Today’s Speakers

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Agenda

- Overview and Key Changes - Brian Renegar
- Outline of Additive Manufacturing Updates - Jason Fox
  - Brief Update of the section
  - What is needed in the future on the project team
- New Section on Functional Correlations - Chris Brown
  - Transition from AM into functional correlations
  - Discrimination and Curvature
- Question and Answer Moderator - Dan Schertz, B46 Standards Committee Vice Chair
Overview of Changes

• All Sections
  o Minor updates, fixes, tweaks
• Section 1
  o Definition changes
  o Changes to several Figures
  o $RSm$ – updates to calculation & examples
• Section 11
  o Table revisions for clarity
• App. B
  o Additive Manufacturing
• App. I
  o Table I-1 updated
• App. K
  o Functional Correlations
## Definition Changes

<table>
<thead>
<tr>
<th>2009</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>profile irregularity</td>
<td>profile element</td>
</tr>
<tr>
<td>def: profile peak + adjacent</td>
<td>def: profile peak + adjacent</td>
</tr>
<tr>
<td>profile valley</td>
<td>profile valley</td>
</tr>
<tr>
<td>def: point of maximum height</td>
<td>def: point of maximum height</td>
</tr>
<tr>
<td>profile peak</td>
<td>profile peak height</td>
</tr>
<tr>
<td>def: portion of profile above</td>
<td>def: max height of profile</td>
</tr>
<tr>
<td>mean line</td>
<td>peak</td>
</tr>
<tr>
<td>profile valley</td>
<td>profile valley depth</td>
</tr>
<tr>
<td>def: portion of profile below</td>
<td>def: max depth of profile</td>
</tr>
<tr>
<td>mean line</td>
<td>valley</td>
</tr>
</tbody>
</table>
Changes to \textit{RSm} Definition & Figure – 2009

- Only gives general guidance
- Does not include real-world examples

\textit{Mean spacing of profile irregularities, RSm}: the mean value of the spacing between profile irregularities within the evaluation length. In Fig. 1-13

\[ RSm = \frac{1}{n} \sum_{i=1}^{n} Sm_i \]

\text{NOTE:} The parameter \( RSm \) requires height and spacing discrimination. If not otherwise specified, the default height discrimination shall be 10\% of \( Rz \) (i.e., ±5\% of \( Rz \) from the mean line) and the default spacing discrimination shall be 1\% of the sampling length; both conditions shall be met.
Changes to $RSm$ Definition & Figure - 2019

New definition:

mean spacing of profile elements, $RSm$: the mean spacing of the profile elements calculated in both directions along the evaluation length.

$$RSm = \left( \frac{1}{n} \right) \sum_{i=1}^{n} S_{mi}$$

The parameter $RSm$ requires height and spacing discrimination. Profile elements are initiated or completed by full crossings of the mean discrimination band. Each profile element must also exceed a minimum lateral width.

If not otherwise specified, the default height for the mean discrimination band shall be 10% of $Rz$ (i.e., ±5% of $Rz$ from the mean line) and the default minimum profile element width shall be 1% of the sampling length; both conditions shall be met.

NOTES:
1. The default discrimination tolerances may not be appropriate for certain types of surfaces, such as plateau honed surfaces.
2. In Figure 1-4.2-1, see graphical and annotated examples of the application of the height and width discrimination rules.
Changes to RSm Definition & Figure - 2019

Legend:

A = the start of the profile.
B = in Direction 1, the first mean line crossing of the profile; it does not count as the beginning of a valid profile element because the profile does not fully cross the mean discrimination band.
B = in Direction 2, the termination point for Sm12; it is the last mean line crossing prior to the last full crossing of the mean discrimination band.
C = the start of Sm1; it is the last mean line crossing prior to a full crossing of the mean discrimination band.
D = a candidate mean line crossing where the profile does not exceed the lower limit of the mean discrimination band. Because it is not a full crossing, it does not count in either direction.
E = a candidate profile element where both the upper and lower limits of the mean discrimination band are crossed but the width of the candidate profile element is insufficient to meet the width requirement (see inset graph). This section of the profile will be combined with the next profile element.
F = the end of Sm6 and the beginning of Sm7. Such congruence is not always the case, as illustrated in C and B for Sm1 and Sm12.
New Fig. - Indications of Surface Lay

• Figure updated
• Same types of directionality are indicated
• Reference changed from ISO 1302:2002 to ASME Y14.36-2018
Section 11 - Updated Tables

- Tables have been updated for readability
- Gives guidance for Type C1, C2, & C4 periodic profile surfaces

### Table 11-7.3-1 Typical $Ra$ and $RSm$ Values for Type C1

<table>
<thead>
<tr>
<th>Mean Spacing of Profile Elements, $RSm$, mm</th>
<th>Selected Cutoffs, mm, to Check $Ra$</th>
<th>$Ra$, $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.08</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>0.03</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>0.1</td>
<td>0.8</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>0.3</td>
<td>2.5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

