

A Brief History of the Development of 2-D Surface Finish Characterization and More Recent Developments in 3-D Surface Finish Characterization

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ABSTRACT

Surface roughness measurement is an important area in quantifying engineered surfaces. Many modes of surface measurement have been in existence for a number of years, the most common of which is the stylus profilometer. Three-dimension surface measurement is gaining recognition as a means to understand surface finish for improved functional and manufacturing purposes.

New possibilities available with three-dimensional surface texture measurement are explored in this paper, including a procedure for generating surface replicas from hard-to-reach places for three-dimensional analysis. With this new technology, cylinder bore finish measurements can be made on the production floor without the destruction of the component permitting the generation of three-dimensional images of the surface for analysis. Three-dimensional measurements allow improved functional correlation in the calculation of volume for fluid retention, amount of wear on a surface, number and percentage of particle distribution in a surface, and many more surface finish characteristics.

With the ability to make replicates of surfaces for three-dimensional measurement, a range of options exists for efficiently generating finish or wear data from specific surface locations or areas of interest within a cylinder bore.

INTRODUCTION

Since the introduction of machined components, it has been recognized that surface finish on one or both of two moving components in contact with each other can determine if a system will operate initially or have varying life expectancy. Early efforts to define surface finish utilized identified reference surfaces with different visual appearances that could be compared for qualitative surface characterization. General Electric was an early U.S. developer and supplier of standardized visual standards. Similar standards produced by Flex-Bar and other manufacturers are still available for purchase and use.

The first quantitative surface finish measurement system was the light section microscope developed by Gustav Schmaltz¹ in Germany during the 1930s. This microscope projected a backlighted slit at an angle to the vertical on the surface being measured. Distortions in the reflection magnified the surface irregularities. Peak and valley heights could be read from the microscope eyepiece. Components of specific size and geometry necessitated the removal of sections in order to utilize this device.

Taylor and Hobson subsequently developed a simple instrument which enabled a variation in an analog electrical signal caused by a probe moving across a surface to represent peak-to-valley deviation of the surface. This signal utilized a simple analog computer to produce a *centerline average* roughness (CLA). This work eventually resulted in standards for measuring and computing the value which we now term *average roughness* (R_A).

Further evolution of surface finish quantification led to the development of some of the two-dimensional parameters that are currently widely utilized for specifying cylinder bore finish. Some surface parameters and the country of origin are summarized below:

Table 1
2-D Surface Parameters and Country of Origin

England	R_A, R_Q
Germany/Russia	R_T, R_{TM}, R_Z
Japan	R_{3Z}^*
*closely approximates R_Z	

The introduction of solid-state technology enabled data from the stylus to be digitized and manipulated. This has resulted in the establishment of more than 100 surface finish parameters.

Two-dimensional surface parameters can be compared with traveling from Canada to Mexico in a straight line in the area of the Rocky Mountains. A detailed profile of the variation in height for the specific route traveled can be developed, but little is known about the variation in height to the east or west of the line traveled. In order to support loads, knowledge of the area at some distance from the top of the mountain as well as the combined areas of multiple mountains at that location is desirable. In order to store lubricant, knowledge of the valleys and volume between the mountains is desirable.

In the 1960s and 1970s various investigators began to develop a three-dimensional visual image of the wear surface by making closely spaced multiple passes with a conventional profilometer². A number of European companies and universities initiated the development of three-dimensional surface measuring units during the 1980s and early 1990s. This work led to funding and organizing programs to define three-dimensional surface parameters and associated filters as summarized in the following table:

Table 2³
3-D Surface Parameter Development

April 1990	Start of project "Development of Methods for the Characterisation of Roughness in Three Dimensions" under the leadership of Birmingham University
April 1993	End of project "Development of Methods for the Characterisation of Roughness in Three Dimensions" under the leadership of Birmingham University
Sept 1993	"Blue book" published containing the Birmingham 14 Parameters
May 1998	Start of SURFSTAND project under the leadership of Huddersfield University [with industrial partners Volvo, Volkswagen, and SKF]
May 2001	End of SURFSTAND project under the leadership of Huddersfield University
Jan 2002	SURFSTAND & AUTOSURF projects presentation to ISO/TC213 in Madrid, Spain
June 2002	Surface texture taskforce set up by ISO/TC213 to determine requirements for standardisation of areal surface texture
Jan 2003	ISO TC213 set up new Working Group WG16 to develop a new surface texture system as part of GPS 2002
2006	Publication of areal surface texture technical specification documents by ISO
2007	Publication of areal surface texture standards documents by ISO

The effect of oil consumption on catalyst life in gasoline automotive engines is well documented as is the effect of oil consumption on particulate emissions in diesel engines. Beginning in the 1960s, Hesling⁴ and subsequent investigators have repeatedly shown that cylinder bore finish and geometry can affect the rate of oil consumption. During the 1980s Mercedes-Benz in conjunction with manufacturers of surface measuring equipment introduced the use of R_{PK} , R_K , R_{VK} , and M_2 parameters for plateau-honed

cylinder bore surfaces. These parameters provide a two-dimensional insight into the components of the plateau-honed surface.

