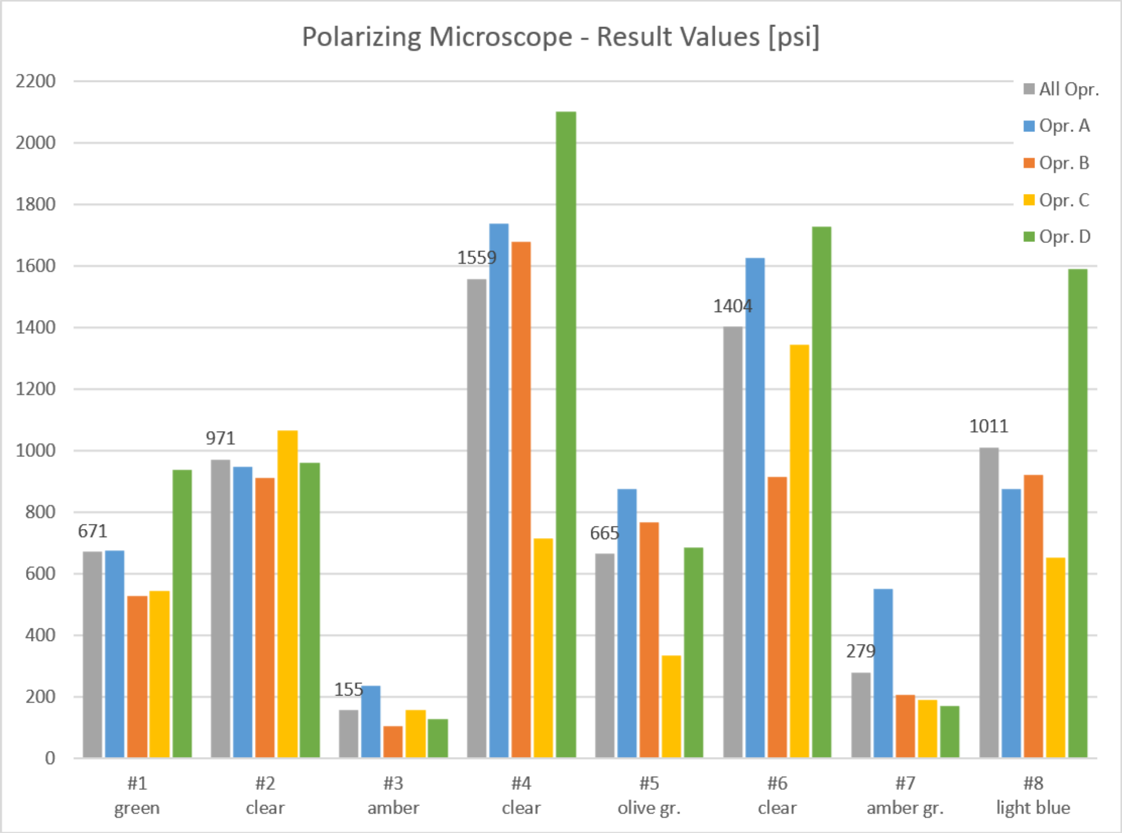
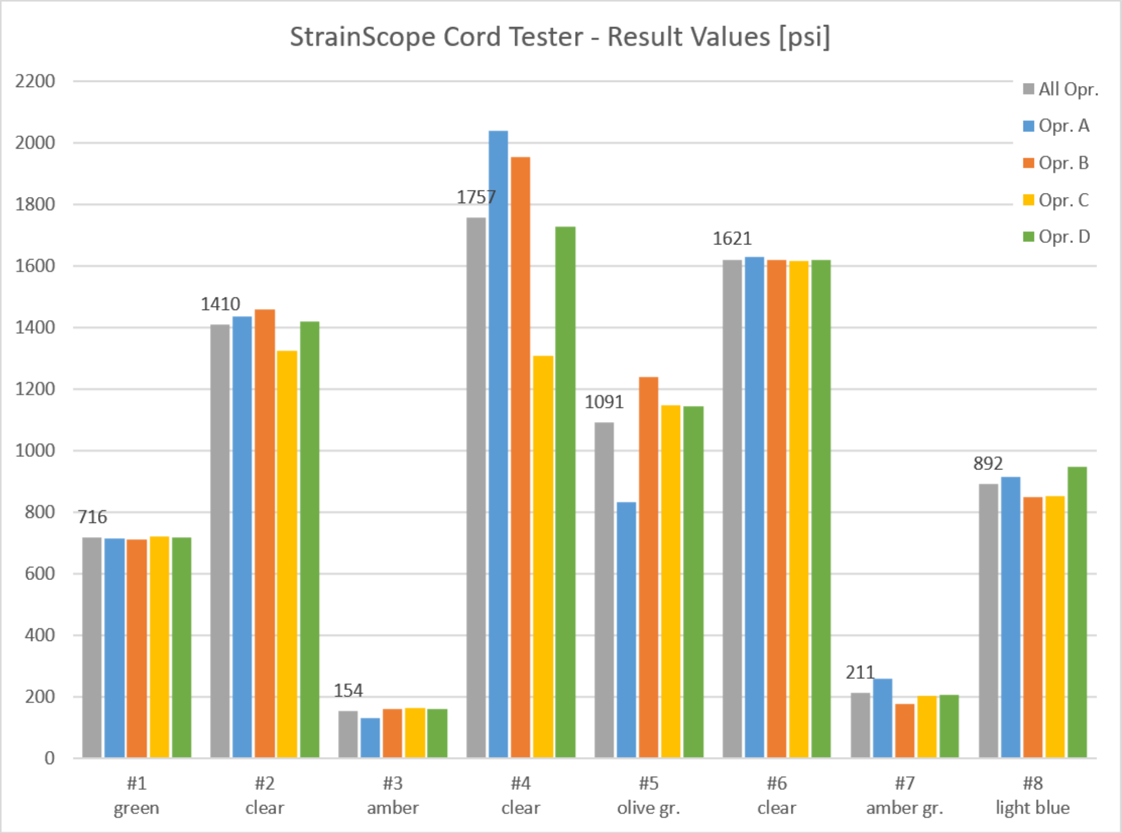
Measurement Results (Operator Averages)





