Characterization Of Shot Size And Shape Distribution

Abstract

Dynamic image analysis facilitates characterization of shot media size and shape distributions. This paper discusses the acquisition of 2D image data, thresholding, statistical analysis, and graphical representation. The image data enable analysis of several size and shape features; these are discussed in relation to their relevance to media production and legacy specifications. Quantitative media characterization opens opportunities for optimization of shot-peening processes.

Introduction

Image analysis for particle size and shape characterization has been practiced for many years, especially in context of lab-based academic research. Recent advances in imaging technology have enabled more routine practice, including in-line and on-line process sensing with dynamic image analysis (DIA). DIA captures 2D images of a flowing stream of randomly-oriented particles, typically gathering thousands of images for statistical analysis. In relation to shot peening, the DIA method is posed to complement and/or supersede legacy methods including mass-based sieving (e.g., SAE J444), counting and weighing (e.g., AMS 2431), and static microscopy for shape and appearance analyses. While it is essential to obtain representative samples in all cases, DIA provides a robust statistical platform for quantitative shape analyses and high-resolution size distributions.

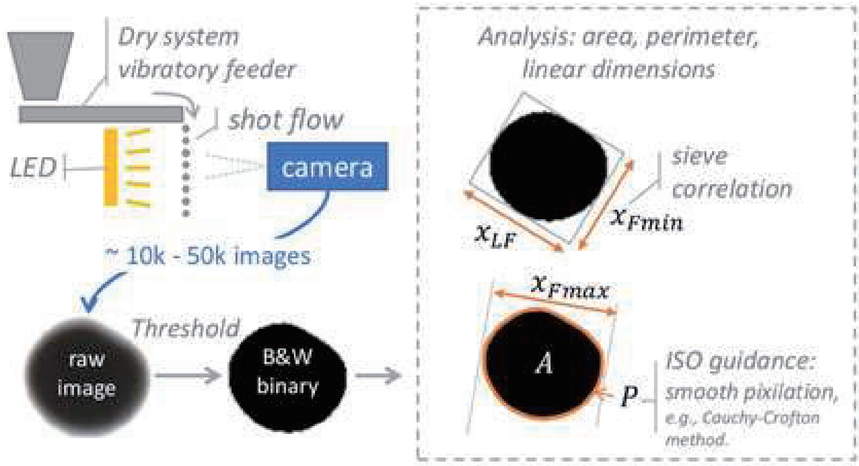

Figure 1. Dynamic image analysis experimental setup, image thresholding, and feature analysis

Size Features (length, area, volume)	Shape Factors (dimensionless)
• x_{Fmin} : Minimum Feret length • x_{LF} : Feret length orthogonal to x_{Fmin}, i.e., making a bounding box. • x_{Fmax} : Maximum Feret length • A : Area • P : Perimeter • $x_A = \sqrt{4A/\pi}$: Equivalent area diameter • $V = (4/3) \cdot A^{3/2}/\sqrt{\pi}$: Volume	• $AR_{ISO} = x_{Fmin}/x_{Fmax}$: Aspect Ratio • $AR_{box} = x_{Fmin}/x_{LF}$: Aspect Ratio based on x_{Fmin} bounding box (non-ISO) • $FF = 4\pi A/P^2$: Form Factor • $EFF = \beta\pi A/P^2$; $\beta = \left(\frac{1.5\cdot(AR+1)}{\sqrt{AR}} - 1\right)^2$: Elliptical FF, orthogonal to AR (non-ISO).

Table 1. Summary of size features and shape factors obtained using dynamic image analysis

Dynamic Image Analysis (DIA)

A typical DIA setup is shown in Figure 1. The shot sample is loaded into a small hopper, and discharged via a feeder which controls the rate of shot particles falling between a backlight (e.g., LED panel) and camera. The camera captures a 2D grayscale projection of discrete particles, typically with multiple particles per frame. Image analysis software then identifies image projections, first using a threshold to convert 8-bit (0-255) grayscale to a black & white binary image, and then analyzing image characteristics including Feret diameters (x), area (A), and perimeter (P) of each shot particle. Details of size and shape characteristics are shown in Table 1, and are consistent with ISO-9276-6 unless otherwise noted.

