DIGITAL MEASUREMENT OF CORD STRESSES IN CONTAINER GLASS

Henning Katte
ilis gmbh
Erlangen, Germany

ABSTRACT

The presence of so-called cord stresses (also known as striae) in glass products indicates local variations in the glass composition due to problems in the batch preparation (mixing) or glass conditioning. Cord stresses can have a very negative impact on the breaking strength of glass containers (especially in thin-walled disposable bottles) and remain undetected with polariscopes or polarimeters used for measuring annealing stress (another form of residual stress in container glass that must be clearly distinguished from cord stress).

Facing the ever-increasing pressure to reduce costs and use low-grade raw materials and recycled glass, the challenging task of measuring cord stresses in container glass has become increasingly important. For decades, measurements have been carried out in a manual/visual way using conventional polarization microscopes. Consequently, the measurement results depend very much on the operator’s skills and experience. In addition, documentation options are very limited, which makes traceability in case of complaints difficult or even impossible.

The availability of novel measurement technologies based on polarization-sensitive cameras and digital image processing makes it possible to automate the measurement of residual stresses in glass and thus to objectify it to a high degree. In this way, factory staffers can reliably monitor cord stresses close to production, document the results automatically to ensure optimal traceability and shorten response times to minimize production losses.

Whether it is possible to completely replace conventional polarizing microscopes with digital measurement technologies has been the subject of some controversial discussions in the container glass industry in recent time. In order to put this discussion on a data-driven and fact-based foundation, a comprehensive Gage R&R study was conducted in which several representative samples (bottle rings) were measured multiple times by different operators using a conventional polarizing microscope with Berek compensator and an automated device.

CORD DETECTION

The polarization of light is influenced by mechanical stresses, this effect is called ‘photoelasticity’. Because of the effect of stress birefringence, linearly polarized light waves experience a retardation, the value of which is proportional to the magnitude of stress. Polariscopes and polarimeters can be used to only visualize or also quantify stresses in prepared ring sections of container glass. Cord can also be detected indirectly by closely monitoring the glass composition (density measurement or XRF) or by physical testing (for example, abraded thermal shock).

SAMPLE PREPARATION

To prepare a sample for measurement, a glass ring must be cut from the cylindrical part of the glass container (bottle or jar). A diamond saw or hot wire technique are typically used for this purpose. Cutting the ring open as shown in Figure 1 relaxes circumferential annealing stresses. It is important that the thickness (cylinder height) is uniform (approximately 10 mm for clear glass and 5 to 10 mm for colored glass) and that the surfaces are smooth.

In order to compensate for uneven surfaces (as seen with hot wire technique) or rough surfaces (as produced by diamond saws) the ring should be immersed in index-matching liquid, for example, dimethyl phthalate (DMP).

Figure 1: Prepared Glass Ring Sample

MANUAL MEASUREMENT

The simplest setup to visualize cord stresses is a polariscope with two crossed polarizers. An additional tint plate (also called full-wave plate) enables the distinction between tension and compression. Sénarmont method (rotatable analyzer) or Berek method (tilting compensator) are typically used to measure the retardation and thus quantify stresses. A relatively high optical magnification is necessary to detect thin cord, so a polarizing microscope as shown in Figure 2 is typically used for this purpose.

Figure 2: Polarizing Microscope with Berek Tilting Compensator

Manual measurement of cord stresses with a polarizing microscope is a complex two-step process. In the first step, with the Berek compensator removed and the full-wave plate installed, the location of the highest tensile stress near the inner or outer glass surface is sought. In the second step, with the full-wave plate removed and the Berek compensator installed, the stress is quantified.

Since the depth of field is very small due to the high magnification of the microscope optics, the working distance must be constantly corrected via the microscope stage, so that the top surface of the glass ring always stays in focus. It is also important that the specimen is aligned in the image so that tensile stresses appear in yellow during the scanning process. For that, the visible section of the ring must be oriented at 45° to the image axes.

To quantity the tension in the second step, the Berek compensator is set to neutral position and then turned clockwise using its dial until the identified cord is compensated. Then, starting from the neutral position, the compensator is turned anti-clockwise until the cord is compensated again. The compensator positions from both measurements are subtracted and divided by two. Calibration tables provided with the Berek compensator are used to convert the resulting value to optical retardation in nm. The following formula is used to ultimately convert the optical retardation into a stress value in units of MPa or psi (where R is the retardation, d the sample thickness and C the photoelastic coefficient, a material constant):

$$S = R / (d \cdot C) \tag{1}$$

DIGITAL MEASUREMENT

Novel polarization-sensitive matrix cameras make it possible to measure the optical retardation automatically and in real time. The applied physical principles are the same as described in the previous section, but image acquisition and result value calculation are automatic and instant. The measurement is thus one-step, which eliminates many possible sources of error and makes the measurement more independent of the operator. In addition, digital measurement enables documentation of the measurement process and thus traceability of measurement results.

Figure 3 shows a commercially available apparatus that uses such a polarization camera to provide a rapid assessment of cord stresses in container glass.

