Size and Shape Characterization for Shot-Peening Impingement Models

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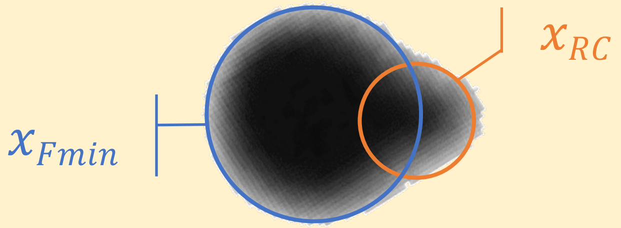

- Dynamic image analysis can quantify size and shape distributions of cast and cut-wire shot.
- Size and shape characteristics are used in a peening impingement model:
  - Model accounts for shot momentum and radius of curvature (ROC) at the point of impact.
  - Parameters include shot particle's size-dependent mass, shape-dependent ROC, and probability function for ROC selection based on orientation of the shot particle.

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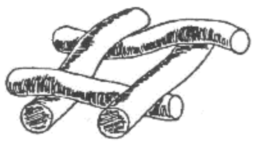
Characterization of shot size and shape distributions

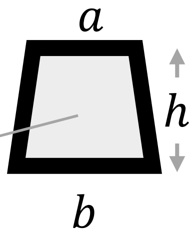
Legacy methods & specifications:

- **Size analysis**; mass fraction through sieve openings.

wstyler.com



$D = \sqrt{(a+b)\cdot h/2}$

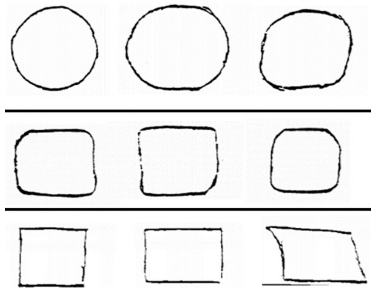


- **Shape inspection**; qualitative comparison to 2D archetypes.

Acceptable

Marginal

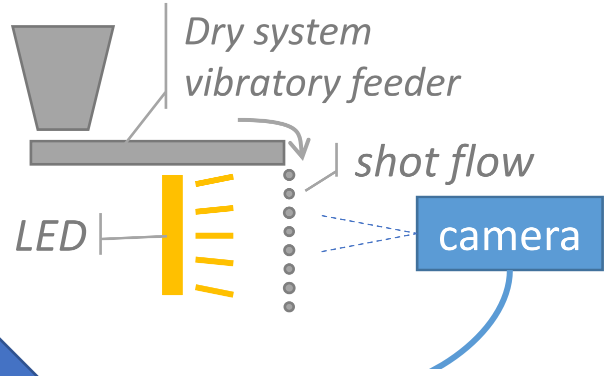
Unacceptable



Dynamic image analysis of Shot Particles:

Dry system: size 100 - 3000 um;
Wet system: 10 – 300 um.

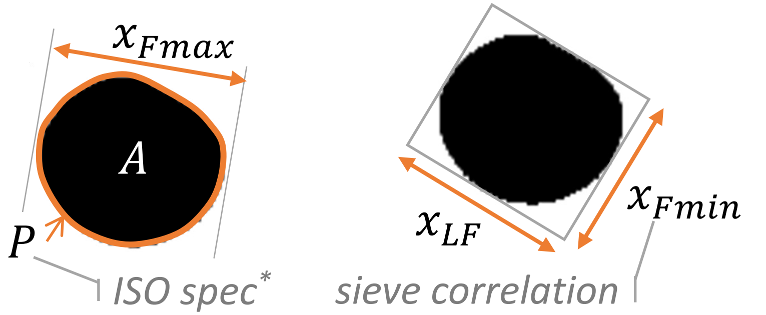
- 2D projections of shot particles, randomly oriented.[†]



~ 10k - 50k images

- **Quantitative analysis for BOTH size and shape:**
  - Shot size and mass (~ peening work):
    $x_A = \sqrt{4A/\pi};\ M = \rho \frac{\pi}{6} {x_A}^3$
  - Shot Shape (~ impact stress): $FF = 4\pi A/P^2$
    - Elongation: $AR_{box} = xF_{min}/x_{LF}$
      $AR_{ISO} = xF_{Fmin}/xF_{Fmax}$
    - Irregularity: $EFF = \beta\pi A/P^2$;
      $\beta = \left(1.5\cdot(AR+1)/\sqrt{AR}-1\right)^2$

Analysis: area, perimeter, linear dimensions



[†]*Dry system: Canty SolidSizer (JM Canty, Buffalo, NY): 5-15 um/pixel.* *ISO 9276-6 (2008), Cauchy-Crofton perimeter.

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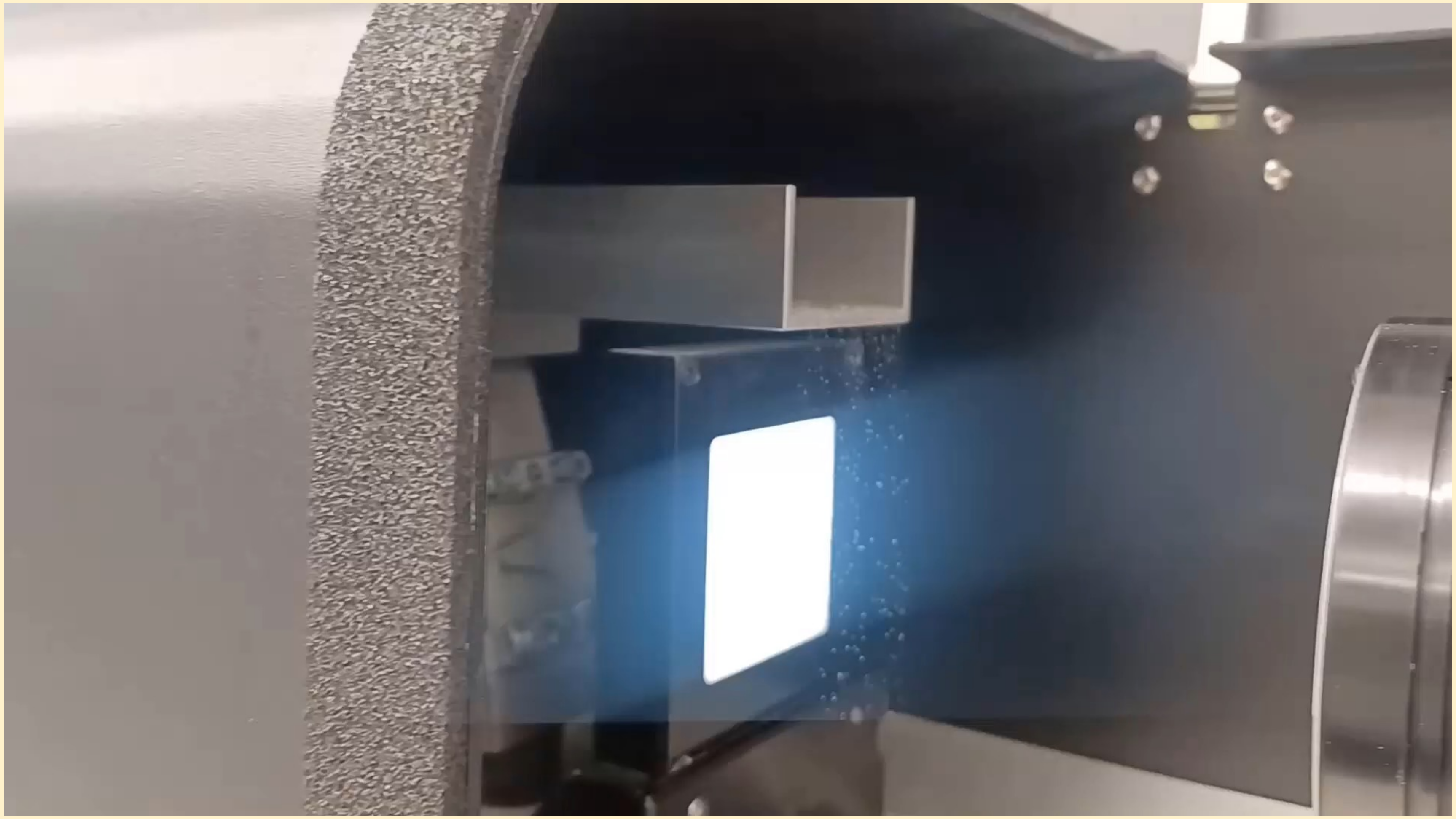
Dynamic imaging, S170 cast shot



