

Article

Classification of Metallic Powder Morphology Using Traditional and Automated Static Image Analysis: A Comparative Study

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Abstract: Characterizing powder feedstock is crucial for ensuring the quality and reliability of parts produced through metal additive manufacturing (AM). The morphology of particles impacts the flowability, packing density, and spreadability of powders, affecting productivity and part quality. A new methodology has been developed to classify particle morphological features in AM powder feedstocks, such as spherical or elongated shapes, and the presence of satellites and facets. This approach uses multiple descriptors for quantitative evaluation. The results from shape descriptors can vary based on image resolution, gray/color thresholding, and software algorithms. There are various commercial systems available for characterizing particle shape, some of which use images taken of static particles, while others use images of particles in motion. This diversity can lead to differences in powder characterization across laboratories with different equipment and methods. This paper compares results from a particle classification approach using two software programs that work with metallographic images with those from an automated static particle analyzer. While traditional methods offer higher resolution and precision, this study shows that automated systems can achieve similar particle shape classification using different shape descriptors and thresholds.

Keywords: metallic powder; image analysis; shape descriptors; morphological features; additive manufacturing



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1. Introduction

The manufacturing of metal additive parts with predictable and stable properties requires a deep understanding of the characteristics of the powder feedstock. Powder qualification is based on various factors such as chemistry, flowability, particle size distribution, density, and shape. Additionally, processes such as gas, water, or plasma atomization, along with reuse and recycling, can also impact particle characteristics [1,2]. For instance, the blasting of powder cakes after Electron Beam Powder Bed Fusion (EB-PBF) can cause impact marks on the particles, as demonstrated by Ghods et al. with titanium alloy Ti-6Al-4V [3] and Tang et al. [4].

The influence of morphological features, including shape, size, and form, on powder flow, packing, and behavior in additive manufacturing (AM) processes has been extensively studied in the literature [5–8]. Here are a few notable examples. A recent study from Mussato et al. showed that highly spherical particles containing satellites and irregular and fine particles restrict the flowability of particles in powder bed fusion technology [9]. Zhao et al. demonstrated that the use of spherical Inconel 718 alloy powder in EB-PBF resulted in parts with fewer defects, pores, and lack of fusion compared to elongated and

irregular particles containing satellites [10]. Riener et al. compared AlSi10Mg gas and plasma atomized powders in the Laser Powder Bed Fusion of metals (LPBF-LB/M) and found that the use of spherical plasma atomized powder led to higher bulk and tap density, better flowability, and a decrease in the laser absorption rate. They also observed a relation between laser absorption and layer/part density, suggesting that irregular particles could form additional laser beam traps or cavities, resulting in lower powder bed density. The use of spherical powders in LPBF-LB/M led to higher powder layer and final part density, slightly higher ultimate tensile strength and elongation at break, and significantly lower surface roughness [11].

Particle shape is often described using a single descriptor such as circularity or aspect ratio, but due to the intrinsic complexity of particle shape, this may not provide an adequate representation [12,13]. This can lead to a biased evaluation whereby particles of significantly different shapes end up with similar descriptor values. Until recently, it was challenging to relate commonly used descriptors to specific features such as elongation, the presence of satellites, or deformation observed on AM particles. While particle shape outlines the external surface, it encompasses the evaluation of its form, roundness, and surface texture [14]. The ISO 9276-6 standard proposes three levels of shape related to particle geometrical proportions, shape, and surface texture [15].

Until recently, no standard was available to address the classification of AM powder particle morphology [16]. The ASTM F3571 Standard Guide for Additive Manufacturing (Feedstock—Particle Shape Image Analysis by Optical Photography to Identify and Quantify the Agglomerates/Satellites in Metal Powder Feedstock) was recently developed to tackle this issue. It recommends using a pair of shape descriptors, either aspect ratio or ellipse ratio coupled with solidity, to distinguish and quantify spherical and non-spherical particles [17].

A quantitative methodology based on the use of several shape descriptors was recently developed to classify particle shapes commonly observed in additive manufacturing powder feedstocks, namely elongated, faceted, spherical, and particles with satellites [13]. The methodology was developed with an assortment of schematized particles and validated on metallographic images of different metallic powder samples. The method produces a particle shape fingerprint by sequentially categorizing particles with satellites, then elongated particles, and finally faceted particles from remaining spherical particles. The method was initially developed using commercial image analysis software.

With the growing demand for AM parts, several morphological analysis software programs have emerged to meet users' needs. However, differences in measuring and interpreting basic dimensions and commonly used descriptors across various commercial image analysis software programs can lead to divergent results. For instance, the measurement of circularity, which is calculated with the projection of a perfect sphere in 2D, differs from sphericity, which is calculated based on the surface area of a sphere [18]. In systems like Clemex and ImageJ, the same equation is defined as sphericity in Clemex and circularity in ImageJ. This highlights the importance of establishing standardized terminology and methodology to eliminate discrepancies, minimize human bias, and ensure reliable measurement of powder fingerprinting. Additionally, with the advent of automatic particle analyzers, it is crucial to compare results obtained using different techniques to maintain consistency and accuracy.

The objective of this work is to test the reproducibility of results obtained with a group of image analysis software, namely Clemex Vision PE (version 8.0.197, commercial software, 2D static image analysis), ImageJ (version 1.53, open-source, 2D static image analysis), and Morphologi G3 (version 8.23, commercial software, fully automated static image analysis). The focus is on verifying if reliable particle morphology analysis is achievable using these

different characterization tools through the application of a multi-descriptor particle shape classification methodology proposed recently.

2. Materials and Methods

2.1. Shape Descriptors and Sequential Methodology

In this study, five shape descriptors were employed: convexity (C_x), ellipse ratio (E_r), extent ratio (E_c), irregularity index (IR), and roundness index (R_n). While the general approach remains consistent, the formulas used for their calculation vary slightly among the software tools.

Convexity is consistently defined across Clemex Vision PE (version 8.0.197), ImageJ (version 1.53), and Morphologi (version 8.23) as the ratio of the convex hull perimeter (P_C) to the perimeter (P):

$$C_x = P_C / P. \quad (1)$$

The roundness index (R_n) is also uniformly defined across all software as follows:

$$R_n = 4A / (\pi X_{Fmax})^2. \quad (2)$$

However, the ellipse ratio (E_r) is calculated differently. In Clemex and ImageJ, it is the ratio of the best-fit ellipse width (E_W) to its length (E_L):

$$E_r = E_W / E_L, \quad (3)$$

while in Morphologi, it is defined as the width (W)-to-length (L) ratio:

$$E_r = W / L, \quad (4)$$

where the width (W) is based on the longest major axis projection passing through the particle centroid, oriented based on minimal rotational energy, and the length (L) is the longest projection on the minor axis passing through the centroid of the particle, perpendicular to the major axis.