Figure 1⁵
Approximation of Bearing Curve as Three Straight Lines

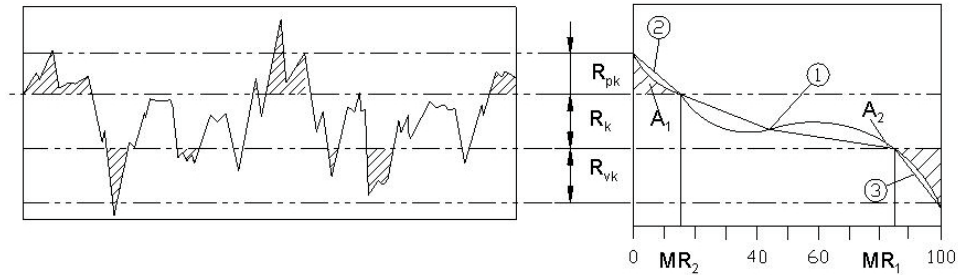
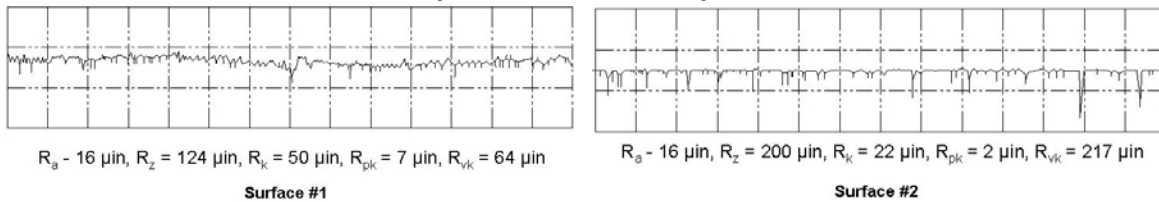
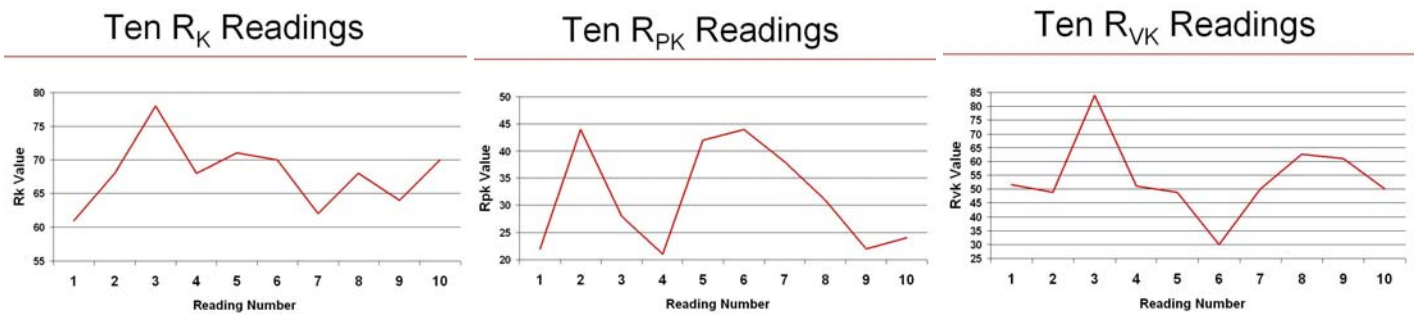


Figure 2
Comparison of Two Workpieces⁵



The R_{PK} , R_K , R_{VK} , M_2 two-dimensional system was a significant improvement in quantifying cylinder bore finish. Although of general use, the detailed implementation is difficult in terms of specification due to the inherent variation as shown below when ten readings closely adjacent to one another are made in a cylinder liner:

Figure 3
Variation Inherent in Surface Finish Measurement



The above dispersions in two-dimensional profile measurements on a single surface are well known and reluctantly accepted. To overcome this variation, the common approach is to develop a number of measurements and utilize the mean value to establish the surface finish value of interest. ISO 4288 provides a standard procedure for dealing with this problem. This specification states that it is acceptable for 16% of the finish measurements to be beyond the specified finish tolerance and still consider the part to meet the specification.

In addition to requiring multiple readings in order to provide an estimate of surface finish with some degree of confidence, two-dimensional finish parameters are limited in terms of providing information relative to surface porosity, bearing area based on an area rather than extrapolation of a line value, and volume available within the surface for the retention of lubricating oil. Initial work has shown that gas flows across the ring face due to pressure differentials above and below the compression rings result in the formation of aerosols within the ring belt of a reciprocating compressor or internal combustion engine. This work is enhancing the understanding of the mechanism relating cylinder bore finish and its variation to oil consumption. Significant work is currently under way to develop theoretical models linking the effect of differential pressure across the ring face, microchannels between the ring face and honed cylinder bore surface, the amount of oil available in the reservoirs, and the oil properties (viscosity, surface tension) to predict the effect of surface characteristics on oil consumption. Three-dimensional surface finish characteristics are required as input data for this modeling.

3-D SURFACE FINISH MEASUREMENT PROCEDURES AND INFORMATION AVAILABLE

During early development of the three-dimensional measurement process, it was anticipated that finish data developed utilizing three-dimensional surface characteristics would provide improved consistency of readings. Comparison of the number of readings required to keep the parameter value within $\pm 10\%$ at the 95% confidence level utilizing 2-D and 3-D surface measuring techniques is shown below.

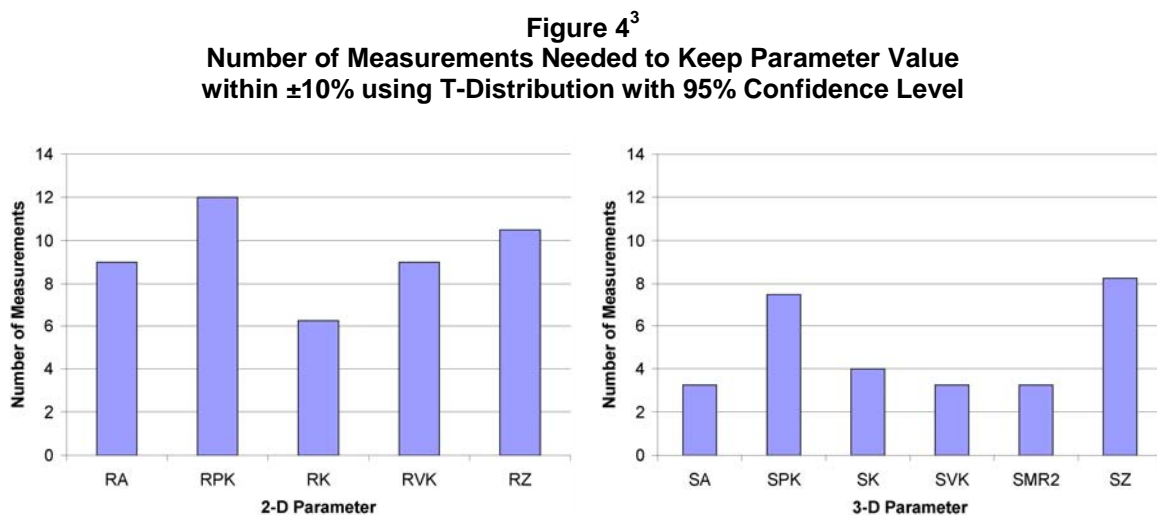
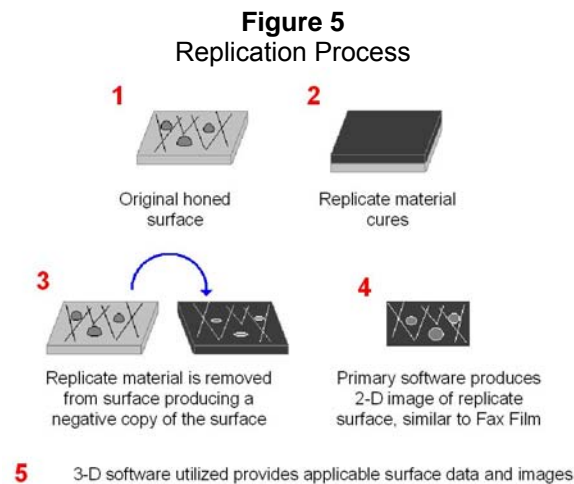


Figure 4 shows that although the use of three-dimensional finish measurement techniques can reduce the number of readings by some amount as compared with two-dimensional data, multiple readings are still required if statistical confidence is to be developed with respect to the finish parameter being measured.