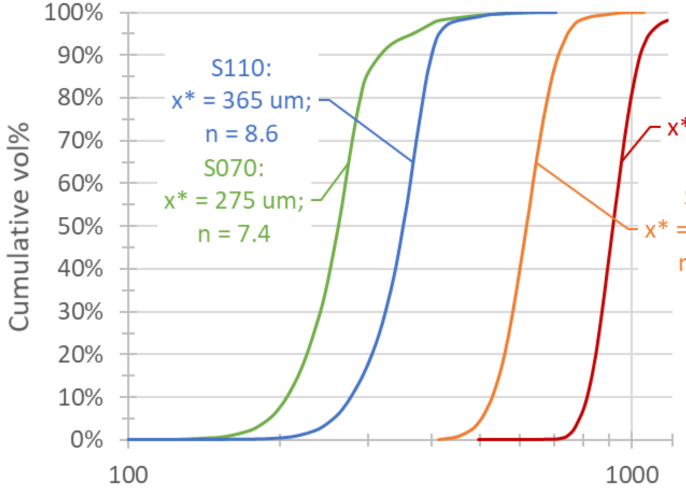
Size & shape distributions, selected cast and cut-wire steel shot

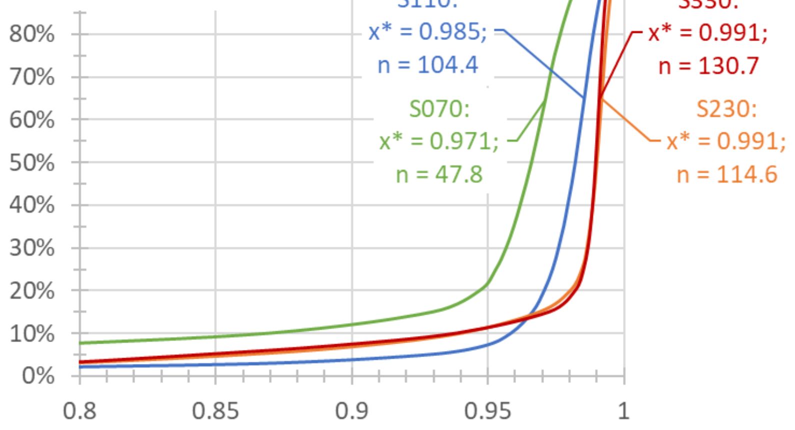
Size: area eq. dia., x_A

Shape: Form Factor, FF

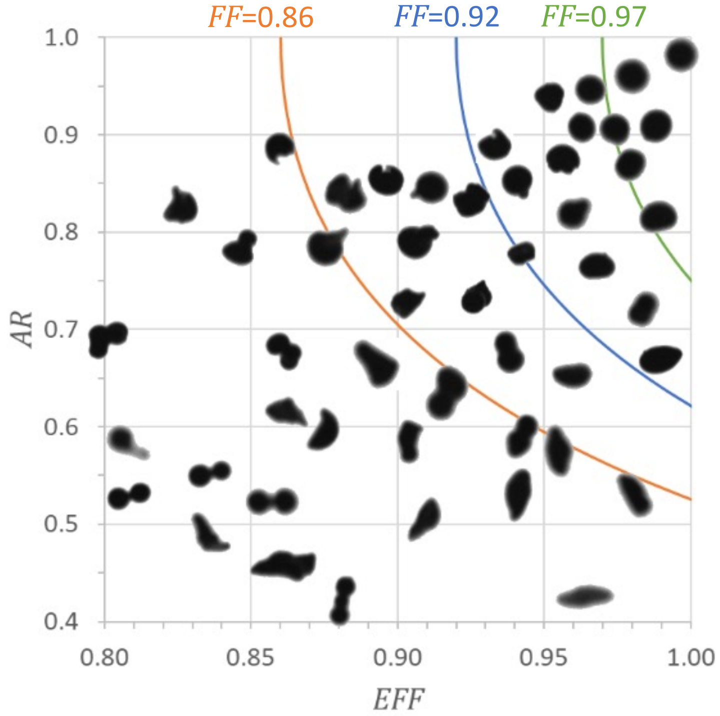
Detailed Shape Map (S70)

Cast (Ervin Industries)