The corrected extent ratio (E_c) is defined as the ratio between the particle's area (A) and the area of an ellipse having, as diameters, the maximum Feret (X_{Fmax}) and minimum Feret (X_{Fmin}) of the particle. In Clemex and ImageJ, E_c is therefore obtained with the following expression:

$$E_c = 4A / (\pi X_{Fmin} X_{Fmax}). \quad (5)$$

In Morphologi, since the minimum Feret is not available, the width and length of the particle are used to calculate the surface of the representative ellipse.

$$E_c = 4A / (\pi WL). \quad (6)$$

The irregularity index (IR) quantifies the shape deviation of an object from a perfect circle or ellipse. Due to the limited availability of identical shape descriptors across software, different expressions were used to estimate IR. In Clemex, the expression used is as follows:

$$IR = (E_L ID) / (E_W OD), \quad (7)$$

where ID and OD are the inner and outer circle diameters centered on the particle's centroid. In ImageJ, the formula is as follows:

$$IR = (E_L MIC) / (E_W X_{Fmax}), \quad (8)$$

where MIC is the maximum inscribed circle. Finally, in Morphologi, the equation used is as follows:

$$IR = (D_{eq}W)/(LX_{Fmax}), \quad (9)$$

where D_{eq} is the equivalent diameter, defined as the diameter of a circle having the same projected area as the image of the particle. Altogether, these descriptors were used to assess particle morphology.

The sequential methodology, which we developed in our previous work using Clemex software to classify powder morphology, is illustrated in Figure 1 [13]. The threshold for each descriptor was meticulously established in this prior research, starting with an analysis of schematized particles, which are software-designed representations of typical morphologies for validation purposes, and subsequently validated on metallic powder samples. For instance, it was determined that applying a threshold of 0.95 to the convexity index (C_x) effectively highlights particles with numerous satellites, as C_x decreases with an increasing number of satellites. Similarly, an extent ratio (E_c) below 0.95 distinguishes particles with a single satellite, and an ellipse ratio (E_r) lower than 0.90 discerns remnant elongated particles. Lastly, spherical particles are sorted from faceted ones by applying a double constraint with both the roundness index (R_n) and the irregularity ratio (IR) lower than 0.90. R_n approximates the sharpness of the particles, while the IR indicates irregularities. Through this comprehensive approach, all particles are accurately labeled according to their morphology, ensuring that any remaining powder after applying the sequential methodology is classified as spherical.

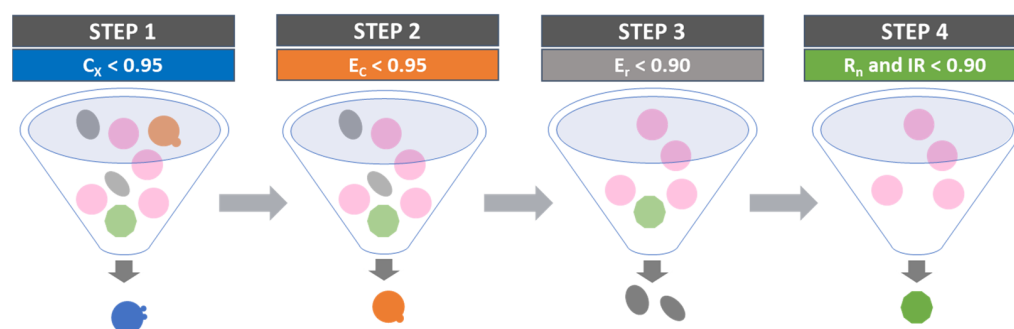


Figure 1. Sequential methodology for the classification of powder morphology.

2.2. Schematized Particles

To test the performance of the image analysis software, a collection of fifty-four schematized particles, as presented in Figure 2, was used, covering a wide range of shapes.

These specific shapes have been selected to reflect common morphologies found in metallic powders used for AM, such as particles with satellites, elongated particles, faceted particles, and spherical particles. The particle images were used to evaluate measurement discrepancies based on the following metrics: area, convex perimeter, perimeter, minimum and maximum Feret lengths, and ellipse length/width. Additionally, the shape descriptors from Clemex and ImageJ, presented in Section 2.1, were calculated using these metrics to further assess measurement discrepancies.

Images were acquired using a scanning electron microscope (SEM, Hitachi S4700, Hitachi, Tokyo, Japan, 15 kV) with a backscattered electron (BSE) detector. While image resolution is not the ultimate criterion, it is crucial to achieve a sufficient number of pixels per particle to ensure accurate analysis. To meet the ISO 9276-6 standard, the magnification was selected to provide between 100 and 5000 pixels per particle for accurate analysis of the smallest particles [15]. At a magnification of $250\times$, a particle with a diameter of $30\text{ }\mu\text{m}$ consists of approximately 4500 pixels. In this study, all analyzed particles contained at

least 3000 pixels to maintain precision. The metallographic cross-sections of all samples are shown in Figure 3, and a total of 10 images were captured for each powder sample.

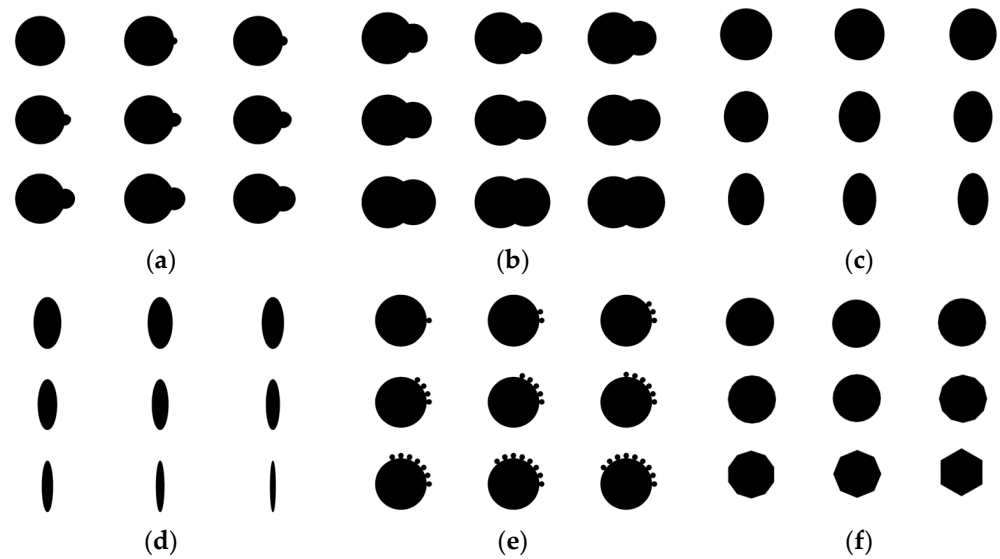


Figure 2. Collection of schematized particles used for the evaluation of basic measurements and shape descriptors for a single satellite (a,b), elongated (c,d), multiple satellites (e), and faceted (f) particles.

