Statistical Discrimination Methods for Forensic Source Interpretation of Aluminum Powders in Explosives

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Disclaimer

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Names of commercial products are provided for identification purposes only, and inclusion does not imply endorsement of the manufacturer, or its products or services by the FBI. The views expressed are those of the author(s) and do not necessarily reflect the official policy or position of the FBI, the U.S. Government, or the NIJ.

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Disclaimer

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Introduction

- Al powder is often used as a fuel in IEDs
- Individuals attempting to make IEDs often obtain it from legitimate commercial products or make it themselves using readily available Al starting materials
- The characterization and differentiation between sources of Al powder may provide investigative and intelligence value
- Our goal is to use micromorphometric features of Al powder particles from a variety of different source types to apply statistics!

Data

Sample Type	# of Samples
Ball-milled Al Foil	29
Al-containing Spray Paint	36
Binary Exploding Targets	40
Industrial Manufacturers	47
Other	2
Total	**154**

Sample Preparation

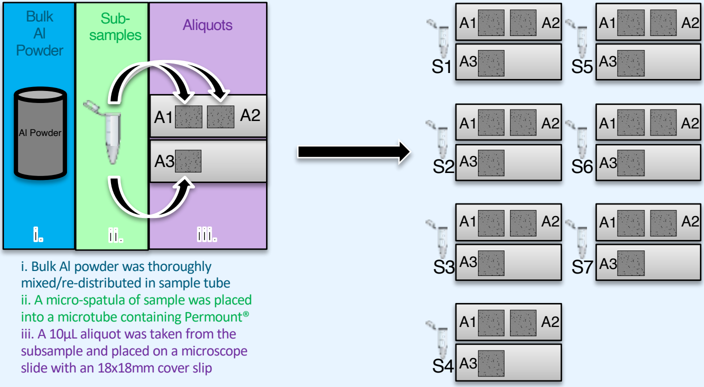


Figure: reprinted with permission from Ommen et al. [1]

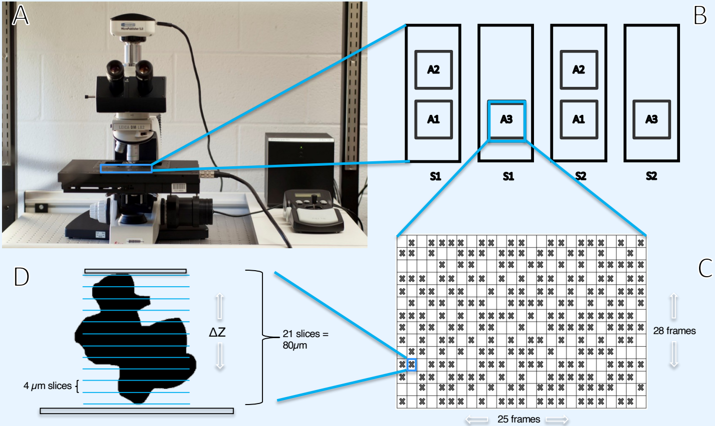


Figure: reprinted with permission from Ommen et al. [1]

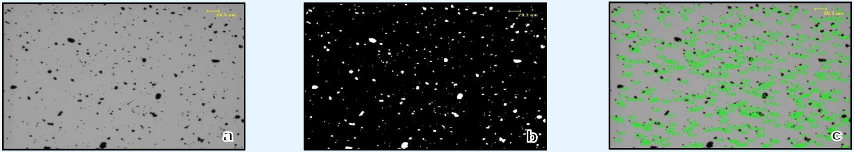
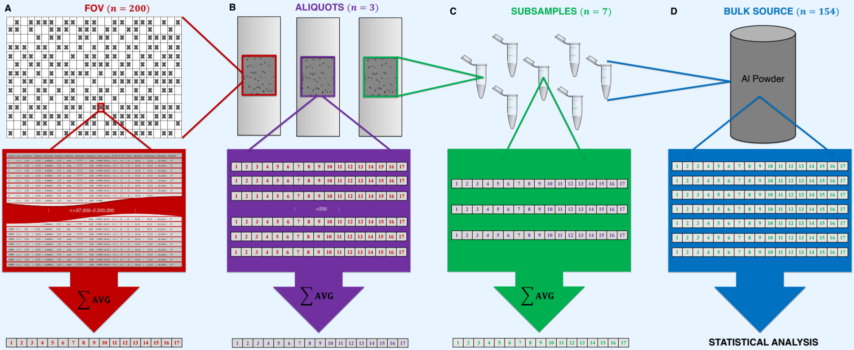
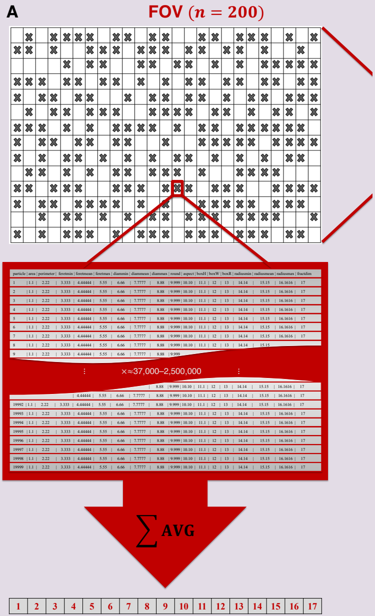


