Direct Image Comparison to Replicate Image SEE-3D Report

Preliminary Technical Report
TR-363

Objective:

To statistically compare the surface finish and image quality between direct imaging and replicate imaging of the cylinder bore surface

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Introduction

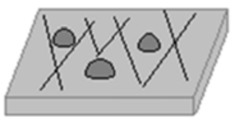
The CKE SEE-3D cylinder bore surface finish qualification system utilized in this study consists of three components. The first is the SEE-3D replicate head, which is a nondestructive cylinder bore replicating device utilizing a proprietary replicate material to create high resolution molds of the bore surface. The second component to the SEE-3D system is the white light interferometer used to map the surface of the mold in three dimensions. And the third is the customized SPIP software that quantifies up to thirty 2D and 3D surface characteristics. This system allows for quick, accurate and nondestructive cylinder bore surface finish analysis that can be used to control finishing processes and reduce wear and oil consumption in internal combustion engines. The four main steps of the process can be seen in the images on page 3.

The CKE Replicate process provides indirect quantification of the surface utilizing state of the art interferometer technology that provides data for characterizing the surface of the replicate over the length of the ring travel. Established surface finish systems quantify the cylinder bore finish by direct imaging of a section of the cylinder surface utilizing a section of a core containing the surface to be quantified. Alternatively profilometers have been utilized to provide a 2D trace (Line of data for a 2 or 3 mm distance).

Replicate material is dispensed into replicate bar

Replicator head is inserted into bore

a

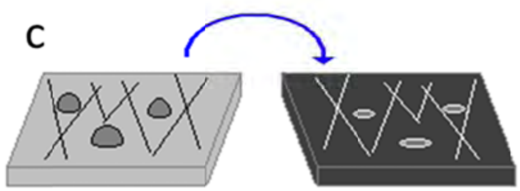


Original honed surface

b

Replicate material cures

c



Replicate material is removed, producing a copy of the original surface

SEE-3D replicate is examined with interferometer

3D Images are processed using customized SPIP software to generate surface finish data

The customized SPIP software can quantify a variety 3D surface finish characteristics (See Table 1) as well as their 2D counterparts. From this large list, eight functional parameters that have been shown to have a strong correlation to oil consumption and wear in cast iron bores are examined and compared to CKE recommendations (See Table 2). These correlations were first determined through research conducted by Dana Corp. and Volvo Corp., detailed in "Cylinder Bore Finishes and Their Effect on Oil Consumption" (Hill, SAE 2001-01-3550, 2001) and "Advanced Techniques for Assessment Surface Topography" (Kogan Page Science, 2003). These correlations have since been validated by years of CKE experience in the field. Additionally, the SEE-3D system can quantify surface porosity size/distribution and surface finish with porosity removed with regards to sprayed coatings, as well as hard particle height/distribution for 390 Aluminum or Nikasil® bores.

Table 1: Possible Surface Finish Parameters Provided by the SEE-3D System

Sa	Sq	Ssk	Sku	Sy	St	Sz	S10z
Sz tph	Sds	Ssc	Sv	Sp	Smean	Sdq	Sdq6
Sdr	S2A	S3A	Sbi	Sci	Svi	Spk	Sk
Svk	Smr1	Smr2	Std	Stdi	Srw	Srwi	Shw
Sfd	Scl20	Str20	Scl37	Str37	Sdc0-5	Sdc5-10	Sdc10-50
Sdc50-95	TFM	X-hatch					

Table 2: 3D Functional Surface Finish Parameters Used to Characterize the Bore

CKE Recommended 3-D parameters	Optimal Parameter Range
S_{10z}: Ten Point Height	(Optimal range: 8-24 µm)
S_{vk}: Reduced Valley Depth	(Optimal range: 0.5-1.2 µm)
S_k: Core Roughness Depth	(Optimal range: 0.4-0.8 µm)
S_{pk}: Reduced Peak Height	(Optimal range: 0.4-1.5 µm)
S_{bi}: Surface Bearing Index	(Optimal range: 0.8-1.5)
S_{ci}: Core Fluid Retention Index	(Optimal range: 0.3-1.0)
TFM: Torn and Folded Material	(Optimal range ≥6, 1-10 scale)
X-Hatch: Hone Cross-hatch angle	(Optimal range: 25-35 Degrees)

Procedure

In this study the CKE SEE-3D system was utilized to quantify the surface characteristics at the top, middle and bottom of the bore in the cylinder and the two cycle engine Sleeve (See Figure 1). This was completed by first making replicates at Thrust° and 180° circumferential locations around the bores (See Figure 2) using the SEE-3D hardware. 3D mapped images were then taken at the Top, Mid and Bottom axial locations along each replicate utilizing the white light interferometer. Additional images were taken at an area of interest on the Sleeve that had a visually different finish than the surrounding areas. Finally, the mapped images were processed, quantifying critical surface characteristics at each location. The surface characteristics were then compared to the CKE recommended specifications.

