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Scale-Dependent GD&T Conformity and Surface Roughness in PLA Parts Manufactured by Material Extrusion: A Metrological Assessment

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Abstract

Dimensional accuracy and surface roughness in material extrusion (MEX) have been widely studied; however, the effect of part scale on the simultaneous fulfilment of geometrical tolerances and surface finish remains less clearly established. This study evaluates the scale-dependent quality of PLA parts manufactured by material extrusion (MEX) using a full $3 \times 3 \times 3$ factorial design, combining three scales ($1\times$, $0.75\times$, and $0.5\times$), three commercial PLA filaments, and three printing speeds (40, 60, and 80 mm/s). A dedicated test artefact was inspected by a coordinate measuring machine to quantify GD&T-related deviations, including flatness, perpendicularity, parallelism, angularity, circularity, cylindricity, and coaxiality. Surface roughness was characterized by 2D profilometry using R_a , R_z , and R_q on representative horizontal and vertical surfaces. Results showed that part scale was the dominant factor affecting geometrical conformity, especially for orientation- and location-related tolerances such as perpendicularity, parallelism, and coaxiality, which deteriorated markedly as specimen size decreased. Filament type also influenced several geometrical responses, whereas printing speed showed no significant main effect on geometrical tolerances within the evaluated range. Surface roughness exhibited clear anisotropy, with vertical surfaces showing higher values and stronger statistical dependence on process factors. Unlike studies focused only on dimensional accuracy or surface roughness, this work provides an integrated GD&T-based and surface-texture assessment of scale-dependent quality loss in PLA parts manufactured by MEX. These findings may help designers and manufacturers define inspection criteria, select suitable commercial PLA filaments, and identify critical geometrical features when scaled MEX parts are intended for functional applications.



Academic Editor: Steven Y. Liang

Received: 22 June 2026

Revised: 14 July 2026

Accepted: 23 July 2026

Published: 27 July 2026

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Keywords: material extrusion; MEX; PLA; geometrical tolerances; GD&T; dimensional accuracy; surface roughness; part scale; coordinate measuring machine; design of experiments; process quality

1. Introduction

Material extrusion (MEX) is one of the most widely used additive manufacturing technologies for the fabrication of polymer components, particularly for prototyping and low-volume production. According to ISO/ASTM 52900:2021 [1], this process can be

classified for thermoplastic polymers as MEX-TRB/P, where bonding is achieved through thermal reaction in polymeric materials. In scientific and technical literature, the terms fused deposition modelling (FDM) and fused filament fabrication (FFF) are also commonly used to refer to filament-based polymer material extrusion processes. In this context, PLA is employed because of its low cost, accessibility, and ease of processing [2,3]. As MEX/FFF is increasingly used beyond visual prototyping and toward functional applications, the quality requirements imposed on printed parts become more demanding and must be assessed from a broader perspective than nominal dimensions alone. In such cases, geometrical conformity and surface finish are both relevant, since they directly affect fit, assembly, contact behaviour, repeatability, and overall part performance [4,5].

In parts manufactured by material extrusion, geometrical quality and surface texture are strongly influenced by the layer-by-layer deposition strategy. Characteristic process-induced features such as staircase formation, bead overlap, and local path discontinuities may simultaneously affect form, orientation, and location deviations, as well as roughness levels [6–8]. In addition, surface texture in MEX is inherently anisotropic, since the measured roughness depends on the orientation of the evaluated surface and on the relation between the measurement direction and the dominant deposition pattern [9–11]. Consequently, geometrical deviations and roughness should be regarded as complementary quality responses rather than as isolated outputs.

Several process variables may modify this combined quality response. Parameters such as material formulation, printing speed, layer thickness, and deposition strategy can influence the final geometry and surface texture of printed parts, often with non-uniform effects and interactions [10,12–14]. Under these conditions, structured experimental approaches based on design of experiments (DOE) and analysis of variance (ANOVA) are especially useful, since they allow the relative contribution of the different variables to be identified and support the definition of more robust processing conditions.

Although dimensional accuracy and surface roughness have been widely studied in MEX/FFF processes, many published works still address these responses separately or consider only a limited number of quality indicators under specific processing conditions [7,8,15]. Recent studies have analysed the influence of process parameters and material-related factors on dimensional accuracy, geometrical quality, and surface roughness in PLA parts manufactured by filament extrusion [16,17]. In addition, the effect of material-related variability is often examined using a single filament, which restricts the generalization of conclusions when commercial PLA materials differ in rheological behaviour, additives, pigmentation, or processing stability [18–20]. Another practically relevant aspect is part scale. The presence of smaller features and reduced geometrical dimensions may alter the process response and amplify quality losses, yet scale is not always explicitly incorporated into comparative quality studies [21–23]. In smaller parts, the relative influence of process-related limitations becomes more critical, since nozzle diameter, layer height, deposited bead width, and positioning resolution remain essentially constant while the nominal dimensions of the features are reduced. Therefore, local deviations associated with material deposition, corner formation, path discontinuities, and layer stacking may represent a larger fraction of the functional geometry. This effect can amplify form, orientation, and location errors, particularly in features such as holes, cylinders, reference planes, and geometrically related surfaces [24]. This combined assessment is relevant for functional components because GD&T deviations affect datum relationships, axes, orientation, location, and assembly, whereas surface texture influences contact behaviour, fitting conditions, and local surface quality.

These limitations highlight the need for studies in which geometrical conformity and surface roughness are assessed within the same experimental framework, particularly

when part scale is explicitly considered. While previous studies have mainly focused on dimensional accuracy, surface roughness, or isolated process parameters, fewer works have evaluated how scaling affects different families of GD&T-related deviations, including form, orientation, and location tolerances, together with surface finish. This aspect is relevant because the same absolute manufacturing deviation may represent a much larger functional error when feature size is reduced.

Therefore, the main contribution of this work is an integrated metrological assessment of scale-dependent quality loss in PLA parts manufactured by material extrusion. Unlike studies focused mainly on dimensional deviation, isolated geometrical characteristics, or surface roughness, the present study evaluates different families of GD&T-related deviations and surface texture within the same experimental framework. The novelty does not lie in demonstrating the already known effects of scale or surface anisotropy but in comparing the relative sensitivity of form-, orientation-, and location-related responses and identifying which metrological characteristics become more critical when part dimensions are reduced.

To this end, a full $3 \times 3 \times 3$ factorial design was applied, combining part scale, commercial PLA filament, and printing speed. The specimens were inspected by a coordinate measuring machine to quantify flatness, perpendicularity, parallelism, angularity, circularity, cylindricity, and coaxiality, while surface roughness was evaluated on representative horizontal and vertical surfaces. This approach enables the identification of the geometrical tolerance families and surface orientations most sensitive to downscaling and provides practical criteria for manufacturing-condition selection, metrological inspection, and quality control of scaled MEX components.

2. Materials and Methods

2.1. Additive Manufacturing

Three commercial PLA filaments from different manufacturers were selected to introduce inter-brand variability while maintaining the same polymer family. Their main characteristics are summarised in Table 1. Filament colours were not selected as an independent experimental factor but corresponded to the commercially available materials used in the study. Previous research has shown that colourants, pigments, and additives associated with different commercial formulations can modify the thermal, mechanical, and processing behaviour of PLA [25,26]. However, because the filaments studied also differed in manufacturer, finish, additives, and proprietary formulation, the filament factor is interpreted in this work as the overall effect of each commercial material rather than as the isolated effect of colour.

Table 1. Main characteristics of the commercial PLA filaments used in the study.

Code	Commercial Designation	Manufacturer	Colour/Finish	Nominal Diameter	Recommended Extrusion Temperature
F1	PLA Matte	Shenzhen Elegoo Technology Co., Ltd., Shenzhen, China	Grey, matte	1.75 mm	190–220 °C
F2	Easy Print PLA	Smart Materials 3D Printing, S.L.U., Alcalá la Real, Spain	White	1.75 mm	200–220 °C
F3	PLA Matte	Zhuhai SUNLU Industrial Co., Ltd., Zhuhai, China	Black, matte	1.75 mm	200–230 °C

The spools were identified by batch and stored under controlled humidity and temperature conditions of 50% RH and 25 °C. To prevent extrusion temperature from acting as a confounding factor, all specimens were manufactured at 210 °C, a value within the ranges recommended by the three manufacturers.

The manufacturers do not provide, in a homogeneous and comparable manner, a specific optimal printing speed for the three filaments; therefore, the differences between filaments are interpreted in this study as the global effect of the commercial material within a common processing window and not as the isolated effect of an individual optimum condition for each filament.