Figure: Each image (a) was converted to a binary image (b) to enhance edge detection. The particles were then counted (c), eliminating any particles along the border of the image, and measured. Seventeen parameters were measured for each identified particle within the image FOV: area; perimeter; feret diameter (minimum, maximum and mean); diameter (minimum, maximum, and mean); roundness; aspect ratio; box (height, width, and ratio); radii (minimum, maximum, and mean distance from particle centroid to edge); and fractal dimension. The data from thousands of particles were exported to a large text data file for further statistical analysis. (reprinted with permission from Ommen et al. [1])

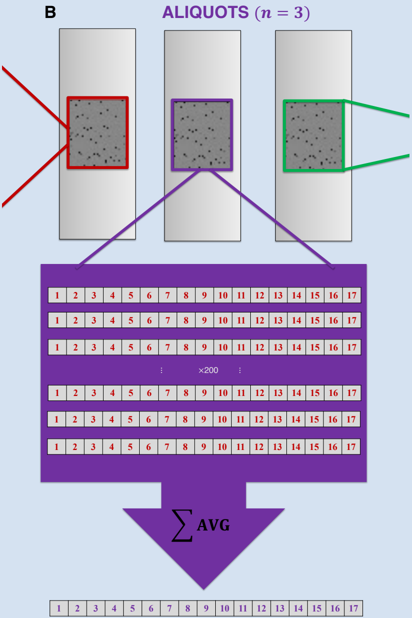
Data Processing



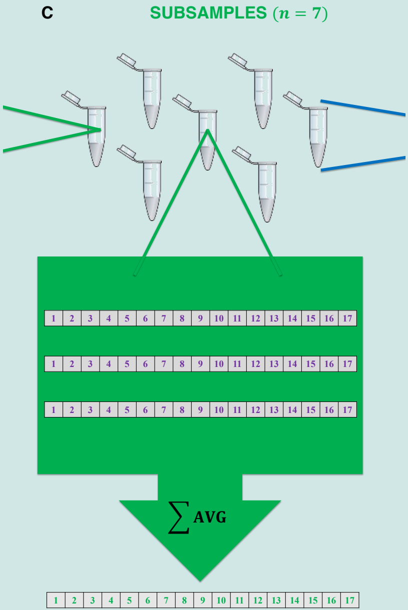
First Mean Summary



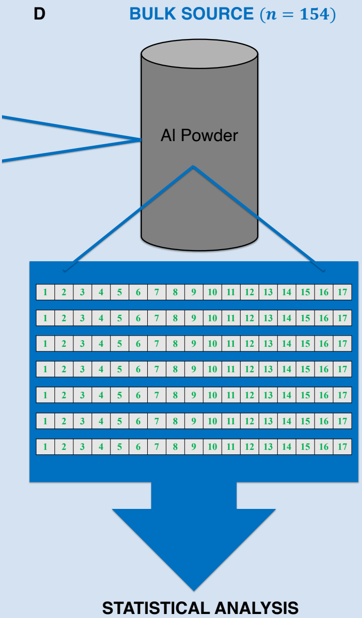
Second Mean Summary



Third Mean Summary



Final Data (MoMoM)