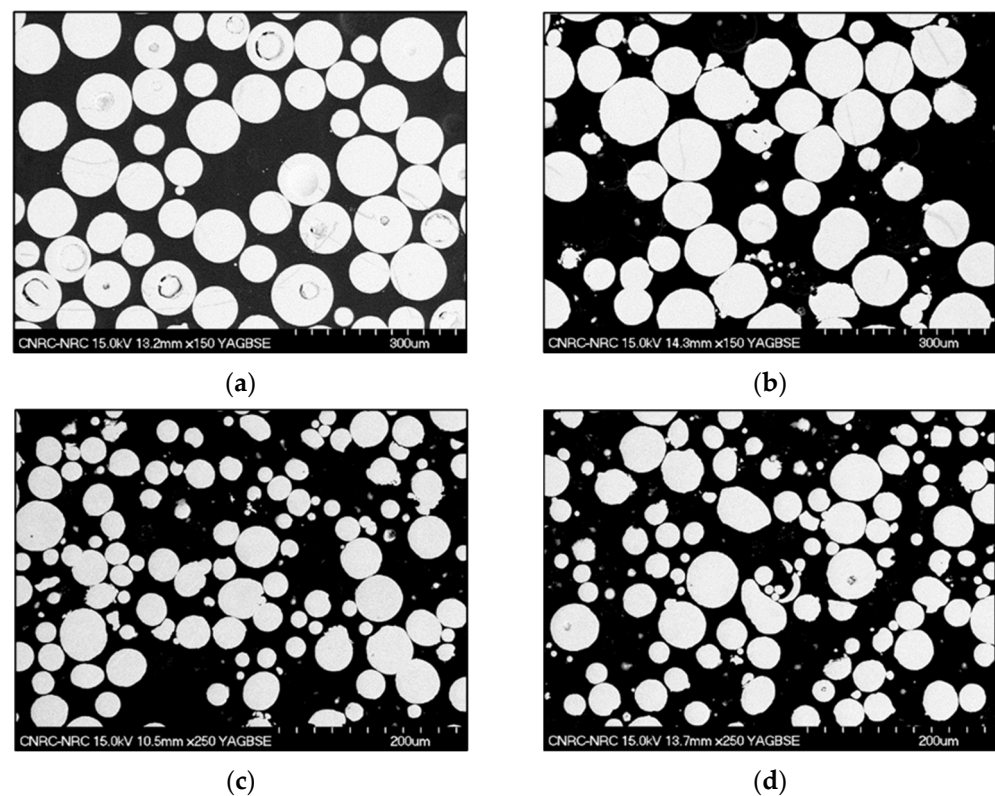


Figure 3. Micrographs of the cross-sections of the powder embedded in epoxy resins: (a) aluminum, (b) titanium, (c) as-received stainless steel, and (d) recycled stainless steel powder samples.

2.3. Measurements

Images of the metallographic samples were analyzed using Clemex and ImageJ software (Figure 4). For both systems, pixels were converted to the international system of length units. In Clemex, image quality was enhanced using a pruning function to remove

single-pixel-wide peaks and valleys. The images were segmented using automatic gray thresholding; holes were filled, and connected particles were split using automatic bridge removal. In ImageJ, the images were binarized, holes were filled, and connected particles were separated using a watershed tool. Particles intersecting the frame of the picture, incomplete or indistinct, and those outside the chosen particle size distribution were excluded from the analysis. The characteristics of the particles were then measured individually. Static automated imaging was accomplished using Morphologi (Malvern Panalytical), a fully automated system with an integrated sample dispersion unit that captures images and provides particle size and shape information.

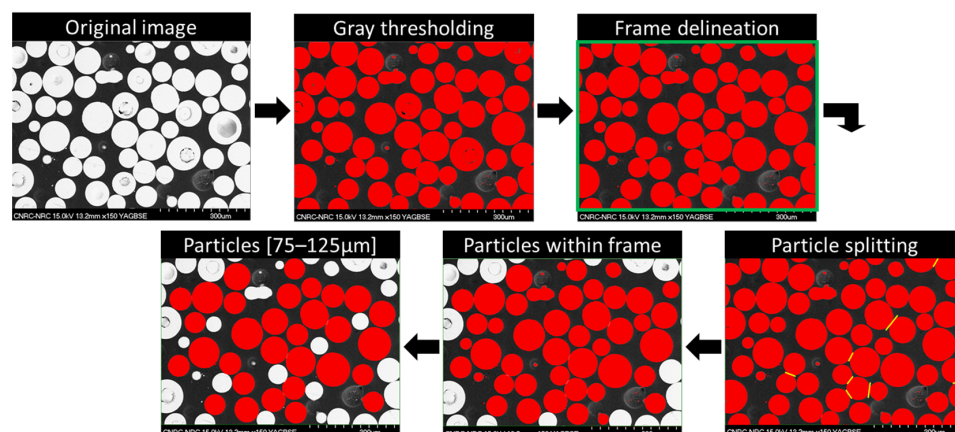


Figure 4. Image processing of metallographic samples.

3. Results

3.1. Image Analysis of Schematized Particles

The use of schematized particles allows to outline morphological features frequently detected in AM powders and comparing basic measurements with their resulting calculated descriptors. Table 1 summarizes basic measurement differences (Δ) obtained using Clemex and ImageJ:

$$\Delta = (M_{\text{Clemex}} - M_{\text{ImageJ}}) / M_{\text{Clemex}} \times 100, \quad (10)$$

where M_{Clemex} and M_{ImageJ} correspond to Clemex and ImageJ measurements.

It shows that the results obtained with these two software programs can be significantly different. This discrepancy may negatively impede the comparison of morphological features and shape analysis between laboratories.

Clemex generally reports higher values than ImageJ, with variations of less than 1% for most measurements. However, the perimeter values differ, with Clemex reporting 3 to 5% smaller values than ImageJ. This difference is due to the distinct methods each software program uses to calculate the perimeter (Figure 5).