The CAD model was created using SolidWorks 2025 (Dassault Systèmes, Vélizy-Villacoublay, France), and slicing was performed with Ultimaker Cura 5.8.1 (UltiMaker, Utrecht, The Netherlands). The factors varied in the experimental design were part scale, commercial PLA filament, and printing speed. The remaining manufacturing and slicing parameters were kept constant throughout the study and are listed in Table 2.

Table 2. Manufacturing and slicing parameters kept constant for all specimens.

Parameter	Value or Setting
Layer height	0.20 mm
Wall thickness	1.60 mm
Number of wall lines	4
Horizontal expansion	0.00 mm
Z-seam alignment	Sharpest corner
Top thickness	0.80 mm
Number of top layers	4
Bottom thickness	0.80 mm
Number of bottom layers	4
Infill density	20%
Infill pattern	Grid
Printing temperature	210 °C
Build plate temperature	60 °C
Flow compensation factor	100%
Nozzle material	Brass
Nozzle diameter	0.40 mm

These conditions were kept constant to isolate the influence of part scale, filament type, and printing speed within a controlled and comparable experimental framework.

2.2. Measurement Equipment

The evaluation of geometrical deviations was carried out using a coordinate measuring machine (CMM), DEA Metris C3 V7-7-5 (Hexagon AB, Stockholm, Sweden), with a bridge-type architecture and a measuring volume of 700 × 700 × 500 mm (X × Y × Z). The system is equipped with a granite table and an aluminium structure with air bearings, requiring a compressed air supply of 5 bar for guidance. The scale resolution is 0.5 µm, and the machine allows positioning speeds up to 52 m/min with maximum accelerations of 9360 m/min².

Measurements were performed by contact probing, with the specimens rigidly fixed to the machine table. A Ø 3 mm ruby stylus (Renishaw plc, Wotton-under-Edge, UK),

mounted with a 50 mm extension on the probe head in vertical configuration, was used. Prior to each measurement campaign, axis referencing (homing) and probe calibration using a reference sphere were performed. System control and probe management were conducted via UCC Server (Renishaw plc, Wotton-under-Edge, UK), while measurement routines, alignments, and report generation were programmed using MCOSMOS (Mitutoyo Corporation, Kawasaki, Japan).

Each geometrical deviation was measured three times on each specimen. The three repeated measurements were averaged to obtain one specimen-level response, while the dispersion among repeated measurements was used only to assess metrological repeatability. For each experimental condition, the reported mean and standard deviation were subsequently calculated from the specimen-level responses of the three independently manufactured replicates. Probing was carried out using sampling strategies adapted to each evaluated feature, with at least five points acquired per feature. According to the current calibration certificate, the expanded uncertainty associated with the reference measurement condition was $U = 5 \mu\text{m}$ for $k = 2$. The selected measurement procedure was intended to ensure consistent comparison across the experimental conditions rather than to establish a full uncertainty budget for each geometrical response.

CMM measurement offers important advantages for this study because it allows geometrical reference systems to be established and different form, orientation, and location deviations to be evaluated at high resolution using a common procedure. This facilitates consistent comparison among the different experimental conditions and is particularly suitable for characteristics defined by relationships between surfaces and axes. Nevertheless, because it is a contact technique based on a discrete number of points, it does not provide a complete characterisation of the entire surface. The results may be affected by probe accessibility, stylus-tip radius, sampling strategy, and local irregularities of the printed surfaces, especially in internal elements and reduced-scale specimens. Therefore, the values obtained should be interpreted as comparative estimates of geometrical deviations within the defined measurement procedure.

Figure 1 shows the experimental setup used for CMM inspection, including the specimen fixturing system and a detail of stylus contact during point acquisition.

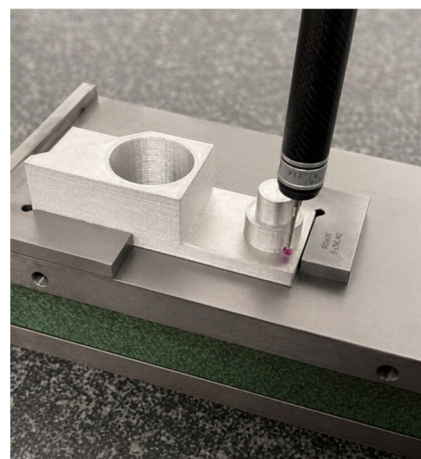


Figure 1. Experimental configuration for CMM inspection.

Surface roughness measurements were performed using a contact profilometer, Mitutoyo SJ-201P (Mitutoyo Corporation, Kawasaki, Japan). To ensure measurement stability and minimise the influence of vibrations during stylus scanning, the instrument was mounted on a magnetic base fixed to a rigid metallic block, with the entire system placed on a stable reference surface (granite table). Specimens were secured using a dedicated

fixture manufactured by 3D printing, designed to ensure repeatable positioning and to prevent displacement during measurement. The profilometer was connected to a computer via an RS-232 interface for data acquisition and storage using the manufacturer's software.

For each specimen, two representative surfaces were evaluated to capture the potential anisotropy associated with filament deposition: (i) a surface normal to the build plane and (ii) a transverse surface (perpendicular to the former). For each surface, three independent measurements were performed, shifting the evaluation area between measurements to sample different regions and improve representativeness. Prior to each acquisition, the approach and alignment of the stylus were adjusted using the fine positioning mechanism of the support, ensuring that the probe was perpendicular to the surface and that the stylus displacement was parallel to it during scanning. Measurement parameters were set to a cut-off length of $L_c = 0.8$ mm and an evaluation length of 2.4 mm, using a PC50 filter setting and the DIN 90 evaluation mode. Roughness parameters (R_a , R_q , and R_z) were obtained directly from the recorded profiles. The three repeated measurements on each surface were averaged to obtain one specimen-level response. For each experimental condition, the mean and standard deviation reported in the Supplementary Materials were calculated from the specimen-level responses of the three independently manufactured replicates. R_a represents the arithmetic mean deviation of the profile from the mean line, R_q the root mean square of these deviations, and R_z the characteristic vertical amplitude between profile peaks and valleys.

2.3. Specimen Geometry

The test artefact was designed to enable the evaluation of geometrical deviations associated with form, orientation, and location features by CMM inspection. Several reference planes were defined, including parallel and perpendicular surfaces, as well as external and internal cylinders, flat faces, and an inclined surface for angularity assessment. For roughness measurements, stylus accessibility was ensured by incorporating chamfers and sufficient clearances, avoiding internal radii smaller than the stylus tip radius. The specimen was conceived as an integrated metrological artefact rather than as a reproduction of a specific functional component. Its design was guided by four main criteria: the inclusion of representative form, orientation, and location features; the availability of stable datum surfaces and geometrically related elements; accessibility for contact probing and profilometry; and geometric scalability without altering the relative arrangement of the evaluated features. Accordingly, the artefact combines planar, inclined, cylindrical, internal, and external elements in a single geometry, enabling the assessment of multiple GD&T-related deviations and surface roughness under the same manufacturing conditions.

The build-plate contact surface was deliberately excluded from the evaluation of geometrical deviations and surface roughness. Its formation is governed by specific first-layer conditions, including nozzle-to-bed distance, bead spreading, adhesion to the tempered-glass surface, and local compression against the build plate. Therefore, its surface morphology and geometrical response differ from those of the free horizontal and vertical surfaces generated during subsequent layer-by-layer deposition. Because the present study focused on geometrically related features and representative free surfaces formed under comparable deposition mechanisms, the build-plate contact surface was not included in the experimental assessment.

The specimen allowed the measurement of flatness, parallelism, perpendicularity, circularity, cylindricity, coaxiality, and angularity, as well as surface roughness parameters R_a , R_z , and R_q . Figure 2 shows the test artefact manufactured at $1\times$ scale (1:1).

