Why use areal surface texture measurement?

DMAC Meeting
University of Huddersfield
12th Oct 2006

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Taylor Hobson Chair of Surface Metrology
Limitations Of Profile Analysis

- Profile measurement is line measurement not area assessment
- Significant parameter variation on within a surface 20%+
- No relationship between surface finish & function
- “Parameters rash”
- Single line cannot identify pits or valleys, peaks or ridges
Comparing of $Ra$ values for the Profile of Different Surfaces

- Honed
- Turned
- Ground
Profile and Surface Plots
-- of a scratched lapped surface

Pits or scratches
2D vs 3D measurement

- Surface topography is three dimensional in nature;
- Any measurement and analysis of 2-D profiles or sections, even if properly controlled, will give an incomplete description of the real surface topography;
- The information to be provided by 3-D measurement is far more comprehensive than 2-D profiles or sections previously available.
Textured Rolled Steel Sheet
Areal Surface Classification:
*Pits Or Valleys, Peaks Or Ridges*
New Areal Parameters
for surface texture parameters are either

• **Field Parameters**
  use all the available data from the texture surface; Field parameters include the S-parameter and V-parameter sets.

  or

• **Feature Parameters**
  use only data from previously identified segments from the texture surface.
**S–Parameter Set (13)**

- **Amplitude Parameters** (6)
  - Root mean square deviation – Sq
  - Skewness – Ssk
  - Kurtosis – Sku
  - Maximum peak height – Sp
  - Maximum valley height – Sv
  - Maximum height of texture surface – Sz

- **Spacing Parameters** (2)
  - Fastest decay auto-correlation length – Sal
  - Texture aspect ratio – Str

- **Hybrid Parameters** (2)
  - Root mean square slope of the assessed texture surface – Sdq
  - Developed interfacial area ratio – Sdr

- **Fractal Parameter** (1)
  - Fractal dimension – Sfd

- **Other Parameters** (2)
  - Texture direction of the texture surface – Std
  - Peak Extreme Height – S95p
V – Parameter Set (9)

- **Linear areal material ratio curve parameters (5)**
  - Core roughness depth – Sk, Spk, Material portion – Svk;
  - Reduce peak height / valley depths – SMr1, Smr2

- **Void Volume (2)**
  - Core void volume of the texture surface – Vvc
  - Valley void volume of the texture surface – Vvv

- **Material Volume (2)**
  - Material volume of the texture surface – Vmp
  - Core material volume of the texture surface – Vmc
Feature Parameter Set (5)

- Surfstand (3)
  - Density of Summits – $S_{ds}$
  - Arithmetic mean peak curvature – $S_{sc}$
  - Ten point height of surface - $S_{5z}$

- Autosurf (2)
  - Closed void volume – $S_{va}$
  - Closed Peak Volume – $S_{pa}$
What is New
compared with ISO 4287, 13565 and 12085

Areal parameters are not simply an extension of 2D to 3D case:-

- Traditional profile parameters are only a simplified approach for manufacturing process control, they can not be used to diagnose product functional performance;
- Values of profile parameters are less robust because true surface texture is areal in nature.

With areal parameters
- Texture shape and direction can be assessed;
- Feature attributes can be estimated correctly;
- Connected and isolated features can be differentiated.
New Areal Parameters

for Surface Texture

• Field Parameter
  use all the available data from the texture surface;

• Feature Parameter
  use only data from previously identified segments from the texture surface.
S - Parameter Set (15)

- Amplitude Parameters (6)
- Spacing Parameters (3)
- Hybrid Parameters (3)
- Fractal Parameter (1)
- Other Parameters (2)

V - Parameter Set (9)

- Linear areal material ratio curve parameters (5)
- Void Volume (2)
- Material Volume (2)
S – Parameter Set
S - Parameter Set (15)