Method 1: Linear Discriminant Analysis (LDA)

For each subsample in the dataset, perform the following analysis to infer bulk Al powder source:

1. **Remove the MoMoM vector corresponding to the query subsample from the dataset (*leave-one-out = LOO*)**
2. **Use the remaining subsample MoMoM vectors in the dataset to train LDA to classify subsamples according to bulk Al powder source assuming equal prior source probabilities (*cross-validation = CV*)**
3. **Use the trained LDA to classify the query subsample to its most likely bulk Al powder source as determined by its MoMoM vector**

The LDA method was implemented in R© using the `lda` and `predict` functions from the MASS package.

Method 2: Modified ASTM Approaches

Goal: create an ASTM [2,3] *vector of scores (VOS)* for the micromorphometic parameters of Al powder given Q and K_i, $i = 1, \ldots, N$.

Known source sample mean

$$\bar{K} = \sum_{i=1}^{N} K_i$$

Known source sample variance

ASTM VOS

Method 2: Modified ASTM Approaches

Goal: create an ASTM [2,3] *vector of scores (VOS)* for the micromorphometic parameters of Al powder given Q and K_i, $i = 1, \ldots, N$.

Known source sample mean

Known source sample variance

$$s_K^2 = \frac{1}{N}\sum_{i=1}^{N}(K_i - \bar{K})^2$$

ASTM VOS

Method 2: Modified ASTM Approaches

Goal: create an ASTM [2,3] *vector of scores (VOS)* for the micromorphometic parameters of Al powder given Q and K_i, $i = 1, \ldots, N$.

Known source sample mean

Known source sample variance

ASTM VOS

$$\delta = \frac{|\bar{K} - Q|}{s_K}$$

Method 2: Modified ASTM Approaches

The ASTM VOS can be used to classify subsamples as either *micromorphometrically indistinguishable* ("matching," $C = 1$) or *micromorphometrically distinguishable* ("nonmatching," $C = 0$) according to the following methods:

Traditional ASTM Multiplier

$$C_{max} = \mathcal{I}\left[\left(\max_{p}\ \delta_p\right) < \tau_{max}\right]$$

Modified ASTM Multiplier

Marginal ASTM Multiplier

Method 2: Modified ASTM Approaches

The ASTM VOS can be used to classify subsamples as either *micromorphometrically indistinguishable* ("matching," $C = 1$) or *micromorphometrically distinguishable* ("nonmatching," $C = 0$) according to the following methods:

Traditional ASTM Multiplier

Modified ASTM Multiplier

$$C_{sum} = \mathcal{I}\left[\left(\sum_{p} \delta_p\right) < \tau_{sum}\right]$$

Marginal ASTM Multiplier

The ASTM VOS can be used to classify subsamples as either *micromorphometrically indistinguishable* ("matching," $C = 1$) or *micromorphometrically distinguishable* ("nonmatching," $C = 0$) according to the following methods:

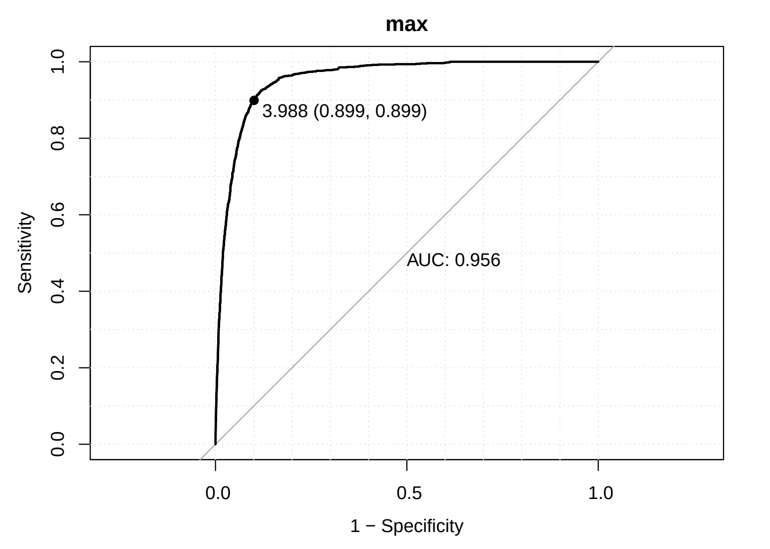
Traditional ASTM Multiplier

Modified ASTM Multiplier

Marginal ASTM Multiplier

$$C_{marg} = \mathcal{I}\left[\left(\sum_p \mathcal{I}[\delta_p < \tau_p]\right) > \tau_{marg}\right]$$