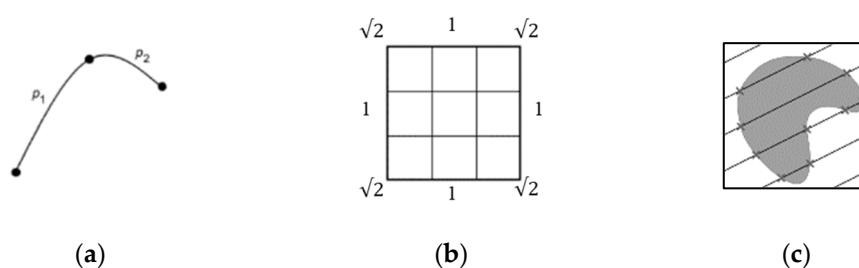
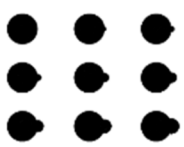
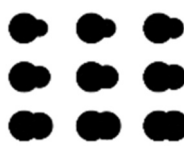
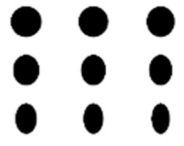
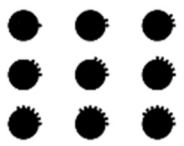
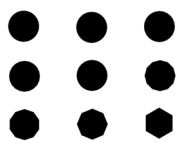


Figure 5. Perimeter measurements using (a) Clemex, (b) ImageJ, and (c) MorphoLibJ plug-ins.

Table 1. Variation (Δ) and standard deviation (SD) between Clemex and ImageJ measurements.

Basic Measurement		Δ (%)	SD (%)	Basic Measurement		Δ (%)	SD (%)
	A	0.53	0.04		A	0.84	0.03
	P _C	0.12	0.02		P _C	0.29	0.01
	P	−3.83	0.23		P	−3.48	0.27
	X _{Fmax}	0.18	0.11		X _{Fmax}	0.35	0.05
	X _{Fmin}	0.23	0.13		X _{Fmin}	0.48	0.20
	E _L	0.57	0.21		E _L	0.80	0.17
	E _W	0.55	0.24		E _W	0.87	0.13
	A	1.61	0.13		A	1.83	0.64
	P _C	0.64	0.04		P _C	0.48	0.05
	P	−3.48	0.24		P	−3.23	0.61
	X _{Fmax}	0.68	0.13		X _{Fmax}	0.61	0.16
	X _{Fmin}	0.61	0.39		X _{Fmin}	0.56	0.20
	E _L	0.74	0.05		E _L	0.73	0.24
	E _W	0.88	0.14		E _W	1.16	0.49
	A	0.40	0.12		A	1.46	0.04
	P _C	0.00	0.03		P _C	0.61	0.04
	P	−4.57	0.65		P	−3.56	0.96
	X _{Fmax}	0.13	0.06		X _{Fmax}	0.54	0.08
	X _{Fmin}	0.10	0.07		X _{Fmin}	0.57	0.13
	E _L	0.50	0.13		E _L	0.76	0.05
	E _W	0.40	0.17		E _W	0.77	0.07

Clemex calculates the perimeter by summing the lengths of borders on a selected plane, interpolating each segment using three points. The software considers each segment of the particle's outline and approximates it as a series of straight lines, each defined by three points. This approach can smooth out irregularities and provide a continuous approximation of the perimeter.

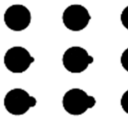
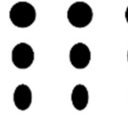
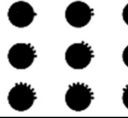
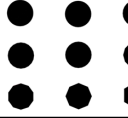
ImageJ, on the other hand, uses a method whereby it counts a straight edge between pixels as one unit and a diagonal connection as slightly longer, approximately 1.4 units. ImageJ accounts for the diagonal distances between pixels, thus providing a more precise measurement for pixelated images.

The MorphoLibJ plug-in in ImageJ uses Crofton's formula, which estimates the length of a curve by considering the expected number of times a random line would intersect it. Essentially, it involves projecting random lines through the image and counting the intersections with the shape's boundary. This approach, more focused on the shape's overall complexity, results in perimeter values that are 3 to 5% lower than those from Clemex.

These differing methodologies lead to variations in the measured perimeter values, reflecting the inherent differences in how each software program processes and interprets the image data. Understanding these methods is crucial for interpreting the results and making informed comparisons between different software outputs.

These results underscore the importance of thresholding to achieve consistent results across different systems. Table 2 presents the average percentage difference and standard deviation of the descriptors used in the sequential methodology for the schematized particles, as acquired using Clemex and ImageJ. For most of the descriptors, the values obtained from Clemex and ImageJ vary by less than 1%.

Table 2. Variation between Clemex- and ImageJ-calculated morphological descriptors.

Morphological Descriptor			Δ (%)	SD (%)	Morphological Descriptor			Δ (%)	SD (%)
	C_x		3.80	0.21		C_x		3.64	0.27
	E_C		0.11	0.11		E_C		0.00	0.18
	E_r		−0.02	0.07		E_r		0.07	0.06
	R_n		0.16	0.19		R_n		0.14	0.11
	C_x		4.01	0.22		C_x		3.56	0.60
	E_C		0.33	0.36		E_C		0.98	0.94
	E_r		0.14	0.17		E_r		0.43	0.35
	R_n		0.26	0.26		R_n		0.63	0.81
	C_x		4.37	0.60		C_x		4.02	0.84
	E_C		0.41	0.22		E_C		0.36	0.18
	E_r		−0.10	0.09		E_r		0.01	0.05
	R_n		0.52	0.29		R_n		0.40	0.15

Nonetheless, one descriptor stands out, the convexity index, which involves the convex perimeter and perimeter measurements. Figure 6 illustrates that the convexity index values measured with ImageJ software are significantly lower than those measured with Clemex. The thresholds for identifying particles with more than one satellite—0.95 for Clemex and 0.90 for ImageJ—are derived from the data shown in Figure 6.