Subsequent to the above study, sections of the liner, corresponding to the areas measured above using the indirect replicate imaging, were cored. These cored sections were then directly captured using the Zygo white light interferometer. The resultant data was then plotted as bar charts comparing the Indirect and Direct imaging. Statistical analysis was undertaken to determine, at the 95% confidence level, if a difference in variation (F Test) and a difference in average value (T Test) existed between the replicate and direct imaging processes.

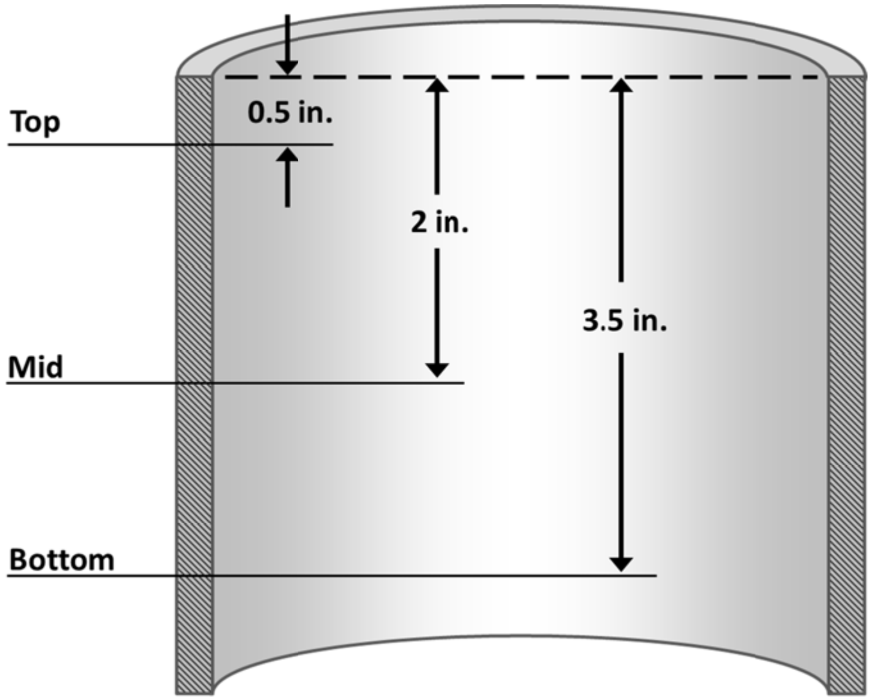


Figure 1: Cylinder/Sleeve Replicate Axial Locations

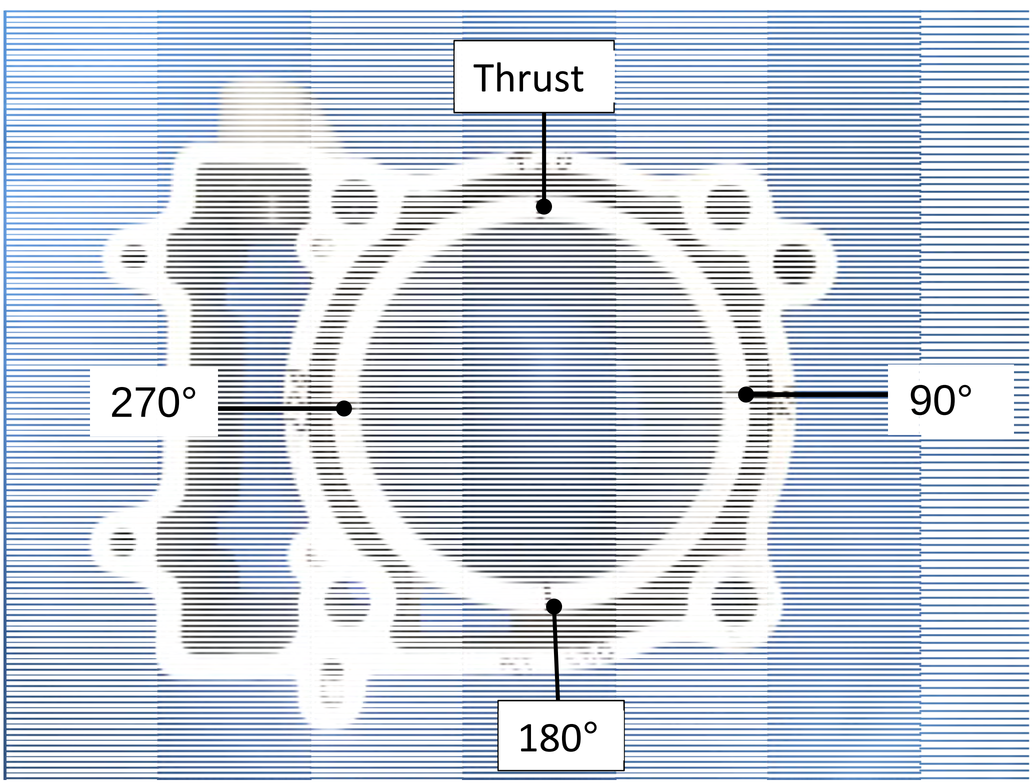


Figure 2: Cylinder/Sleeve Circumferential Replicate Locations

Results

1. Surface Finish Data (Values not meeting specifications are flagged in red)

    1.1. Replicate Image (For complete data see Appendix 1)

When looking at the replicate images, some of the finish values at the axial locations indicate some parameters varying from CKE recommended specifications.