A SolidSizer system (JM Canty, Lockport NY, USA and Dublin, Ireland) was used in the current work. It uses a PID-controlled vibratory feeder with the objective of maintaining a target fraction of the image area occupied by a steady feed of shot particles. In our lab, we use a 0.2% target occupancy, balance counting rate and image separation. With a zoom lens, the size of the image area (and corresponding pixel resolution) can be adjusted depending on the grade of shot being analyzed. The ideal magnification balances the need for smooth pixilation in shape analysis with counting speed – i.e., having multiple images per frame. As a guideline, imaging resolution with about 1000 to 2000 pixels per shot particle is reasonable. The need for such high resolution relates to the perimeter measurement as described in ISO-9276-6; for a pixelated image, perimeter smoothing is essential (e.g., using the Cauchy-Crofton method). While the ISO spec recommends a minimum of 5000 pixels for irregular particle perimeters, we find that 1000 pixels is suitable for shot morphology. With current digital camera technologies (i.e., at least 2-megapixel), imaging a stream of 10k particles with a resolution of ~1000 pixels/particle and ~0.2% frame occupancy captures an average of at least 4 particles/frame. Bottom line, a typical 10k particle image acquisition takes less than ~5 minutes.

Science Update

Threshold Scaling

Finding the right threshold setting for the conversion of grayscale to binary images depends on lighting conditions, imaging parameters, and shot material properties. Lighting depends on LED settings, optionally using a strobe controller. Camera settings include lens aperture, gain, and exposure time if not using a strobe. The refractive index and optical absorption of the shot material also has an effect. To create a threshold model (Figure 2), we set up the lighting and flat-field correction to achieve a uniform white background (255), and then recorded raw image data (grayscale) in video format. Experiments included different sizes of steel and ceramic shot. Video data were analyzed over a series of threshold settings from 150 to 220 (equation 1), where d_g and σ_g are the geometric and standard deviation of each shot sample measured at a reference threshold (T_{ref} = 190), θ is a scaling function for the size distribution quantile, Q (equation

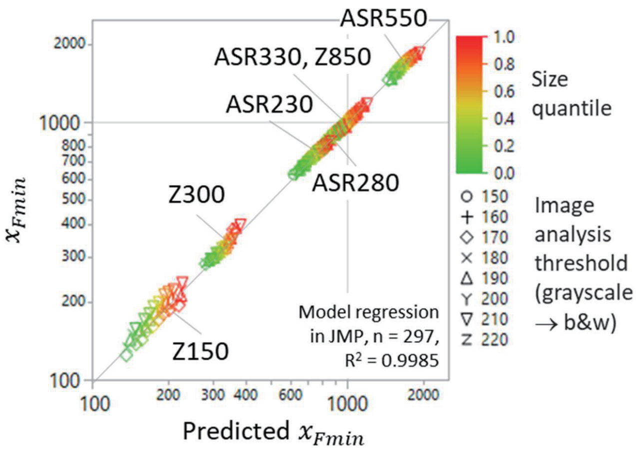

Figure 2. Regression model relating threshold with size

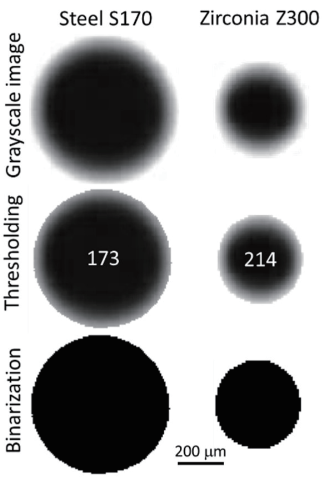

Figure 3. Example of thresholding for steel (*T=173*) and zirconia (*T=214*) against a white (*255*) background. Both samples were imaged with a magnification of 10 µm/ pixel

2), and τ is a threshold scaling parameter (equation 3). The best-fit threshold, T, was derived by comparing the predicted minimum Feret diameter (x_{Fmin}) to sieve results using equation 4, where x and θ are values from sieving and d_g and σ_g are from image analysis. For steel shot (ASR grades provided by Ervin Industries, Adrian MI, USA), 173 was the best-fit threshold. Zirconia shot (Zirpro Z-grades provided by Saint Gobain, Courbevoie, France) required a higher threshold (214) due to its marginal translucency and refractive index scattering. A comparison of thresholding is shown in Figure 3.