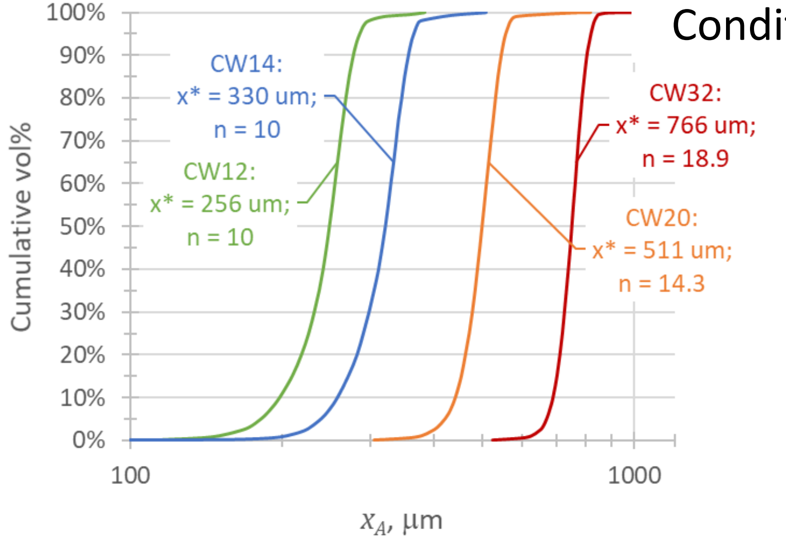


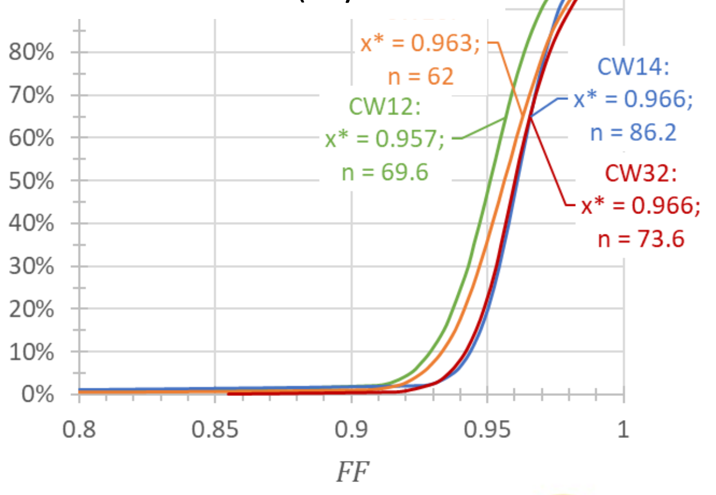


Thresholded grayscale images illustrate detailed features.



Conditioned Cut Wire (Toyo Seiko





Shape factor mapping using orthogonal factors:

- (1,1) is a spherical projection (circle)
- Aspect ratio, AR, → elongation;
- Elliptical Form Factor, EFF, → perimeter irregularity;
- ISO Form Factor, FF, is a lumped-sum measure of both.

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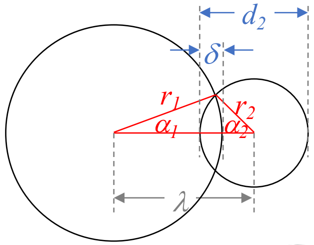
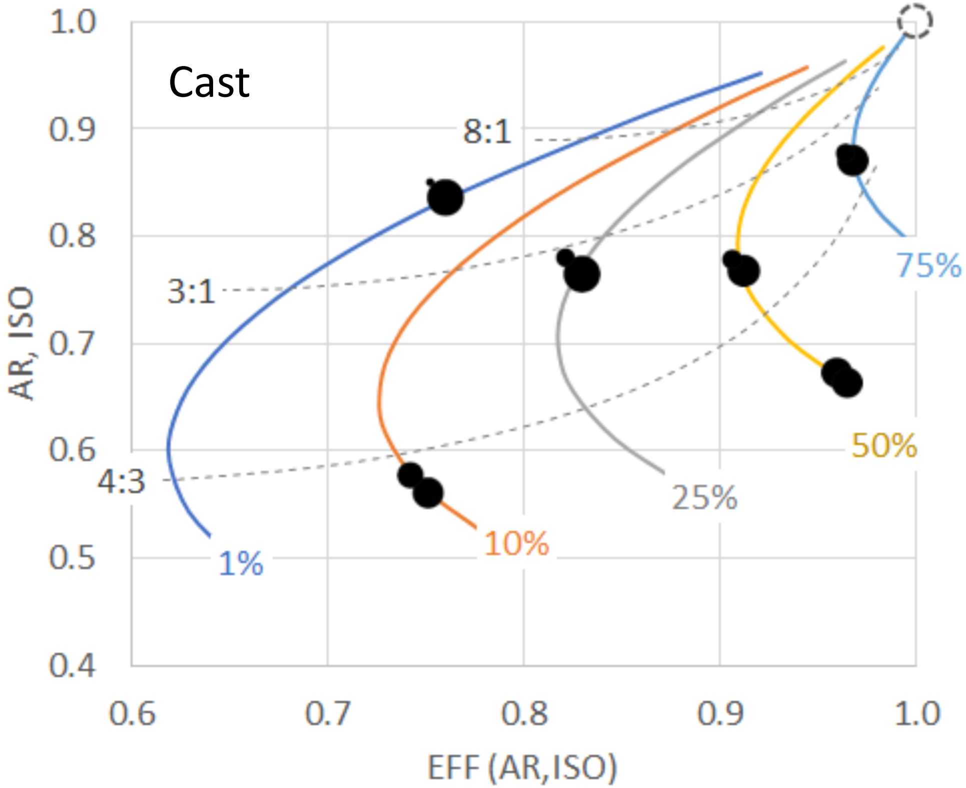
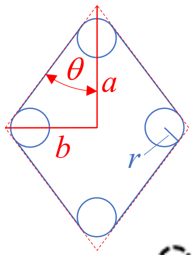
Shape archetypes → contact curvature

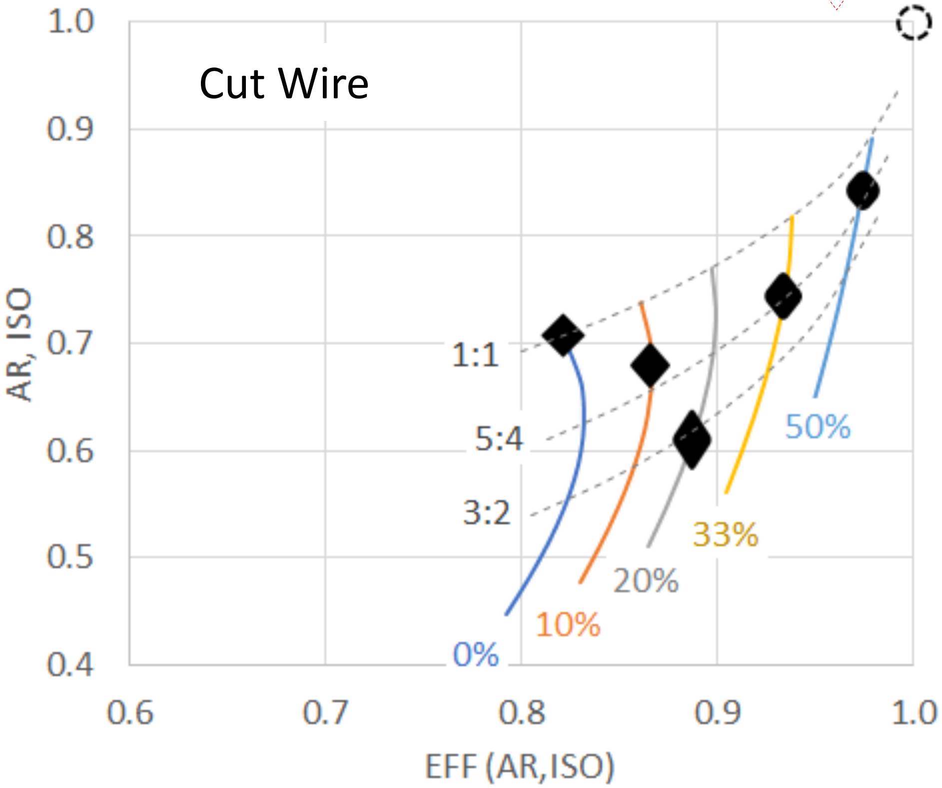
Cast w/ satellites:
- Degree of overlap (in color)
- Satellite size ratio (dashed)