- Ten Point Height (S_{10z}) varies from the CKE recommended specifications for 4 of the axial locations.
- Reduced Valley Depth (S_{vk}) is within recommendations at all but one of the axial locations.
- Core Roughness (Sk) is within the recommended values at all axial locations.
- Reduced Peak Height (S_{pk}) is within the recommended values at many of the axial locations.
- Fluid Retention Index (S_{ci}) is above CKE recommendations at all axial locations.

Table 3.1: 3D Surface Finish of Replicate at Each Location

			Sa	Sq	Sz	S10z	Sci	Spk	Sk	Svk
			µm	µm	µm	µm		µm	µm	µm
Replicate	Thrust	Bottom	0.26	0.37	9.63	7.95	1.48	0.68	0.68	0.55
Replicate	Thrust	Middle	0.29	0.44	9.56	8.68	1.20	0.50	0.71	0.98
Replicate	Thrust	Top	0.23	0.33	5.57	5.28	1.36	0.48	0.63	0.52
Replicate	180	Bottom	0.29	0.45	15.05	13.61	1.18	0.65	0.71	0.97
Replicate	180	Middle	0.29	0.44	8.52	7.11	1.14	0.54	0.71	0.95
Replicate	180	Top	0.23	0.31	7.14	6.81	1.59	0.52	0.64	0.37
AVERAGE			0.26	0.39	9.25	8.24	1.32	0.56	0.68	0.72

Table 3.2: 2D Surface Finish Values of Replicate at each Location

			Ra	Rq	Rz	R10z	Rv
			µm	µm	µm	µm	µm
Replicate	Thrust	Bottom	0.217	0.288	2.224	1.599	1.074
Replicate	Thrust	Middle	0.239	0.332	2.323	2.087	1.605
Replicate	Thrust	Top	0.212	0.312	3.331	2.187	2.189
Replicate	180	Bottom	0.228	0.303	2.005	1.724	0.926
Replicate	180	Middle	0.273	0.401	2.862	2.555	1.713
Replicate	180	Top	0.250	0.322	2.051	1.787	0.933

1.2. Direct Imaging

When looking at the direct images, some of the finish values at the axial locations indicate some parameters varying from CKE recommended specifications.

- Ten Point Height (S_{10z}) varies from the CKE recommended specifications for 2 of the axial locations.
- Reduced Valley Depth (S_{vk}) is within recommendations at all but one of the axial locations.
- Core Roughness (Sk) is within the recommended values at all axial locations.
- Reduced Peak Height (S_{pk}) is within the recommended values at many of the axial locations.
- Fluid Retention Index (S_{ci}) is above CKE recommendations at all axial locations.

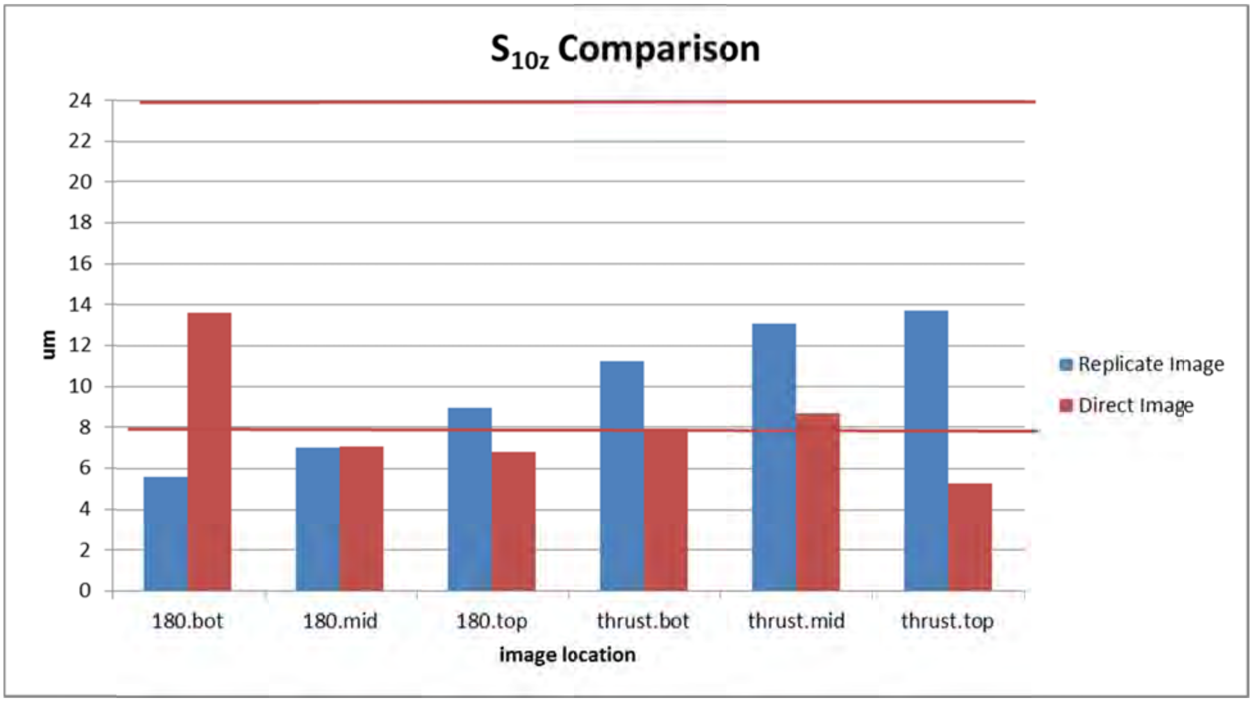
Table 4.1: 3D Surface Finish of Cylinder B at Each Location