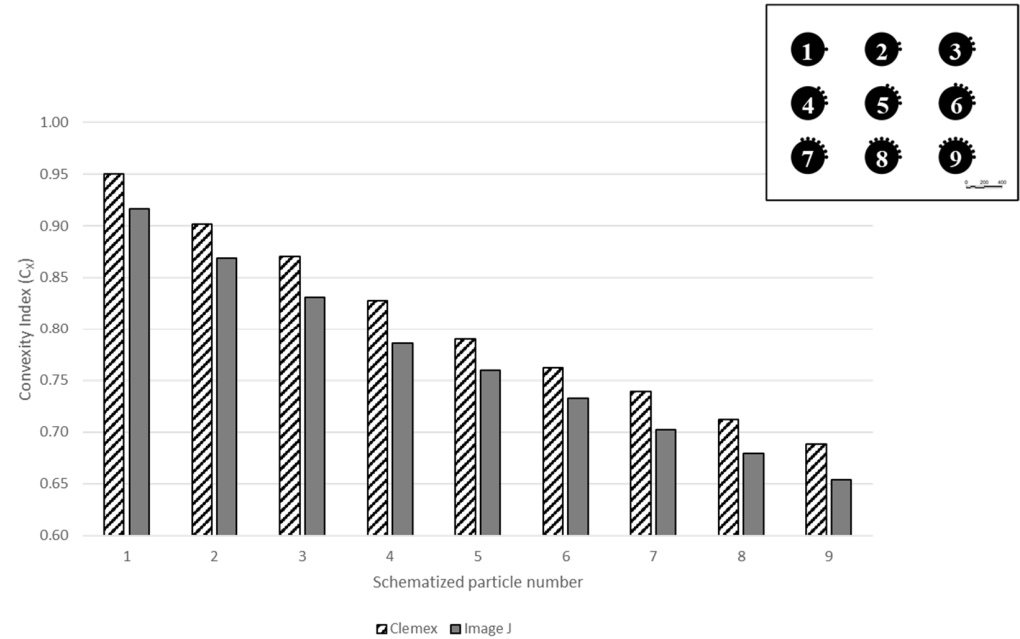


Figure 6. Convexity index (C_x) for particles with multiple satellites.

As illustrated in Figure 7, the extent ratio descriptor used to identify particles with a single growing satellite shows equivalent behavior with both Clemex and ImageJ. The same holds true for the descriptors used to identify elongated particles (ellipse ratio, E_r), as shown in Figure 8, and one of the two ratios used to categorize faceted particles (roundness index, R_n), as shown in Figure 9.

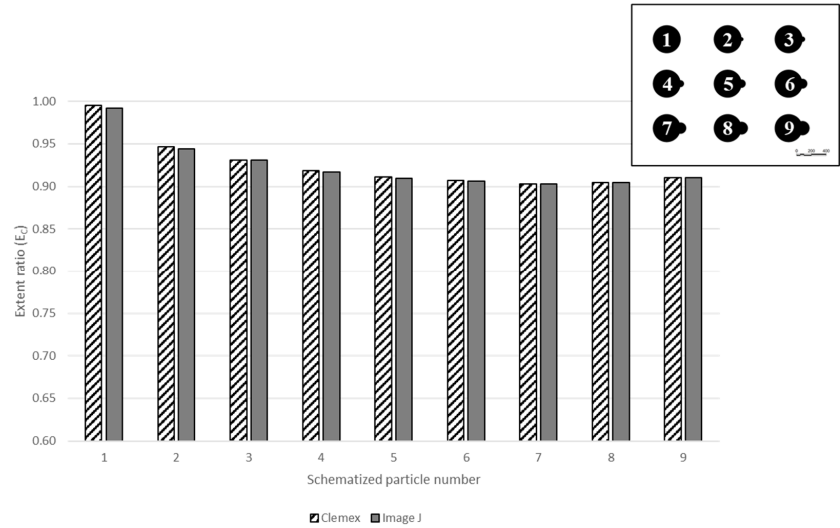


Figure 7. Extent ratio (E_C) for particles with single growing satellites.

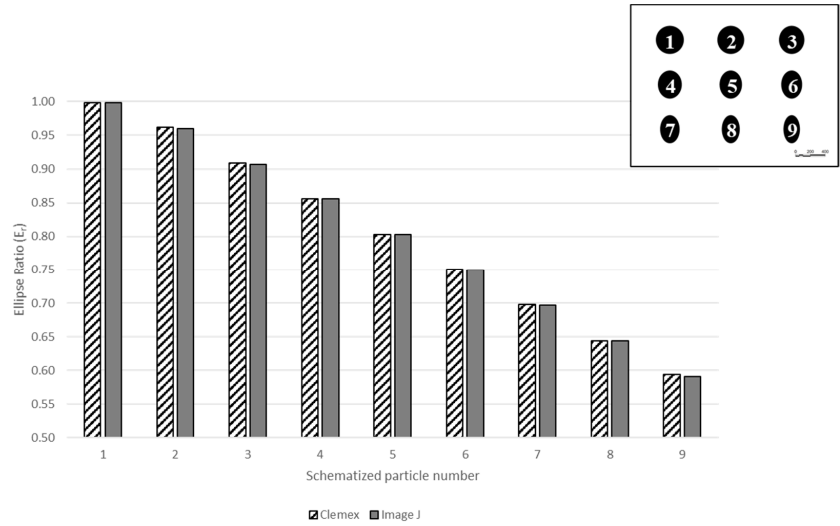


Figure 8. Ellipse ratio (E_r) for elongated particles.

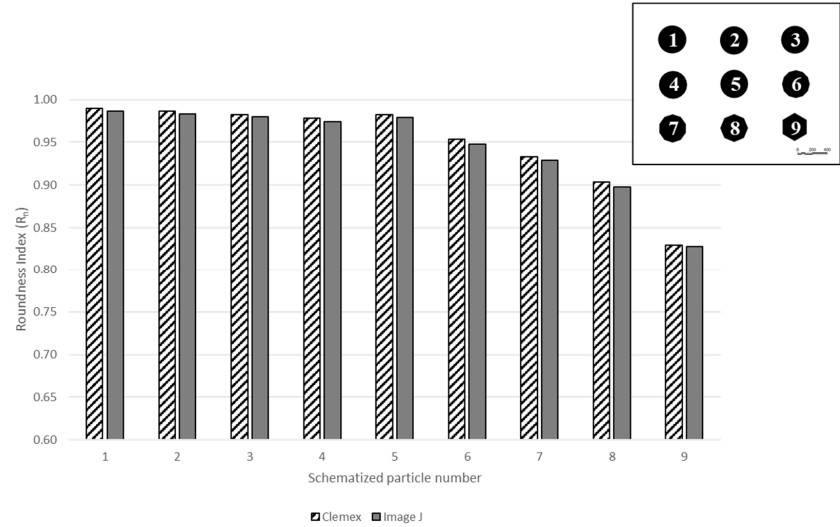


Figure 9. Roundness index (R_n) for faceted particles.

However, it is worth noting that ImageJ does not calculate the internal and external diameters, which are defined as the inner and outer circle diameters centered on the centroid of the particle. The adaptation of the irregularity index (IR) is discussed in the next section with the analysis of the metallic powders.