**GENERAL NOTE:** The values given assume negligible attenuation by the stylus or filter.

### Table 11-7.3-3 Typical Values of $Ra$ and $RSm$ for Type C2

<table>
<thead>
<tr>
<th>Mean Spacing of Profile Elements, $RSm$, mm</th>
<th>$Ra$, $\mu$m</th>
<th>$\alpha$, deg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>0.1</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>145</td>
</tr>
<tr>
<td>0.1</td>
<td>3.0</td>
<td>153</td>
</tr>
<tr>
<td>0.25</td>
<td>0.3</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>145</td>
</tr>
<tr>
<td>0.8</td>
<td>1.0</td>
<td>179</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>176</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>169</td>
</tr>
<tr>
<td></td>
<td>30.0</td>
<td>145</td>
</tr>
</tbody>
</table>

### Table 11-7.3-4 Typical Values of $Ra$ for Type C4

<table>
<thead>
<tr>
<th>Mean Spacing of Profile Elements, $RSm$, mm</th>
<th>$Ra$, $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
</tr>
<tr>
<td>0.8</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>25.0</td>
</tr>
</tbody>
</table>

**GENERAL NOTE:** Neglecting any attenuation by the filter.

**NOTE:** (1) The filter cutoff, $\lambda_c$, must be at least 5 times larger than the $RSm$ values shown here.

**GENERAL NOTE:** The nominal values given assume negligible attenuation by the stylus or filter.
Outline of Additive Manufacturing Updates

Dr. Jason Fox
Mechanical Engineer
Engineering Laboratory at the National Institute of Standards and Technology (NIST)
Outline of AM Updates

- Problems characterizing additive manufacturing (AM) surfaces
- How B46.1 addresses these problems
- PT 53: What’s next and how to get involved

Challenges for AM Surface Measurement

• Complex fabrication process
  o Dependent on many variables
  o Inconsistent
• Complexity in the AM surface
  o Large height variations
  o Steep slopes
  o Overhangs and undercuts
• Large variation in scales
  o Sub-micrometer to centimeters

Problems Characterizing AM Surfaces

- Large variations across the surface

Problems Characterizing AM Surfaces

- Strong dependence on the roughness average (Ra)
- Ra is likely insufficient for describing AM surfaces

Problems Characterizing AM Surfaces

- Lack of overlap in areas of expertise
  - Leads to miscommunication
  - *Did anyone notice I didn’t specify the filters used on the previous slide?*
- Key goal is to increase this overlap
How B46.1 Addresses These Issues

All contained in Appendix B-5:

• References to standard AM terminology, characterization best practices, and other relevant standards are provided
• Handling issues from cracks and porosity (similar to casting)
• Cautionary statements on limited knowledge base and wide range of AM systems and materials
PT53: What’s Next and How to Get Involved!

• Needs for non-metal materials (i.e., polymers, ceramics) is also required
• Goals:
  o Develop a stronger understanding of…
    ▪ Available parameters, filters, and their use with AM surfaces
    ▪ Sensitivity of parameters
    ▪ Uncertainty
  o Closing the knowledge gap
  o Development of functional correlations for AM
• Participation in PT 53 does not require ASME membership!
• Contacts:
  o Jason Fox: jason.fox@nist.gov
  o Kate Hyam: hyamk@asme.org
New B46.1 Section on Functional Correlations

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September 10, 2020

NONMANDATORY APPENDIX K
SUGGESTED TERMINOLOGY AND PROCEDURES FOR THE
EVALUATION OF *FUNCTIONAL CORRELATIONS* OF SURFACE
TEXTURES WITH PROCESSING AND PERFORMANCE
Where is Value in Measuring and Analyzing Surface Textures?

• Repeatability and reproducibility
  o Quality assurance
  o Agreement between buyer and seller
    ▪ Supports commerce

• Ability to discriminate with confidence
  o Quality assurance
  o Anthropology, Archaeology and Forensics

• Discovery of functional correlations
  o Product and process design
  o Dimensioning and Tolerancing roughness, waviness and lay
Two Functional Correlation Types: Processing & Performance

1st Texture vs Processing
2nd Performance vs Texture

Texture: combination of roughness, waviness, & lay is 1st a dependent variable & 2nd an independent variable

$y = 1.1571x + 0.9464$

$R^2 = 0.993$
Support: Evidenced-Based Specs for Product & Process Designs

**Design of manufacturing processes**
uses correlations of the 1st kind - between processing parameters and textures

**Design of products**
uses correlations of the 2nd kind - between textures and performance parameters
Rationale: New Manufacturing Methods Can Require New Texture Characterizations

Friction and fatigue performance should be markedly different for similar values of conventional height parameters like $S_a$ and $S_t$, or $R_a$ and $R_t$.