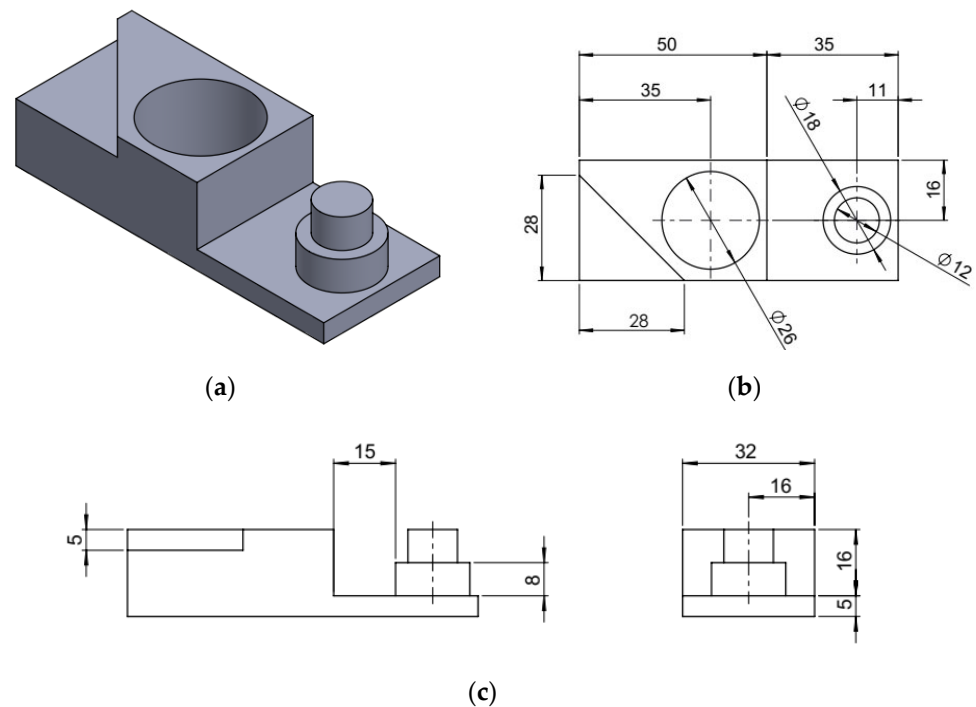


Figure 2. Test artefact used to evaluate geometrical deviations and surface roughness (1× scale): (a) isometric view; (b) top view; (c) front and side views. Dimensions in mm.

All specimens were manufactured in the orientation shown in Figure 2, with the base of the artefact parallel to the XY build plane and the axes of cylindrical features K, L, and M parallel to the Z direction. Consequently, their nominal circular cross-sections were generated in planes parallel to the XY plane. This build orientation was kept constant throughout the experimental design.

The surfaces and features used for each geometrical deviation are described in detail below.

2.3.1. Flatness (PL)

Flatness was measured using the CMM by fitting a least-squares plane to the sampled point cloud. PL is the minimum distance between two parallel planes that enclose the surface. Four planes were selected for evaluation, as shown in Figure 3.

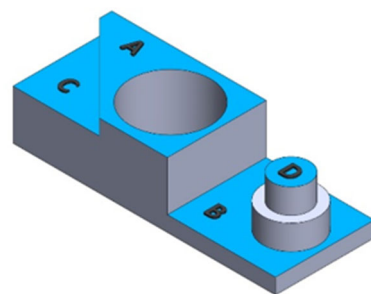


Figure 3. Surfaces evaluated for flatness (PL): A, B, C, and D.

2.3.2. Parallelism (PAR)

After probing, both the datum plane and the measured surface plane were fitted using a least-squares method. Parallelism (PAR) is defined as the minimum distance between two planes parallel to the datum that enclose the surface. The evaluated surface–datum pairs are shown in Figure 4.

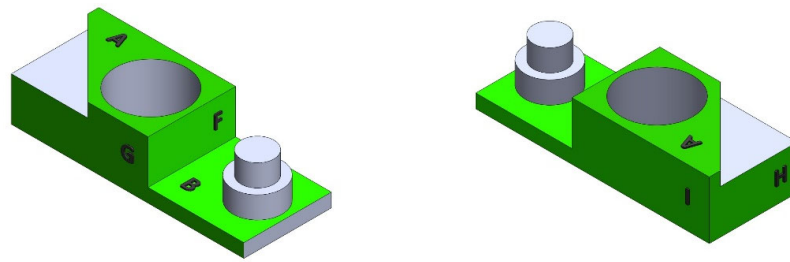


Figure 4. Combinations evaluated for parallelism (PAR): A–B, F–H, and G–I.

2.3.3. Perpendicularity (PP)

The datum plane and the measured surface plane were fitted using a least-squares approach. Perpendicularity (PP) is defined as the minimum distance between two parallel planes that are perpendicular to the datum and enclose the measured surface, as illustrated in Figure 5.

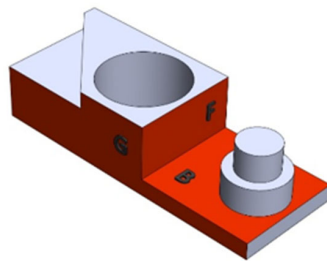


Figure 5. Combinations evaluated for perpendicularity (PP): B–F and G–B.

2.3.4. Angularity (ANG)

After probing with a $\varnothing 3$ mm stylus, the datum was established using a least-squares fit. Angularity (ANG) is defined as the minimum distance between two parallel planes oriented at the nominal angle with respect to the datum that enclose the surface, as illustrated in Figure 6.

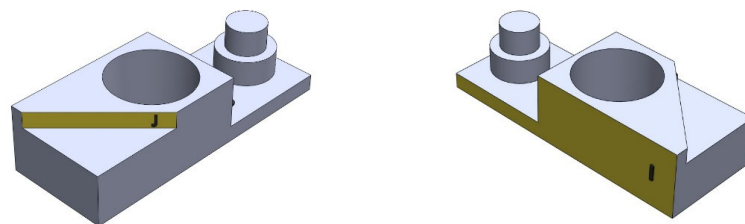


Figure 6. Combination evaluated for angularity (ANG): I–J.

2.3.5. Circularity (CIR)

For each circular section, a least-squares circle was fitted. Circularity (CIR) is defined as the minimum radial separation between two concentric circles that enclose the measured points (maximum–minimum radial difference), as illustrated in Figure 7.

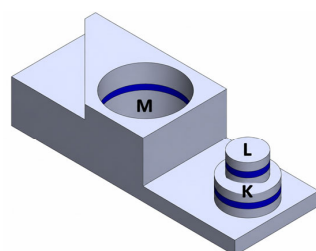


Figure 7. Elements evaluated for circularity (CIR): circles inscribed in M, L, and K.

2.3.6. Cylindricity (CYL)

A cylindrical surface was fitted using a least-squares method. Cylindricity (CYL) is defined as the minimum radial separation between two coaxial cylinders that enclose the surface. The cylindrical surface selected for evaluation is shown in Figure 8.

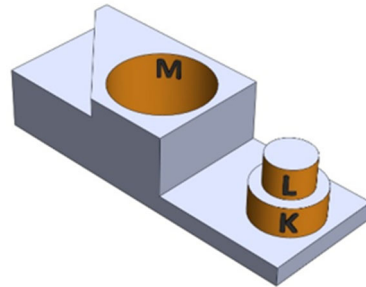


Figure 8. Elements evaluated for cylindricity (CYL): M, L, and K.

2.3.7. Coaxiality (COX)—Internal vs. External Axis

For each cylinder, the axis was determined using the least-squares fit. Coaxiality (COX) is defined as the maximum radial deviation of the measured axis relative to the datum axis (equivalent to the minimum zone bounded by two coaxial cylinders enclosing the axis), as illustrated in Figure 9.

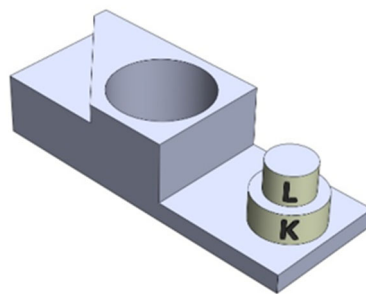


Figure 9. Axes evaluated for coaxiality (COX): L and K.

2.4. Surface Roughness Measurement Surfaces and Directions

Surface roughness was evaluated through linear measurements on two representative surfaces of the specimen, identified in the CAD model as the horizontal face B and the vertical face G (Figure 5). Face B corresponds to the upper horizontal platform of the step, whereas face G corresponds to the vertical lateral surface of the main prism.

In all cases, the measurement direction was defined as perpendicular to the predominant filament deposition direction observed on each surface, i.e., the direction of the beads or striations generated by the printing path. This criterion was adopted to capture the most representative height variation between adjacent filaments, corresponding to a critical condition in terms of surface finish. At the same time, it ensured consistent comparison across specimens under the same directional condition, rather than providing a full directional characterisation of surface topography.

On face G, the perpendicular direction involved crossing the layer-stacking marks (contour striations), whereas on face B, the perpendicular measurement was performed across the dominant deposition lines of the top layer (infill pattern and/or contours, depending on the region). Prior to each measurement, the orientation of the surface pattern was visually identified, and the stylus path was aligned orthogonally to this direction.

To minimise edge effects and local discontinuities, such as start/end points of the toolpath or seam regions, measurements were carried out in representative internal areas of each surface, avoiding proximity to edges and geometric transitions.