3.2. Image Analysis of Metallic Powder Samples

The first step of the sequential methodology is to discriminate particles with multiple satellites from those with a single satellite, as well as elongated, faceted, and spherical particles. Analyses using Clemex and ImageJ were performed on the same images. Since both software programs allow for the tracking of particles, it was possible to compare, particle by particle, the values of the descriptors calculated with the exported results. This direct comparison ensures that discrepancies in descriptor values can be attributed to the software's analytical methods rather than differences in the sample images themselves.

As discussed earlier, the convexity index showed inconsistent results between Clemex and ImageJ, even after making threshold adjustments. This index, which is the ratio of the convex perimeter to the perimeter measurements, helps in identifying whether a particle has more than one satellite. However, due to notable differences in perimeter values between the two software programs, the results for the convexity index can be unreliable. To overcome this issue, particles can be assessed without depending on the convexity index. Instead, by using the extent ratio alone, as illustrated in Figure 10, it is possible to classify all particles with one or more satellites together effectively.

The black bars on the graph represent the percentage of particles with satellites identified using the Convexity threshold approach. The striped and white bars show the percentage captured without the convexity index, employing corrected thresholds of 0.955 for Clemex, and 0.95 for ImageJ. These thresholds were determined through an iterative trial and error process to achieve maximum consistency in particle categorization across the software platforms. By adjusting the extent ratio, the overall percentage of particles with satellites was maintained, allowing for a robust comparison despite discrepancies in measurement calculations.

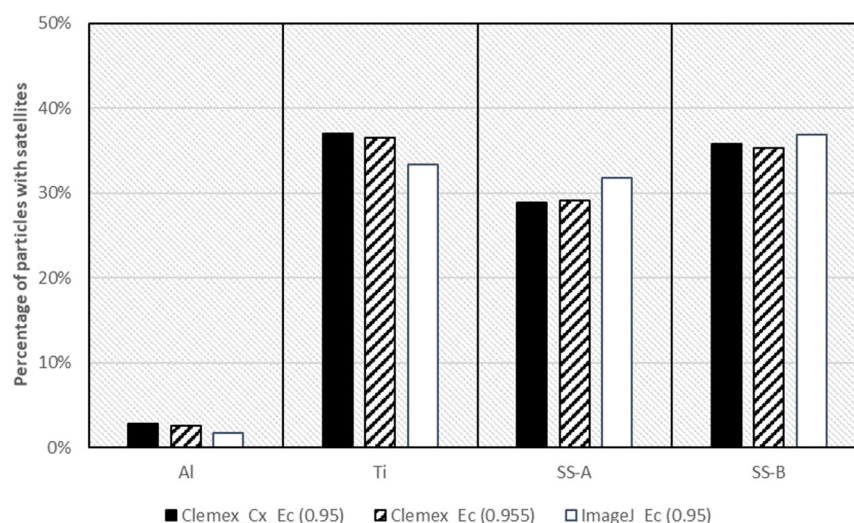


Figure 10. Percentage of particles with satellites in aluminum (Al), titanium (Ti), stainless steel (SS-A), and recycled stainless steel (SS-B).

An ellipse ratio with a threshold of 0.90 provided the best results across all powders, as shown in Figure 11. This threshold was determined using an iterative approach similar to that used for the extent ratio, where various values were tested to achieve optimal classification of different powders. The ellipse ratio is a robust parameter referenced in

ISO 9276, which supports its use in distinguishing elongated particle shapes within image analysis contexts [15]. While the ellipse ratio demonstrates effectiveness across various types of metallic powders, it is important to consider the potential variability between different imaging systems and the need for further validation in diverse analytical contexts.

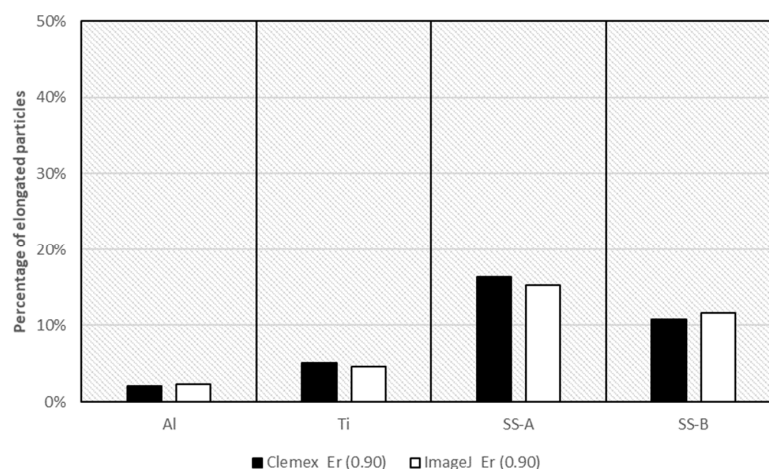


Figure 11. Percentage of elongated particles in aluminum (Al), titanium (Ti), stainless steel (SS.-A), and recycled stainless steel (SS.-B).

At this stage of the analysis, the remaining particles are neither associated with satellites nor exhibit elongated shapes. To classify a particle as spherical, it must meet both the roundness and irregularity index constraints with a threshold above 0.90; otherwise, it is considered faceted. This dual-criterion approach ensures a more precise categorization of particle shapes, distinguishing clearly between spherical and faceted forms based on their geometric properties.

The roundness index provided similar results when measured with both ImageJ and Clemex software, indicating consistency in this descriptor across different analysis platforms. However, the irregularity index, as defined in Equation (7), presents challenges in standardization due to varying measurement capabilities across software. ImageJ does not directly measure internal (ID) and external (OD) diameters but uses the maximum inscribed circle (MIC) via the MorphoLibJ plug-in. Therefore, in the absence of direct ID and OD measurements in ImageJ, ID was substituted with MIC, and OD was replaced with the maximum Feret diameter.

Figure 12 illustrates the differences between ID, OD, and MIC, highlighting how these substitutions impact the calculation of the irregularity index. This adaptation allows for a more uniform application of the irregularity index across different software programs, ensuring that the analysis remains robust despite the inherent discrepancies in measurement capabilities. This method preserves the accuracy of particle shape analysis, especially in differentiating between spherical and faceted particles.

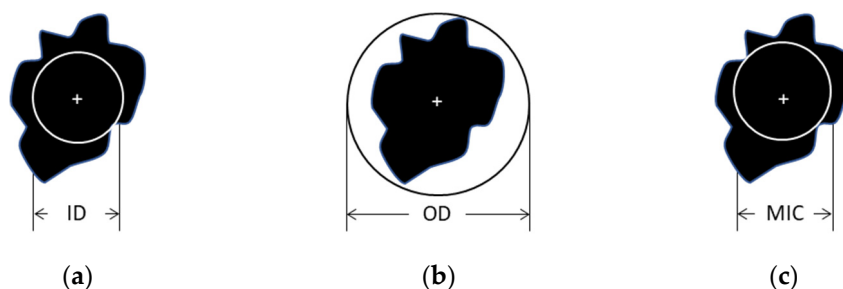


Figure 12. (a) Internal diameter, (b) external diameter, and (c) maximum inscribed circle.