The internal combustion engine industry is faced with currently scheduled 2010 reduced emission level requirements with discussions ongoing as to lower emission levels beyond 2010. Models for gas flow, oil flow, oil consumption, and wear prediction of the ring and liner surfaces have progressed to the point at which piston ring and piston geometric effects on oil consumption can be quantitatively predicted.

Work is in progress to develop models that can be utilized to quantitatively predict the effect of surface finish on oil consumption. In parallel, integral aluminum cylinder bores or aluminum liners with hypereutectic aluminum metallurgical structures are being adopted. This requires improved methods of quantifying bore surface finish and the character of the silicon (size, percent height above matrix) and other hard particles after honing as well as porosity.

The replicate method (Appendix) described in this paper can be utilized to determine these characteristics at the point of manufacture or testing over the length of piston ring travel without requiring the destruction of the surface. The replication process can be illustrated as follows:



This replicate system consists of the following components:

- Replicate material
- Rod for containing replicate material
- Fixture for applying uniform pressure to the replicate material and cylinder bore
- Interferometer with well-developed software providing 3-D data for the surface, hard particles (if used in bore material or coatings), and surface porosity

Many useful 2-D and 3-D cylinder bore surface finish parameters are available from the validated software of this system as summarized in the following tables. A significant number of other 2-D and 3-D surface finish parameters are available but are not included here as they are not utilized with cylinder bore surface finish measurement.

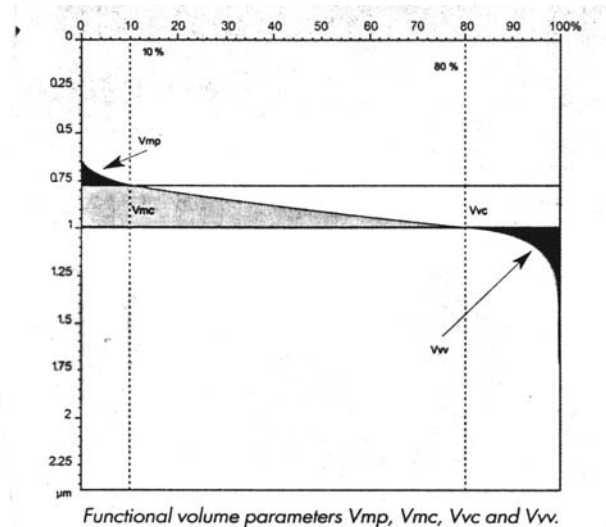
A general relationship exists between the three-dimensional finish parameters and two-dimensional finish parameters in the case of height.

Table 3
Height Parameters
Quantify Z Axis Perpendicular to Surface

ISO 25178 – New 3-D Finish Standard (to be published)		Din 4776 – Current Related 2-D Parameters	
S_A	Arithmetical mean height (mean surface roughness)	R_A	Arithmetical mean of roughness from the mean line
S_Z	Maximum height – numerical average between the five deepest valleys and the five highest peaks	R_Z	Numerical average height between the five highest peaks and the five deepest valleys within a sampling length
S_P	Maximum peak height – height between the mean plane and the highest plane	R_{PK}	Reduced peak height that will quickly wear away
S_V	Maximum valley height – height between the deepest valley and the mean plane	R_{VK}	Trough depth – provides oil retaining capability
S_K	Core roughness depth – height difference between intersections points of the found least mean square line	R_K	Kernel roughness depth – the long-term running surface that will determine the life of the cylinder

Functional parameters are calculated from the Abbott-Firestone curve obtained by the integration of the height distribution on the whole surface.

Figure 6
Abbott-Firestone Curve



Three-dimensional finish data provides a series of functional values. These values are required in the development of effective models and an understanding of finish on oil consumption and wear.

Table 4
3-D Functional Parameters

New ISO 25178 Standard	Functional Parameter	Unit	Current DIN Standard
S_{MR}	Surface bearing area ratio or areal material ratio	%	
S_{MC}	Height of surface bearing area ratio or inverse areal material ratio	μm	S_{bi}
S_{XP}	Peak extreme height	μm	S_{MAX}
V_V	Void volume of the scale limited surface at a given height	$\mu\text{m}^3/\mu\text{m}$	
V_{MC}	Core material volume of the scale limited surface	$\mu\text{m}^3/\mu\text{m}^2$	
V_{VC}	Core void volume of the scale limited surface	$\mu\text{m}^3/\mu\text{m}^2$	S_{ci}
V_{VV}	Valley void volume of the scale limited surface		S_{vi}

Three-dimensional finish data provides information relative to materials and porosity in the cylinder bore surface:

Table 5
Newly Available 3-D Bore Surface Finish Data

Porosity in surface	<ul style="list-style-type: none"> Percent area of surface porosity at location beneath mean core finish Distribution of porosity size
Particles in surface	<ul style="list-style-type: none"> Percent area occupied by aluminum particles (in hypereutectic aluminum surfaces) or silicon carbide or other hard particles (in Nikasil-type coatings) Particle size distribution – height of particle surface above mean of kernel roughness
Wear	<ul style="list-style-type: none"> At top ring turn-around through $10\mu\text{m}$ At specific location between top and bottom turn-around <p>Wear $\mu\text{m} = (S_K + S_{PK})$ before test – $(S_K + S_{PK})$ after test</p>

SURFACE FINISH MEASUREMENT OF CAST IRON CYLINDER BORES

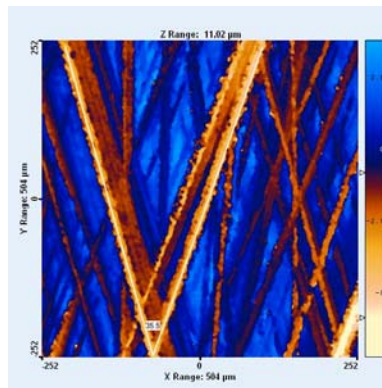
The software developed in conjunction with the effort described in Table 2 combines with the well-developed white-light interferometer and the replicate process described in the Appendix provides a robust, capable system for determining three-dimensional cylinder bore characteristics. The base process developed to economically and functionally permit three-dimensional surface finish analysis of cylinder bores is described in the Appendix. Typical cast iron cylinder bore finish data for one cylinder developed utilizing this system is summarized as follows:

Table 6
Typical Cast Iron Cylinder Bore Finish Data

From Top (in)	3-D Parameters from Replicate Scan (μin)									2-D Parameters from Line Profile (μin)			
	S_A	S_{PK}	S_K	S_{VK}	S_{MIN}	S_{MAX}	$S_{1\text{ ht}}$	S_{bi}	S_{ci}	R_A	R_{PK}	R_K	R_{VK}
0.4	33.504	60.157	86.732	65.394	-187.244	208.346	395.591	32.126	53.937	31.654	86.299	80.315	59.803
1.2	29.370	35.157	90.630	43.228	-232.402	118.701	351.102	24.134	61.417	30.591	47.362	80.433	35.591
2.2	26.220	46.496	68.346	54.606	-144.331	208.937	353.268	30.906	54.331	30.630	63.110	83.740	35.551
3	28.386	45.236	88.268	32.795	-126.496	192.756	319.252	26.102	62.992	29.134	26.772	98.071	33.976
4	31.850	47.559	86.299	46.417	-141.299	183.701	325.000	27.480	58.661	35.118	59.016	98.858	44.764
Average	29.866	46.921	84.055	48.488	-166.354	182.488	348.843	28.150	58.268	31.425	56.512	88.283	41.937
Min	26.220	35.175	68.346	32.795	-232.402	118.701	319.252	24.134	53.937	29.134	26.772	80.315	33.976
Max	33.504	60.157	90.630	65.394	-126.496	208.937	395.591	32.126	62.992	35.118	86.299	98.858	59.803

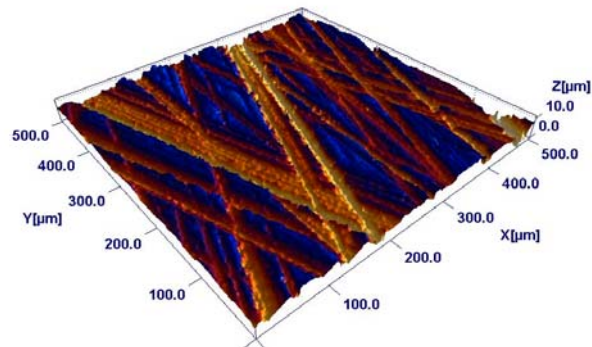
A two-dimensional view of the surface at specific locations along a cylinder bore length can be selected for analysis. In addition, a 2-D view of the surface provides information that is normally developed with a faxfilm impression of the surface and can be utilized to check for torn or folded material from the honing operating as well as to determine the nominal crosshatch angle.

Figure 7
Typical 2-D Image of Cast Iron Cylinder Bore Surface



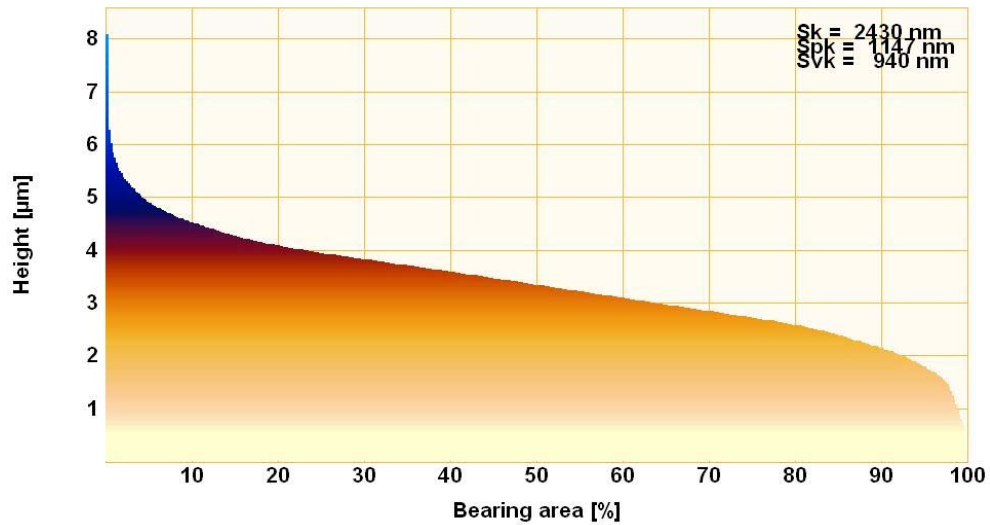
Other data is readily available from a three-dimensional view of the surface finish. .

Figure 8
Typical 3-D Image of Cast Iron Cylinder Bore Surface



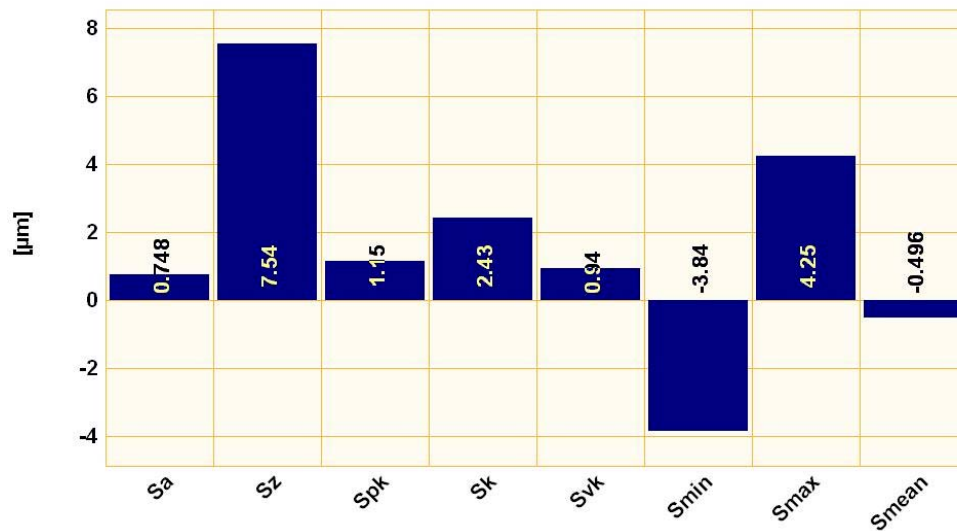
In addition to numerical values, a plot of the percent bearing area at a distance from the highest peak in the surface is available as S_{bi} , S_{MR} , or S_{MC} parameters.