2.5. Design of Experiments

A full factorial 3^3 design (27 combinations) was conducted, considering scale ($1\times$, $0.75\times$, $0.5\times$), filament (F1–F3), and printing speed (40, 60, and 80 mm/s) as factors. The selected factor levels were defined to represent a practical and controlled experimental domain: the three scales were used to evaluate geometrical downscaling effects, the three PLA filaments to include commercial material variability within the same polymer family, and the printing speeds of 40, 60, and 80 mm/s to cover a common printing window for the desktop MEX printer used, rather than filament-specific optimal speeds. For each combination, three specimens were manufactured ($n = 3$), and for each specimen, metrological measurements of geometrical deviations and surface roughness were repeated three times to estimate measurement repeatability.

The manufacturing order of the 81 specimens was randomized. During metrological inspection, specimens were grouped by scale to maintain a consistent fixturing, alignment, and probing strategy for specimens of comparable dimensions. Within each scale group, the inspection order was randomized to reduce possible order-related effects. This grouping was adopted for procedural consistency and was not treated as an additional experimental factor in the statistical analysis. A summary of the experimental design is provided in Table 3.

Table 3. Experimental design (DOE): factors, levels, and replication.

Factor	Levels	Values/Definition	Experimental Replication	Measurement Replication
Scale	3	$1\times$, $0.75\times$, $0.5\times$ (equivalent to 1:1; 2:3 and 1:2)	3 specimens per combination	3 per specimen and response
Filament (PLA, $\varnothing$ 1.75 mm)	3	F1 = PLA Matte Elegoo; F2 = PLA Easy Print SmartFil; F3 = PLA Matte Sunlu		
Printing speed [mm/s]	3	40; 60; 80		

In addition, Figure 10 shows one representative specimen for each of the 27 experimental combinations of the factorial design, arranged by scale ($1\times$, $0.75\times$, and $0.5\times$) and differentiated by filament type: F1 (grey), F2 (white), and F3 (black). Three independent specimens were manufactured for each combination, giving a total of 81 specimens. This overview allows the variations associated with scale and commercial filament to be visually identified.

This design enabled the combined analysis of geometrical quality and surface roughness under the same controlled manufacturing conditions.

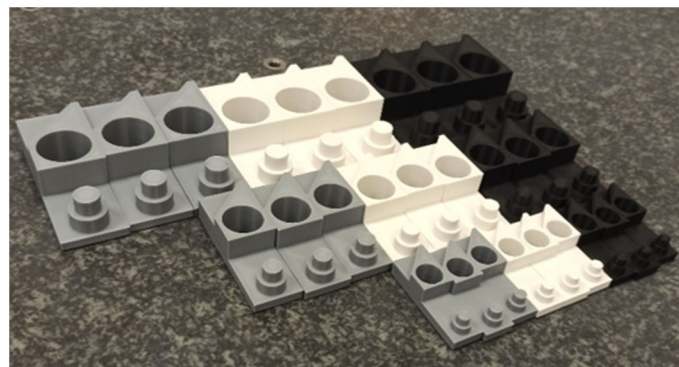


Figure 10. Representative set showing one printed specimen for each of the 27 experimental combinations of the $3 \times 3 \times 3$ factorial design, arranged by scale and distinguished by filament type. Three independent specimens were manufactured per combination, giving a total of 81 specimens.

2.6. Statistical Methods and Software

The analysis was performed using Minitab Statistical Software (Minitab, LLC, State College, PA, USA, version 19.1). For each manufactured specimen, the three repeated metrological measurements were averaged, and the resulting specimen mean was used as the experimental response. Thus, the manufactured specimen was considered the experimental unit, providing three independent experimental replicates for each of the 27 factor combinations and a total of 81 observations for each response. The repeated measurements were used exclusively to assess measurement repeatability and reduce local probing or profilometry variability.

A general linear model (ANOVA) including the main effects of scale, filament type, and printing speed, as well as their first-order interactions, was fitted for each geometrical and roughness response. A significance level of $\alpha = 0.05$ was adopted. Higher-order interactions were not included in the final models in order to preserve interpretability and to focus on the dominant process effects within the experimental domain considered. The coefficient of determination (R^2) was used as a complementary indicator of model fit.

As an exploratory complementary analysis, Pearson and Spearman correlation coefficients were calculated between selected geometrical and roughness responses. For this analysis, the three specimen-level responses corresponding to each experimental combination were averaged, resulting in 27 paired condition-level observations for each variable combination. Correlations were calculated both from these raw condition means and from the residuals of general linear models including scale, filament type, printing speed, and their first-order interactions. The correlations were interpreted only as measures of association within the experimental domain and not as evidence of causal relationships.

3. Results and Discussion

This section presents the geometrical and surface roughness results obtained for the 27 experimental conditions defined in the DOE. The geometrical analysis includes the main GD&T-related deviations evaluated in the specimens: flatness (PL), perpendicularity (PP), parallelism (PAR), angularity (ANG), circularity (CIR), external and internal cylindricity (CYL+ and CYL−), and coaxiality (COX). Surface roughness is described through R_a , R_z , and R_q , measured on representative horizontal and vertical surfaces in directions perpendicular to the predominant deposition pattern.

3.1. Descriptive Analysis of Geometrical Deviations

The mean values and standard deviations of the geometrical deviations for the 27 experimental conditions are provided in the Supplementary Materials. For each condition, these statistics were calculated from the specimen-level responses of the three independently manufactured replicates. Specifically, Table S1 reports flatness (PL), perpendicularity (PP), parallelism (PAR), angularity (ANG), and circularity in shafts (CIR+), whereas Table S2 reports circularity in holes (CIR−), cylindricity in shafts and holes (CYL+ and CYL−), and coaxiality (COX). The specimen code combines the three factors considered in the DOE: scale, filament, and printing speed. Thus, in a code such as S1x-F2-V60, S identifies the part scale ($S1 \times = 1 \times$, $S075 \times = 0.75 \times$, and $S05 \times = 0.5 \times$), F denotes the filament type ($F1 = \text{PLA Matte Elegoo}$, $F2 = \text{PLA Easy Print SmartFil}$, and $F3 = \text{PLA Matte Sunlu}$), and V indicates the printing speed in mm/s.

The results in Tables S1 and S2, together with the graphical summary in Figure 11, reveal clear differences among the evaluated geometrical responses. Flatness (PL) remained the most stable characteristic, with deviations generally limited to a few tens of micrometres and relatively low dispersion. Angularity (ANG), circularity (CIR $\pm$), and cylindricity (CYL $\pm$) occupied an intermediate range, with higher values and more visible variability

depending on the experimental condition. The largest deviations were found for perpendicularity (PP), parallelism (PAR), and especially coaxiality (COX), indicating that orientation- and location-related tolerances were the most sensitive to the manufacturing conditions considered in this study.

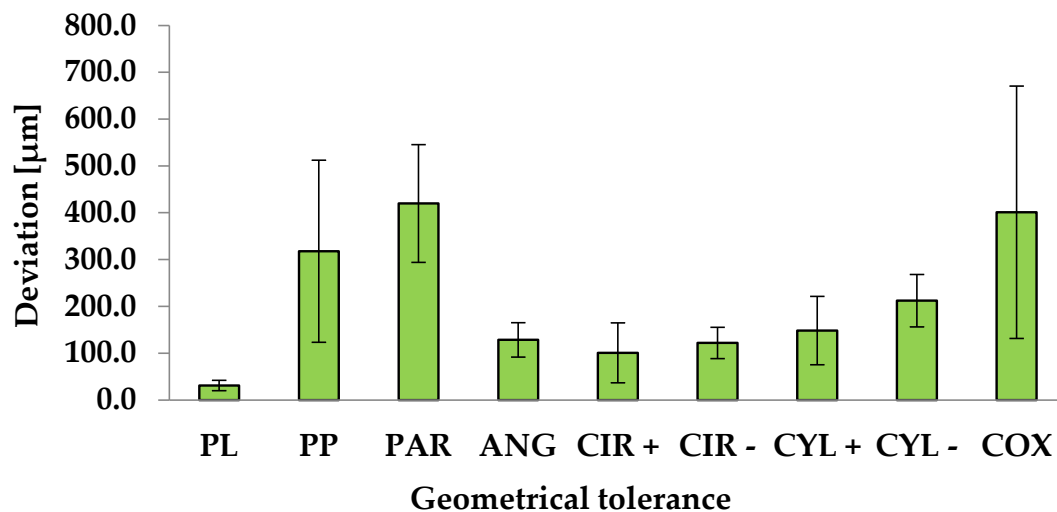


Figure 11. Overall mean values and standard deviations of the geometrical deviations obtained for the 27 experimental conditions.