Conditioned Cut Wire:
- Degree of rounding (in color)
- Cut orientation (dashed)





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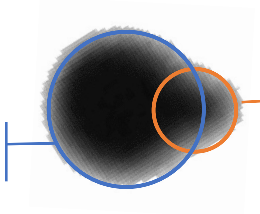
Size and shape: Express shape as glued-spheres

x_{Fmin} and x_{RC} are contact curvatures, mass (energy) ~ x_A^3



S70	D5	D15	D25	D50	D75	D85	D95
x_A	191	218	234	261	283	297	367
x_{Fmin}	183	206	220	245	267	278	296
x_{RC}	113	152	170	199	220	229	240

CW12	D5	D15	D25	D50	D75	D85	D95
x_A	182	209	226	248	264	272	285
x_{Fmin}	173	196	210	228	242	249	263
x_{RC}	120	139	150	171	190	199	214

S110	D5	D15	D25	D50	D75	D85	D95
x_A	256	292	315	351	379	391	413
x_{Fmin}	251	282	304	341	364	376	394
x_{RC}	190	229	251	289	315	327	345

CW14	D5	D15	D25	D50	D75	D85	D95
x_A	239	271	290	320	340	350	365
x_{Fmin}	223	251	270	295	311	318	333
x_{RC}	163	185	199	227	251	263	282

S230	D5	D15	D25	D50	D75	D85	D95
x_A	502	545	570	617	667	694	745
x_{Fmin}	476	521	548	595	641	666	705
x_{RC}	336	427	466	524	577	603	645

CW20	D5	D15	D25	D50	D75	D85	D95
x_A	421	453	469	498	524	535	554
x_{Fmin}	380	401	414	437	455	464	477
x_{RC}	298	325	341	369	396	411	432

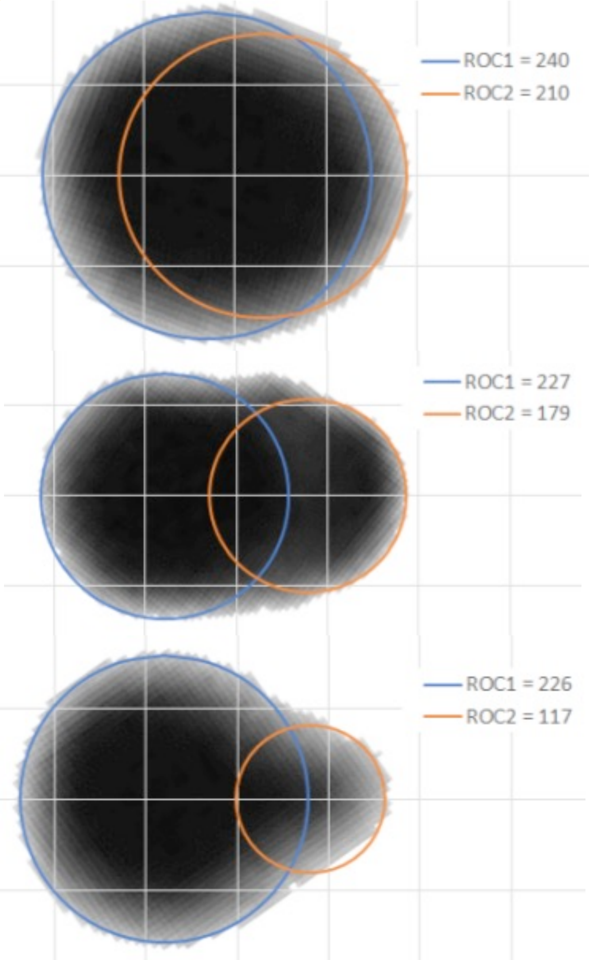
S330	D5	D15	D25	D50	D75	D85	D95
x_A	786	832	859	916	978	1013	1082
x_{Fmin}	761	805	831	886	942	969	1019
x_{RC}	523	681	729	800	862	896	944

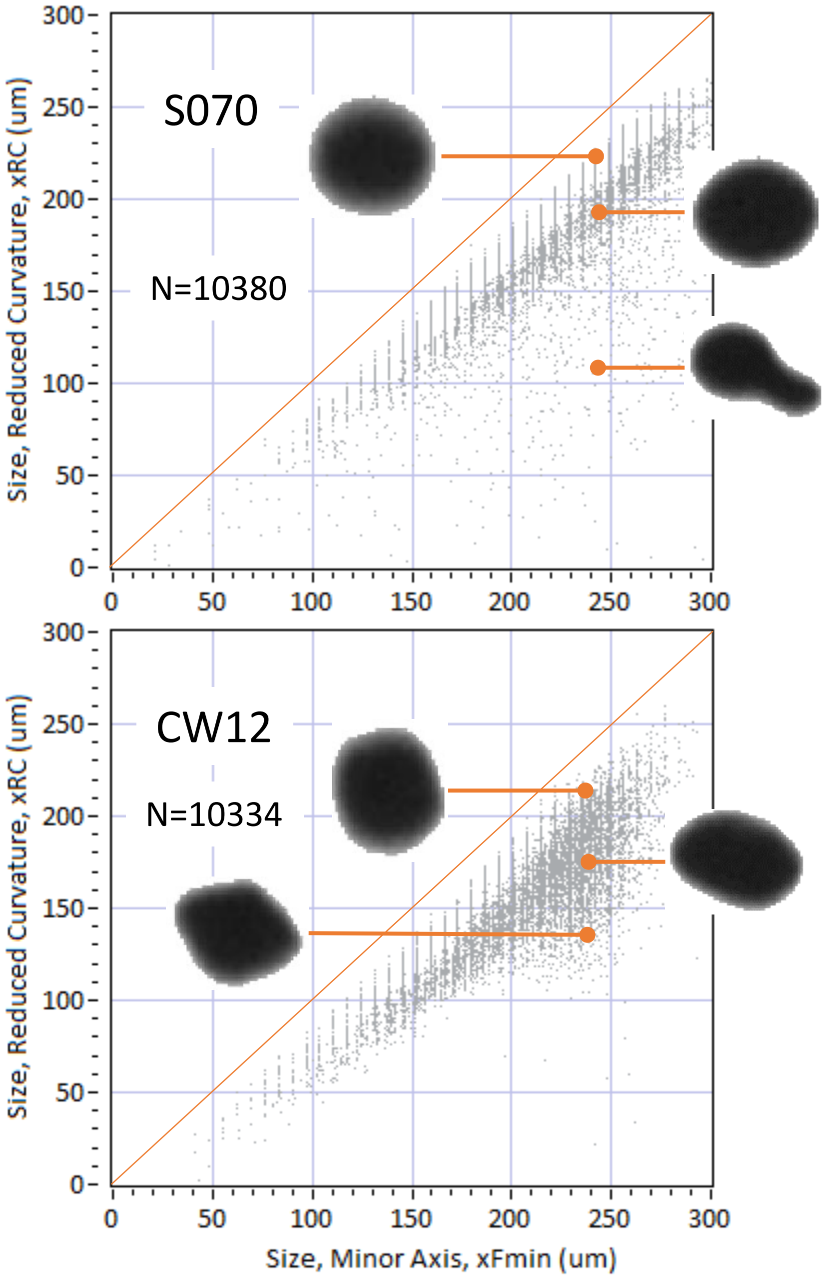
CW32	D5	D15	D25	D50	D75	D85	D95
x_A	668	701	718	750	779	794	818
x_{Fmin}	615	638	650	677	700	711	726
x_{RC}	441	494	522	569	608	628	661

