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Relevance of Accurate Dimensional Metrology in Smart Manufacturing

Dimensional accuracy and stability analysis of laser powder bed fusion (LPBF) samples for waste reduction and improved efficiency in Additive Manufacturing (AM) processes

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The Challenge

Over the past two decades, additive manufacturing (AM), also known as 3D printing, has revolutionized prototype creation. Compared to conventional processes such as machining or molding, 3D printing is more material- and energy-efficient, thereby reducing waste. Laser Powder Bed Fusion (LPBF) is a metal additive manufacturing technique that uses a laser beam to fuse the metal powder into a 3D shape. LPBF technology is widely used in the aerospace, biomedical, and automotive sectors to fabricate intricate metallic parts while minimizing material wastage. Although LPBF offers numerous benefits, industries have only partially adopted this AM technique due to a lack of standardization, limited material availability, insufficient material data, compatibility issues, poor part accuracy, inconsistency, poor repeatability, compromised quality, and a lack of certification.

Greater design freedom of AM techniques, compared with conventional methods, requires advanced measurement tools to achieve high levels of accuracy and quality. Hence, it is important to focus on the dimensional stability of 3D-printed parts for real-world applications. Currently, the ASTM F42 and ISO/TC 261 communities are working to standardize AM process parameters for component dimensional stability. At present, AM components are being fabricated without any stringent dimensional tolerance scheme. Thus, there are significant risks of rework, false rejections, faulty assemblies, and low productivity. Accurate dimensional metrology and evaluation of measurement uncertainty reduce the risk of false acceptance and false rejection during conformity assessment. According to JCGM 106:2012, lower measurement uncertainty improves confidence in compliance decisions and reduces unnecessary rejection of acceptable products. By optimizing LPBF process parameters and establishing traceable dimensional measurements, the present work improved dimensional conformity and process repeatability, thereby reducing rework, material waste, and production inefficiencies.

Precise dimensional measurement is an essential consideration in AM, particularly in the aerospace, medical, and automotive industries, to ensure accurate component fitting during assembly. It helps the industry make informed decisions on product acceptance or rejection and ensures the right product is delivered the first time, ultimately saving time and costs. It has been observed from previous studies¹ that with the implementation of a rigorous geometric dimensioning and tolerancing strategy to neutralize the thermal warping,

¹ Bilby 3D. Tolerances in Additive Manufacturing — A Deep Dive. January 2026.
https://b3d.com.au/articles/Art_Additive_Manufacturing_Tolerances.asp?srsItd=AfmBOor4eTmZAi4mGJlxHuE9Z3qzRwzifb_bkos6TaVAqwg0NloVoDVSj

shrinkage, and compromised surface finish in 3D printed components, the false rejections may drop by approximately 40 %, and the rework may be curtailed by 30-50 %, essentially underpinning the quality control.

Inaccurate measurements of 3D-printed components may also significantly affect cross-border trade. Disturbances in the global supply chain for 3D-printed parts are inevitable due to defective shipments caused by dimensional inaccuracies, primarily driven by additive manufacturing process parameters. For example, a 3D-printed industrial manifold (manufactured via fused deposition modeling) imported into an EU country was held at the border for many weeks due to a 2 mm deviation caused by a print layer shift. Noncompliance in the part was identified using a coordinate measuring machine. In another case, 3D-printed brackets were imported into a North American country with a specified 10 mm bolt-hole tolerance. Due to thermal shrinkage, the printed hole size was reduced by 0.4 mm, resulting in an assembly failure.² Furthermore, process variability may have compromised the reliability of manufactured components, leading to reduced industrial trust and limited adoption of AM techniques. The direct negative impacts due to these inaccurate measurements include delayed customs clearances, demurrage charges, interrupted manufacturing/assembly lines, inventory shortages, massive rejections, and a tarnished reputation in international trade.

“A 2 mm deviation...on a 3D-printed industrial manifold was held at the border for many weeks”

The dimensional and geometrical accuracy of parts produced by 3D printing is also an important yet underexplored aspect that has received limited attention in past efforts. Though many proposed guidelines for designing AM products are available in the literature, they are still evolving. Designers need

to explore further to identify the uncertainties associated with specific applications. The concept of measurement uncertainty has been critical since the earliest stages of measurement. For the past decades, the study of AM has mainly focused on process mechanisms, mechanical properties, and dimensional stability comparison. Very few researchers have discussed measurement uncertainty in additive-manufactured parts, which directly affects product conformity.