The review of the individual measurements included in Tables S1 and S2 also shows that the scale effect was not homogeneous for all filaments. For example, at $0.5\times$ scale and 80 mm/s, perpendicularity reached 745.60 μm for F1, whereas it decreased to 370.05 μm for F2 under the same scale and speed conditions. Similarly, coaxiality reached 865.00 μm for S05x-F1-V80, compared with 258.50 μm for S05x-F2-V80. These results show that the loss of geometrical conformity cannot be interpreted only as an average scale effect but depends on specific scale–filament combinations.

This hierarchy suggests that the main geometrical limitations of the printed parts were not associated with local surface flatness, but rather with the preservation of angular and positional relationships between different features.

Overall, the descriptive results indicate that geometrical deviations were generally greater in the reduced-scale specimens and varied among the commercial filaments, whereas printing speed produced smaller and less consistent changes within the evaluated range. The statistical significance and interaction effects associated with these trends are examined in Section 3.3.

These results are in line with previous studies showing that part size can affect dimensional and geometrical accuracy in MEX/FFF processes, particularly when smaller features increase the relative effect of process-induced deviations [23]. The influence of filament type is also consistent with the fact that commercial materials may differ in diameter regularity, conditioning state, and processing stability, all of which can affect the consistency of the deposited paths [19,20]. In this sense, the descriptive results reinforce the need to consider scale and material variability when assessing the geometrical quality of MEX-printed parts [14].

From a metrological perspective, these results indicate that the effect of scale should not be interpreted only as a proportional reduction in part size. Instead, scaling modified the relative severity of the geometrical deviations, making orientation- and location-related tolerances more critical than local form deviations. This behaviour suggests that reduced MEX parts may require specific inspection criteria, since dimensional downscaling can

amplify the functional relevance of small absolute errors in datum relationships, axes, and geometrically linked features.

3.2. Surface Roughness Results

The linear surface roughness parameters R_a , R_z , and R_q were determined on two representative surfaces of the specimens: (i) the horizontal surface (face B) and (ii) the vertical surface (face G). To distinguish the results according to the evaluation plane, the subscripts H (horizontal) and V (vertical) are used hereafter. Accordingly, R_{aH} , R_{zH} , and R_{qH} correspond to face B, whereas R_{aV} , R_{zV} , and R_{qV} correspond to face G. The mean values and standard deviations for the 27 experimental conditions are provided in Table S3 of the Supplementary Materials. For each condition, these statistics were calculated from the specimen-level responses of the three independently manufactured replicates, which include R_a , R_z , and R_q measured on both the horizontal surface (H, face B) and the vertical surface (V, face G).

The roughness results in Table S3 were first examined descriptively to compare the behaviour of the horizontal and vertical surfaces. Boxplots were used for this purpose (Figure 12), as they provide a direct view of the central tendency, dispersion, and possible outliers for each roughness parameter.

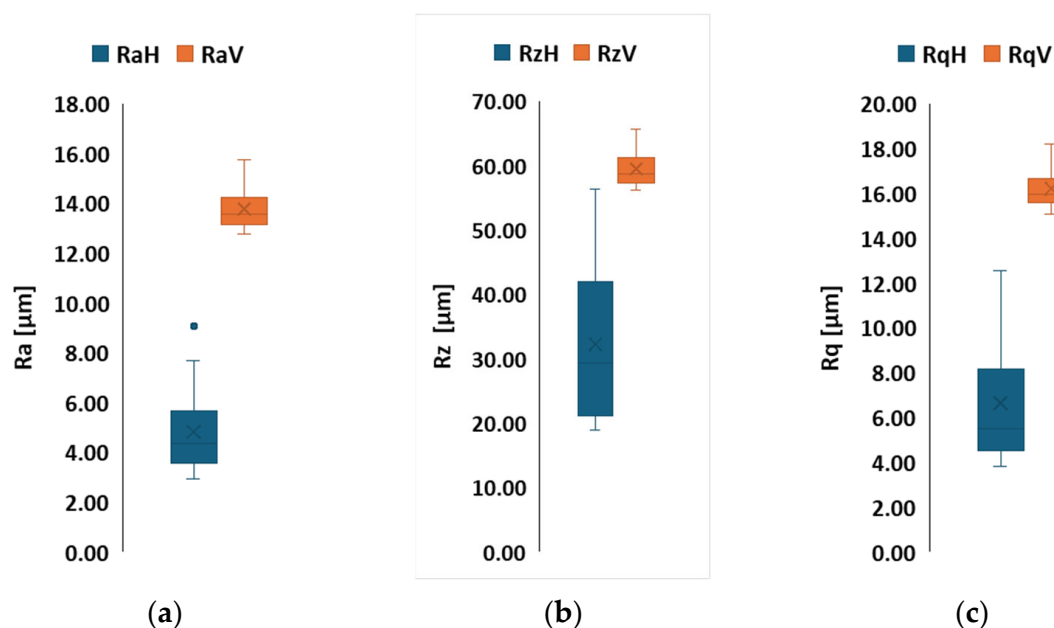


Figure 12. Boxplots of linear surface roughness parameters measured on the horizontal plane H (face B) and the vertical plane V (face G): (a) R_a , (b) R_z , and (c) R_q . Each boxplot was constructed using the mean values of the 27 DOE combinations ($n = 27$); the box represents the interquartile range (Q1–Q3), the central line indicates the median, and the whiskers represent data dispersion, with outliers shown when present. Measurements were performed along a path perpendicular to the predominant filament deposition direction on both surfaces.

The comparison revealed clear differences between the two evaluated surfaces. Vertical faces generally exhibited higher R_a , R_z , and R_q values than horizontal faces, confirming the strong influence of surface orientation on the measured roughness. This difference is associated with the distinct formation mechanisms of the two surfaces. On horizontal faces, roughness is mainly governed by the arrangement, overlap, and continuity of the top-layer beads. On vertical faces, the measured profile crosses the successive layer-stacking marks and is therefore affected by layer height, interlayer alignment, contour stability, and the staircase effect. In addition, the rounded and flattened cross-sectional geometry of the

deposited beads may generate valleys between consecutive layers, increasing the profile amplitude measured perpendicular to the stacking direction [27].

These trends are consistent with previous findings reported for MEX/FFF processes [9]. Surface roughness in such processes is strongly influenced by the layer-by-layer morphology and by the staircase effect, which tends to increase profile amplitude, particularly on lateral or vertical surfaces [28]. Likewise, previous studies have shown that roughness is sensitive to deposition-related variables such as layer thickness and raster orientation, whereas the effect of printing speed is often more dependent on the specific process window and machine configuration [6,29].

These descriptive results identify the vertical face as the most demanding condition for roughness evaluation and confirm that surface finish cannot be interpreted as isotropic in the printed specimens. The statistical relevance of these patterns is examined in Section 3.3.

3.3. Statistical Analysis

3.3.1. Geometrical Deviations

A three-factor ANOVA was performed to quantify the influence of part scale, filament type, and printing speed on each geometrical response. The corresponding p -values, together with the coefficients of determination (R^2), are summarised in Table 4.

Table 4. ANOVA p -values for the main effects of scale (S), filament (F), and printing speed (V), as well as their first-order interactions, on geometrical tolerances. Statistical significance is considered for $p < 0.05$ (marked with *).

	p -Value						
	S	F	V	S $\times$ F	S $\times$ V	F $\times$ V	R^2 [%]
PL	0.000 *	0.548	0.199	0.036 *	0.365	0.591	92.47
PP	0.000 *	0.000 *	0.603	0.029 *	0.215	0.931	98.01
PAR	0.000 *	0.014 *	0.756	0.104	0.215	0.966	91.76
ANG	0.017 *	0.096	0.391	0.121	0.361	0.554	83.72
CIR+	0.000 *	0.001 *	0.555	0.001 *	0.479	0.607	95.63
CIR−	0.039 *	0.022 *	0.443	0.094	0.440	0.566	84.47
CYL+	0.003 *	0.003 *	0.704	0.055	0.334	0.080	92.77
CYL−	0.001 *	0.000 *	0.111	0.021 *	0.047 *	0.381	94.52
COX	0.000 *	0.000 *	0.315	0.000 *	0.949	0.291	90.23

The ANOVA models explained a high proportion of the variability in all geometrical responses, with R^2 values between 83.72% and 98.01%. The strongest fits were obtained for perpendicularity (PP), circularity in shafts (CIR+), and cylindricity in holes (CYL−), while angularity (ANG) and circularity in holes (CIR−) showed lower, but still reasonable, explanatory capacity.