Figure 9
Typical Percent Bearing Area Referenced to Distance Below Highest Peak
 (for the 3-D surface shown in Figure 8)



Finish parameters can be displayed in a bar chart format.

Figure 10
Typical 3-D Finish Data



3-D SURFACE FINISH MEASUREMENT OF HYPEREUTECTIC ALUMINUM BORES

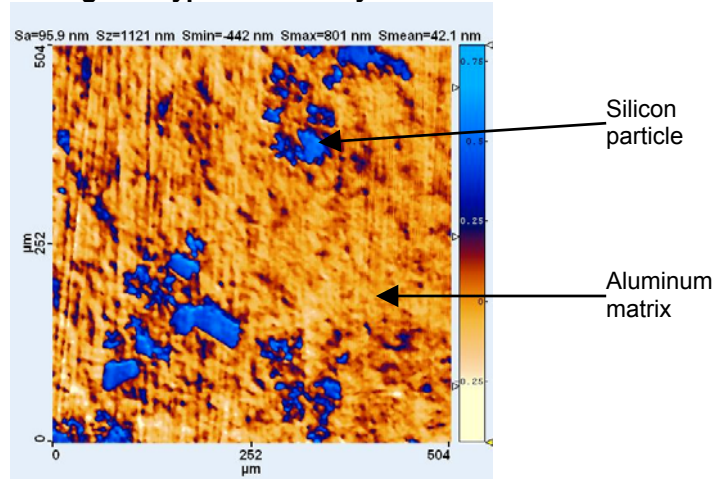
Typical hypereutectic aluminum cylinder bore finish data for one cylinder developed utilizing the system described in the Appendix is summarized as follows:

Table 7
Typical Hypereutectic Aluminum Cylinder Bore Finish Data

From Top (mm)	3-D Parameters from Replicate Scan (μm)											
	S _A	S _Z	S _{PK}	S _K	S _{VK}	S _{MIN}	S _{MAX}	S _{1 ht}	% Si	% Pores	S _{bi}	S _{ci}
45	0.082	1.056	0.212	0.222	0.098	-0.508	0.628	1.136	29.7	0.83	0.479	1.820
60	0.083	1.208	0.253	0.215	0.072	-0.436	0.952	1.388	18.4	0.85	0.509	1.760
75	0.103	1.110	0.315	0.269	0.080	-0.367	0.820	1.187	30.8	2.72	0.419	2.040
90	0.113	1.646	0.322	0.307	0.117	-0.909	1.095	2.004	23.8	0.11	0.484	1.820

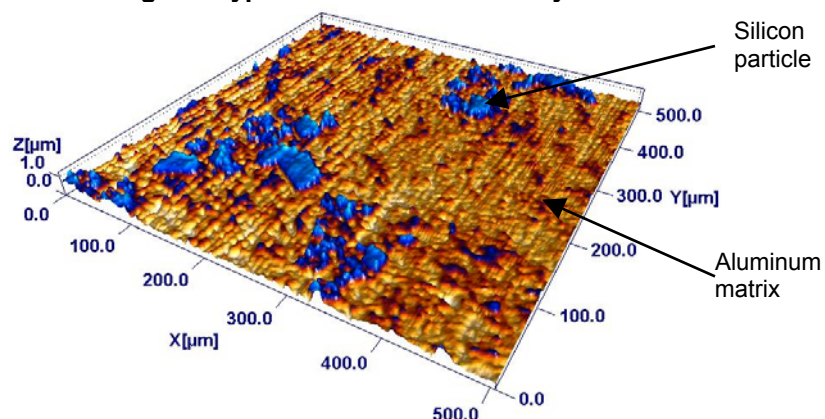
A two-dimensional view of the surface at specific locations along a cylinder bore length can be selected for analysis. This 2-D view provides information that is normally developed with a faxfilm impression of the surface and can be utilized to check for torn or folded material from the honing operating.

Figure 11
Typical 2-D Image of Hypereutectic Cylinder Bore Surface



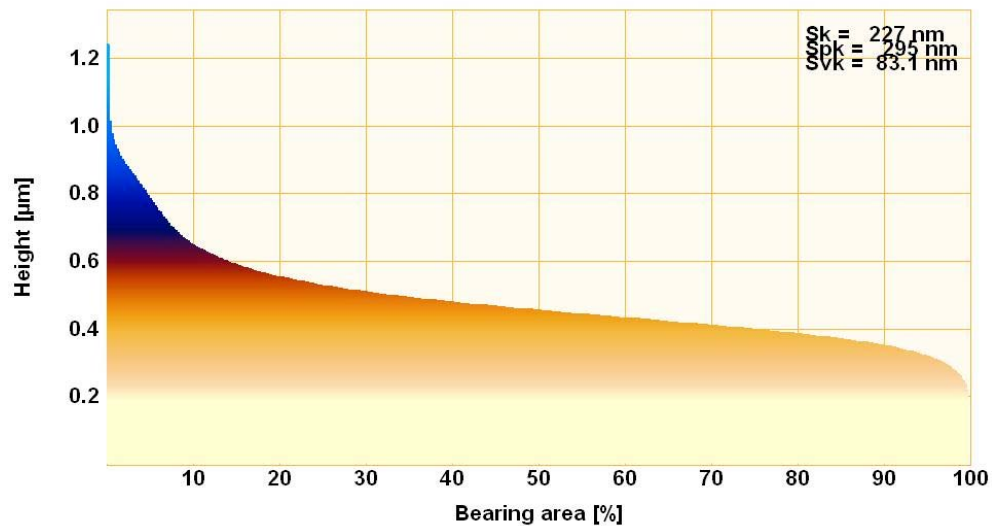
Other data is readily available from a three-dimensional view of the surface finish.