Amplitude Parameters (6)
- Root mean square deviation – Sq
- Skewness – Ssk
- Kurtosis – Sku
- Maximum peak height – Sp
- Maximum valley height – Sv
- Maximum height of texture surface – Sz

Spacing Parameters (3)
- Density of Summits* – Sds
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- Texture aspect ratio – Str

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- Arithmetic mean peak curvature* – Ssc
- Root mean square slope of the assessed texture surface – Sdq
- Developed interfacial area ratio – Sdr

Fractal Parameter (1)
- Fractal dimension – Sfd

Other Parameters (2)
- Texture direction of the texture surface - Std
- Ten point height of surface - S5z

* = feature parameter
Amplitude Parameters

Sq = 1.693 μm, Sz = 3.46 μm, Ssk = -0.153, Sku = 3.20

Ground Surface
Spatial Parameters

Vertical Milling

Sds = 4.76 $1/mm^2$ Str = 0.043 $\mu$m, Sal = 0.029 mm, Std = -7°

EDM

Spatial Parameters

Sds = 1.09 $1/mm^2$ Str = 0.55 $\mu$m, Sal = 0.016 mm, Std = *
V - Parameter Set
V - Parameter Set (10)

- **Core roughness depth** – Sk, Spk, Material portion - Svk; Reduce peak height / valley depths - SMr1, Smr2

- **Linear areal material ratio curve parameters** (5)

- **Void Volume (3)**
  - Core void volume of the texture surface – Vvc
  - Valley void volume of the texture surface – Vvv

- **Material Volume (2)**
  - Material volume of the texture surface - Vmp
  - Core material volume of the texture surface – Vmc

Material volume of the texture surface - Vmp
Core material volume of the texture surface – Vmc
V - Parameter Set

- Core roughness depth – Sk, Spk, Material portion – Svk;
- Reduce peak height / valley depths – Smr1, Smr2

Linear areal material ratio curve parameters (5)

- Spk = 1.666 (um)
- Sk = 4.182 (um)
- Svk = 1.775 (um)
- Smr1 = 9.6 (%)  Smr2 = 89.8 (%)
V - Parameter Set

Void Volume (3)
- Core void volume of the texture surface: $V_{vc}$
- Valley void volume of the texture surface: $V_{vv}$

Material Volume (2)
- Core material volume of the texture surface: $V_{mc}$
- Material volume of the texture surface: $V_{mp}$
V - Parameter Set

- Inverse areal material ratio of the texture surface – Smr\%(tp\%)
- Core void volume of the texture surface – Vmc, Vvc
- Valley void volume of the texture surface – Vvv
- Linear areal material ratio curve parameters – Sk, Spk, Svk, SMr1, Smr2

Areal Material Ratio of the topographic surface Smr(c)

Void Volume of the Topographic Surface

Areal material ratio curve of the Topographic Surface

Material Volume

(2)

Material volume of the texture surface - Vmp
Core material volume of the texture surface – Vmc
Functional Parameters Volume Family

Volume Family
\[ V_{mp} = 7.09 \times 10^3 \mu m^3/mm^2 \]
\[ V_{vc} = 4.07 \times 10^5 \mu m^3/mm^2 \]
\[ V_{vv} = 3.48 \times 10^5 \mu m^3/mm^2 \]
“3D surface texture case studies”

Case studies

• Case 1: Wear of UHMWPE Pins against TiN Coated Plates for use in Total Knee Implants
• Case 2: Wear Ranking of Hard on Hard Bearings for Prosthetic Hip Joints
• Case 3: Steel Sheet 2D vs 3D Characterisation
• Case 4: 2D VS 3D IC Engine Tests
• Case 5: Hard Disc Landing Zones
• Case 6: Diamond Turning of Micromoulds
Case 1: Wear of UHMWPE Pins against TiN Coated Plates for use in Total Knee Implants