Glued-sphere representation of contact curvature

Model shot shape effects as overlapping spheres having characteristic Radii of Curvature (ROC):

- x_{Fmin} → $ROC1$
- x_{RC} → $ROC2$
- Reduced curvature, x_{RC}, and impact probabilities determined using:
  - x_{Fmin},
  - x_{Fmax},
  - A
- Details in report.





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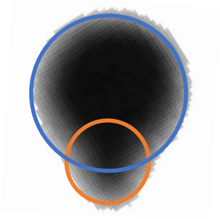
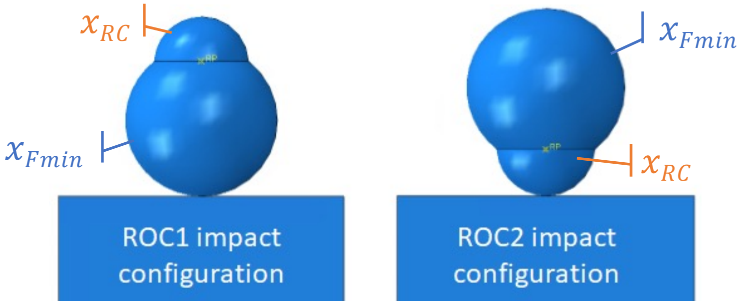
Peening impact w/ glued-sphere model

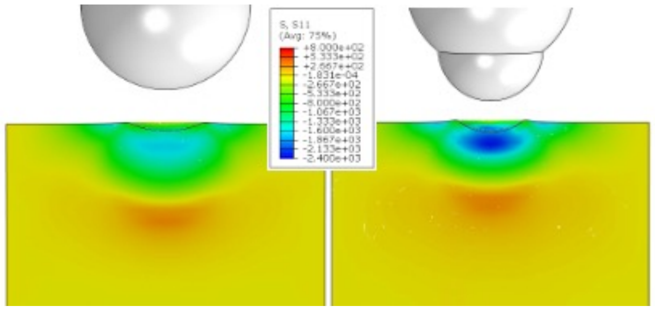


Example from DIA characterization:

- $A \;= 0.181\ mm^2$
- $x_A = 480\ \mu m$
- $V \;= 0.058\ mm^3$
- $\rho = 7.8\ g/ml$
- $m \;= 0.45\ mg$
- $x_{Fmin} = 453\ \mu m$
- $x_{Fmax} = 573\ \mu m$
- $x_{RC} \;= 235\ \mu m$

Discrete impact effects – shape dependent

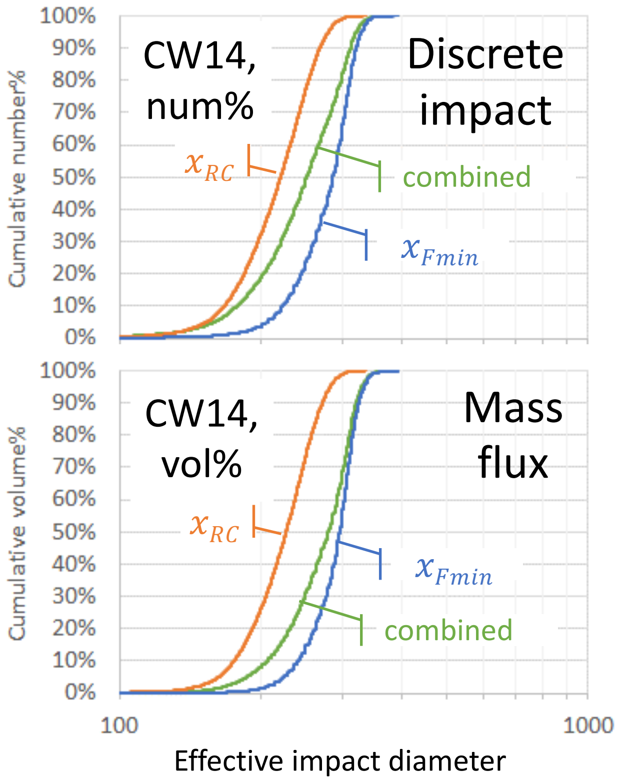




FEM using simple Hertzian contact model – sphere on plate

(ABAQUS Inc.)

Distribution of impact curvature



Shape broadens the distribution of impact curvature. It affects:

- Dimple size,
- Compressive depth profile.

Glued-sphere model incorporates shape effects into simplified statistical frameworks:

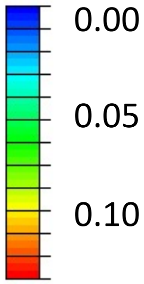
- Discrete impacts (# distribution);
- Mass flux (volume distribution).