Figure 12
Typical 3-D Image of Hypereutectic Aluminum Cylinder Bore Surface



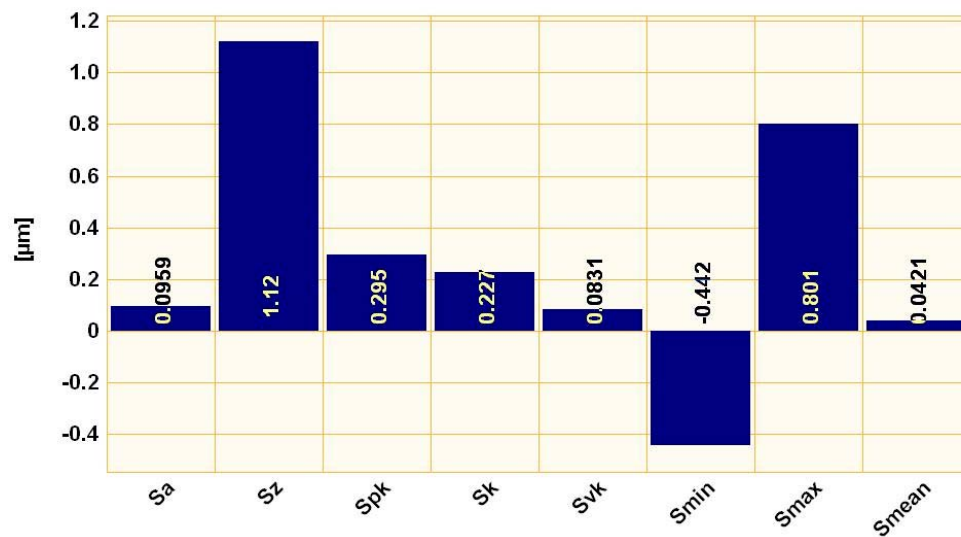
In addition to the numerical values, a plot of the percent bearing area at a distance from the highest peak in the surface is available.

Figure 13
Typical percent Bearing Area Referenced to Distance Below Highest Peak



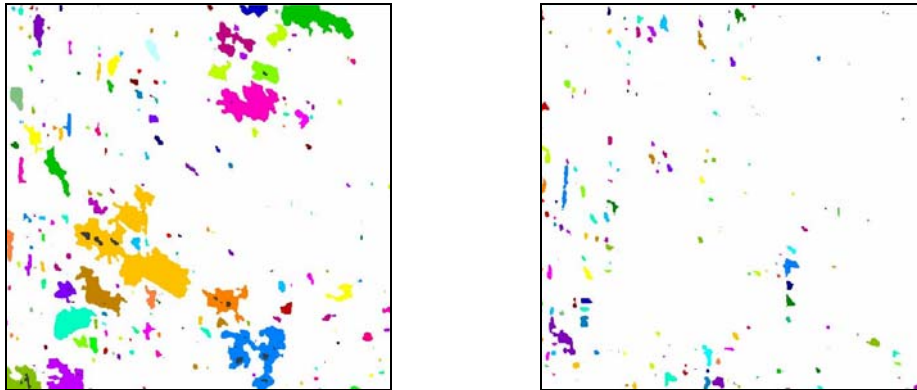
Roughness parameters can be displayed in a bar chart format.

Figure 14
Typical Roughness Data



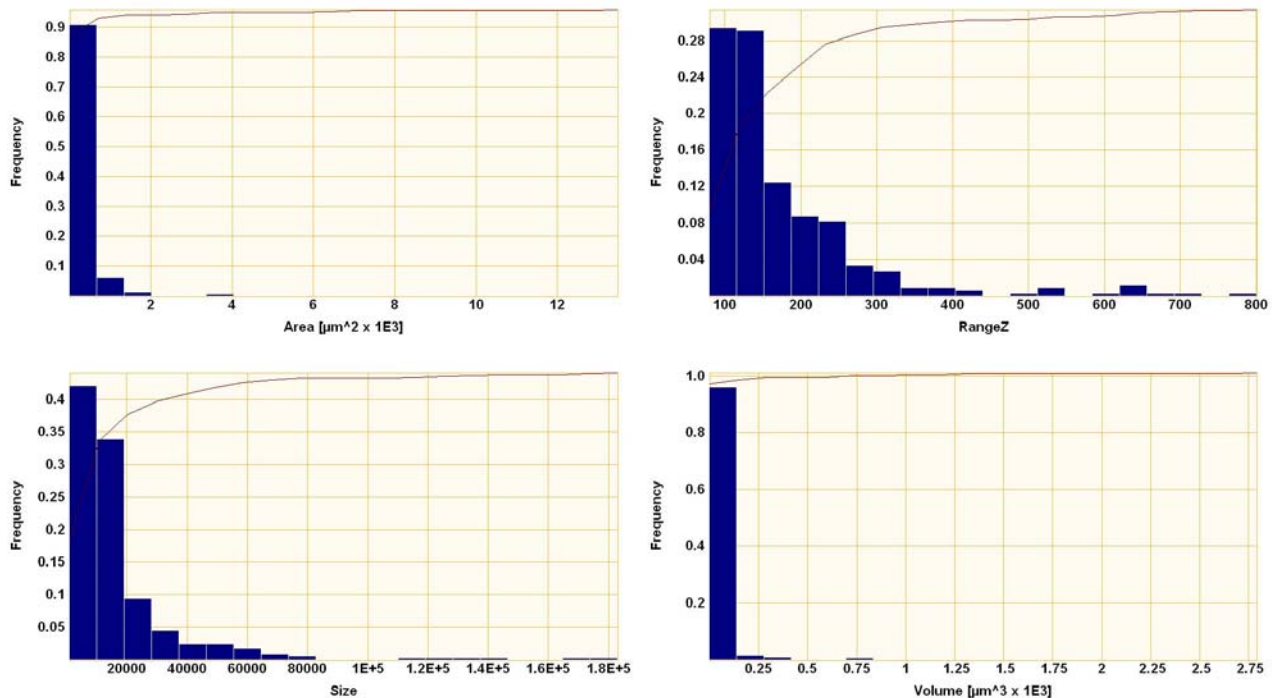
The software is capable of discriminating between particles and pores on the surface of aluminum or Nikasil-coated cylinder bores. Provisions are made for choosing the level of detection with outputs including percent area particle (silicon)/pore (porosity) coverage, height and size distribution, particle area/perimeter, particle volume, graphical representation of distribution, volume available for fluid retention, bearing surface index, and material/void volume.

Figure 15
Percent Silicon Particle & Casting Porosity Distribution
Particle Area at Surface Porosity Area at Surface



Numerical data available for silicon (hard) particles includes particle size area vs. frequency of occurrence, particle height vs. frequency of occurrence, frequency of occurrence of varying size particles, and frequency of occurrence of particles with specific volumes as shown in Table 7 and Figure 15.