- To enhance the wear properties of the metallic articulating surfaces of total knee implants femoral components have been coated with a layer of TiN.
- Two suppliers of nominally identical coatings.
- Coatings in specification $Ra = 30-50\text{nm}$.
- Vastly different wear properties.
- Can the 3D characterisation give parameters which show differences in wear of pins?
Case 1: Wear Test Results of UHMWPE Pins on TiN Coating

Material loss after 1 week ($10^6 = 1$ year in service)
Case 1: Wear Test Results of UHMWPE Pins on TiN Coating: Low Wear Surface

Plates measured using optical interferometer
Case 1: Wear Test Results of UHMWPE Pins on TiN Coating: High Wear Surface

M2 pre-test

TiN4

TiN6
For the M2 surface it is the peaks which function as load bearing asperities. For a given load the no of asperities will be of the order of tens/mm² rather than tens of thousands as is the case for the low wear M1 surface. It is therefore considered that at these contacting asperities the stress will be very high and will consequently induce wear in the form of a cutting action in the UHMWPE pins thus increasing the wear significantly.

Case 1: Wear Test Results of UHMWPE Pins on TiN Coating: The Functional Surface
Case 1: Wear Test Results of UHMWPE Pins on TiN Coating: Conclusions

- The origin of the high wear of the M2 surface is due to the presence of the large peaks in the surface topography.
- It is these peaks which act as load bearing asperities during function. Providing a suitable sample spacing of filtering is utilised Sds would be an ideal discriminator for wear performance.

<table>
<thead>
<tr>
<th>Amplitude Parameters</th>
<th>Spatial Parameters</th>
<th>Hybrid Parameters</th>
<th>Functional Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq</td>
<td>Sz</td>
<td>Ssk</td>
<td>Ska</td>
</tr>
<tr>
<td>〇</td>
<td>○</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Sds</td>
<td>Str</td>
<td>Sal</td>
<td>Std</td>
</tr>
<tr>
<td>●</td>
<td>○</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Sq</td>
<td>Ssc</td>
<td>Sdr</td>
<td>Sbi</td>
</tr>
<tr>
<td>●</td>
<td>●</td>
<td>●</td>
<td>○</td>
</tr>
<tr>
<td>Sbi</td>
<td>Svi</td>
<td>Vmp</td>
<td>Vvc</td>
</tr>
<tr>
<td>○</td>
<td>○</td>
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</tr>
</tbody>
</table>

Useful parameters for surface characterisation:

• The origin of the high wear of the M2 surface is due to the presence of the large peaks in the surface topography.
• It is these peaks which act as load bearing asperities during function. Providing a suitable sample spacing of filtering is utilised Sds would be an ideal discriminator for wear performance.
Case 2: Wear Ranking of Hard on Hard Bearings for Prosthetic Hip Joints

To minimise wear, hard on hard bearing surfaces are being considered for replacement hip joints.

<table>
<thead>
<tr>
<th>Material pairings on total hip replacements</th>
<th>Overall clinical wear rate (μm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femoral Head</td>
<td>Acetabular cup</td>
</tr>
<tr>
<td>metal</td>
<td>UHMWPE</td>
</tr>
<tr>
<td>Ceramic</td>
<td>UHMWPE</td>
</tr>
<tr>
<td>Metal</td>
<td>metal</td>
</tr>
<tr>
<td>ceramic</td>
<td>ceramic</td>
</tr>
</tbody>
</table>

Study: to relate surface topography and plasticity index to experimentally measured wear rankings

Semlitsch and Willert 2000
## Case 2: Wear Ranking of Hard on Hard Bearings for Prosthetic Hip Joints: Experimental Results