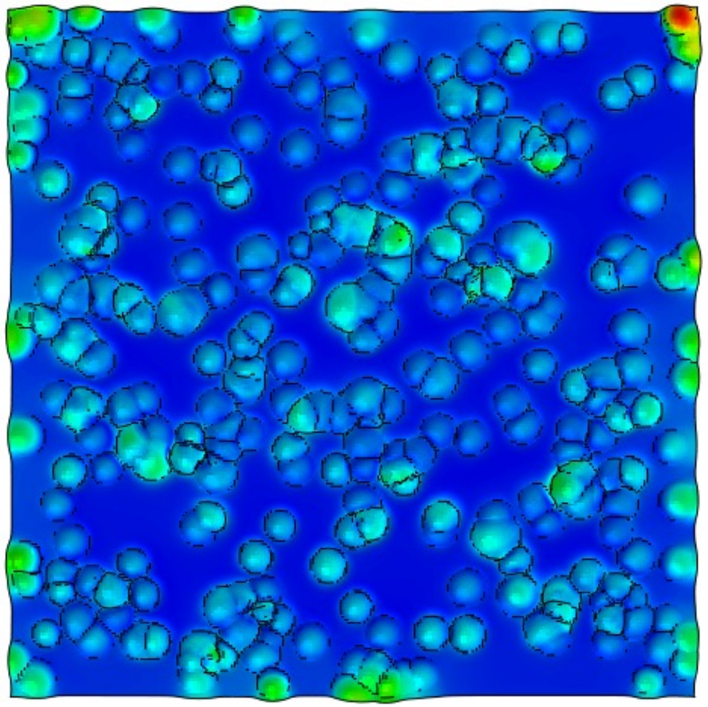
Peening texture with random impacts, (312 impacts → ~100% coverage)

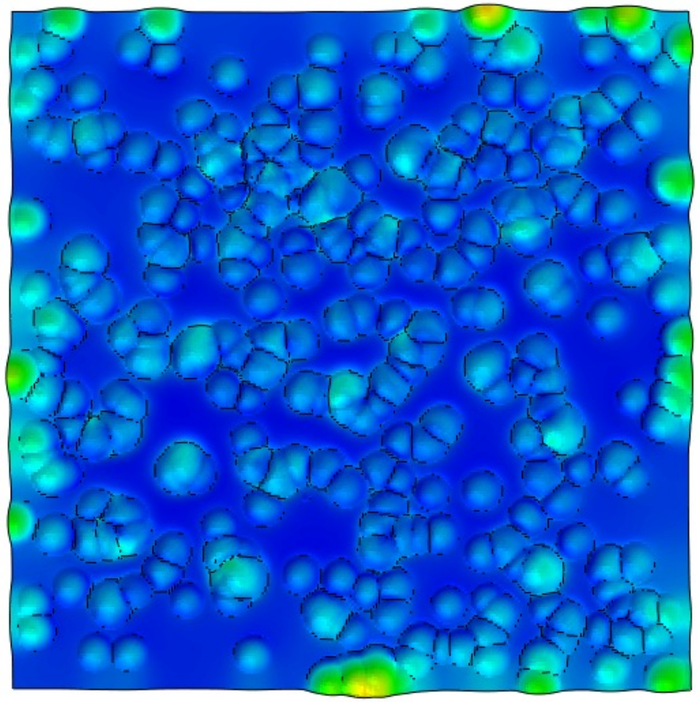
Glued-sphere model (x_{Fmin}, x_{RC})

Area-Equivalent (x_A) Diameter Model

Characteristic depth
of compression, mm







Qualitatively, x_A simulations appear more uniformly distributed..

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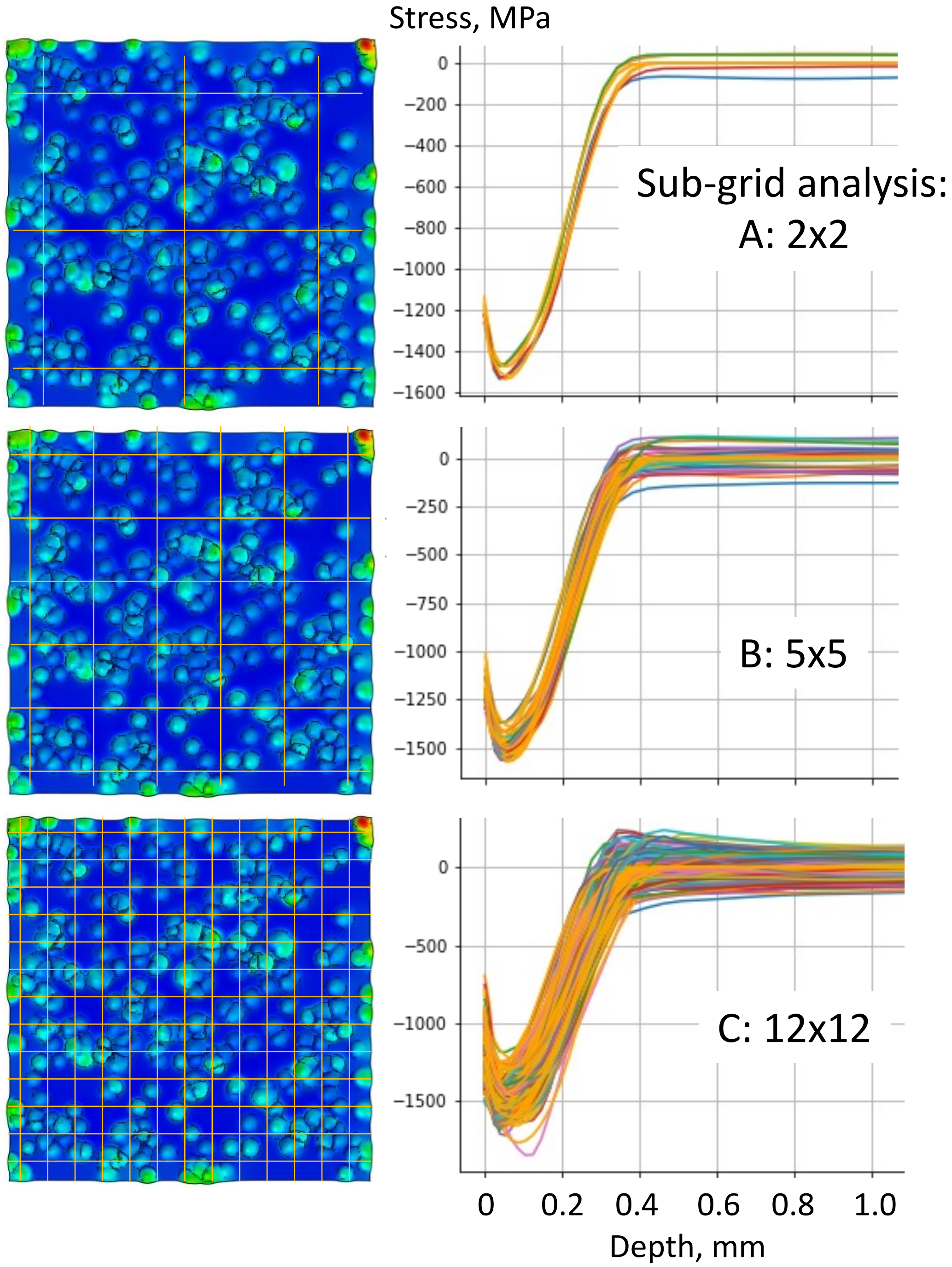
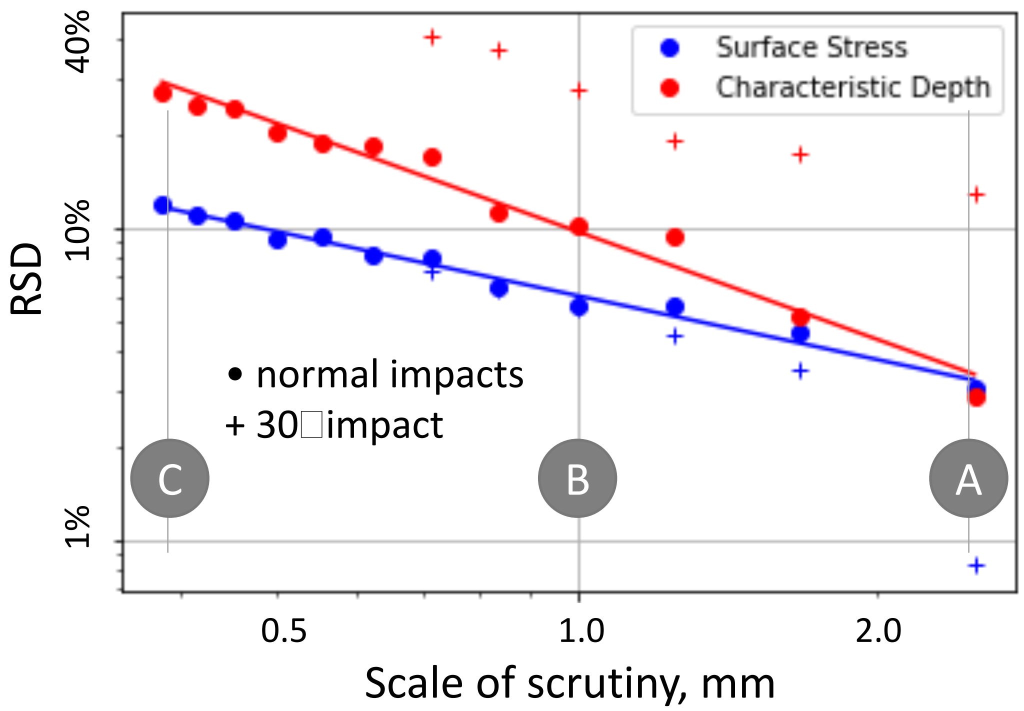