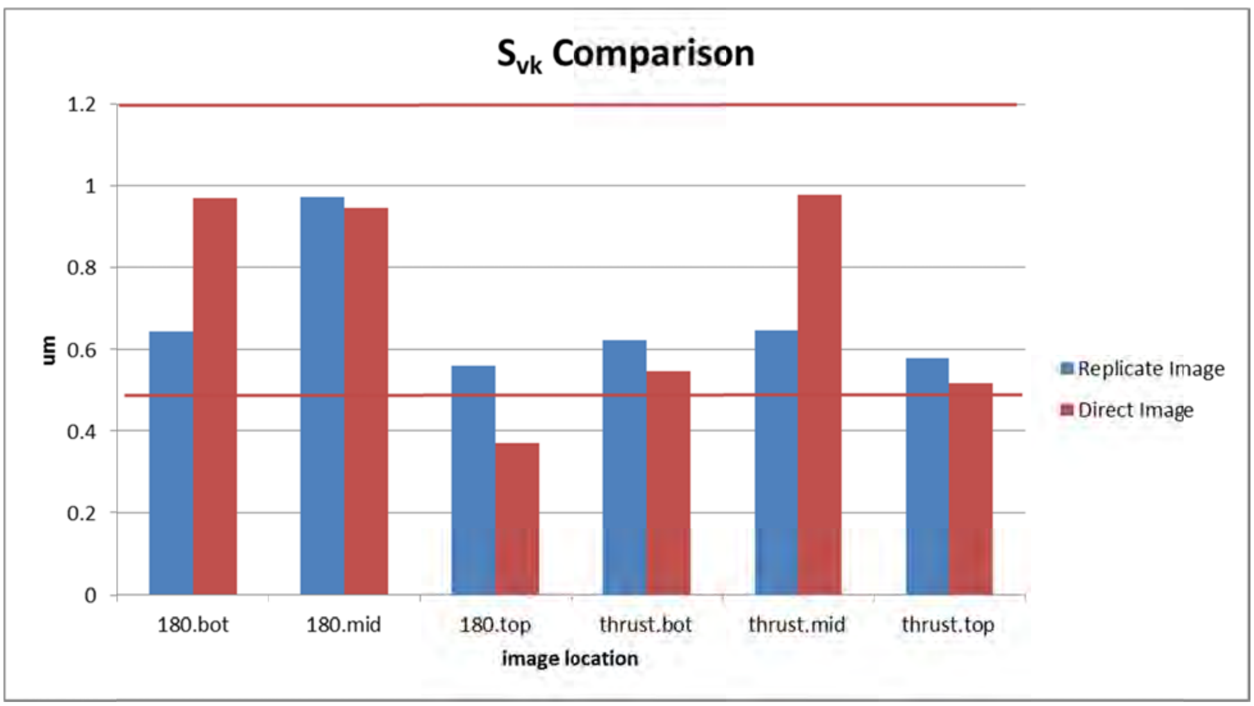
			Sa	Sq	Sz	S10z	Sci	Spk	Sk	Svk
			µm	µm	µm	µm		µm	µm	µm
Direct	Thrust	Bottom	0.24	0.36	17.04	11.24	1.38	0.82	0.65	0.62
Direct	Thrust	Middle	0.25	0.38	22.00	13.09	1.41	1.13	0.65	0.65
Direct	Thrust	Top	0.27	0.39	15.14	13.72	1.33	1.03	0.70	0.58
Direct	180	Bottom	0.18	0.24	4.06	3.82	1.52	0.38	0.54	0.29
Direct	180	Middle	0.29	0.46	7.74	7.06	1.09	0.51	0.71	0.97
Direct	180	Top	0.25	0.34	10.01	8.97	1.38	0.51	0.67	0.56
AVERAGE			0.25	0.36	12.66	9.65	1.35	0.73	0.65	0.61