$$ln(x_{Fmin})=ln(d_g)+\theta \cdot ln(\sigma_g)+0.276 \cdot \tau \quad (1)$$

$$\theta=\sqrt{2} \cdot erf^{-1}(2Q-1) \quad (2)$$

$$\tau=(T-T_{ref})/T_{ref} \quad (3)$$

$$T=190+688[ln(x/d_g)-\theta \cdot ln(\sigma_g)];\ \text{at}\ T_{ref}=190 \quad (4)$$

Graphical Case Study of Size and Shape Distributions

We present a case study comparing two types of as-received steel shot: cast S110 (provided by Ervin Industries, Adrian MI, USA) and G2-conditioned cut-wire CW14 (provided by

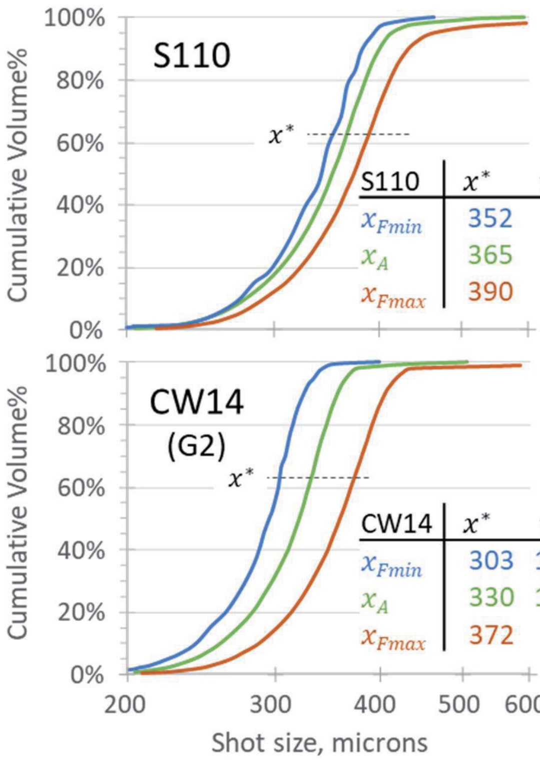

Figure 4. Size distributions for selected cast (*S110*) and cut-wire (*CW14*) samples

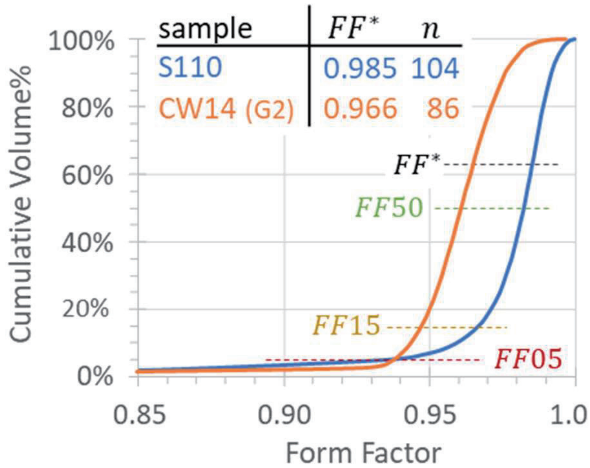

Figure 5. Form Factor shape distributions; quantiles (dashed line intersections) correspond to *FF* overlays in Figure 6

Toyo Seiko America, South Bend IN, USA). The comparison is shown graphically as size and shape distributions (Figure 4 and 5); both samples follow cumulative distribution functions (*cdf*) having stretched exponential forms, per equation 5, where x^* represents the mode and and n the steepness of the distribution. Figure 6 shows a further refinement of shape analysis, where individual particle data (~10k for each) are coarse grained to form contour maps (in gray) plotted on an orthogonal grid defined by the Elliptical Form Factor (*EFF*) and Aspect Ratio (*AR*). *AR* is a measure of elongation. *EFF* shows other perimeter irregularities, e.g., due to angularity or satellite features. Form Factor (*FF*) quantiles are overlaid (in color); *FF* combines the two effects into an overall measure of roundness. Selected image data are shown along *FF* quantiles.