Statistical quantification of surface coverage and depth profile texture (RSD)

- Relative standard deviation (RSD) as a function of sampling scale.
- At a given scale of scrutiny, heterogeneity of discrete impacts contributes to higher RSD of the stress field; as scale ↓, RSD ↑.



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Work in progress: Shot peening process flowsheet model

At steady state:

- Mass balance of media replenishment with breakage removal:

$$\dot{M}_{replenish} = \dot{M}_{breakage} + \dot{M}_{leakage}$$

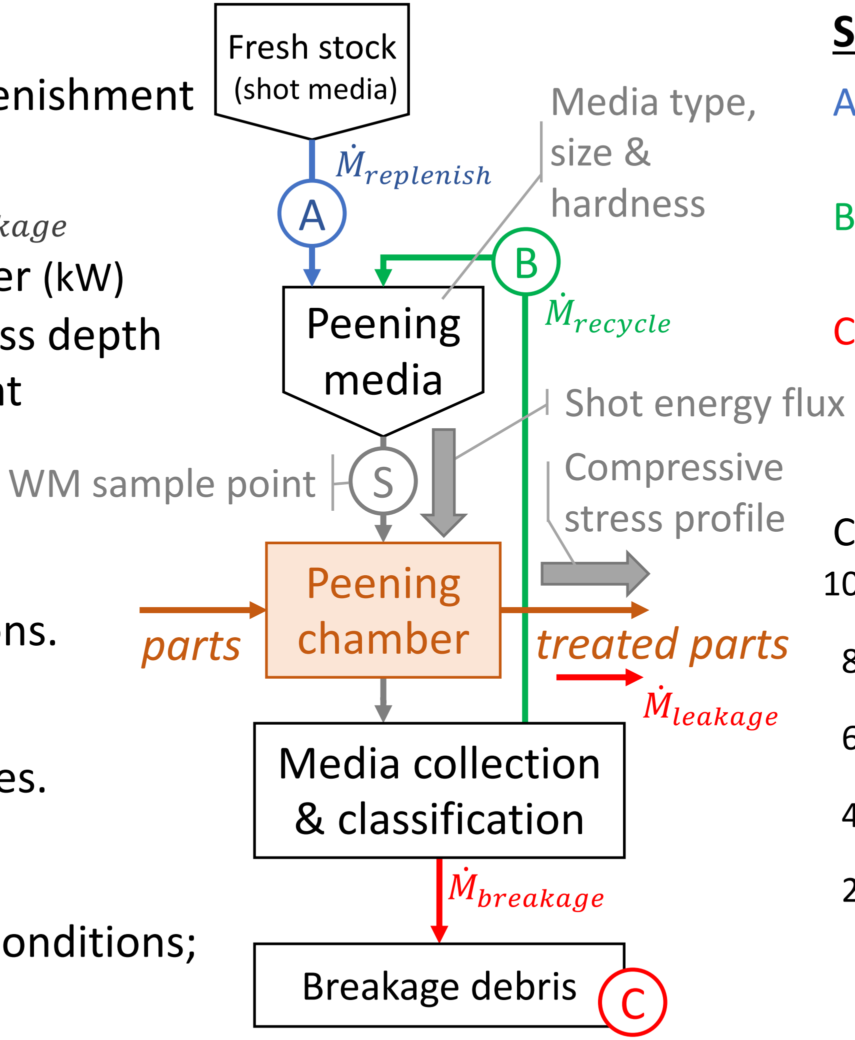
- Energy balance of shot power (kW) with part's compressive stress depth profile obtained at treatment throughput (Pa·m)·(m^2/s).
- Details of stress profile depend on work mix (WM) shot size & shape distributions.

Steady-state flowsheets:

Control on centerline objectives.

Dynamic flowsheets:

- Manage transient or upset conditions;
- Optimize:
  - Startup & shutdown;
  - Changeovers (e.g., shot size).