<table>
<thead>
<tr>
<th>Description</th>
<th>Wear rate (cu.mm/million cycles)</th>
<th>Overall</th>
<th>Bedding period</th>
<th>Steady State</th>
</tr>
</thead>
<tbody>
<tr>
<td>large dia Alumina/Alumina</td>
<td>0.076</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>large dia Alumina/CoCr cup</td>
<td>0.145</td>
<td>1.264</td>
<td>0.062</td>
<td></td>
</tr>
<tr>
<td>large dia CoCr/CoCr (Ultima)</td>
<td>0.829</td>
<td>0.975</td>
<td>0.602</td>
<td></td>
</tr>
<tr>
<td>small dia CoCr/CoCr</td>
<td>6.300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>medium dia CoCr/CoCr</td>
<td>4.850</td>
<td></td>
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**Wear Ranking Femoral head Acetabular cup $H$ (GPa) $E'$ (GPa)**

<table>
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<tr>
<th>Wear ranking</th>
<th>Femoral head</th>
<th>Acetabular cup</th>
<th>$H$ (GPa)</th>
<th>$E'$ (GPa)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Large dia ceramic</td>
<td>Large dia ceramic</td>
<td>22.0</td>
<td>378</td>
</tr>
<tr>
<td>2</td>
<td>Large dia metal</td>
<td>Large dia ceramic</td>
<td>4.2</td>
<td>370</td>
</tr>
<tr>
<td>3</td>
<td>Large dia metal</td>
<td>Large dia metal</td>
<td>4.2</td>
<td>363</td>
</tr>
<tr>
<td>4</td>
<td>Small dia metal</td>
<td>Small dia metal</td>
<td>4.2</td>
<td>363</td>
</tr>
<tr>
<td>5</td>
<td>Medium dia metal</td>
<td>Medium dia metal</td>
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<td>363</td>
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</table>

Test to $5 \times 10^6$ cycles of wear measured using CMM procedure and Gravimetric method.
Case 2: Wear Ranking of Hard on Hard Bearings for Prosthetic Hip Joints

• Wear is influenced by some combination of material and topographic properties. However wear mechanisms are so complex, particularly in a biological environment, that it may be unrealistic to look for an explicit and comprehensive wear model.

• Correlation of dimensionless parameters with wear might prove to be of more general applicability.

\[
\psi_{GW} = \left( \frac{E'}{H} \right) \sqrt{\frac{S_q}{\beta}} \\
\psi_{M} = \left( \frac{E'}{H} \right) \theta
\]

Greenwood & Williamson

Mikic

\[
S_q \beta S_{ds} \\
\beta = \text{mean summit radius of curvature } S_{sc}, \text{ where } \theta \text{ is the mean absolute profile slope } S_{dq}
\]

Whitehouse

Thomas & Blunt
Case 2: Wear Ranking of Hard on Hard Bearings for Prosthetic Hip Joints: Results

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Case 2: Wear Ranking of Hard on Hard Bearings for Prosthetic Hip Joints: Conclusions

A reasonable correlation with dimensionless parameters

Plasticity indexes poor, could be due to close hardness of surfaces

Hybrid parameters essential, especially if correct sample spacing is selected

Useful parameters for surface characterisation

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<td>Sku</td>
</tr>
<tr>
<td>●</td>
<td>o</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>
2D vs 3D as a measure of function

- Can 3D relate to function better?
- Can less measurements be made?
- How does optical compare to stylus?

Automotive Cylinder Liners
Blow by
Wear
Oil Consumption

Textured Steel Sheet
Friction BUT
Case 3: Steel Sheet
2D vs 3D Characterisation

EBT texture

SBM texture

ECD texture

Wyko-Somicronic Sa

3D parameter on Wyko (25 measures)

3D parameter on somicronic (3 measures)
Comparison between Sa and Ra. The bars are the mean value of 25 measurements for each steel sheet both in 2D and 3D and the error bars are calculated according to the 95% confidence level.
Steel Sheet 3D Measurement