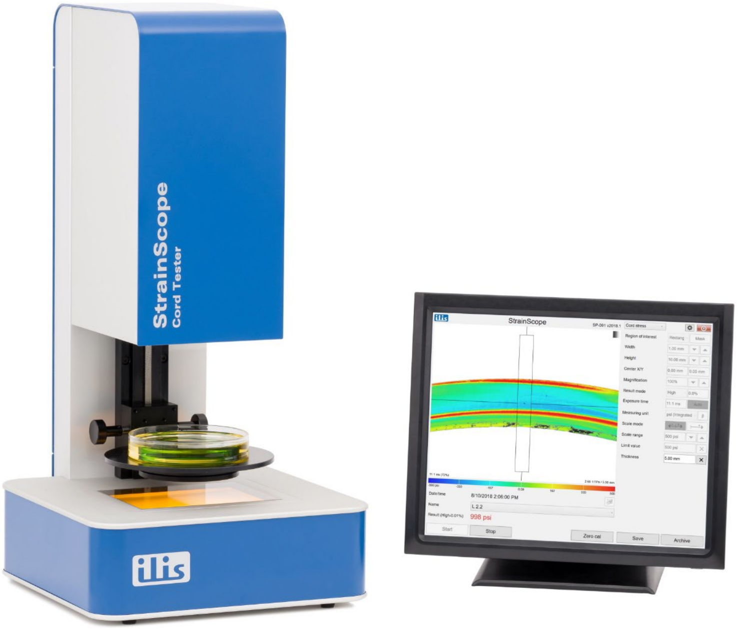
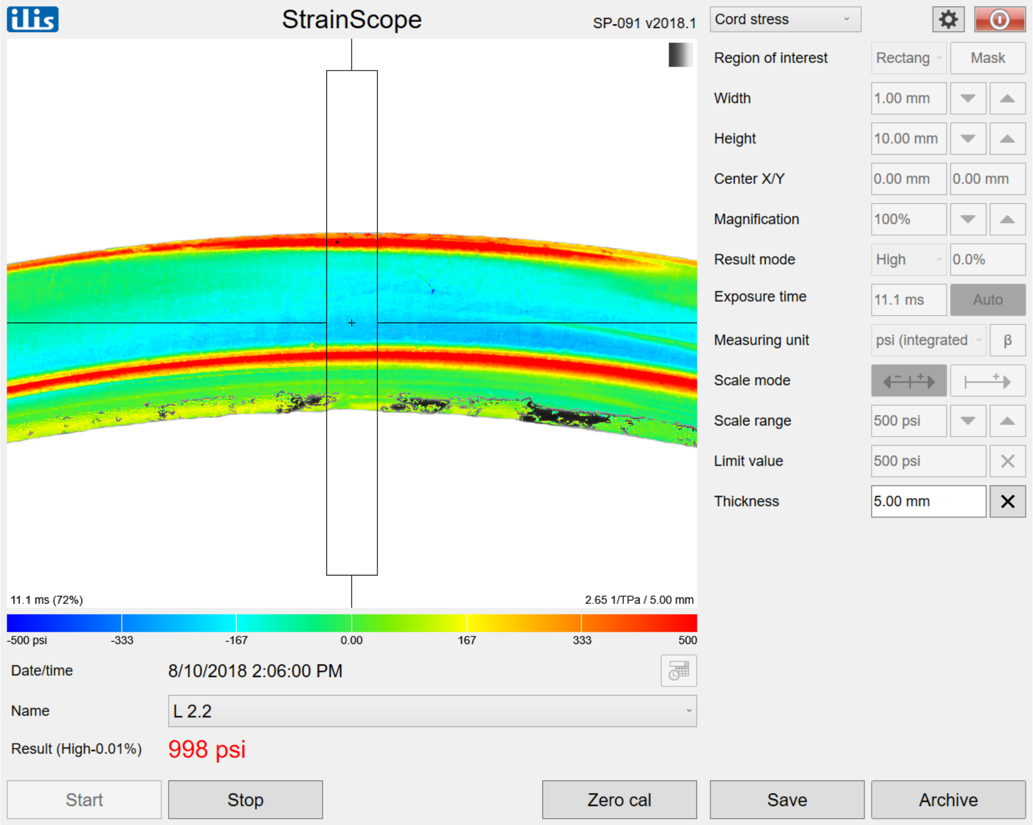


Figure 3: StrainScope Cord Tester Apparatus

The apparatus is based on the classical Sénarmont polarimeter setup and essentially consists of a linearly polarized monochromatic light source, a polarization camera with telecentric macro lens and quarter-wave plate, a stage for height adjustment and a computer system for control and data analysis. In contrast to most polarization microscopes, the linear polarization axis is selected in such a way that the sample is not aligned at 45° to the image axes, but horizontally in the field of view, which makes operation more intuitive. Compared to a polarizing microscope, the magnification is somewhat smaller in favor of a larger field of view and a greater depth of field.

Image acquisition and calculation of stress values simultaneously for all pixels in the image takes place continuously with a frame rate of at least 20 Hz to achieve a smooth and low-latency display. The stress image is displayed in pseudo-colors, with tensile stresses shown in red, compressive stresses in blue, and neutral areas in green. The maximum value within a configurable region of interest (see rectangular area in Figure 4) is computed automatically and displayed below the image in the selected result unit (MPa or psi).



Cord stress
Region of interest: Rectang, Mask
Width: 1.00 mm
Height: 10.00 mm
Center X/Y: 0.00 mm, 0.00 mm
Magnification: 100%
Result mode: High, 0.0%
Exposure time: 11.1 ms, Auto
Measuring unit: psi (integrated, β
Scale mode
Scale range: 500 psi
Limit value: 500 psi
Thickness: 5.00 mm
Date/time: 8/10/2018 2:06:00 PM
Name: L 2.2
Result (High-0.01%): 998 psi

Figure 4: StrainScope Cord Tester User Interface

In order to perform a measurement, the operator first invokes the zero-calibration function to compensate for any residual stresses in the Petri dish or in the optics of the system. After entering the sample thickness (i.e., the average ring height), which is necessary to convert the measured optical retardation values into the selected target unit according to formula (1), the ring is scanned by rotating and moving the Petri dish, similar to a microscope. An archiving function enables the documentation of the measurement result and later analysis.