-98% -10% -72% -43% -22% -98% -83% -86%

67% less operator-dependent variation

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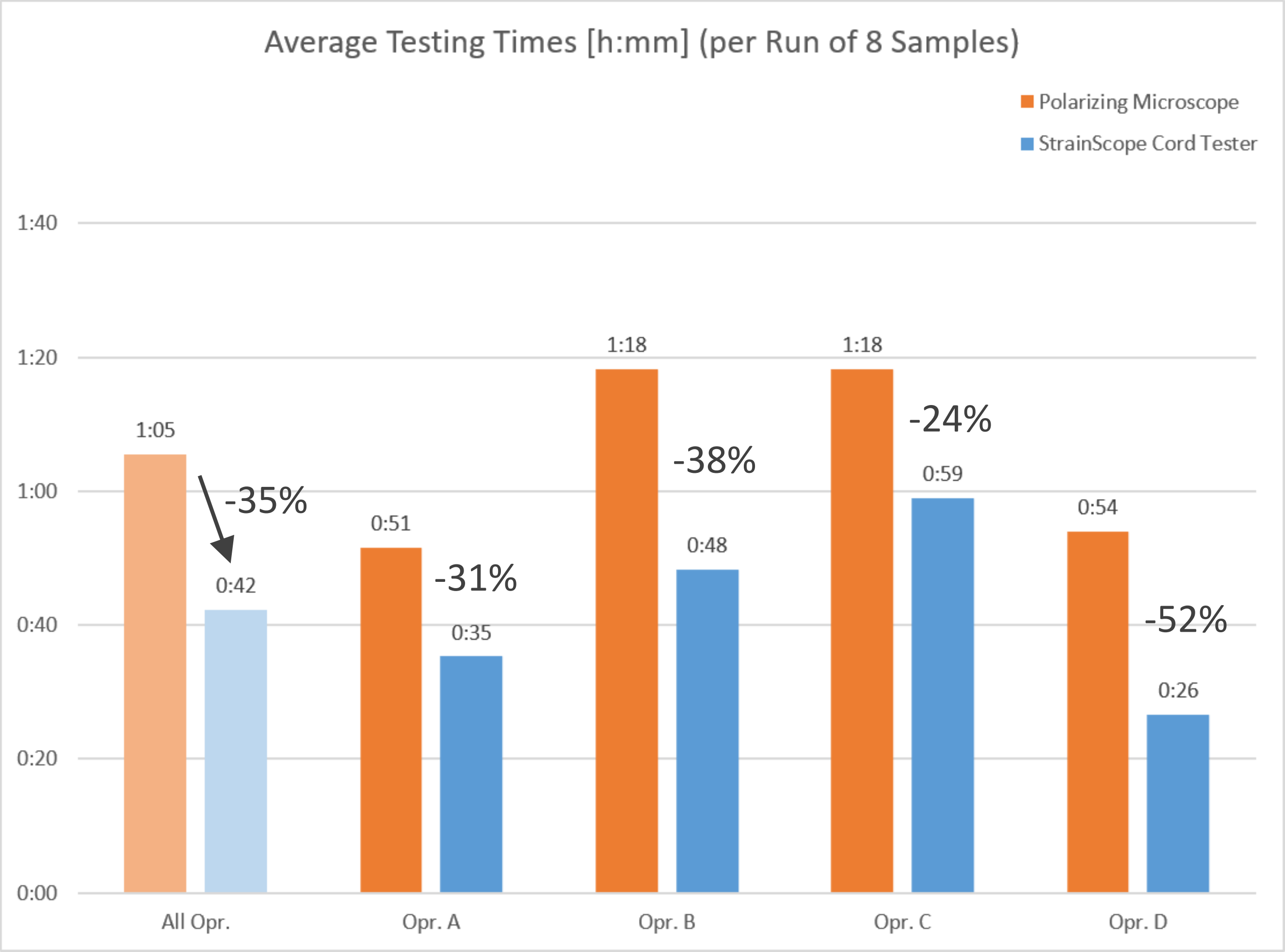
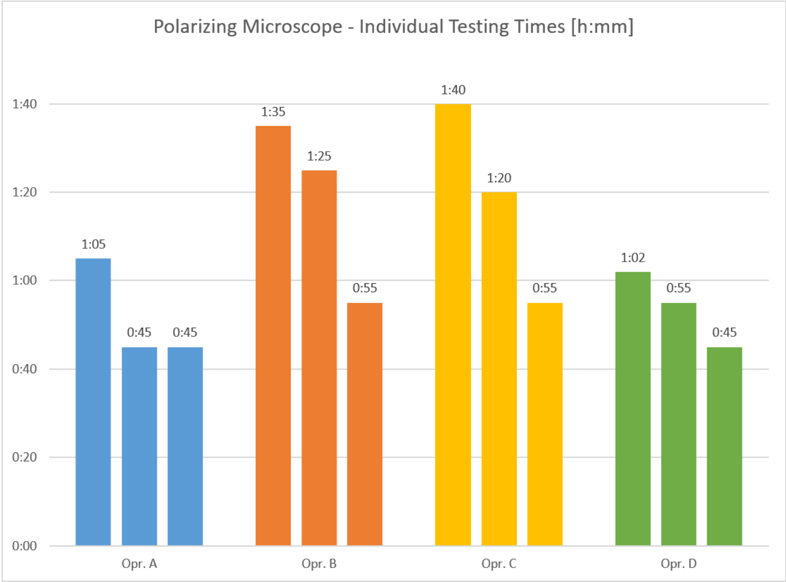
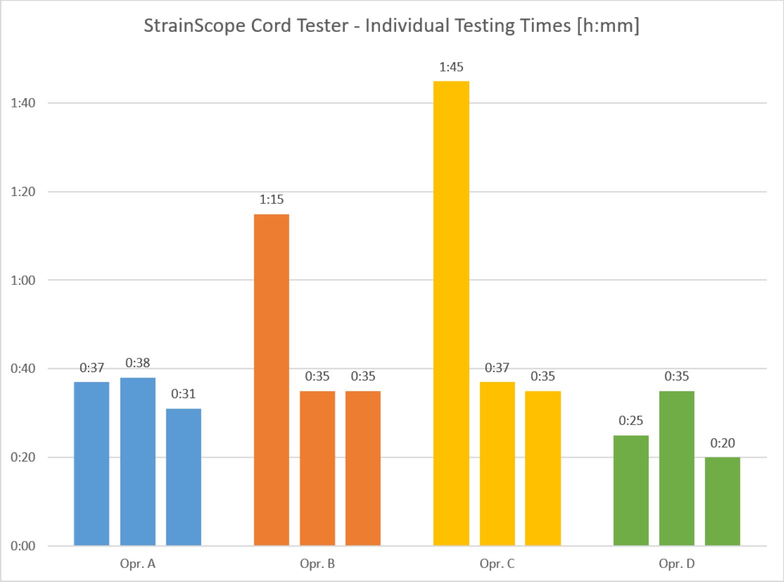
Measurement Times