**Subtractive:**
Conventionally machined surface

**Additive:**
Fused Filament Fabrication (FFF aka FDM)
Average Roughness

\[ Ra = \frac{1}{n} \sum_{n}^{1} |z| \]

Subtractive - machined

\[ Rq = \sqrt{\frac{1}{n} \sum_{1}^{n} z^2} \]

Additive - FFF
Stronger functional correlations increase certainty in processing and performance.

Customer Needs  
((what adds value))

Functional Requirements  
((what it does))

Design Parameters  
((what it looks like))

Process Variables  
((how you make it))

Texture characterization parameter

Manufacturing process parameter

Roughness tolerance

Process tolerance

Abusive processes

\[ R_z = b + K \left( \frac{F}{H} \right)^{\frac{1}{2}} \]

(Brown and Savary 1991 Wear 141, 211)

Supports process design and process control
Example of a Correlation of the 1st Kind (Process-Texture)

Texture-process relations for machining by turning at WPI on a Haas SL10, with a 0.4mm tool nose Kennametal insert. Unpublished 2013. Used in ME1800 at WPI.

\[
R_z = \frac{f^2}{8r} + 1.4\mu m
\]

\[
R_z = \frac{f^2}{8r}
\]

measured

theoretical
Functional Correlations, 2nd Kind: Performance vs Texture

Supports product design

\[ P = P_1(R) \]

- Performance characterization parameter
- Texture characterization parameter
- Performance tolerance
- Roughness tolerance
Functional Correlations, 2\textsuperscript{nd} Kind: Performance vs Texture

Supports product design

\[ P = p_2(R) \]
Functional Correlations, 2\textsuperscript{nd} Kind: Performance vs Texture

Supports product design

\[ P = \rho_3(R) \]
Conventional Height Parameters Do Not Provide Strong Correlations

Conventional characterization parameters, e.g., Ra, Sa, do not describe textures adequately.

Stylus instruments often lack sufficient resolution.

Current specifications for product are based on experience with machining and grinding, which cannot be extended to additive.

How can:
- Measurement instruments and methods be chosen
- Appropriate characterization parameters be selected
- New characterization parameters be developed
- Useful statistical analyses be designed
R^2 Metric for the Strength of a Correlation

“…comparison of the strength of correlations of different texture characterization parameters, different measurement methods, or different filtering”

B46.1 appendix K
Strengths of Functional Correlations Depend on

- Measurements
- Texture characterization parameters
- Statistical analyses
- Scales
  - filtering cutoffs and multiscale characterizations (ch. 10 B46.1)

“If you cannot measure it, you cannot improve it”
William Thomson, 1st Baron Kelvin
1st Kind of Functional Correlation

Examples:
- 3-D printed
- Laser melted metal powder surfaces

Inconel-nickel based powder laser sintered parts

Lemoine, Adam Christopher; Velez, Joseluis Angel; Mancini, Matthew Philip, 2016, Multi-scale Surface Metrology of Additive Manufactured Surfaces, Worcester Polytechnic Institute, MQP
Laser Melted Metal Powder
As Measured and Outlier Filtered

Which provides stronger correlations with processing and performance variables?
Height Parameter vs Laser’s Linear Energy Density (LED)

Sv @500 Modes
$R^2 = 0.898$

Sv @250 Modes
$R^2 = 0.8574$
Area-Scale Analyses: Multiscale Geometric Characterization

B46.1 Section 10 Terminology and Procedures for Evaluation of Surface Textures Using Fractal Geometry

![Graph showing relative area vs. scale for different orientations (0°, 15°, 45°, 75°, 90°).]
Multiscale Regression Analyses
$R^2$ for Relative Area vs LED
Relative Areas at Strongest Scales: Two Different Angles of Deposition

![Graph showing relative areas at different linear energy density values for 0° Filtered in Mountains and 90° Unfiltered with respective R² values and scales.](image_url)
Fatigue Limit of Machined Parts: 2nd Kind of Functional Correlation

Example of a strong correlation using multiscale curvature analysis and regression testing.

Renderings of Measurements

-3° stress relieved transverse loading

45° stress relieved longitudinal loading
Fatigue Test Results
R^2 for Fatigue Limit vs Curvature vs Scale
Fatigue Limit and Curvature Correlation

Correlation (R²=0.96) between fatigue limit and curvature at 610μm
Procedure for Determining Functional Correlation
Strengths, $R^2$

Further reading:
Thank You Very Much For Your Kind Attention!
Moderator - Dan Schertz, B46 Standards Committee Vice Chair

- They’re living documents, the work has just begun!
- Interested in learning more about ASME B46.1 Surface Texture or how to get involved with the Committee?
  - Contact Kate Hyam (hyamk@asme.org)
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