MEASUREMENT CHALLENGES

The many steps of the measuring process with a polarizing microscope require precise work and highly qualified, experienced operating personnel. The Berek method is difficult to use especially with colored glass, as polarization colors are altered and color streaks can easily be confused with cord. Residual stresses in the optical elements of the microscope and in the Petri dish can falsify the measurement because there is no way to take them into account. Moreover, the field of view and the depth of field of a polarizing microscope are very small, so it is easy to miss the point of highest tension. And finally, working on the microscope is very tiring and time-consuming.

With digital measurement, as realized with the StrainScope Cord Tester, the optical resolution is fixed. Consequently, a cord thinner than the pixel size cannot be detected. The applied Sénarmont method is limited to half the light wavelength. This means that retardations higher than approximately 300 nm (equivalent to 14 MPa or 2000 psi at 8 mm thickness) can lead to confusion of tension and compression. However, this is not a practical limitation, since such high values are considered as rejects in any case.

PERFORMANCE COMPARISON WITH GAGE R&R ANALYSIS

Whether it is possible to completely replace conventional polarizing microscopes with digital measurement technologies has recently been a subject of some controversy. To put this discussion on a data-driven foundation, a comprehensive comparison study was conducted in which a set of representative samples (bottle rings) were examined multiple times by different operators using a conventional polarization microscope with Berek compensator and an automated apparatus (StrainScope Cord Tester).

In order to assess the suitability of a measurement system for a specific measuring task, a Gage Repeatability & Reproducibility Study (short Gage R&R) can be performed using the ANOVA method, which is widely used in the automotive industry and other sectors. In a Gage R&R Study, typically 5 to 10 samples are measured by at least 3 operators and at least 3 times, using the same gage. A Gage R&R provides information on the practically achievable reproducibility of a measurement system under real operating conditions, considering all relevant factors (operator, sample, measuring device, method and environment). The overall result of a Gage R&R study is the Gage R&R % Study Var, which describes the suitability of a measurement system with only one percentage number, see Table I. The second class (10% - 30%) is often further subdivided as many difficult measuring tasks fall into this category.

Table I: 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

Another handy outcome is the Number of Distinct Categories (NDC), which represents the ability of a measurement system to distinguish between parts. The NDC value should be 5 or larger.

SAMPLE SELECTION

Sample selection is key when planning a Gage R&R Study. The samples must be representative of the production. In particular, the samples must cover the entire process spread and be evenly distributed with regard to the measured property.

For this Gage R&R study, 8 ring samples of different glass color, wall thickness, ring diameter and ring thickness have been selected, designated with #1 to #8, see Table II and Figure 5. The samples cover a measuring range of approximately 150 to 1600 psi (1 to 11 MPa) evenly, as shown in Figure 6.

Table II: Bottle Ring Samples Used in the Gage R&R Study

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

Figure 5: Selected Bottle Ring Samples #1 to #8 (from top left to bottom right)

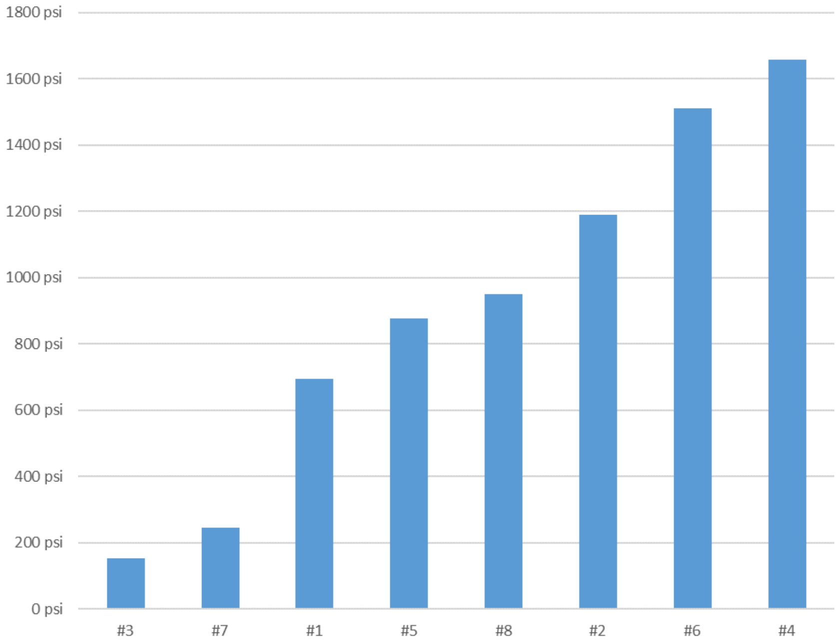


Figure 6: Mean Measurement Values of the Selected Samples

TEST PLANNING AND EXECUTION

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).

In accordance with the best practice recommendation, the 8 samples were each measured three times by the four operators on each of the two measuring devices (polarizing microscope and StrainScope Cord Tester), resulting in a total of 8 x 3 x 4 x 2 = 192 measurements. The testing was partly randomized, i.e., the order of samples was changed in each test run.

The measurement task was to find and measure the highest tension (in units of psi) for each sample. In addition to the measurement results, the time required for each test run was recorded.

MEASUREMENT RESULTS

Table III shows all 192 individual measurement results as well as the mean values and standard deviations across both measuring devices. Figure 7 visualizes the mean values and standards deviations as bar charts.

The data indicates that the standard deviation as a measure of measurement uncertainty varies widely between samples, ranging from 40 psi for sample #3 to 482 psi for sample #4.