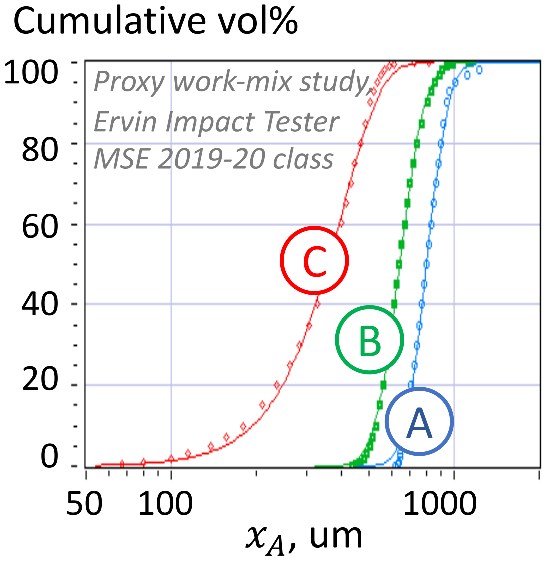


Size tracking, x_A

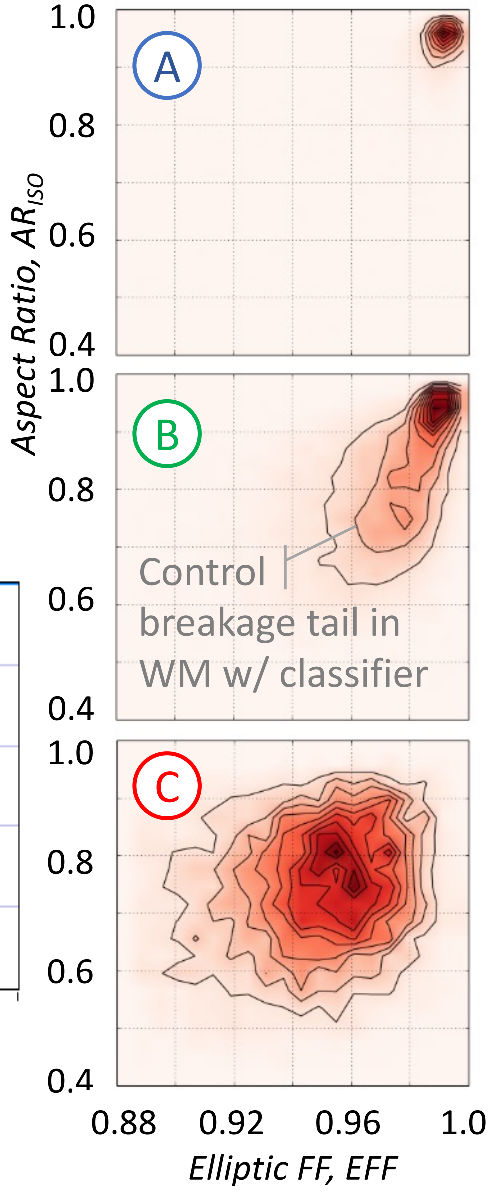
A) Lognormal
d_g = 800 um, σ_g = 1.15

B) Lognormal
d_g = 643 um, σ_g = 1.18

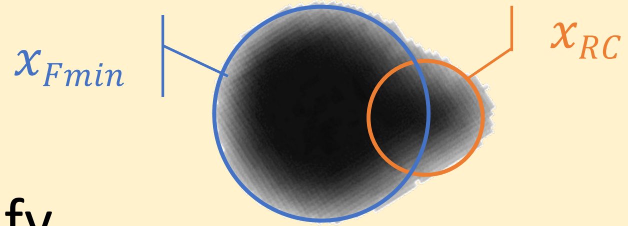
C) Weibull (breakage)
d^*= 403 um, n = 3.1

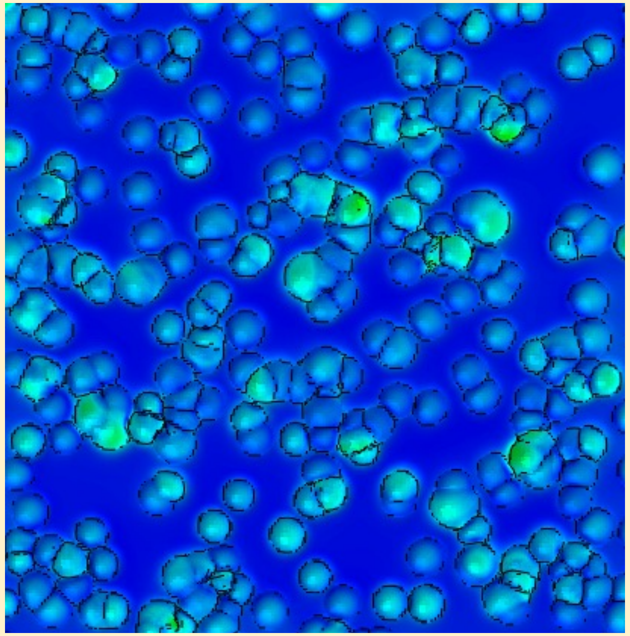


Shape tracking



Conclusion





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  - Parameters include shot particle's size-dependent mass, shape-dependent ROC, and probability function for ROC selection based on orientation of the shot particle.
- Work in progress: Process flowsheet with including size and shape effects.

Thanks to the organizers of ICSP14! Enjoy the banquet!

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Size Features	Impact curvatures & probabilities	Shape Factors (dimensionless)
□ x_{Fmin} = min Feret length □ x_{LF} = Feret length orthogonal to x_{Fmin} □ x_{Fmax} = max Feret length □ A = area □ P = perimeter □ x_A = equivalent area diameter, $x_A = \sqrt{4A/\pi}$ □ V = volume, $\frac{4}{3}A^{3/2}/\sqrt{\pi}$	□ x_{RC} = reduced curvature diameter, $x_{RC} = \frac{-b+\sqrt{b^2-4ac}}{2a}$; $a = \frac{\pi-2}{8}$; $b = \frac{x_{Fmax}-x_{Fmin}}{2}$; $c = \frac{4\cdot x_{Fmax}\cdot x_{Fmin}+(\pi-2)x_{Fmin}^2}{8} - A$ □ $ROC1$ = major curvature ~ $x_{Fmin}/2$ □ $ROC2$ = minor curvature ~ $x_{RC}/2$ □ $d_{cc} = x_{Fmax} - (x_{Fmin} + x_{RC})/2$ □ $cos(\alpha) = (ROC1 - ROC2)/d_{cc}$ □ $\Phi1$ = major probability, $(\pi - \alpha)/\pi$ □ $\Phi2$ = minor probability, α/π	□ AR_{ISO} = aspect ratio, ISO definition, x_{Fmin}/x_{Fmax} □ AR_{box} = aspect ratio, bounding box, x_{Fmin}/x_{LF} □ FF = form factor, $\frac{4\pi A}{P^2}$ □ EFF = elliptical FF, $\frac{\beta\pi A}{P^2}$; $\beta = \left(\frac{1.5\cdot(AR+1)}{\sqrt{AR}} - 1\right)^2$