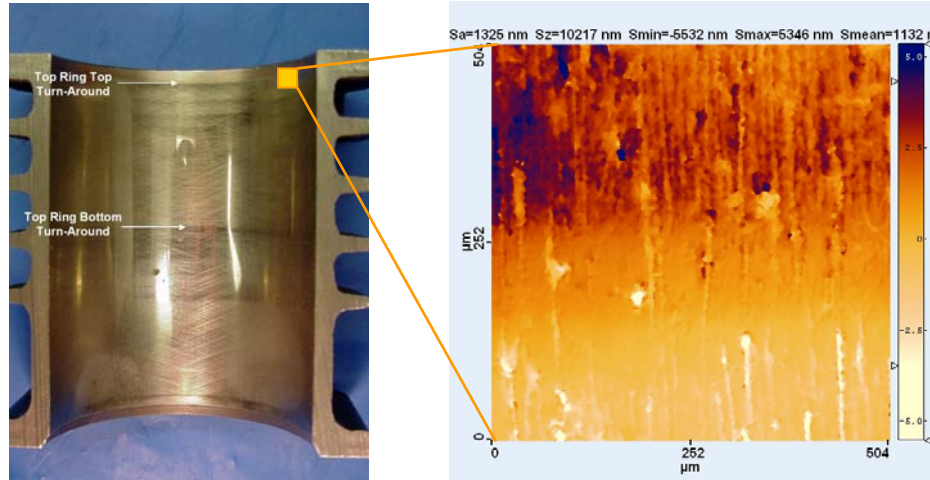
Figure 16
Silicon (Hard) Particle Dimension Data



3-D CYLINDER BORE WEAR MEASUREMENT

Another application of the 3-D replicate system is the measurement of wear depth in the area of ring travel.

Figure 17
Cylinder Bore Top Ring Turn-Around Area & Replicate Image



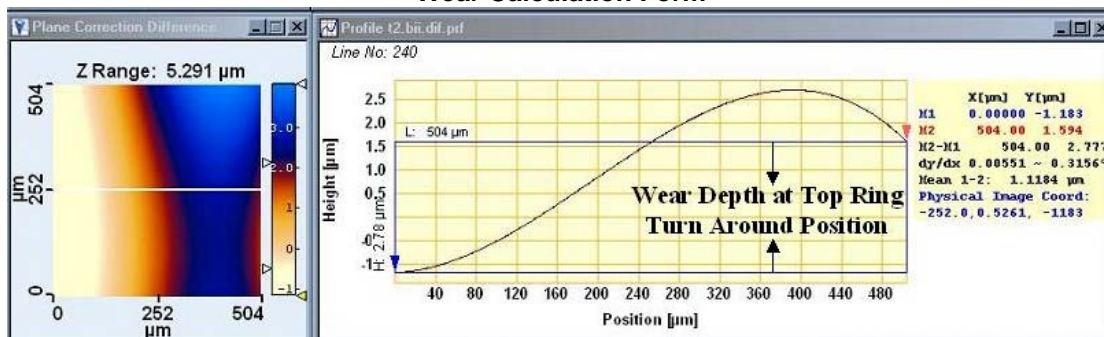
The software is able to separate form and roughness. In this example of an image from the top ring turn-around area of a cylinder, the following figure represents plane correction of the original image in order to obtain three-dimensional surface roughness parameters.

Figure 18
Plane-corrected Image and Profile



The form from which wear can be determined is represented in the generated profile:

Figure 19
Wear Calculation Form



A model for wear separate from top ring turn-around wear within the cylinder bore has been suggested⁶. The model is based on the material ratio curve and calculated from:

$$\text{Wear} = (S_K + S_{PK})_{\text{before test}} - (S_K + S_{PK})_{\text{after test}}$$

These values are derived from relocated 3-D measurements performed before and after engine tests. This relocation technique and the material ratios strongly correlate to the important part of the topography for describing wear.

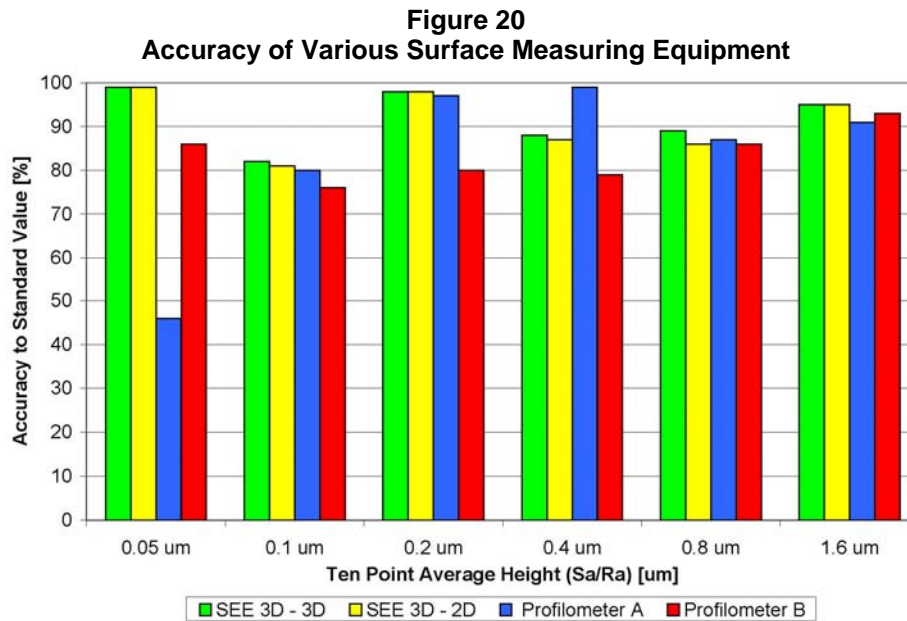
3-D REPLICATE SYSTEM ACCURACY

Extensive data has been collected from experiments in which the surface parameters from a replicate are compared with direct surface parameters from the same location on the specimen. The replicate material is designed to transfer the microfinish of a surface to a highly accurate and stable replicate which behaves like a metallic surface under an optical microscope. The replicate has very high resolution up to 0.1µm enabling accurate measurement of three-dimensional shapes.