Table III: 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%

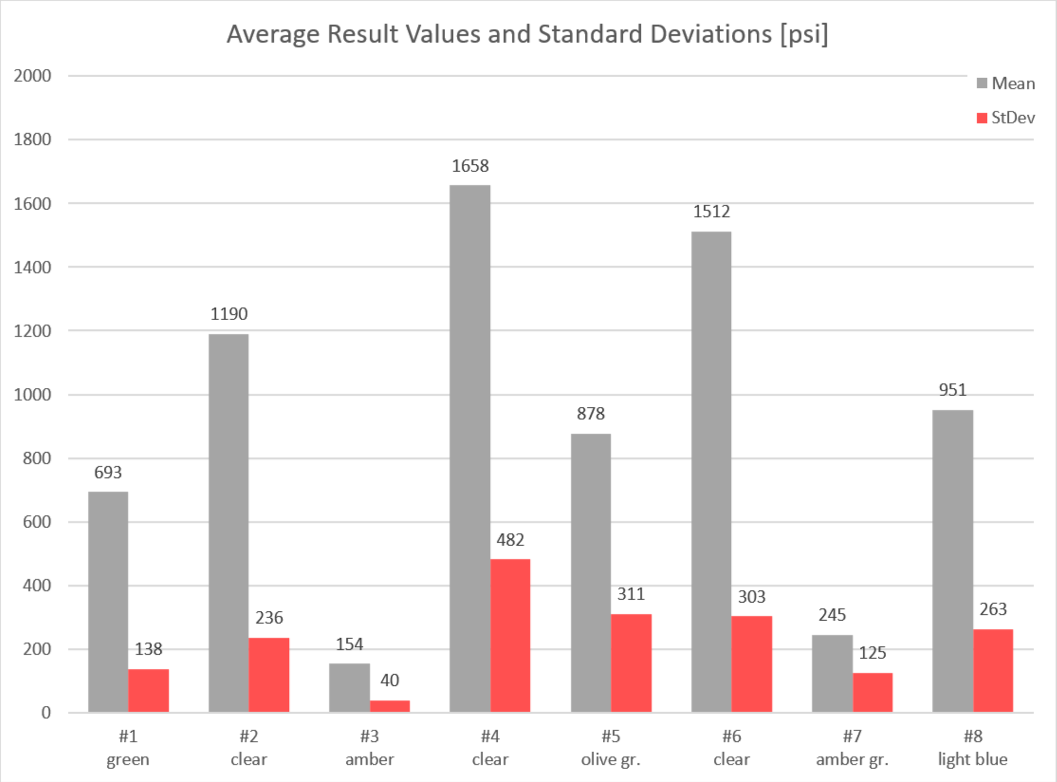


Figure 7: Average Result Values and Standard Deviations Across Both Measuring Devices

Looking at the data separately for each measuring device, it is noticeable that the measurement uncertainty of the polarizing microscope with an average standard deviation of 264 psi (over all measurements) is significantly larger than the measurement uncertainty of the StrainScope Cord Tester with an average standard deviation of 88 psi; see Table IV and Figures 8 and 9.

The data also shows that the variation between operators is much greater for the polarizing microscope than for the StrainScope Cord Tester, see Figures 10 and 11.

Table IV: Measurement Results Separated by Measuring Device and 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**