By performing metrologically traceable dimensional measurements and uncertainty evaluation for metal additive manufacturing, this work supports the broader objectives of national quality infrastructure. Improved confidence in dimensional measurements can enhance industrial credibility, facilitate participation in global supply chains, and strengthen export competitiveness for high-value sectors such as aerospace, biomedical devices, and automotive manufacturing.

² ING. 3D Printing: a threat to global trade. 28 September 2017.
https://think.ing.com/uploads/reports/3D_printing_DEF_270917.pdf

The Solution. Over 3 years (2022-2024), the Council of Scientific and Industrial Research – National Physical Laboratory (CSIR-NPL), India's NMI, and its academic partners have conducted dimensional metrological characterizations of 3D-printed components using metrologically traceable measurements. This was followed by a detailed evaluation of measurement uncertainty to assess the impact of various process variables and possible error sources on the dimensional stability and accuracy of the printed parts.

Specifically, in this investigation, the dimensional assessment of the Laser Powder Bed Fusion/Selective Laser Melting (LPBF/SLM)-built 316L SS pin-type specimens was conducted. The influence of predominant key process parameters, such as laser power, scan speed, and hatch spacing, on the dimensional stability of the manufactured part was explored using a coordinate measuring machine, 3D laser scanner, and statistical analysis (see **Table 1**).

The dimensional measurements for the printed pin-type specimens (see **Figure 1**) were obtained using a coordinate measuring machine. Various dimensional characterization data were collected for the fabricated specimens, including height, diameter, and cylindricity. The percentage of dimensional errors and measurement uncertainty was evaluated. The relevant scanning electron microscope (SEM) microstructure images were also obtained (see **Figure 2**).

As observed in the SEM images in **Figure 2**, the presence of cellular microstructures and equiaxed grains in the specimens influences dimensional stability by resisting deformation and pin dislocation motion, aided by an internal network. They also ensure isotropic material properties, hence restraining directional warping.

Data quality was ensured through repeated measurements, controlled laboratory environmental conditions (temperature and humidity) during the measurements, calibrated instruments for metrological traceability, comparisons with nominal computer-aided design (CAD) values, and a detailed evaluation of measurement uncertainty.^{3,4,5}

³ Pant, Meena; Nagdeve, Leeladhar; Moona, Girija; Kumar, Harish (2022). Estimation of Measurement Uncertainty of Additive Manufacturing Parts to Investigate the Influence of Process, MAPAN, 37, 765-775.

⁴ Pant, Meena; Nagdeve, Leeladhar; Moona, Girija; Kumar, Harish; Sharma, Anuj (2022). Tribological behavior investigation of 316L stainless steel specimens processed by selective laser melting, Proc IMechE Part J: J Engineering Tribology, 237 (4), 718-731

⁵ Brauer, D., & Cesarone, J. (2022). Total Manufacturing Assurance: Controlling Product Quality, Reliability, and Safety. CRC Press

Table 1. Process parameter combinations as per the Taguchi L9 array for specimen printing.

Sample No.	Scan Speed	Laser Power	Hatch Spacing
S1	700	250	80
S2	700	300	90
S3	700	350	100
S4	900	250	90
S5	900	300	100
S6	900	350	80
S7	1100	250	100
S8	1100	300	80
S9	1100	350	90