Threshold Determination



Decision Thresholds

Parameter	AUC	Threshold	Parameter	AUC	Threshold
Traditional	0.956	$\tau_{max} = 3.988$	radius_min	0.929	$\tau_8 = 1.948$
Modified	0.953	$\tau_{sum} = 31.57$	radius_ratio	0.760	$\tau_9 = 1.195$
Marginal	0.934	$\tau_{marg} = 8.5$	roundness	0.757	$\tau_{10} = 1.173$
area	0.910	$\tau_1 = 1.769$	diameter_max	0.923	$\tau_{11} = 1.872$
aspect	0.811	$\tau_2 = 1.342$	diameter_mean	0.930	$\tau_{12} = 1.944$
feret_max	0.922	$\tau_3 = 1.876$	diameter_min	0.933	$\tau_{13} = 1.983$
feret_mean	0.925	$\tau_4 = 1.912$	box_height	0.923	$\tau_{14} = 1.905$
feret_min	0.929	$\tau_5 = 1.935$	box_width	0.924	$\tau_{15} = 1.886$
perimeter	0.913	$\tau_6 = 1.824$	box_ratio	0.613	$\tau_{16} = 0.955$
radius_max	0.920	$\tau_7 = 1.860$	fract_dim	0.717	$\tau_{17} = 1.091$

LOOCV LDA

- Results are multi-class labels ($n = 154$) for each single query subsample.
- Result is correct if the LOOCV LDA recovers the true source of the query subsample.
- Result is incorrect if the query sample is classified to any source other than the true source.
- Baseline accuracy is 0.65%.

ASTM Methods

- Results are binary decisions of "match" or "nonmatch" for each Q-K pair.
- Result is correct if the ASTM method determines a "match" ($C = 1$) for the Q-K pair when they are truly from the same source or a "nonmatch" decision ($C = 0$) when the Q-K pair are truly from different sources, and incorrect otherwise.
- False positive error occurs when the ASTM method determines a "match" when the Q-K are truly from different sources.
- False negative error occurs when the ASTM method determines a "nonmatch" when the Q-K are truly from the same source.
- Baseline accuracy is 50%.

Method	Accuracy	Baseline Comparison
Traditional ASTM	89.92%	1.80 $\times$ (+)
Modified ASTM	88.87%	1.78 $\times$ (+)
Marginal ASTM	87.13%	1.74 $\times$ (+)
LOOCV LDA	56.96%	87.6 $\times$ (+)

Conclusion

- Of all the modifications to the ASTM method tested, the traditional threshold worked best.
- Most of the misclassifications for the LOOCV LDA method where due to classifying a query subsample to a source from the same manufacturer or production lot.
- These *closed-set* methods do not address the *open-set* problem of interest.

Future Work

- Test the accuracy of the methods on a dataset consisting of just one sample from each manufacturer and production lot.
- Use the ASTM VOS to develop a *value-of-evidence* or *likelihood-ratio-style* quantification to address the open-set problem.
- Explore whether machine learning methods can be used to improve the results.

Thanks for listening!

Questions

Email me: dmommen@iastate.edu

References

1 Ommen DM, Baldaino J, Saunders CP, Hietpas J, Buscaglia J. Characterization and differentiation of aluminum powders used in improvised explosive devices. Part 2: Micromorphometric method refinement and preliminary statistical analysis. J Forensic Sci. 2022;67:505–515. https://doi.org/10.1111/1556-4029.14946

2 E2927-16e1 Standard Test Method for the Determination of Trace Elements in Soda-Lime Glass Samples Using Laser Ablation Inductively Coupled Plasma Mass Spectrometry for Forensic Comparisons, ASTM International, 2022.

3 E2330-19 Standard Test Method for Determination of Concentrations of Elements in Glass Samples Using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for Forensic Comparisons, ASTM International, 2022.