The application of a threshold of 0.90 with the modified irregularity index in ImageJ resulted in a similar proportion of categorized particles for titanium powder samples as obtained with the Clemex system. However, for stainless steel and aluminum powder samples, this threshold led to an underestimation of proportions, as shown in Figure 13. This discrepancy suggests that while the modified index works well for certain materials, it may not be universally applicable across different types of metallic powders without further adjustments. To address this issue, adjusting the threshold for each powder type might be necessary to preserve the accuracy of individual particle categorization, thereby maintaining the overall percentage of faceted particles.

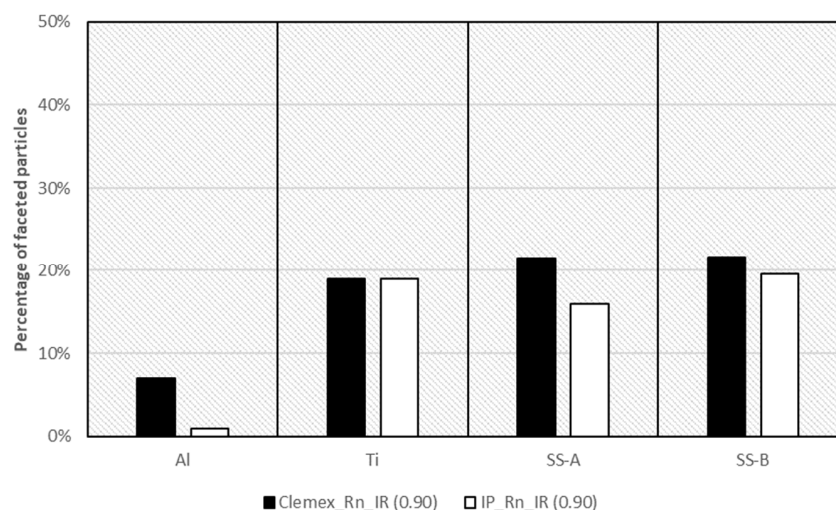


Figure 13. Percentage of faceted particles in aluminum (Al), titanium (Ti), stainless steel (SS-A), and recycled stainless steel (SS-B).

When analyzing aluminum particles classified as faceted by Clemex, it was observed that many classifications were influenced by touching particles that had been separated using the automatic bridge removal tool. This tool, found in Clemex, is applied to differentiate and isolate binary objects that are juxtaposed or partially overlapping. This separation process often creates an artificial aspect on the surface, which can influence the irregularity index (as shown in Figure 14). This issue is not limited to aluminum particles; it potentially affects all powder materials. However, the impact might be more pronounced for spherical particles, like aluminum, compared to more irregularly shaped particles from the other powders. Additionally, the internal and external diameters calculated by Clemex are generally smaller and larger, respectively, compared to the MIC and maximum Feret diameter calculated by ImageJ. This discrepancy affects the irregularity index, leading to an overestimation of faceted particles.

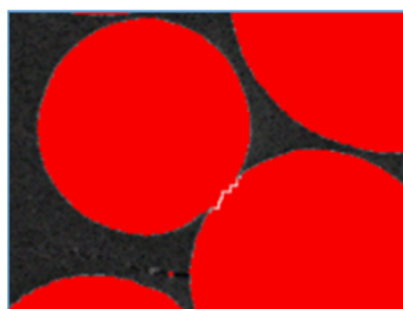


Figure 14. Clemex bridge removal between touching particles.

To mitigate these inconsistencies and improve the accuracy of particle classification, it would be beneficial to exclude touching particles from the analysis. This approach would avoid the artificial effects introduced by particle separation tools, ensuring that the classification of particles as faceted is based on their inherent morphological characteristics rather than artifacts introduced during image processing. Such a strategy would help standardize results across different software programs and provide a more reliable understanding of particle morphology.

3.3. Automated Static Image Analysis of Metallic Powder Samples

Morphologi, as an automated imaging system, employs an integrated sampler to disperse the powder and analyze it. This method involves analyzing particles dispersed on a substrate, contrasting with the analysis of polished cross sections discussed in the previous sections of this paper. The geometrical measurements and descriptors used in Morphologi differ significantly from those utilized in Clemex and ImageJ software. Specifically, Morphologi does not provide measurements such as minimum Feret, ellipse length, ellipse width, internal diameter, and external diameter. Due to these differences, several descriptors needed to be adapted to ensure the comparability of results across different systems.

The width and length of the particle are introduced for E_C , ellipse, and irregularity ratios. The length of the particle is defined as the maximum span between two points projected on a major axis passing through the centroid, while the width is the maximum projected length of the minor axis, which lies perpendicular to the major axis. With a threshold of 0.955, the proportions of particles with satellites were found to be comparable to the results obtained using both Clemex and ImageJ, as summarized in Figure 15. This indicates that despite the differences in measurement capabilities between the systems, the adapted descriptors can still provide consistent results for certain types of particles.