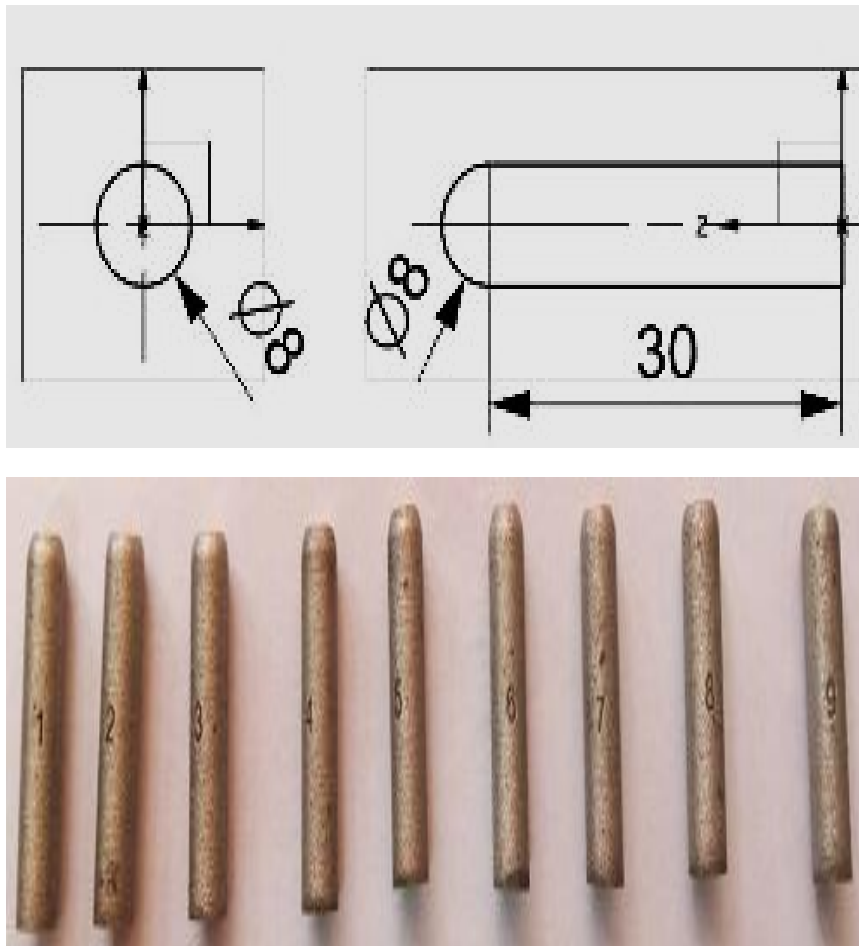


Figure 1. Printed pin-type specimens for dimensional characterization and tribological investigations.

