Surfaces

“If God created Solids, the Devil created Surfaces.”

• Impression: surfaces flat & simple

• Reality: surfaces extremely complex

• Surface properties depend on
  ➢ topography
  ➢ method & history of surface formation
  ➢ surface & bulk composition
  ➢ environment
Surface formation example

- NaCl, FCC structure
  - Bulk properties depend on crystal’s atoms
  - Surface properties can depend on cleavage
  - Cleavage plane influences surface properties:
    Short dashed (plane) exposes white atoms
    Long dashed (plane) exposes blue atoms
    Inclined (plane) exposes white & blue atoms
Surface disrupts crystal structure ⇒ higher energy
- Unshared electrons
- Mechanical deformations

- Bulk: large grains (single crystals) consistent with crystal structure & lower energy levels
- Smaller grains @ surface from intense deformations & higher energy levels (1~100 µm)
- Bielby amorphous layer (~100Å) from machining (work hardened, quenched, alloy mixtures)
- Layer of compounds (~100Å): oxides, sulfides, etc.
- Adsorbed layer via van der Waals forces: hydrocarbons, water, atmospheric impurities, etc.
- Dust particles (~1 µm)
• Surfaces depend on history: how surface was made

• Layers may/or not be important, depending on size & phenomena:
  ➢ Can’t measure effect of thin films on mechanical deformations
  ➢ Same layer can insulate contact & impede electric conduction.
Surface Topography

• All surfaces rough: no smooth or flat

• Surfaces topography: peaks (asperities) & valleys (furrows). Size, shape, and distribution determined by surface production (machined, forged, plated, etched, etc.).

• On a typical 1 cm$^2$ surface, very many asperities.

• “Smooth” on large length scale is “rough” on smaller length scale

  • Characterization of surface texture
    ➢ Long wavelength (10 µm ~ 10 mm) undulations
      o Called “surface waviness”
      o Man made (scratches, machining marks, tool & die shapes, etc.)
      o Fourier series representations
    ➢ Shorter wavelengths (< 10µm))
      o Nature made bumps ⇒ random structure
      o Statistically characterized
SURFACE TOPOGRAPHY

• All surfaces are rough

• Surface features
  hills (asperities)
  valleys (furrows)

• Surface profile trace

surface height $Z \leq 100 \, \mu m$, $X \leq 88 \, cm$, $Y \leq 2.54 \, cm$

• Surface height descriptions

  Surface waviness
    sinusoidal structure
    Fourier series

  Surface roughness (random)
    Gaussian distribution model
    Fractal models
SURFACE TOPOGRAPHY DESCRIBES

Sinusoidal models
- surface heights $Z(x, y)$
- $Z = Z_{\text{wave}} + Z_{\text{rough}}$

$Z = 300 + 100 \sin[2\pi x] + 120 \cos[4\pi x] + 20 \sin[40\pi x] + 10 \sin[100\pi x]$

Surface waviness $Z_{\text{wave}}$
- long wavelengths
- macroscopic features
- man-made (often)

$Z_{\text{wave}} = 100 \sin[2\pi x] + 120 \cos[4\pi x]$

Surface roughness $Z_{\text{rough}}$
- short wavelength
- microscopic features
- deterministic or random
- very short: random

$Z_{\text{rough}} = 20 \sin[40\pi x] + 10 \sin[100\pi x]$
SURFACE WAVINESS EXAMPLE

Surface height $Z(X,Y) \leq 100 \mu m$, $X \leq L_x = 88$ cm, $Y \leq L_y = 2.54$ cm

Fourier series: waviness profile

$$Z(X, Y) = \sum A_{mn} \sin \left( \frac{m \pi x}{L_x} + \phi_m \right) \sin \left( \frac{n \pi y}{L_y} + \phi_n \right)$$

$A_{mn}$: harmonic amplitudes
$\phi_m, \phi_n$: phases of harmonic components
SURFACE ROUGHNESS EXAMPLE

SEM photo: electroplated gold on copper

waviness and roughness apparent

scale: ~200 µm
Measure Surface Topography “Bumps” via

- Profilometer, similar to phonograph tone arm. Stylus “rides” surface ⇒ “trace” signal.
- Optical interference techniques that utilize path differences
- Electron microscope photographs
- Atomic force microscope (micro-profilometer for nano measurements)
SURFACE PROFILE MEASUREMENTS

Profilometer
- stylus travels surface
- motions $Z(x)$ trace profile
- stylus = filter
  - big/small bumps
  - stylus cannot sense

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Optical methods: bumps create optical path difference

- scan surface $\Rightarrow$ three dimensional image
- profile extracted
Optical Interferometric Microscope
Atomic Force Microscope

- Micro-profilometer
- Cantilever beam rides surface
- Stylus: nano-meter curvature
- Laser interferometer detects beam deflections
- Sub-nanometer range

AFM image of graphite atoms
AFM image of “contact bump”
SURFACE TOPOGRAPHY PARAMETERS

- Locating zero-line:
  \[ z_0 = \frac{1}{n} \sum_{i=1}^{n} z_i = \frac{1}{L_x} \int_0^L z(x)dx \]

  \[ \bar{z}_i = z_i - z_0 \]

  \( z_0 \): DC component

  \( \bar{z}_i \): AC component
Historical Quantities

- Centerline Average (CLA)
  \[ R_a = \frac{1}{n} \sum_{i=1}^{n} |z_i| \quad \left( = \frac{1}{L_x} \int_{0}^{L} |z(x)| \, dx \right) \]
  measures roughness excursion from zero-line