EBT Sz

The X-axis: number of measures performed. Y-axis: the confidence interval in percentage for each case. For EBT surface and parameter Sz, the mean of 12 measures needs to be used to be within the tolerance ±10%. This tolerance is used since it is a practical rule-of-thumb that ±10% is an acceptable low value for dispersion of topography.
Conclusion: when measuring these uncoated steel sheets it is sufficient to take a mean value of 5 measurements to get 3D parameter values within ±10% at 95% confidence level, but one would need 10 – 20 2D-measurements.
The WC index (Wihlborg and Crafoord) (theory based on Beck et al.) is defined as:

\[ WC_{Index} = \frac{NIOP_t \times BL_{\alpha \text{fa}}}{\alpha} \]

The number of isolated oil pockets (NIOP\textsubscript{t}) multiplied by the border length of the lubricant area at area fraction of contact (BL\textsubscript{\alpha \text{fa}}) and divided by the area fraction of contact (\(\alpha\)). WC index gives information about the degree to which the contact zone will be supplied with lubricant.
Images of two sheet materials, a) ECD textured with a high WC index and a low friction. The other b) with a low WC index and a high friction coefficient is SB textured. The rolling direction is vertical. The size of the evaluated surfaces was 0.9 x 0.9 mm.
Steel Sheet
WC Index and Friction

Variation in coefficient of friction of different steel sheet topographies
Case 4: IC Engine Tests VOLVO

Factorial Designed Experiment (FDE)

• roughness of the piston ring with two levels (Ra)

• cylinder liners with two variables both with three levels. For the liners these were called “plateauxness” (Rvk/Rk) describing the surface structure and an amplitude parameter (Rz) describing the magnitude of the topography.

• Oil Consumption, Blow-By, Wear TDC & MID

<table>
<thead>
<tr>
<th>Ra ring</th>
<th>Rz</th>
<th>Rvk/Rk</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>0.6</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>0.6</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>0.2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>0.6</td>
<td>4</td>
<td>3</td>
</tr>
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<td>16</td>
<td>3</td>
</tr>
<tr>
<td>0.6</td>
<td>16</td>
<td>3</td>
</tr>
</tbody>
</table>
## IC Engine Tests VOLVO

### Parameter Correlation

#### 2D Parameters

<table>
<thead>
<tr>
<th>Correlation between</th>
<th>1 ; 0.9</th>
<th>0.9 ; 0.7</th>
<th>0.7 ; 0.5</th>
<th>0.5 ; 0.3</th>
<th>0.3 ; -0.3</th>
<th>-0.3 ; -0.5</th>
<th>-0.5 ; -0.7</th>
<th>-0.7 ; -0.9</th>
<th>-0.9 ; -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil consumption</td>
<td>Ra, R, RA, W, W/W, CR, GF, RA, Rp, Rv, Rsk, Rk, Rz</td>
<td>Rm, Rsk, V, AW, CL</td>
<td>AR</td>
<td>Raring, Mr1, Rv/Rk</td>
<td>Mr2</td>
<td>Rku</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blow-by</td>
<td>Ar</td>
<td>Ra, Rp, Rk, W, RA, W/W, CR, GF</td>
<td>Ra, Rp, Rg, Rm, Mr1, Rv/Rk</td>
<td>Rku</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wear</td>
<td>Rsk</td>
<td>Ra, Rp, Rp, Rg, Rm, Mr1, Rv/Rk, Rsk, V, W, W/W, AW, CL</td>
<td>Mr1, Mr2, AR</td>
<td>Rv/Rk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 3D Parameters