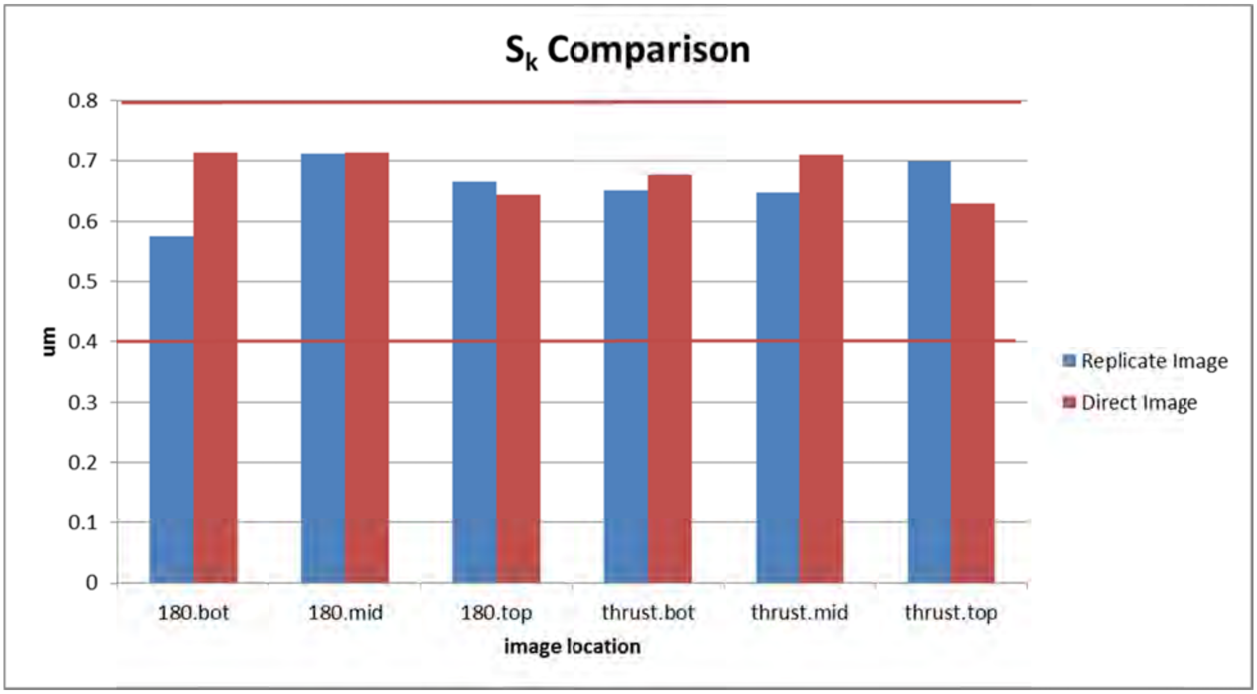
Table 4.2: 2D Surface Finish of Direct Images at each location

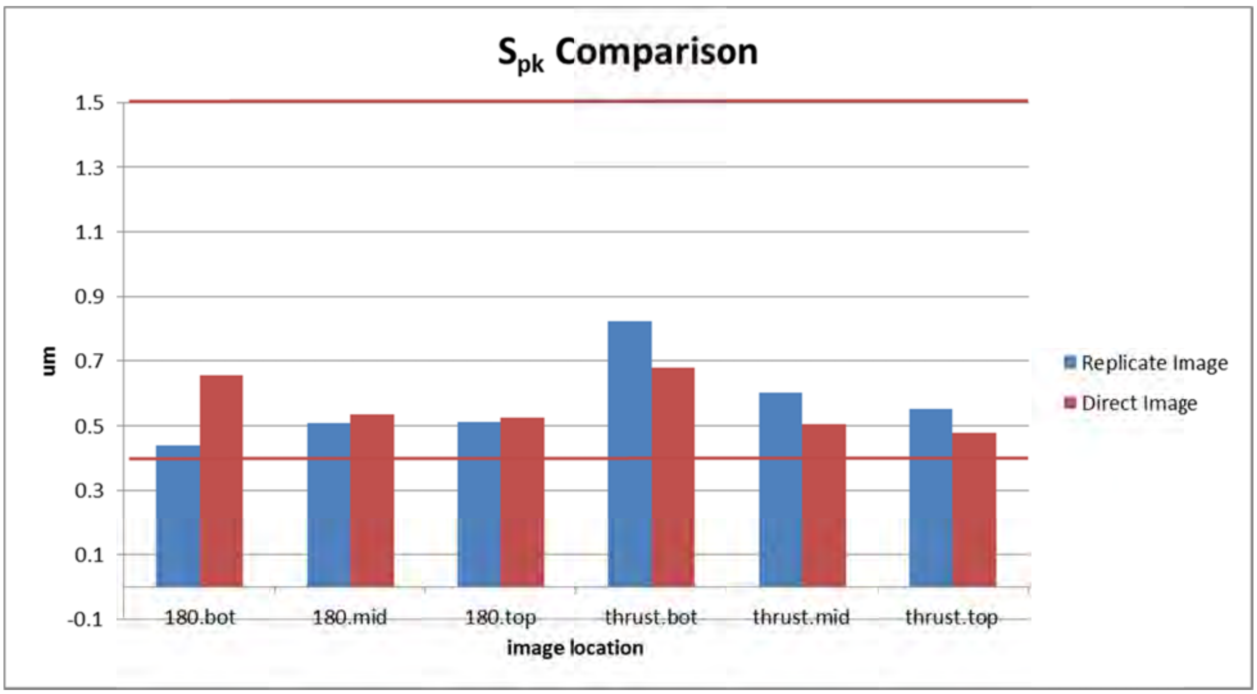
			Ra	Rq	Rz	R10z	Rv
			µm	µm	µm	µm	µm
Direct	Thrust	Bottom	0.210	0.281	2.254	1.674	1.424
Direct	Thrust	Middle	0.229	0.324	2.185	1.825	0.951
Direct	Thrust	Top	0.219	0.295	2.500	1.731	0.995
Direct	180	Bottom	0.167	0.217	1.535	1.263	0.933
Direct	180	Middle	0.202	0.265	1.966	1.600	0.873
Direct	180	Top	0.232	0.320	2.290	1.831	1.138