Table 8
Direct vs. Replicate Comparison Data

	R_A		R_Z		R_{PK}		R_K		R_{VK}	
	Direct	Replicate	Direct	Replicate	Direct	Replicate	Direct	Replicate	Direct	Replicate
	0.433	0.4256	2.195	2.2614	0.4785	0.445	1.1065	1.1918	0.845	0.764
	0.418	0.433	2.455	2.421	0.577	0.5852	1.151	1.1646	0.7535	0.8228
	0.519	0.5146	2.7825	2.7816	0.7185	0.7228	1.4335	1.409	0.72	0.6778
	0.4675	0.4636	2.3015	2.4246	0.4215	0.5866	1.5755	1.5408	0.4505	0.4856
	0.449	0.4706	2.62	2.6794	0.501	0.6366	1.288	1.3064	0.949	0.7784
	0.38	0.4124	2.038	2.424	0.543	0.6708	1.045	1.2386	0.473	0.56
	0.462	0.499	2.363	2.74	0.479	0.403	1.367	1.352	0.566	0.529
	0.469	0.456	2.428	2.596	0.776	0.86	1.349	1.263	0.49	0.731
	0.368	0.377	1.995	1.987	0.598	0.584	1.022	1.21	0.478	0.388
	0.445	0.487	2.411	2.557	0.716	0.612	1.164	1.215	0.519	0.557
	0.581	0.587	3.38	3.317	0.969	0.805	1.375	1.385	1.311	1.261
	0.528	0.538	2.598	2.627	0.869	0.665	1.445	1.587	0.417	0.446
	0.565	0.505	2.955	2.857	0.514	0.5	1.611	1.469	0.663	0.741
	0.367	0.379	1.986	1.884	0.515	0.706	1.05	1.19	0.585	0.622
	0.438	0.422	2.431	2.698	0.651	0.713	1.146	1.329	0.787	0.749
	0.675	0.634	4.385	4.427	0.886	1.101	1.452	1.477	1.691	1.575
	0.447	0.455	2.299	2.116	0.404	0.422	1.355	1.308	0.65	0.612
	0.418	0.434	2.083	2.501	0.517	0.514	1.242	1.249	0.482	0.722
	0.408	0.403	2.155	2.292	0.547	0.527	1.098	1.15	0.683	0.793
	0.296	0.419	1.495	2.469	0.403	0.567	0.858	0.818	0.34	0.656
	0.401	0.451	2.517	2.7	0.707	0.742	0.899	1.205	0.883	0.943
	0.41	0.447	2.099	2.498	0.504	0.791	1.022	1.214	0.816	0.916
	0.501	0.477	2.421	2.431	0.478	0.507	1.773	1.388	0.547	0.623
	0.516	0.493	2.812	2.444	0.359	0.362	1.571	1.712	0.7	0.625
	0.382	0.42	2.54	2.531	0.402	0.335	0.844	1.084	1.005	0.821
	0.434	0.419	2.133	2.248	0.584	0.584	1.345	1.24	0.45	0.451
	0.59	0.563	3.018	3.371	0.583	0.569	1.062	1.37	1.296	1.287
Average	0.458	0.466	2.478	2.603	0.582	0.612	1.246	1.299	0.724	0.746
Maximum	0.675	0.634	4.385	4.427	0.969	1.101	1.773	1.712	1.691	1.575
Minimum	0.296	0.377	1.495	1.884	0.359	0.335	0.844	0.818	0.34	0.388

A set of data was taken using certified surface roughness standard sets from Flexbar and two stylus-based profilometers as shown below:



CONCLUSIONS

Many man-hours have been and are being spent on ways to better quantify cylinder bore surface finish. The advent of 3-D surface measurement has provided a whole new means of finish analysis. When coupled with the ability to make replicates of the surface of interest, especially cylinder bores, without destroying the component, this measurement technique has taken surface finish measurement analysis to a new level. The ability to generate three-dimensional images of surfaces (area) provides the means to specify and measure cylinder bore finish parameters that can be utilized to improve oil consumption. The use of these 3-D parameters provides the ability to reduce oil consumption caused by cylinder finishes through the ability to specify and develop models for predicting the effect on wear and oil consumption. Surface replicates and easy accessibility to interferometers permit three-dimensional surface analysis capability without the destruction of the component. The replicate can then be used for detailed analysis, and repeated measurements can be taken at a location without fear of damaging the surface texture. Replicates can be maintained for future analysis as well. Better functional parameters can be generated to determine wear, particle distribution on the surface, volume available for fluid retention, bearing area available, and much more.

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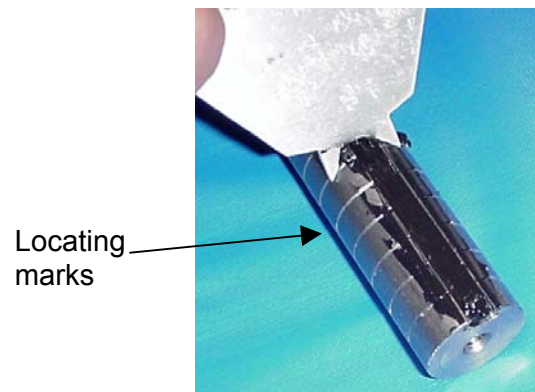
APPENDIX

Steps in Making Replicate and Acquiring Data

1. Clean specimen surface with lint free cloth and surface cleaning solution e.g. MEK
2. Apply replicating material into rod by slightly overfilling the slot



3. Use scraper to remove excess material from rod



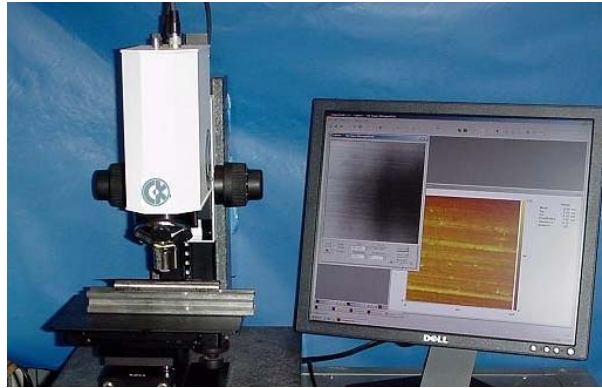
4. Insert rod into fixture, then insert fixture into cylinder



Fixture for bores <2.5"



5. Energize air cylinder with 40 psi opening the valve (flip up) on top of the fixture
6. Let unit set with air pressure for 5 minutes
7. Turn off air valve, separate rod from liner and remove fixture from bore
8. Remove rod from fixture and place under interferometer



9. Make sure image on screen is flat as possible by using tilting knobs in front of holding stage
10. Scan and save image
11. Open 3-D surface finish software with imbedded macros to produce 2-D surface image, 3-D surface image, and surface parameters
12. Use roughness analysis tool to generate surface parameters in 3-D or 2-D data (using line profile)