Scale was significant for all geometrical responses, making it the main factor governing geometrical quality within the evaluated experimental domain. Its effect was particularly clear for perpendicularity, parallelism, and coaxiality, which deteriorated markedly as the part scale decreased.

Filament type also influenced several responses, including perpendicularity, parallelism, circularity in holes, cylindricity, and coaxiality. This indicates that material-related variability contributed to the differences observed in geometrical behaviour. The comparatively favourable results obtained with F2 in several orientation- and location-related metrics suggest that commercial PLA filaments may differ not only in surface formation but also in the stability of the deposited geometry. These differences may be associated with filament diameter regularity, melt flow behaviour, cooling shrinkage, moisture condition, or inter-bead consistency. However, these mechanisms were not directly characterized

in the present study; therefore, the influence of filament type should be interpreted as a commercial material effect rather than as the isolated effect of a specific material property.

Printing speed, in contrast, played a more limited role. Within the 40–80 mm/s range, it did not show a significant main effect on geometrical deviations, suggesting that its contribution was smaller than that of scale and filament type under the selected conditions. This finding should therefore be interpreted within the specific process window evaluated here and not extrapolated to wider speed ranges or substantially different MEX configurations [8,14].

Significant first-order interactions were found only for some responses. The scale–filament interaction affected flatness, perpendicularity, circularity in shafts, cylindricity in holes, and coaxiality, showing that the influence of filament type changed depending on the part scale. The scale–speed interaction was significant only for cylindricity in holes, whereas the filament–speed interaction was not significant for any of the geometrical deviations.

This behaviour can be attributed to the fact that orientation- and location-related tolerances depend on the relative position of several geometrical features. When the part is downscaled, the nozzle diameter, deposited bead width, layer height, and positioning resolution remain constant; therefore, local deposition errors represent a larger fraction of the nominal geometry.

From a practical standpoint, these results indicate that part miniaturization was the primary factor governing the deterioration of geometrical quality, especially for orientation- and location-related responses. Filament selection played a secondary but still relevant role, whereas printing speed had a comparatively limited influence on geometrical deviations within the studied range. In MEX, the final geometry depends on the stability of material flow, inter-bead bonding, cooling-related shrinkage, and the definition of corners and toolpaths. These effects may affect not only the local quality of individual surfaces but also the geometrical relationship between planes, axes, and datum features, which explains why tolerances such as perpendicularity, parallelism, and coaxiality are particularly sensitive. In addition, differences between filaments may be associated with variations in rheological behaviour, extrusion stability, and thermal shrinkage, supporting their significant influence on several geometrical responses [7,9,24].

For clarity, the geometrical responses can be interpreted in three groups. First, flatness behaved as the most stable response, with comparatively low deviations and a significant effect mainly associated with scale. Second, circularity and cylindricity showed intermediate behaviour, affected by both scale and filament, with some interaction effects depending on the specific feature considered. Third, perpendicularity, parallelism, and coaxiality exhibited the strongest statistical dependence on scale and the greatest practical sensitivity, confirming that they were the most critical geometrical responses under the evaluated MEX conditions. The different behaviour observed for CYL– indicates that not all form-related responses scale in the same direction. In particular, internal features may be affected by probing accessibility, the reduced geometrical extent of the measured surface, and local deposition conditions inside the holes. Figure 13 shows the main effects for each of the examined geometrical tolerances.

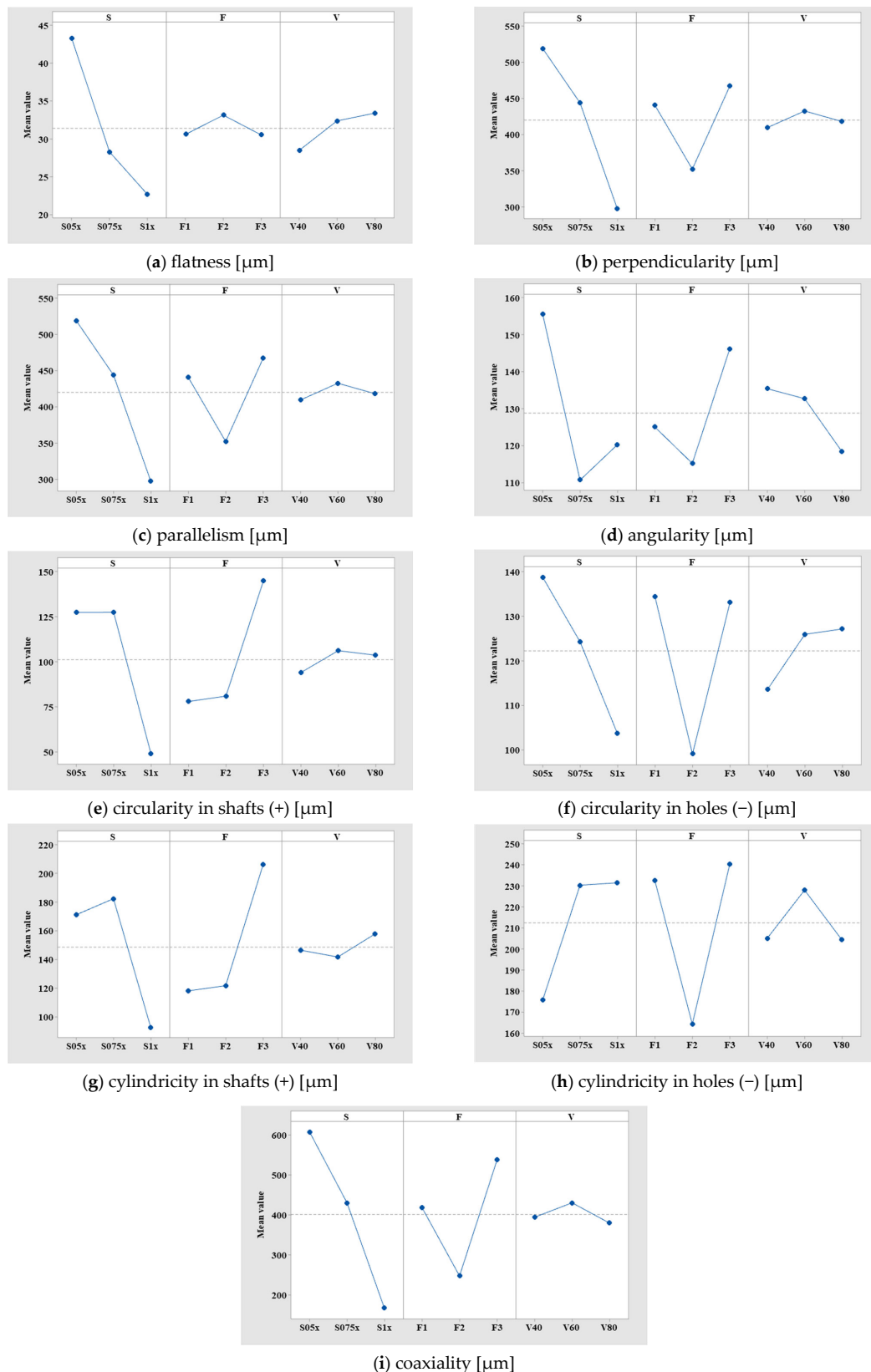


Figure 13. Main effects plots of scale (S), filament (F), and printing speed (V) on the different geometrical tolerances: (a) flatness (PL), (b) perpendicularity (PP), (c) parallelism (PAR), (d) angularity (ANG), (e) circularity in shafts (CIR+), (f) circularity in holes (CIR−), (g) cylindricity in shafts (CYL+), (h) cylindricity in holes (CYL−), and (i) coaxiality (COX).

3.3.2. Surface Roughness

A three-factor ANOVA was also performed to evaluate the influence of part scale, filament type, and printing speed on the linear surface roughness parameters measured on the horizontal (face B) and vertical (face G) surfaces. The corresponding p -values and coefficients of determination (R^2) are summarised in Table 5.

Table 5. ANOVA p -values for the main effects of scale (S), filament (F), and printing speed (V), as well as first-order interactions ($S \times F$, $S \times V$, and $F \times V$), on the linear surface roughness parameters Ra, Rz, and Rq measured on the horizontal plane (H, face B) and the vertical plane (V, face G). Statistical significance is considered for $p < 0.05$ (marked with *).