⇨ 35% less time spent (on average)

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Findings & Remarks

- The mean values obtained with the two gages are comparable within the scope of the measurement uncertainty, but the variance differs considerably
- Especially one sample (#4) with very thin stress cords was difficult to measure on both gages (large spread of the measured values)
- Higher optical resolution does not necessarily lead to higher measured values
- A small field of view and/or a small depth of field makes it difficult to find the maximum tension

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Gage R&R Analysis Results

Gage	Gage R&R % Study Var	NDC
Polarizing Microscope	58.8% ☹	1 ☹
StrainScope Cord Tester	25.1% ☺	5 ☺

Gage R&R % Study Var < 10%	Measurement system is acceptable	✔
10% ≤ Gage R&R % Study Var ≤ 20%	Measurement system may be acceptable for some applications	●
20% < Gage R&R % Study Var ≤ 30%		●
Gage R&R % Study Var > 30%	Measurement system is not acceptable	✖

NDC (Number of Distinct Categories) ≥ 5	Measurement system is acceptable	✔
NDC (Number of Distinct Categories) < 5	Measurement system is not acceptable	✖

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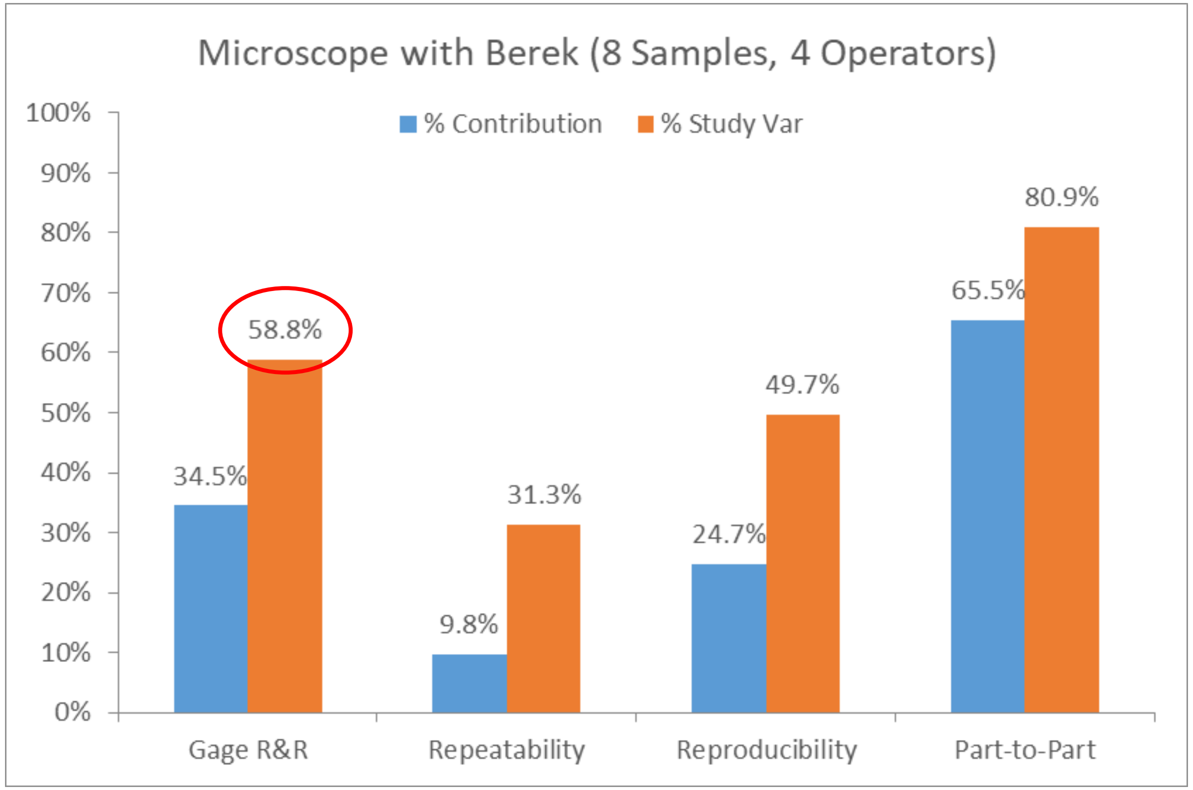
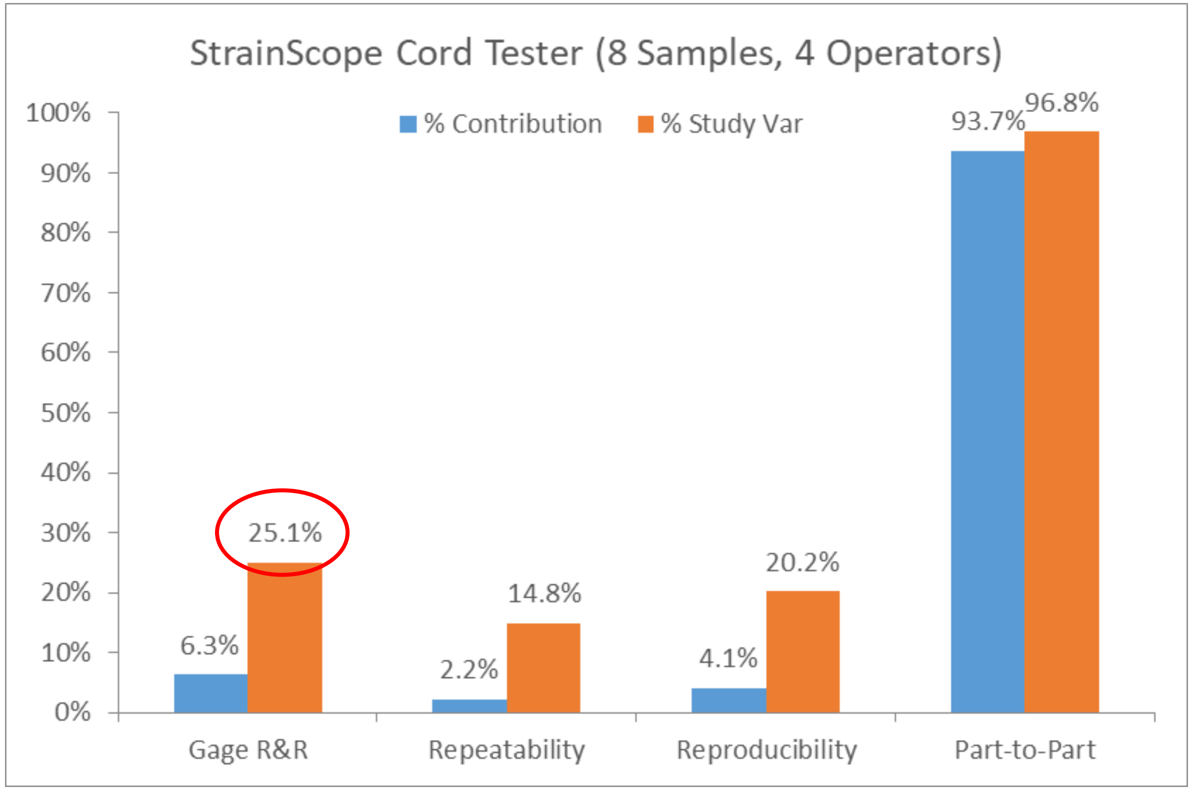
Gage R&R Analysis Results (continued)





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Summary & Conclusions

- The assessment of cord stresses places great demands on the measurement system (consisting of operator, sample, gage, method and environment)
- The Gage R&R analysis shows that the conventional manual/visual measurement method is problematic, especially for inexperienced operators; the Gage R&R results are outside acceptable limits
- With automated measurement (but still manual handling) the Gage R&R results are within the acceptance limits
- Even with digital measurement, quantifying cord stresses remains a challenging task

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Thank you for your attention!

Questions?

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