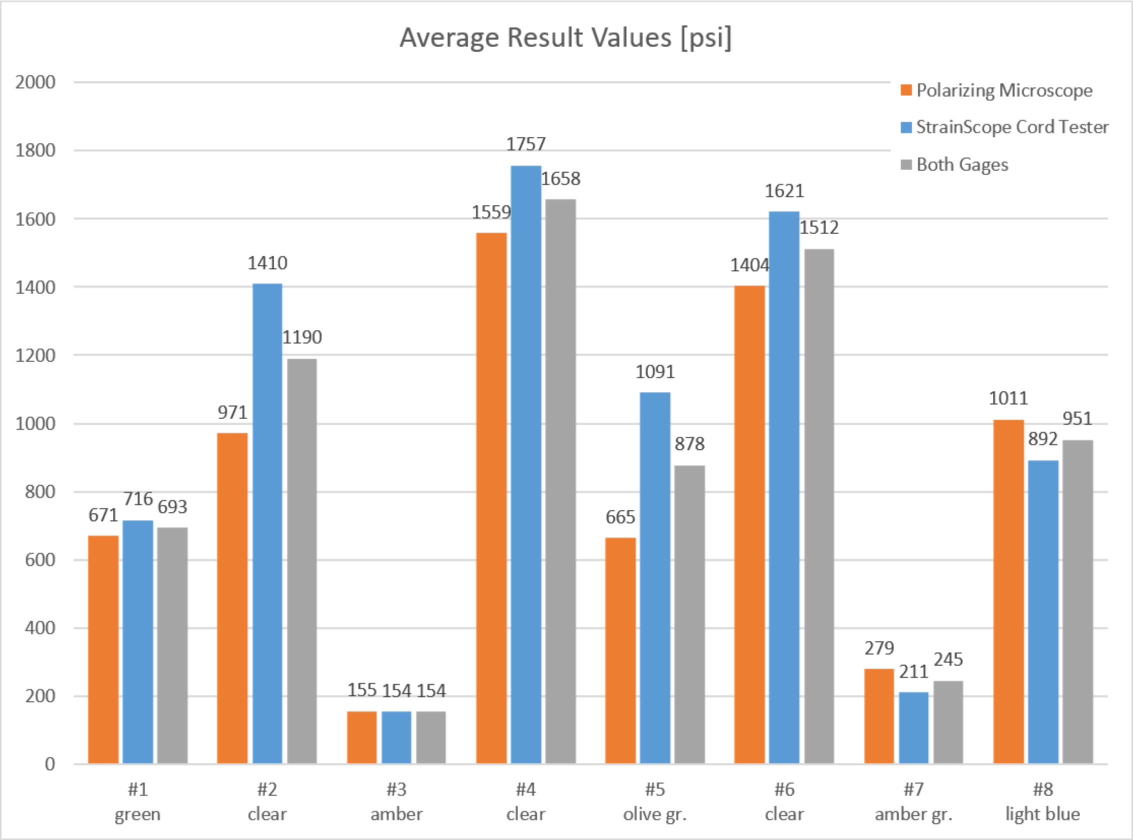


Figure 8: Average Result Values by Measuring Device

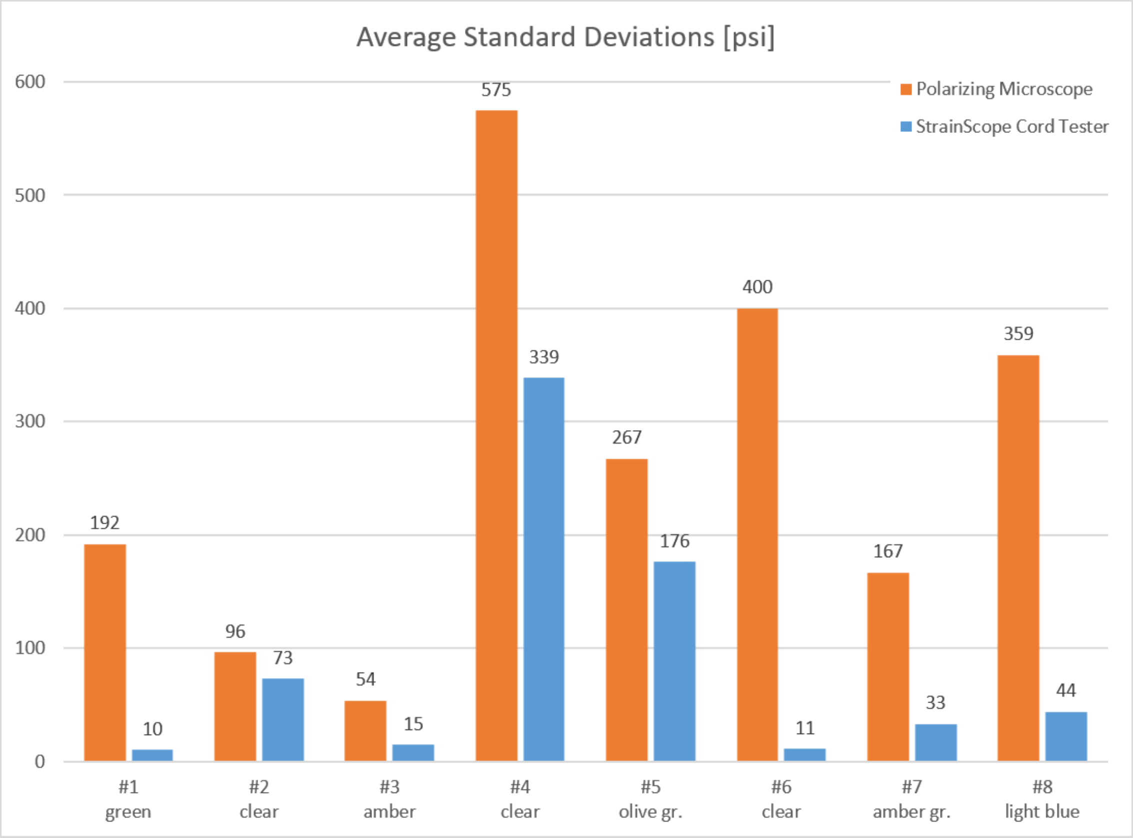


Figure 9: Average Standard Deviations by Measuring Device

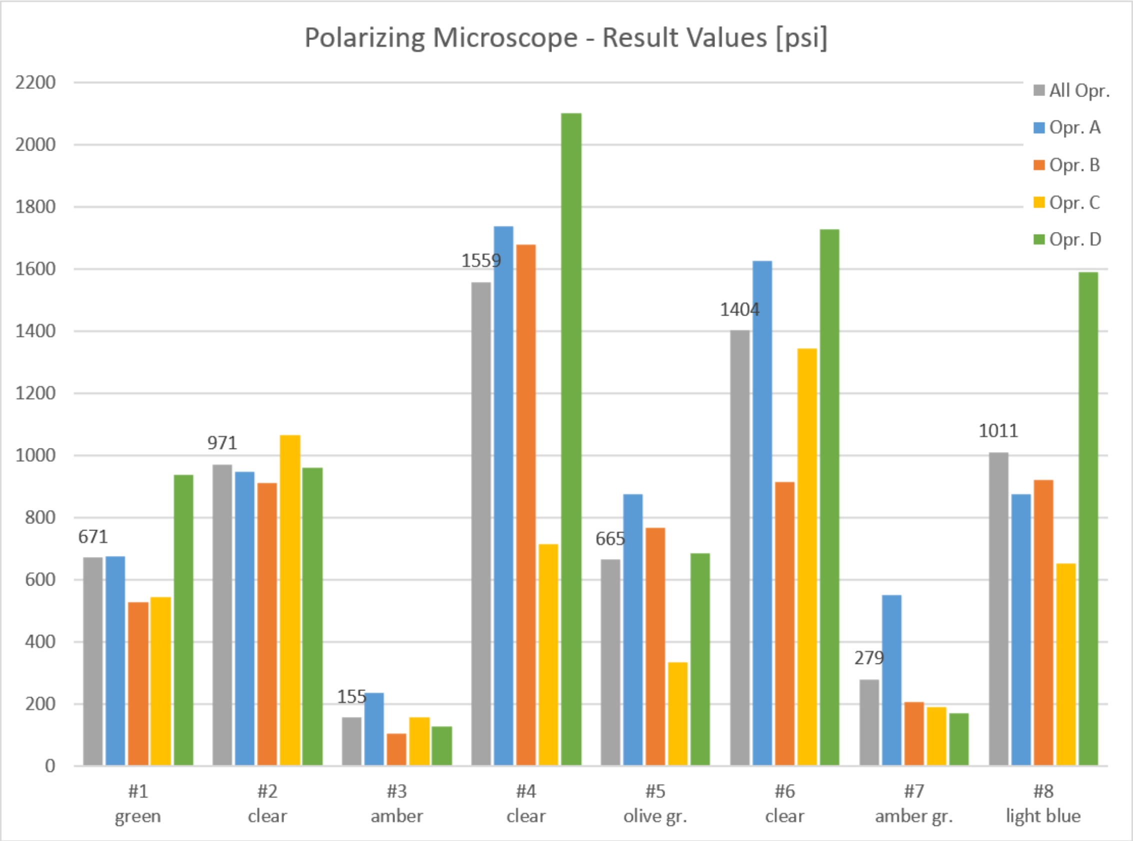


Figure 10: Average Result Values for the Polarizing Microscope

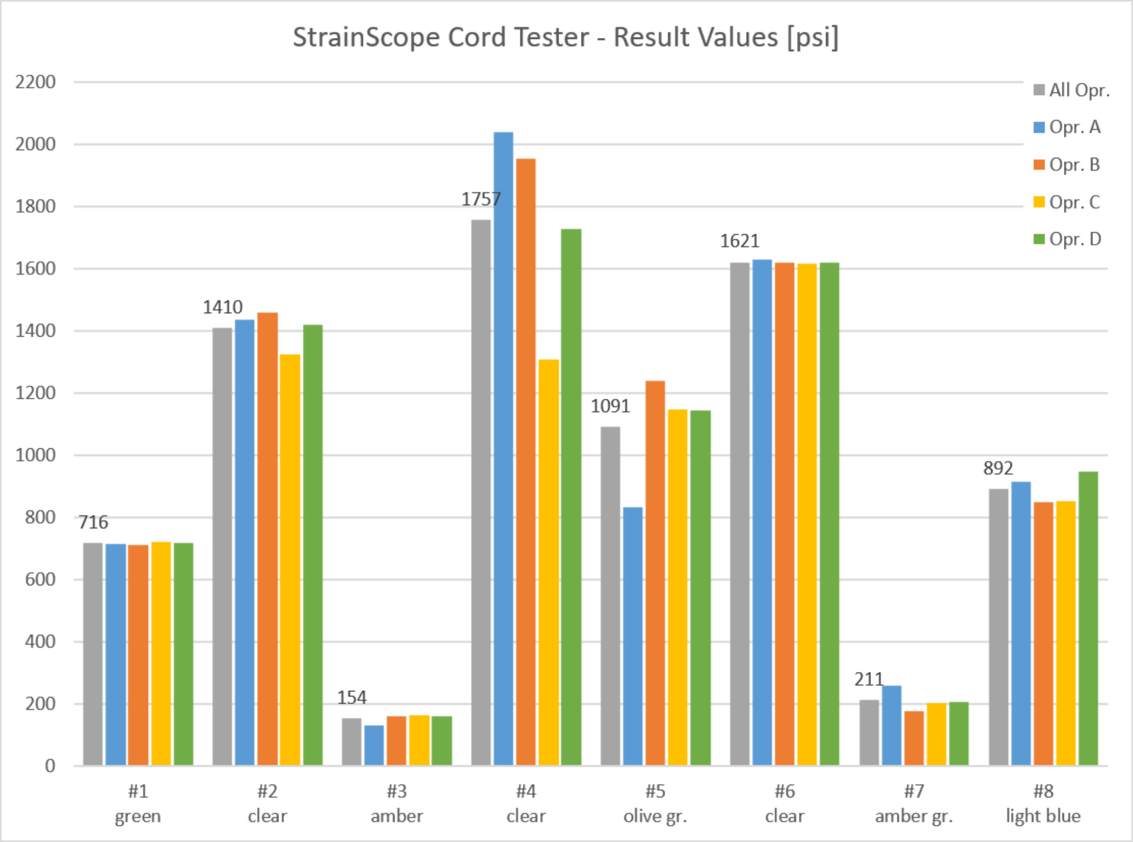


Figure 11: Average Result Values for the StrainScope Cord Tester

MEASUREMENT TIMES

Looking at the measurement times (column “Run Time” in Table IV), it is noticeable that the time required with the StrainScope Cord Tester is generally less than with the polarizing microscope. The average measurement time per run of 8 samples was 65 minutes with the polarizing microscope compared to 42 minutes with the StrainScope Cord Tester, a reduction of 35%; see Figure 12. Figure 13 shows the measurement times for each of the four operators from run to run.