<table>
<thead>
<tr>
<th>Correlation between</th>
<th>1 ; 0.9</th>
<th>0.9 ; 0.7</th>
<th>0.7 ; 0.5</th>
<th>0.5 ; 0.3</th>
<th>0.3 ; -0.3</th>
<th>-0.3 ; -0.5</th>
<th>-0.5 ; -0.7</th>
<th>-0.7 ; -0.9</th>
<th>-0.9 ; -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil consumption</td>
<td>Sq, Sdq, Soc, Sdr, Sci, Sk, Spk</td>
<td>Ssk, Sal, Sc, Spk</td>
<td>Sz</td>
<td>Sr2</td>
<td>Sm</td>
<td>Std, Svi, Sv, Sr1</td>
<td>Ska, Strat, Svk/Sk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blow-by</td>
<td>Sal, Sc, Sk, Sr2</td>
<td>Sq, Sdq, Soc, Sdr, Sci, Sk, Spk, Svk</td>
<td>Sz, Ska, Ska, Strat, Ska, Std, Svi, Sci, Sr1, Svk/Sk</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wear</td>
<td>Svk</td>
<td>Sq, Sdq, Soc, Sdr, Sci, Sk, Spk, Svk</td>
<td>Sal, Svi, Sm, Sc, Sv, Sz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New wear model MID</td>
<td>Sq, Sal, Sdq, Soc, Sdr, Sci, Sk, Spk</td>
<td>Svi, Svk, Sm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>New wear model TDC</td>
<td>Sq, Sal, Sdq, Soc, Sdr, Sci, Sk, Spk</td>
<td>Sz, Ska, Sr2</td>
<td>Svi, Svk, Sm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### New Wear model

\[
\text{Wear} = (Sk + Spk)_{\text{before test}} - (Sk + Spk)_{\text{after test}}
\]
Case 5 Laser Zone Texturing: Parking Read Write Heads

- Laser features “scrape out the air bearing” and land the read write head.
- Manufacturer needs to know the geometry and variation of features and consistency of their spacing.

**raw data**

- Laser features “scrape out the air bearing” and land the read write head.

**levelled data**

- Manufacturer needs to know the geometry and variation of features and consistency of their spacing.
Laser Zone Texturing: Parking Read Write Heads

C: distance between the centres of two features in the same row

D: distance between two rows of features

ΔDia: maximum difference between the largest and shortest diameters of the feature

ΔDb: difference between the diameters of all features

Hmax: maximum height of the highest feature

Have: average height of all feature

Dave: average diameter of all features

Bnum: number of valid features

3D Surface

Best fit ellipse applied to each feature
Laser Zone Texturing: Parking Read Write Heads

Data Segmentation Step Height

<table>
<thead>
<tr>
<th>NO.</th>
<th>Mean (nm)</th>
<th>Max (nm)</th>
<th>Min (nm)</th>
<th>Ft (nm)</th>
<th>Area</th>
</tr>
</thead>
</table>

Laser Zone Texture Analysis
C = 16.177 μm
D = 16.324 μm
dDia = 0.23655 μm
dDb = 0.35777 μm
Hmax = 6.9252 nm
Have = 5.7382 nm
Dave = 8.341 μm
Bnum = 414 pts
Case 6: Diamond Turning of Micro-Mould for Backlight Optics

Diamond turning with rapid tool servo system

Image quality defined by the roundness of individual machined lens moulds. Outer moulds reduced roundness because of machine speed and feed difficulties.
Diamond Turning of Micro-Mould for Backlight Optics

Identify individual pits and assess roundness and waviness of pit edge

Edge detection on single pits

Data Segmentation Step Height

<table>
<thead>
<tr>
<th>Region</th>
<th>Mean (nm)</th>
<th>Max (nm)</th>
<th>Min (nm)</th>
<th>Pt (nm)</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-192.213</td>
<td>-179.497</td>
<td>-154.919</td>
<td>5.313</td>
<td>3622</td>
</tr>
</tbody>
</table>
Diamond Turning of Micro-Mould for Backlight Optics

- Fit LS circle to features
- Compute P-V value and peak count

Graphs showing:
- Good: P-V
- Spindle speed problem: P-V with higher peaks
- Servo problem: P-V with lower peaks and different pattern
Develop a data merging technique for localised pits; dilution using morphological filters
Conclusions

• Areal measurement more representative of functional surface

• Parameter more stable and less measurement needed function usually correlated to a useful subset

• Edge detection techniques combined with pattern analysis facilitates improved metrology

• Metrology extending into structured surface analysis using pattern analysis and CMM type geometrical descriptors.