$$cdf = 1 - \exp\left(-\left(\frac{x}{x^*}\right)^n\right) \qquad (5)$$

Shot media manufacturing processes are made evident by their size and shape characteristics. Cast shot made by melt atomization are highly spherical over most of their distribution. Cut wire shot is made by cutting drawn wire into cylindrical segments, then rounding by conditioning and/or working in-process. Cut wire media have a consistent minimum Feret diameter, i.e., the steep slope of CW14 x_{Fmin} shown in Figure 4, and marginally extended cut-lengths shown by the spread between min and max Feret dimensions. The relation between elongation and conditioning of CW shot is illustrated in Figure 6, for example along the Form Factor 5% quantile (*FF*05). While all particles along a given *FF* quantile have the same overall "roundness", those with lower *EFF* are marginally angular (i.e., less conditioned) while those with lower *AR* are more elongated.

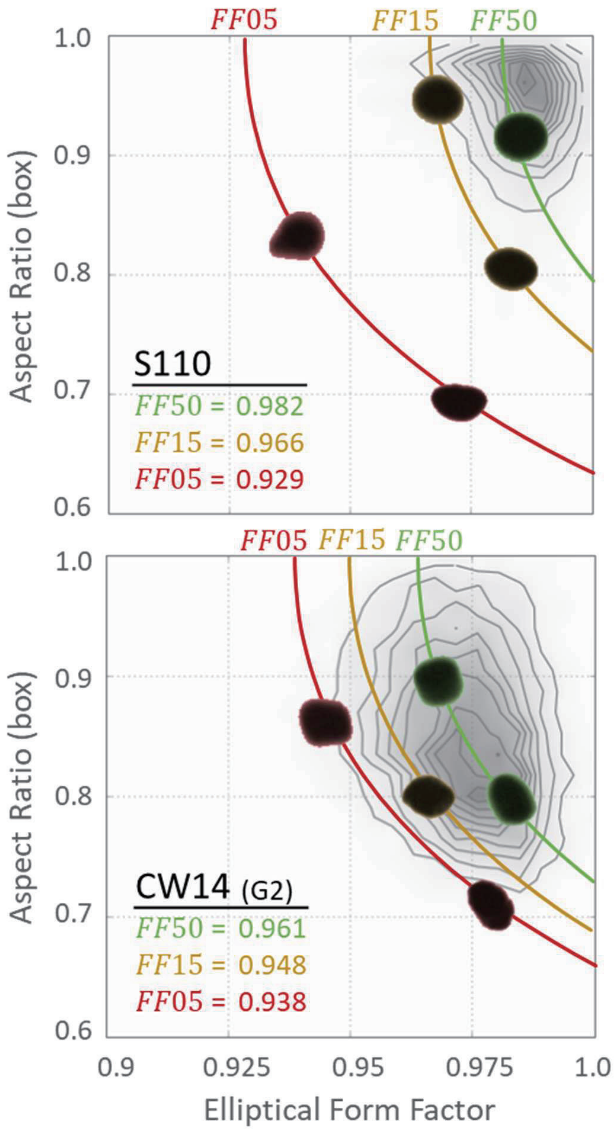

Figure 6. Coarse-grained shape mapping overlaid with example particle images. Orthogonal factors (*EFF* and *AR*) contribute to perimeter and elongation components of the Form Factor (*contours*); (*1,1*) represents an ideal spherical projection

Conclusion

This brief communication provides examples of shot size and shape characterization using dynamic image analysis, providing higher resolution of size distributions and quantitative assessment of shape. The detailed steps needed to correlate DIA analyses with legacy methods, e.g., via control of sample feeding and image thresholding, is also discussed. Current shot-peening work at the Purdue Center for Surface Engineering and Enhancement (CSEE) links characterization with impingement modeling, predicting residual stress fields as a function of peening parameters and shot characteristics. Shape effects are based on reduced-order models of archetypes describing cast and cut wire media. Next steps include characterization of working-mix samples, and integration of size and shape into process flowsheet models for industrial applications.

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