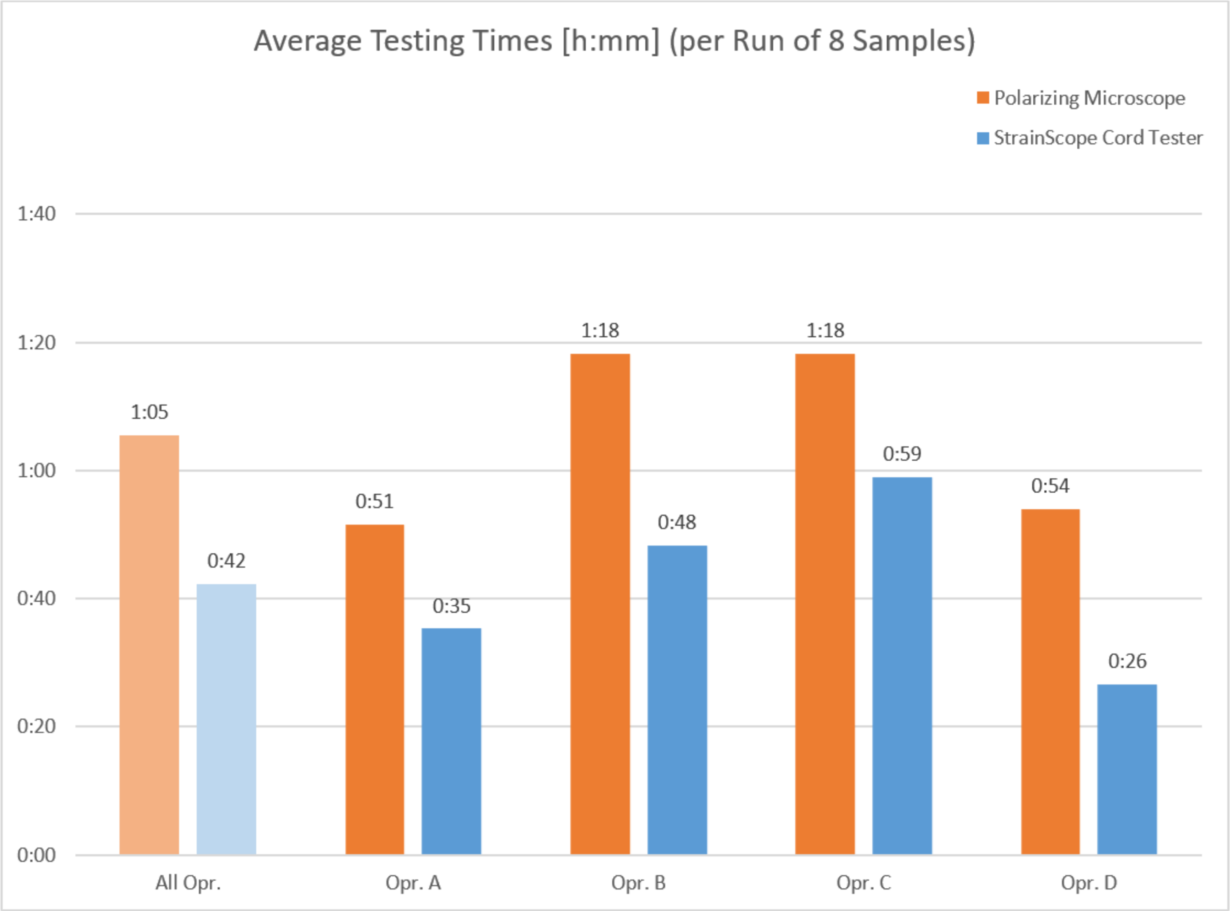


Figure 12: Average Testing Times

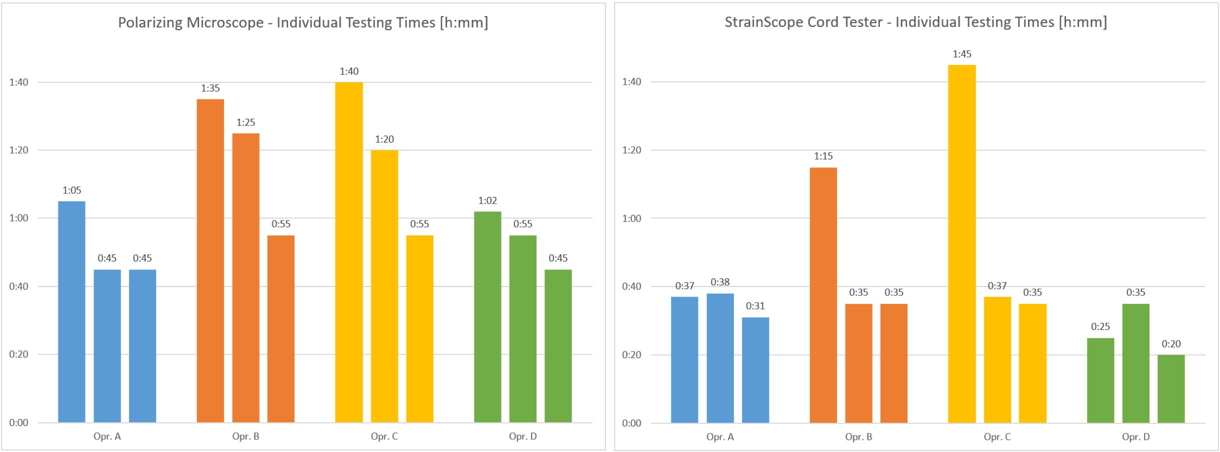


Figure 13: Individual Testing Times

OBSERVATIONS

The mean values obtained with the two measuring devices are basically comparable within the scope of the measurement uncertainty, but the variance differs considerably. Basically, the large scatter shows the difficulty of the measurement task.

Especially one sample (#4) with very thin stress cords was difficult to measure on both gages (large spread of the measured values). But contrary to expectations, the higher optical resolution of the polarization microscope did not lead to higher readings for this sample. A possible explanation is, that the small field of view and the small depth of field make it difficult to find the maximum tension.

Good sample preparation (rings of uniform thickness with flat surfaces) is generally of great importance for measurability.