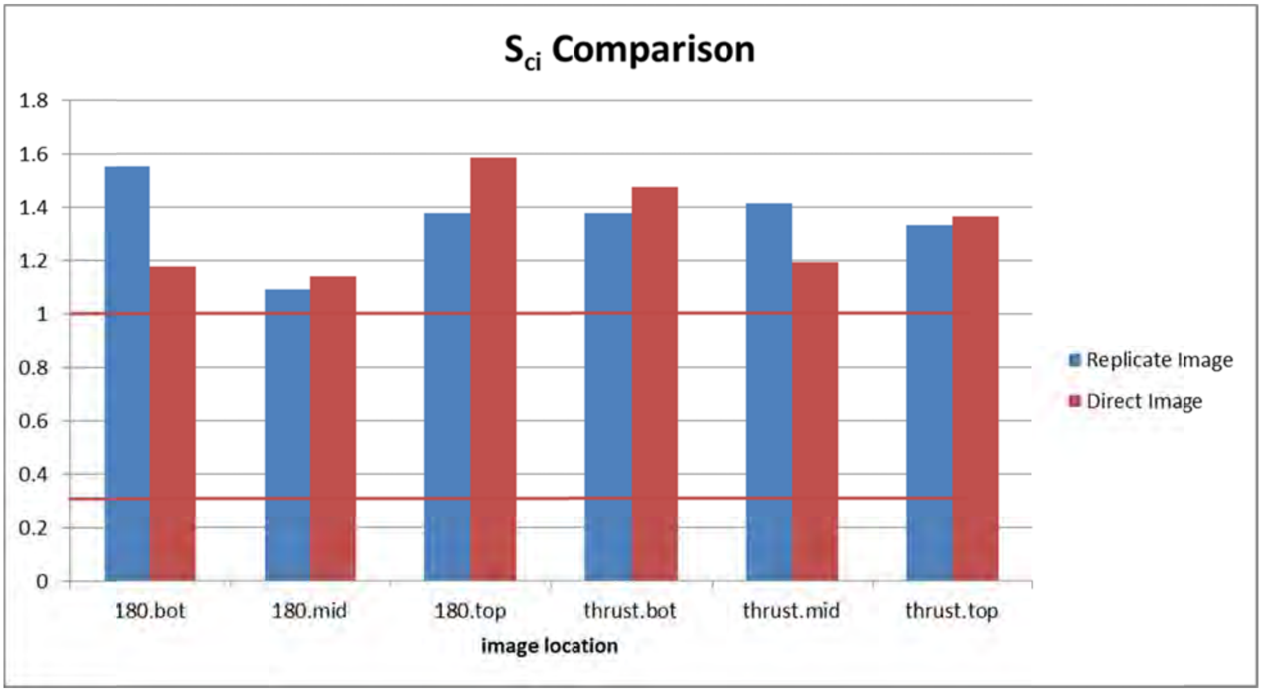
2. Comparison Charts of Wash Cylinder, showing the strong correlation in surface finish values derived from direct surface and replicate analysis.






Sk Comparison
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
um
180.bot
180.mid
180.top
thrust.bot
thrust.mid
thrust.top
image location
Replicate Image
Direct Image


Spk Comparison
1.5
1.3
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
um
180.bot
180.mid
180.top
thrust.bot
thrust.mid
thrust.top
image location
Replicate Image
Direct Image



Figures 14 and 15 show typical 2D traces from Replicate and Direct Images.