Response	S	F	V	p -Value S $\times$ F	S $\times$ V	F $\times$ V	R^2 [%]
RaH	0.553	0.053	0.414	0.603	0.817	0.572	70.84
RaV	0.002 *	<0.001 *	<0.001 *	0.039 *	0.084	0.003 *	98.93
RzH	0.194	0.003 *	0.170	0.809	0.864	0.549	83.49
RzV	0.007 *	<0.001 *	0.001 *	0.440	0.477	0.137	95.81
RqH	0.369	0.016 *	0.253	0.669	0.839	0.477	77.60
RqV	0.001 *	<0.001 *	<0.001 *	0.023 *	0.058	0.001 *	99.32

The ANOVA results showed that roughness behaved very differently on the horizontal and vertical surfaces. For the horizontal face, the models explained a moderate proportion of the variability, with R^2 values between 70.84% and 83.49%. Factor effects were limited in this case, and filament type was the only variable with a significant main effect for some responses, mainly RzH and RqH. The vertical face showed a much clearer statistical pattern: the models reached R^2 values between 95.81% and 99.32%, and scale, filament type, and printing speed were significant for the three roughness parameters analysed.

This statistical behaviour is consistent with the surface-formation mechanisms discussed in Section 3.2. The vertical surface was not only rougher but also showed a stronger and more clearly defined dependence on the factors included in the DOE.

The main effects plots showed a consistent pattern for RaV, RzV, and RqV: roughness reached its lowest values at $0.75\times$, increased for filament F2, and generally decreased as printing speed increased within the studied range.

This behaviour also shows that geometrical accuracy and surface texture did not necessarily respond in the same way to filament-related variability. Although F2 tended to provide more favourable results for several geometrical responses, it did not lead to the lowest roughness on the vertical face. This contrast suggests that geometry is more closely related to the stability of deposited paths and the accumulation of errors between features, whereas vertical roughness is governed more directly by layer stacking and bead-contour morphology.

Interaction effects were less widespread, but they were relevant for some vertical roughness parameters. RaV and RqV showed significant scale–filament and filament–speed interactions, meaning that the influence of material and speed depended partly on the specific experimental condition. RzV followed the same general trend, although without significant first-order interactions, suggesting a more additive response.

From a practical point of view, these findings show that roughness measurements on horizontal and vertical faces should not be treated as interchangeable indicators. Each surface reflects different aspects of the deposition process: the horizontal face was comparatively stable, whereas the vertical face was more demanding in both roughness magnitude and statistical sensitivity. This reinforces the need to account for surface orientation when assessing the surface quality of MEX-manufactured parts.

Figure 14 illustrates these trends through the corresponding main effects plots.

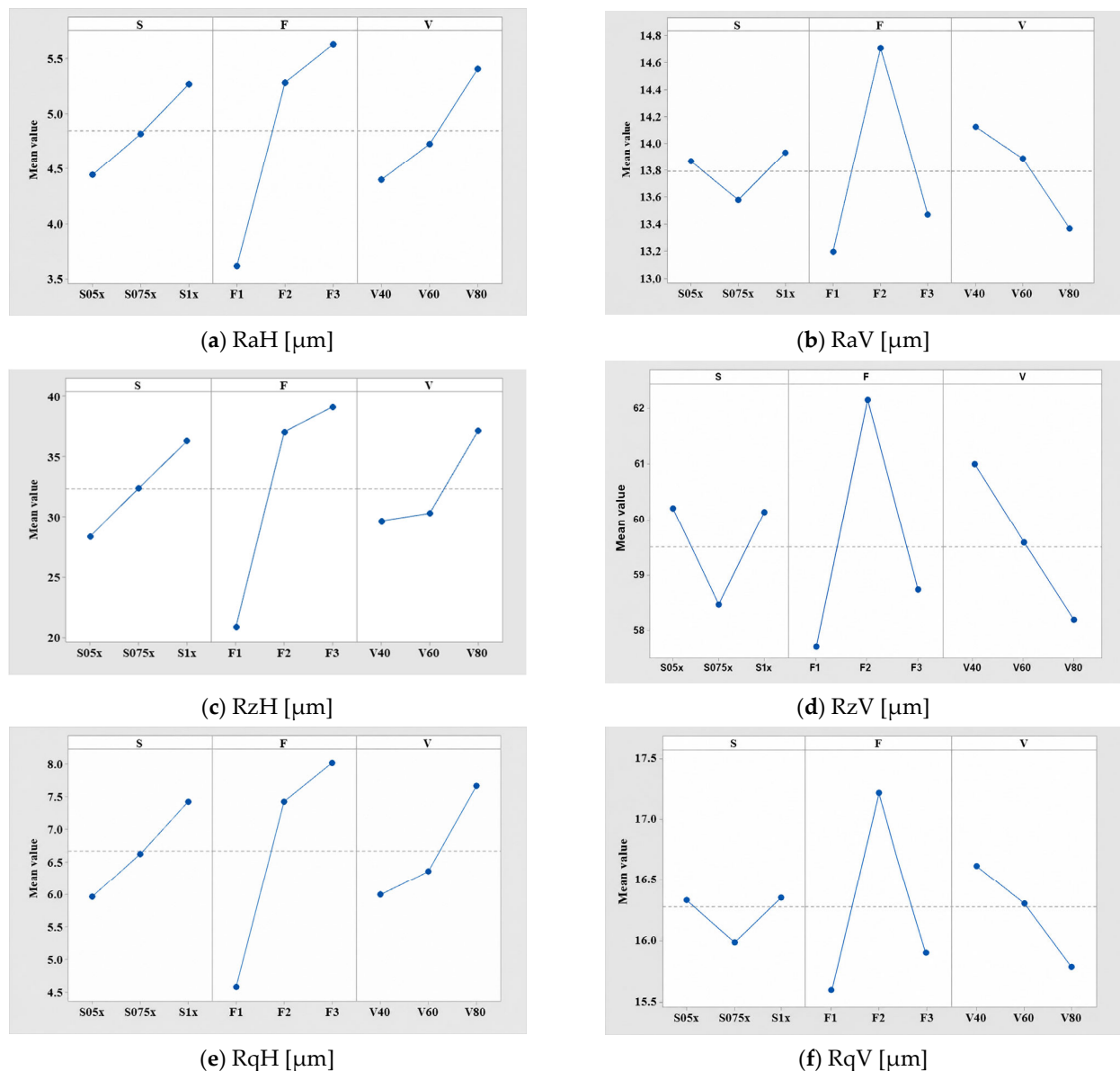


Figure 14. Main effects plots of scale (S), filament (F), and printing speed (V) on the linear surface roughness parameters measured on the horizontal (H, face B) and vertical (V, face G) planes: (a) RaH, (b) RaV, (c) RzH, (d) RzV, (e) RqH, and (f) RqV.

3.3.3. Correlation Between Surface Roughness and Geometrical Deviations

The relationship between surface texture and geometrical quality was further examined through a correlation analysis. This analysis was exploratory and was interpreted only in terms of association within the experimental domain considered here. No causal relationship was assumed, since both roughness and geometrical deviations may be influenced by the same process factors. The correlation analysis was based on the mean response of the three independently manufactured specimens for each of the 27 experimental combinations.

The analysis focused on RaV and RzV, which were used as representative descriptors of mean profile amplitude and profile extremes on the vertical surface. These parameters were correlated with PP, PAR, COX, CIR−, and CYL−, selected as relevant indicators of orientation/location deviations and internal form errors. Pearson's coefficient (r) and Spearman's coefficient (ρ) were both calculated.

Correlations were also calculated from the residuals of a general linear model including scale, filament type, printing speed, and their first-order interactions. This made it possible

to check whether the roughness–geometry associations persisted after the systematic contribution of the DOE factors had been removed.

When the 27 condition-level means were considered, vertical roughness showed moderate negative associations with some internal geometrical deviations, particularly CIR– and CYL–. These associations, however, became weaker or disappeared in the residual analysis. This indicates that much of the apparent correlation was driven by the common influence of the process factors included in the experimental design. The complete correlation results are provided in the Supplementary Materials. Table S4 reports the pairwise correlations between the vertical roughness parameters and selected geometrical deviations, whereas Table S5 reports the pairwise correlations among the selected geometrical deviations themselves. Only the main trends are discussed here, since the correlation analysis is intended as complementary statistical evidence.

A similar pattern was found for the correlations among geometrical responses. Several pairs showed strong associations when raw values were used, especially those involving orientation- and location-related deviations. After the DOE-factor contribution was removed, some of these relationships became weaker. However, residual associations remained in specific cases, particularly between PAR and PP and between CYL– and CIR–, suggesting that some geometrical responses shared variation patterns beyond the main experimental factors.

Taken together, these results suggest that the apparent coupling between surface roughness and geometrical deviations was mainly associated with shared process effects rather than with a direct relationship between the two types of response. The correlation analysis should therefore be understood as complementary evidence, useful for interpreting quality variation within the experimental domain studied.