GAGE R&R ANALYSIS RESULTS

Table V shows the overall results of the Gage R&R data analysis. The Gage R&R % Study Var for the polarizing microscope is 58.8%, which is well above the acceptable limit of 30% (see Table I). The Gage R&R % Study Var for the StrainScope Cord Tester is 25.1% and falls in the second category “Measurement system may be acceptable for some applications”. The Number of Distinct Categories (NDC) value for the polarizing microscope is only 1, indicating insufficient discriminatory power. The NDC value for the StrainScope Cord Tester is 5, which meets the minimum requirement.

Table V: Gage R&R Analysis Results

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

Figures 14 and 15 show, for each measuring device, the contribution of the gage (repeatability), the contribution of the operators (reproducibility) and the contribution of the samples (part-to-part) to the total variation of the measurement results. Left bars (in blue) are based on variance, right bars (in orange) are based on standard deviation (6 sigma). The leftmost bars (gage R&R) relate to the overall performance (i.e., the combination of repeatability and reproducibility). Put simply, for good performance, the part-to-part bars should be as long as possible and the other bars as short as possible.

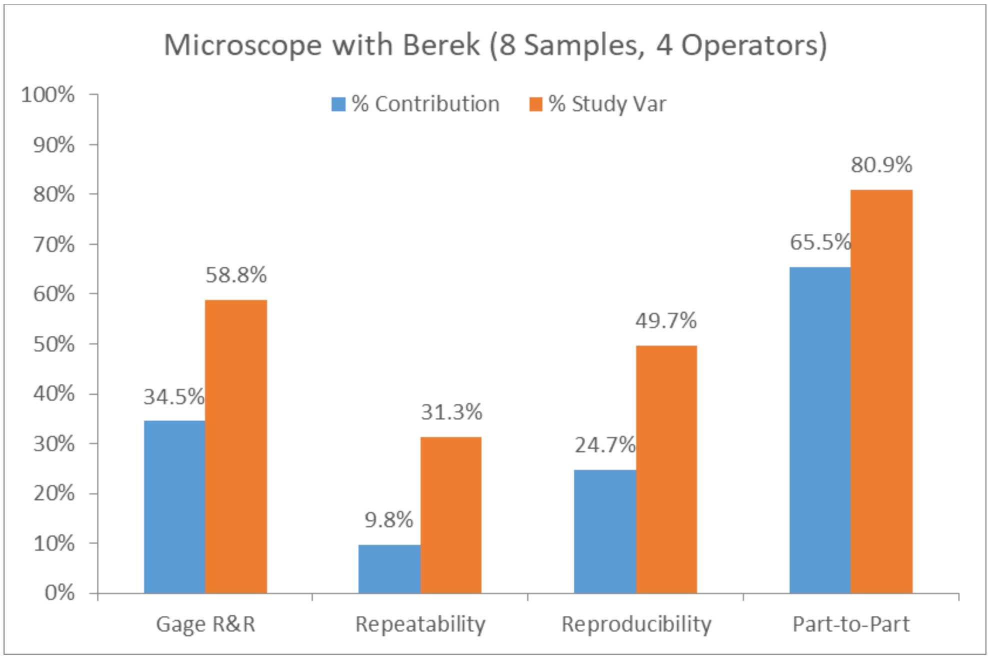


Figure 14: Gage R&R Contributions for the Polarizing Microscope

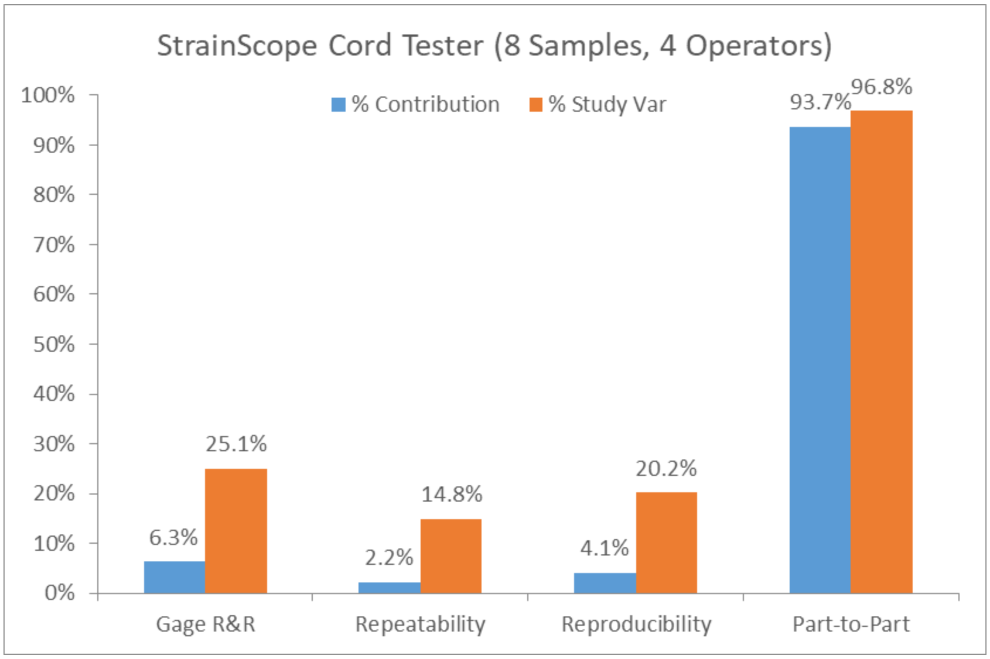


Figure 15: Gage R&R Contributions for the StrainScope Cord Tester

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. But even with digital measurement, quantifying cord stresses remains a challenging task.