- Root Mean Square (RMS)
  \[ R_q = \sqrt{\frac{1}{n} \sum_{i=1}^{n} z_i^2} \quad \left( = \frac{1}{L_x} \int_{0}^{L} z^2(x) \, dx \right) \]
  also measures excursion

- Not unique: different profiles / same \( R_a \), \( R_q \)

- Other measures

  Maximum peak to valley
  \[ R_t = \max \limits_{\text{heights}} z - \min \limits_{\text{heights}} z \]

  Average \( R_t \) over segments: \[ R_z = \frac{1}{n} \sum_{i=1}^{n} R_{ti} \]
STATISTICAL QUANTITIES

• Surface height distributions

\[ Z(x) \]

• Surface height \( z \) treated as random variable

• Some surfaces almost Gaussian

\[
F(z) = \frac{1}{\sigma \sqrt{2\pi}} \ e^{-\frac{1}{2} \left( \frac{z-\mu}{\sigma} \right)^2}
\]

• Expected values of functions with distributions

\[
E \left[ g(z) \right] = \int_{-\infty}^{\infty} g(z) \ F(z) \ dz
\]

• Moments: \( g(z) = z^r \) related to historical & other quantities

\[
E \left[ z^r \right] = \int_{-\infty}^{\infty} z^r F(z) \ dz
\]
- $R_a$: 1\textsuperscript{st} moment
  
  \[ R_a = CLA = \int_{-\infty}^{\infty} zF(z)dz = 2\int_{0}^{\infty} zF(z)dz \]

- $R_q$: 2\textsuperscript{nd} moment
  
  \[ R_q = RMS = \sqrt{E\left[z^2\right]} = \sigma = \int_{-\infty}^{\infty} z^2F(z)dz \]

- Skewedness $s$: 3\textsuperscript{rd} moment ($r = 3$)
  
  \[ s = E\left[z^3\right]/\sigma^3 = \frac{\int_{-\infty}^{\infty} z^3F(z)dz}{\sigma^3} \]

- Kurtosis $k$: 4\textsuperscript{th} moment ($r = 4$)
  
  \[ k = E\left[z^4\right]/\sigma^4 = \frac{\int_{-\infty}^{\infty} z^4F(z)dz}{\sigma^4} \]
• Autocorrelation function

\[ R(l) = \lim_{L \to \infty} \frac{1}{L} \int_{-L/2}^{L/2} z(x)z(x + l)dx \]

\[ R(l) = \frac{1}{N-1} \sum_{x=1}^{N-1} z(x)z(x + l) \]

• Power spectral density function \textit{PSD}

\[ PSD(\omega) = \frac{2}{\pi} \int_{0}^{\infty} R(l) \cos \omega dl \]

= Fourier transform of autocorrelation function

o Frequency domain information on profile
FRACTAL MODELS

• Surface roughness characterization
• Describes natural "random" processes
• Poor model: man-made surfaces

• Roughness characterized via spatial frequency $\omega$:
  o Surface profile $z = z(x)$
  o Fourier transform $Z(\omega) = \int_{-\infty}^{\infty} z(x)e^{-j\omega x} dx$
  o Power spectral density: $PSD = |Z(\omega)|^2$
  o Plot log $PSD$ versus log $\omega$
  o Similar to Bode plot

\[ PSD(\omega) = \frac{C}{\omega^{5-2D}} \]

• Fractal dimension $D$ characterizes surface roughness
  o Valid over several orders of magnitude
  o Describes bump on bump "random" processes
Fractal Dimension & Geometry

- Physical geometry described by fractal dimension $D$

<table>
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<tr>
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- Fractal geometry describes how object fills a space

- Note repeated structure at different lengthscales

- Repeated structure can capture “bumps on bumps” of nature’s surfaces
NATURE OF CONTACT

Rough surfaces contact

Highest peaks on highest peaks

Contact area = discrete islands

Real contact area small fraction of apparent area

Consequence

contact stresses higher
heating (friction) more intense
electrical contacts: local constriction resistance
CONTINENTAL ANALOGY OF CONTACT

- Earth's surface rough: mountains & valleys
- Place South America on North America
- Contact: highest peaks against highest peaks
- Andes/Appalachia Highlands/Rockies
- Apparent contact area large, real contact area small
- Contact between bodies similar
ROUGH CONTACT MODELS

• Greenwood & Williamson

• Rough surfaces contact: current separation = d

• Asperities contact

$$\alpha = (z_1 + z_2) - d$$

$z_1, z_2$ surface heights, upper & lower
• Instrument measures relative to its reference frame

• Zero line location $z_{ref}$:

$$\sum_{i=1}^{n} (z_{i}^{inst} - z_{ref}) = 0$$

• Model asperities as spheres

• Relate contact quantities to surface heights $z = z_1 + z_2$ (random variable)

  on $i^{th}$ asperity, contact force/elastic

  $$P_i(z) = C \alpha^{3/2} = C (z - d)^{3/2} \quad \text{(Hertz)}$$

• Expected values $\Rightarrow$ macroscopic contact parameters
Contact force: \[ P = N \int_{d}^{\infty} P_i(z) F(z) \, dz \]

N: total number asperities
Lower limit: \( d = \) critical \( z \) needed for contact

Similar evaluations \( \Rightarrow \) real contact area, conductance, etc.