3.3.4. Process-Quality Implications of the DOE Responses

Tables 6 and 7 summarize the main outcomes of the DOE for geometrical deviations and surface roughness, respectively. They combine the statistical significance of the main effects and first-order interactions with the main marginal trends observed for each response.

Table 6. Statistical summary of the geometrical responses (ANOVA significance and main marginal trends).

Response	S	F	V	Significant Interactions	Summary of Marginal Trends	R ² [%]
PL	*			S × F	Increases as scale decreases (0.5× worst); the effect of F depends on S	92.47
PP	*	*		S × F	Increases as scale decreases; F2 tends to yield lower PP; ranking depends on S × F	98.01
PAR	*	*			Increases as scale decreases; F2 tends to yield lower PAR	91.76
ANG	*				Minimum at 0.75×; 0.5× tends to be worse	83.72
CIR+	*	*		S × F	1× tends to be better; F3 tends to be worse; ranking depends on S × F	95.63
CIR–	*	*			Increases as scale decreases; F2 tends to yield lower CIR–	84.47
CYL+	*	*			1× tends to be better; F3 tends to be worse (no statistical interaction)	92.77
CYL–	*	*		S × F, S × V	Decreases as scale decreases (0.5× tends to be better); effect depends on S × F and S × V	94.52
COX	*	*		S × F	Increases as scale decreases; F2 tends to yield lower COX; ranking depends on S × F	90.23

* Indicates a statistically significant main effect at $p < 0.05$.

For geometrical deviations, the summary confirms the dominant role of scale across all responses. Filament type also affected several tolerances, whereas printing speed remained secondary within the evaluated range. The most critical responses were perpendicularity, parallelism, and coaxiality, while flatness was the most stable geometrical characteristic.

Table 7. Statistical summary of the surface roughness responses (ANOVA significance and main marginal trends).

Response	S	F	V	Significant Interactions	Summary of Marginal Trends	R ² [%]
RaH					No significant effects detected; marginal trend: F1 lowest	70.84
RzH		*			F dominant: F1 lower; F3 higher	83.49
RqH		*			F dominant: F1 lower; F3 higher	77.60
RaV	*	*	*	S × F, F × V	Minimum at 0.75×; F2 most rough; decreases with increasing V (ranking depends on interactions)	98.93
RzV	*	*	*		Minimum at 0.75×; F2 most rough; decreases with increasing V (additive behaviour)	95.81
RqV	*	*	*	S × F, F × V	Minimum at 0.75×; F2 most rough; decreases with increasing V (ranking depends on interactions)	99.32

* Indicates a statistically significant main effect at $p < 0.05$.

For surface roughness, the contrast between horizontal and vertical surfaces is especially clear. The horizontal face showed a weaker and less structured response, while the vertical face depended more strongly on scale, filament type, and printing speed. This agrees with the anisotropic behaviour identified in the descriptive and inferential analyses.

From an applied perspective, these findings suggest that MEX quality optimization should consider not only nominal process parameters but also the scale and geometrical function of the evaluated features. Reduced-scale parts and orientation/location tolerances require particular attention, and vertical surfaces provide a more demanding condition for assessing surface finish. These results may therefore support more informed decisions in design, filament selection, and metrological inspection of PLA parts fabricated by MEX.

It should be noted that the conclusions of this study are bounded by the experimental domain considered. The results were obtained using a single MEX printer, one test artefact geometry, three commercial PLA filaments, and a printing speed range of 40–80 mm/s, while other process variables such as layer height, nozzle diameter, infill strategy, extrusion temperature, build plate temperature, and build orientation were kept constant. The extrusion architecture and machine enclosure were also kept constant. The open-frame Bowden system used represents a specific desktop MEX configuration; therefore, future studies could assess whether direct-drive extrusion and enclosed or thermally controlled systems modify the scale-dependent geometrical and surface responses observed in this work. Therefore, the observed trends should be interpreted as representative of the selected process window rather than as universal rules for all MEX conditions. Further work including additional geometries, materials, build orientations, and process windows would be useful to extend the applicability of the proposed GD&T-based assessment.

4. Conclusions

The results address the main objective of the study by showing that scale-dependent quality loss in MEX-manufactured PLA parts should be evaluated from an integrated metrological perspective. Among the GD&T-related responses, orientation- and location-related tolerances were the most sensitive to downscaling, establishing a metrological

ranking in which perpendicularity, parallelism, and coaxiality emerged as the most critical indicators, whereas flatness remained comparatively stable. Part scale was the dominant factor affecting geometrical conformity within the evaluated domain, because fixed manufacturing limitations acquired greater relative importance as the nominal dimensions of the features decreased.

Filament type also influenced several geometrical responses, indicating that commercial PLA materials should not be considered equivalent when geometrical conformity is relevant. Printing speed had a comparatively limited effect on geometrical deviations within the 40–80 mm/s range, although it significantly affected the roughness parameters measured on vertical surfaces. Surface texture showed clear anisotropic behaviour: vertical surfaces exhibited higher roughness values and a stronger statistical dependence on scale, filament type, and printing speed than horizontal surfaces.

The correlation analysis further showed that some apparent associations between roughness and geometrical deviations were largely driven by the common influence of the DOE factors rather than by a direct relationship between the two types of response. Taken together, these findings show that geometrical conformity and surface texture should be jointly considered when selecting materials, defining manufacturing conditions, and establishing inspection strategies for functional MEX components, particularly when reduced-scale parts or small geometrical related features are involved.

Surface roughness showed clear anisotropic behaviour. The vertical face was the most demanding condition, with higher roughness values and a more defined statistical response than the horizontal face. The correlation analysis further showed that some apparent associations between roughness and geometrical deviations were largely driven by the common influence of the DOE factors rather than by a direct relationship between both types of response. Taken together, these results provide an integrated view of quality variation in MEX-printed PLA parts and show that geometrical conformity and surface finish should be jointly evaluated when selecting materials, defining process conditions, and establishing inspection strategies for functional components, particularly when scaled parts or small geometrical features are involved.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/jmmp10080265/s1>, Table S1: Complete measured values of flatness (PL), perpendicularity (PP), parallelism (PAR), angularity (ANG), and circularity in shafts (CIR+) for the 27 experimental conditions. All values are expressed in μm ; Table S2: Complete measured values of circularity in holes (CIR−), cylindricity in shafts and holes (CYL+ and CYL−), and coaxiality (COX) for the 27 experimental conditions. All values are expressed in μm ; Table S3: Complete measured values of surface roughness parameters Ra, Rz, and Rq on the horizontal and vertical surfaces for the 27 experimental conditions. All values are expressed in μm ; Table S4: Pearson and Spearman correlations between vertical surface roughness parameters and selected geometrical deviations, calculated from the 27 condition-level means and from residuals after removing the effects of scale, filament type, printing speed, and their first-order interactions; Table S5: Pearson and Spearman correlations among selected geometrical deviations, calculated from the 27 condition-level means and from residuals after removing the effects of scale, filament type, printing speed, and their first-order interactions.

Author Contributions: Conceptualization, Ó.R.-A. and G.G.-V.; methodology, D.C., Ó.R.-A. and G.G.-V.; validation, Ó.R.-A., G.G.-V. and G.M.F.; formal analysis, D.C., G.M.F. and G.G.-V.; investigation, D.C.; resources, Ó.R.-A., G.G.-V. and G.M.F.; data curation, D.C. and G.M.F.; writing—original draft preparation, D.C.; writing—review and editing, G.G.-V., G.M.F. and A.V.-C.; visualization, D.C.; supervision, Ó.R.-A. and G.G.-V.; project administration, G.G.-V. and A.V.-C.; funding acquisition, Ó.R.-A. and G.G.-V. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding. The research stay of G.G. at the Faculty of Engineering of the National University of La Pampa, during which part of the experimental work was carried out, was partially supported by the University of Córdoba.

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Acknowledgments: The authors gratefully acknowledge the Faculty of Engineering of the National University of La Pampa, General Pico, Argentina, for the institutional and technical support provided during the research stay in which part of the experimental work of this study was carried out.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MEX	Material Extrusion
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
PLA	Polylactic Acid
CAD	Computer-Aided Design
CMM	Coordinate Measuring Machine
GD&T	Geometric Dimensioning and Tolerancing
DOE	Design of Experiments
ANOVA	Analysis of Variance
GLM	General Linear Model
Ra	Arithmetic Mean Roughness
Rz	Mean Roughness Depth
Rq	Root Mean Square Roughness
PL	Flatness
PP	Perpendicularity
PAR	Parallelism
ANG	Angularity
CIR	Circularity
CYL	Cylindricity
COX	Coaxiality

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