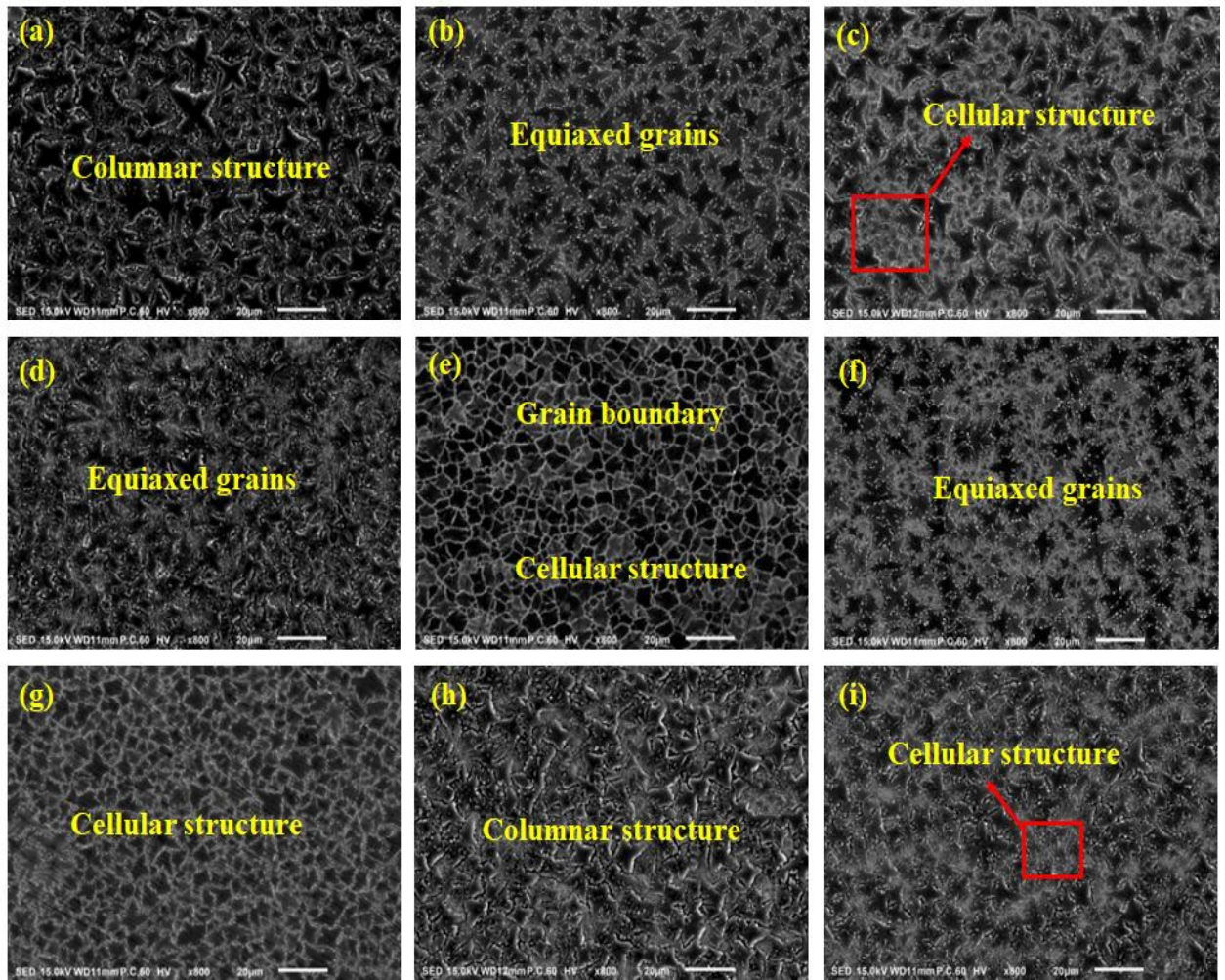


Figure 2. Scanning electron microscope (SEM) microstructure of pin-type specimens, (a) S1, (b) S2, (c) S3, (d) S4, (e) S5, (f) S6, (g) S7, (h) S8, and (i) S9.

A Quantifiable Impact. After the metrological intervention, significant, measurable improvements in dimensional accuracy were observed through optimization of additive manufacturing process parameters. Furthermore, the process parameter optimization reduced measurement uncertainty and increased dimensional conformity within the tolerance range. The lowest percentage deviation of 0.00 % (i.e., undetectable deviation within the measurement uncertainty), an energy density of 45.33 J/mm^3 , and an expanded uncertainty of $\pm 2.19 \text{ }\mu\text{m}$ were observed for the pin diameter with a combination of laser power 250 W, scan speed 1100 mm/s, and hatch spacing 100 μm . The minimum percentage deviation of 0.11 %, the energy density of 83.33 J/mm^3 , and the expanded uncertainty of $\pm 2.58 \text{ }\mu\text{m}$ for pin cylindricity were achieved with a laser power of 350 W, a scan speed of 700 mm/s, and a hatch spacing of 100 μm . The lowest percentage deviation of 0.00 % (i.e., undetectable deviation within the measurement uncertainty), an energy density of 51.33 J/mm^3 , and an expanded uncertainty of $\pm 2.58 \text{ }\mu\text{m}$ were observed for pin height with a laser power of 250 W, a scan speed of 900 mm/sec, and a hatch spacing of 90 μm . These superior

measurement outcomes for individual dimensional parameters, such as diameter/cylindricity/height, have the lowest percentage error and expanded uncertainty for a specific combination of process variables (i.e., laser power, print speed, and hatch spacing) in the laser powder bed fusion additive manufacturing technique.

With this metrological intervention, significant improvements were observed in the reliability of the additive manufacturing process, dimensional accuracy predictions, measurement uncertainty evaluation, and reduction. This also increased measurement confidence and quality-assurance capabilities in metal additive manufacturing, strengthening the overall national quality infrastructure. Furthermore, limited attention had been paid to the dimensional and geometric accuracy of the AM parts before this intervention.

The aim of this case study is to contribute to improved quality control, metrological traceability, and sustainable manufacturing objectives by reducing waste and inefficiencies in the AM process. It is also intended to positively influence the national strategy and enhance the industrial competitiveness of India's manufacturing sector. Furthermore, international cooperation and cross-border trade may be enhanced by adopting these improved, harmonized smart manufacturing techniques. Ultimately, improvements in dimensional metrology for smart manufacturing will build confidence in industrial processes underpinning critical sectors such as aerospace, automotive, and biomedical manufacturing. This is particularly critical for high-value additively manufactured products such as aerospace turbine blades, fuel nozzles, and patient-specific medical implants, where strict dimensional conformity is essential for performance, safety, and regulatory compliance.

With improved dimensional stability and reduced uncertainties in the AM process, many of the production errors can be substantially reduced and, in many cases, avoided. This case study discusses a simple part of a potentially larger manufacturing process: if the assembly is complicated and consists of several such components, the role of stringent dimensional metrology in additive manufacturing increases multiple-fold.

The positive outcomes of such investigations may influence national-level policy decisions on rework, false rejections, false acceptances, and other aspects of quality assurance. Accurate dimensions of 3D-printed parts help increase process repeatability, reduce the need for post-machining treatments, reduce process waste, and thus enhance manufacturing efficiency. As demonstrated, metrologically traceable dimensional measurements and the evaluation of measurement uncertainty enhance confidence in product quality, support supplier qualification, and facilitate acceptance within global supply chains. As a result, improved dimensional metrology strengthens manufacturing reliability, export competitiveness, and international trade.

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