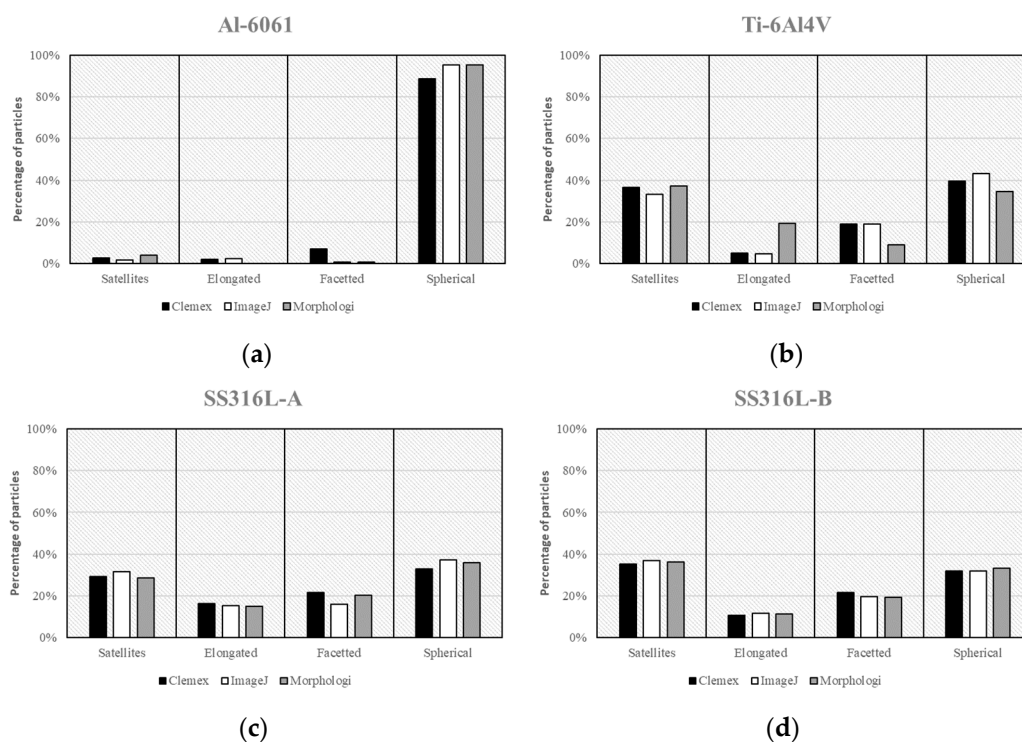


Figure 15. Summary of the results for (a) aluminum, (b) titanium, (c) as-received, and (d) recycled stainless steel with Clemex, ImageJ, and Morphologi software.

However, the modified ratio for elongated particles, akin to the aspect ratio, proved to be a less robust parameter as defined in ISO 9276-6. The results converged for the stainless-steel samples. In contrast, the results for aluminum and titanium powders were under and overestimated, respectively. This discrepancy suggests that while the adapted descriptors work well for some materials, they may not be universally applicable across all types of metallic powders without further refinement.

For analyzing faceted particles, the roundness descriptor can be effectively utilized, but the irregularity ratio poses challenges due to the absence of certain measurements in some systems. To adapt the irregularity ratio for use in systems that do not measure internal and external diameters, a modified approach was taken. This involved multiplying the ratio of the particle's width to its length by the ratio of the equivalent circle diameter to the maximum Feret diameter. Setting a threshold of 0.93 for this modified irregularity ratio yielded results that were comparable to those obtained for stainless steel powders. However, the results for titanium and aluminum powders were under-evaluated using this threshold.

4. Discussion

This study demonstrates that automatic static image analysis software can reliably classify particle shapes, achieving results comparable to methods that use metallographic images. For results to be quantitatively compared between laboratories, it is essential to standardize analysis methods, including image generation techniques (metallographic images or shadow projections), resolution, and the definitions and formulas used for shape descriptors.

For instance, when using metallographic images, the sample preparation requires, prior to being polished, the mixing of powder into an epoxy resin, which allows a good 3D randomization of the particle orientation. While this method captures only a single plane, it still allows for inference of the three-dimensional characteristics, as described by Underwood [19]. Systems that rely on shadow projection images use particle dispersion units involving gravity, which tends to let the particles lie in a preferential orientation, potentially biasing the results.

The choice of scanning electron microscopy (SEM) has the potential to use much greater resolution than optical microscopy and therefore be more capable of observing fine morphological features. [20] Some descriptors and basic measurements are very sensitive to the image resolution used. Increasing the resolution decreases the pixel size, which will lead to a higher measured perimeter length due to the better capture of the particle surface roughness [13]. According to the ISO 9276-6 standard, a minimum resolution is recommended to ensure that each particle is represented by 100 to 5000 pixels, providing the precision needed for reliable analysis of the smallest particles.

Achieving reproducibility between software programs is a major issue in the objective of standardizing the image analysis of particle shape for scientific and industrial applications. The descriptors selected and the chosen threshold values are critical factors that can influence the outcome of the classification. The study reveals significant differences in how various software evaluate parameters such as the perimeter of the powder particle. These differences are often due to the underlying algorithms used by each software program, which can affect the accuracy and comparability of results. The availability of certain measurements, such as ellipse length or minimum Feret diameter, varies between software. This variability can limit the ability to perform consistent and comprehensive analyses across different platforms.

5. Conclusions

Particle shape significantly influences the behavior of powder materials, affecting flowability, packing density, and spreadability in additive manufacturing (AM) processes. This study compared powder shape classification using traditional 2D metallographic image analysis with commercial software (Clemex Vision PE), open-source software (ImageJ), and an automated 2D system (Morphologi). Automated imaging instruments offer significant advantages by allowing for direct sample analysis, eliminating the need for traditional sample preparation.

The key finding of this study is that the three systems used—two employing metallographic cross-sections and one utilizing particle shadow projections—yielded similar classification results with the four selected additive manufacturing (AM)-type metal powders. Classification of particles with satellites using a corrected extent ratio demonstrated high consistency across all three systems. Similarly, the classification of elongated particles using the ellipse ratio showed consistent results, although there were slight variations with one of the powders (Ti6Al4V) when using automated systems.

However, several challenges and recommendations arise. The complexity of particle morphology means that no single shape descriptor fully captures its intricacies. Therefore, a combination of descriptors is essential. Additionally, standardizing measurements and descriptors across software is essential to mitigate discrepancies and ensure reliable powder characterization.

Looking forward, further research is needed to understand the relationship between particle morphology and powder behavior in AM processes, which will enhance predictive capabilities and the control of powder feedstocks. Insights gained from this research can inform the development of new standards, improving the understanding of powder attributes and their impact on final part quality. Moreover, integrating AI tools in particle shape classification offers a promising avenue for enhancing the accuracy and efficiency of powder characterization, facilitating automated analyses, and improving classification methodologies.

By addressing these challenges and pursuing these future directions, the field can advance towards standardized and precise methods for particle shape analysis, thereby enhancing the effectiveness of AM processes.

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Abbreviations

The following abbreviations are used in this manuscript:

A	Area
Al	Aluminum
AM	Additive Manufacturing
BSE	Backscattered Electron
C_x	Convexity Index
D_{eq}	Equivalent Diameter
EB-PBF	Electron Beam Powder Bed Fusion
E_L	Ellipse Length
E_r	Ellipse Ratio
E_W	Ellipse Width
E_C	Extent Ratio
ID	Inner Diameter
IR	Irregularity Ratio
L	Length
LPBF-LB/M	Laser Powder Bed Fusion of Metals
MIC	Minimum Inscribed Circle
OD	Outer Diameter
P	Perimeter
P_C	Convex Hull Perimeter
R_n	Roundness Index
SD	Standard Deviation
SEM	Scanning Electron Microscope
SD	Standard Deviation
SS	Stainless Steel
Ti	Titanium
W	Width
X_{Fmin}	Minimum Feret Diameter
X_{Fmax}	Maximum Feret Diameter

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