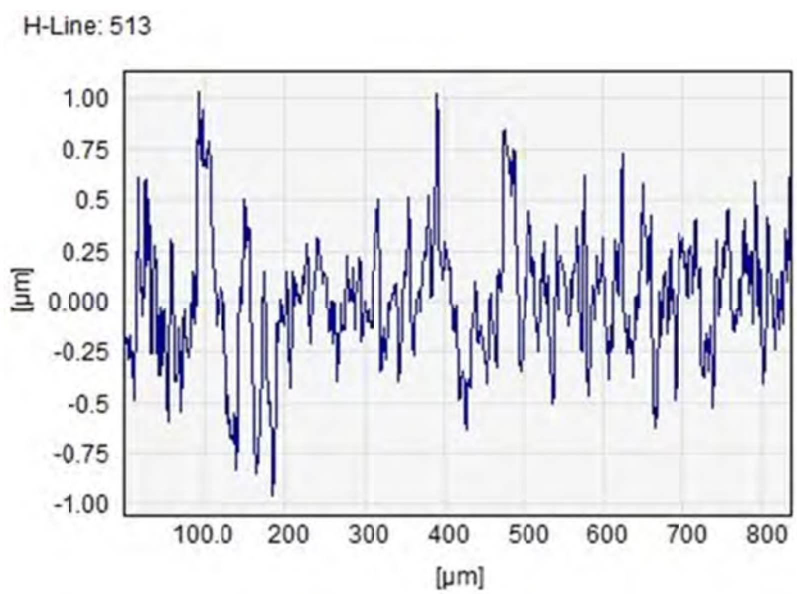


Figure 14: Replicate Surface Roughness Trace Example from Appendix I

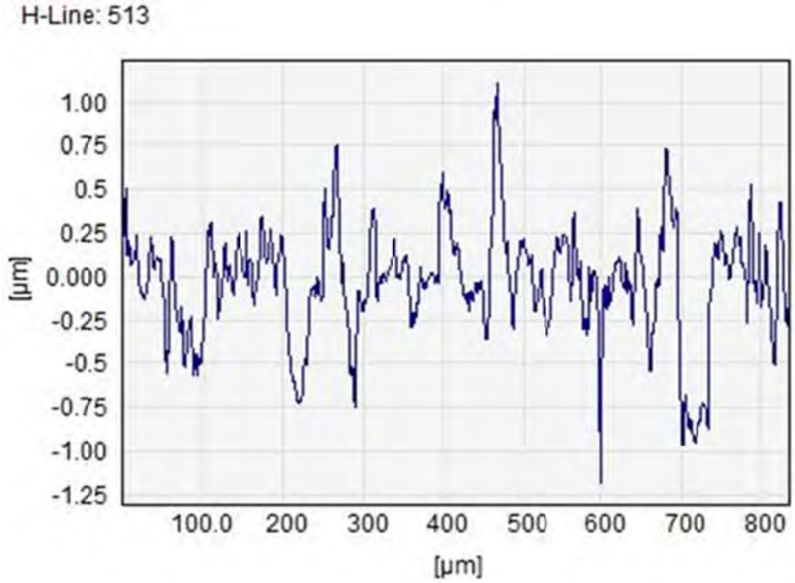


Figure 15: Direct Surface Roughness Trace Example from Appendix I

Statistical Analysis of Data

	Sa	Sq	Sz	S10z	Sci	Spk	Sk	Svk
	μm	μm	μm	μm		μm	μm	μm
AVERAGE of Replicate	0.241	0.353	8.616	7.373	1.335	0.531	0.643	0.609
Standard Deviation of Replicate	0.032	0.062	3.236	2.869	0.181	0.084	0.038	0.274
AVERAGE of Direct	0.255	0.380	9.756	8.262	1.290	0.569	0.668	0.688
Standard Deviation of Direct	0.035	0.070	6.601	3.799	0.141	0.310	0.060	0.217
Minimum of All	0.185	0.244	4.057	3.818	1.094	0.375	0.543	0.293
Maximum of All	0.295	0.458	22.000	13.722	1.586	1.131	0.715	0.979
Average of All	0.256	0.377	10.823	8.890	1.337	0.639	0.669	0.671
Standard Deviation of All	0.032	0.062	5.066	3.159	0.149	0.225	0.048	0.233
Std Dev of Blunt, et. all*	1.02	1.099	0.544	N/A	0.901	1.185	0.844	0.658
6 σ range of Replicate values	**0.1904529**	**0.3704121**	**19.413785**	**17.21241**	**1.088285**	**0.5036004**	**0.2267432**	**1.6427859**
6 σ range of Direct values	**0.207473**	**0.4227109**	**39.604677**	**22.793709**	**0.8484003**	**1.860557**	**0.3597598**	**1.3048649**
8 σ range of Blunt* values	**6.12**	**6.594**	**3.264**	**N/A**	**5.406**	**7.11**	**5.064**	**3.948**

*Ohlsson; Rosen; Westberg. "The Interrelationship of 3D Surface Characterization Techniques with Standard 2D Techniques". *Advanced Techniques for Assessment Surface Topography*. Kogan Page Science. London and Sterling, VA. 2003. Pg 219

The average surface finish values correlate very closely. The average of the replicate values is within one standard deviation of the average of the direct image values for every parameter. Below the standard deviation found in our study is the standard deviation found in measurements for the same parameters from a study done for *Advanced Techniques for Assessment Surface Topography.* Our values show lower standard deviation and 6 sigma range than the outside study in all parameters but Sz.

F Test Analysis					
Sa	*Direct*	*Replicate*	*Sq*	*Direct*	*Replicate*
Mean	0.246998	0.263812	Mean	0.363895	0.388928
Variance	0.001196	0.001008	Variance	0.004963	0.003811
Observations	6	6	Observations	6	6
df	5	5	df	5	5
F	1.186719		F	1.302317	
P(F<=f) one-tail	0.427785		P(F<=f) one-tail	0.389499	
F Critical one-tail	5.050329		F Critical one-tail	5.050329	
Equal variance			Equal variance		

Student's T Test Analysis					
Sa	*Replicate*	*Direct*	*Sq*	*Replicate*	*Direct*
Mean	0.263812	0.246998	Mean	0.388928	0.363895
Variance	0.001008	0.001196	Variance	0.003811	0.004963
Observations	6	6	Observations	6	6
Pooled Variance	0.001102		Pooled Variance	0.004387	
df	10		df	10	
t Stat	0.877398		t Stat	0.654603	
P(T<=t) two-tail	0.400858		P(T<=t) two-tail	0.527492	
t Critical two-tail	2.228139		t Critical two-tail	2.228139	
Not Statistically Different			Not Statistically Different		

Sz	*Direct*	*Replicate*	*S10z*	*Direct*	*Replicate*
Mean	12.66332	9.2454	Mean	9.649183	8.240083
Variance	43.57029	10.46931	Variance	14.43203	8.229641
Observations	6	6	Observations	6	6
df	5	5	df	5	5
F	4.161717		F	1.753665	
P(F<=f) one-tail	0.071838		P(F<=f) one-tail	0.276283	
F Critical one-tail	5.050329		F Critical one-tail	5.050329	
Equal variance			Equal variance		

Sz	*Replicate*	*Direct*	*S10z*	*Replicate*	*Direct*
Mean	9.2454	12.66332	Mean	8.240083	9.649183
Variance	10.46931	43.57029	Variance	8.229641	14.43203
Observations	6	6	Observations	6	6
Pooled Variance	27.0198		Pooled Variance	11.33084	
df	10		df	10	
t Stat	1.138888		t Stat	0.725056	
P(T<=t) two-tail	0.281297		P(T<=t) two-tail	0.485038	
t Critical two-tail	2.228139		t Critical two-tail	2.228139	
Not Statistically Different			Not Statistically Different		

Sci	*Replicate*	*Direct*	*Spk*	*Direct*	*Replicate*
Mean	1.323583	1.352617	Mean	0.728997	0.562273
Variance	0.032899	0.019994	Variance	0.096158	0.007045
Observations	6	6	Observations	6	6
df	5	5	df	5	5
F	1.645446		F	13.64941	
P(F<=f) one-tail	0.299009		P(F<=f) one-tail	0.006137	
F Critical one-tail	5.050329		F Critical one-tail	5.050329	
Equal variance			Unequal variance		

Sci	*Replicate*	*Direct*	*Spk*	*Replicate*	*Direct*
Mean	1.323583	1.352617	Mean	0.562273	0.728997
Variance	0.032899	0.019994	Variance	0.007045	0.096158
Observations	6	6	Observations	6	6
Pooled Variance	0.026446				
df	10		df	6	
t Stat	0.309224		t Stat	1.271239	
P(T<=t) two-tail	0.763498		P(T<=t) two-tail	0.2507	
t Critical two-tail	2.228139		t Critical two-tail	2.446912	
Not Statistically Different			Not Statistically Different		

Sk	*Direct*	*Replicate*	*Svk*	*Replicate*	*Direct*
Mean	0.653102	0.682025	Mean	0.721192	0.612188
Variance	0.003595	0.001428	Variance	0.074965	0.047296
Observations	6	6	Observations	6	6
df	5	5	df	5	5
F	2.517426		F	1.585006	
P(F<=f) one-tail	0.166916		P(F<=f) one-tail	0.312785	
F Critical one-tail	5.050329		F Critical one-tail	5.050329	
Equal variance			Equal variance		

Sk	*Replicate*	*Direct*	*Svk*	*Replicate*	*Direct*
Mean	0.682025	0.653102	Mean	0.721192	0.612188
Variance	0.001428	0.003595	Variance	0.074965	0.047296
Observations	6	6	Observations	6	6
Pooled Variance	0.002512		Pooled Variance	0.061131	
df	10		df	10	
t Stat	0.999605		t Stat	0.763608	
P(T<=t) two-tail	0.341075		P(T<=t) two-tail	0.462736	
t Critical two-tail	2.228139		t Critical two-tail	2.228139	
Not Statistically Different			Not Statistically Different		

Upon conducting an F test to compare variance between the replicate and direct images, it was found that only the Spk values had unequal variance. After a conducting an F test, a Student's T Test was performed on the replicate and direct images to find out if the images had statistically different means at the 95% confidence level. It was found through this test that the replicate and direct images did not have statistically different means for any of the 8 surface finish parameters tested.

Conclusion

It can be seen that the Replicate images and the Direct images correlate strongly have extremely similar surface finish characteristics.