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DETERMINATION OF SURFACE ROUGHNESS MEASUREMENT UNCERTAINTY IN ADDITIVELY MANUFACTURED COMPONENTS

Áron LÓRÁND, Ágota DRÉGELYI-KISS

lorand.aron@bgk.uni-obuda.hu, dregelyi.agota@bgk.uni-obuda.hu

Abstract: Additive manufacturing (AM) is increasingly used due to its design flexibility and material efficiency. However, the layered structure of AM parts often leads to higher surface roughness and irregular topographies compared to traditionally machined components. Surface texture critically affects performance aspects such as friction, wear, and fatigue. This research investigates tactile surface roughness measurements in AM, focusing on the uncertainties introduced by factors like environmental conditions, human influence, probe interaction, and surface geometry, to which tactile measurement is sensitive. Identifying and quantifying these uncertainties is essential for reliable quality control, accredited testing, and regulatory compliance. A clear understanding enables process optimization and improves functional reliability of AM products.

Keywords: tactile surface roughness measurement, profilometry, surface characterization, measurement uncertainty, 3D printed parts.

1. INTRODUCTION

Additive manufacturing (AM), or 3D printing, has transformed manufacturing by enabling complex geometries, material efficiency, and design flexibility [1], and its importance is growing as a key component of the fourth industrial revolution [2]. However, its layer-by-layer fabrication process introduces challenges in surface quality and measurement reliability, often resulting in rougher, more irregular, and anisotropic surfaces compared to CNC machining. Surface roughness (SR) affects critical properties like friction, wear resistance, and optical or thermal performance, and its measurement—typically done using stylus-based (contact) or optical (non-contact) instruments—faces increased uncertainty in AM due to porosity, inhomogeneity, and material elasticity.

The process of calibration of measuring instruments, a process that establishes a relation between known reference values with uncertainties and the corresponding instrument indications and then uses this relation to determine measurement results from future

indications [3], ensures traceability and reliability of SR measurements.

Without a systematic understanding of these factors, results may be metrologically incomparable and inconsistent [4], leading to poor quality control or unreliable product performance [5,6]. Thus, it serves not only academic purposes but is also used in industrial measurement practices.

The purpose of this study is to develop a framework for evaluating measurement uncertainty in contact-type surface roughness measurements, specifically for additively manufactured (AM) surfaces. It addresses a gap in existing research by focusing on selective laser sintering (SLS) with Polyamide 12 (PA12), a combination not previously explored in this context.

Tactile measurement was selected for this study due to its established reliability, traceability, and high vertical resolution, particularly beneficial when evaluating irregular and complex surfaces typical of additively manufactured parts. The contact measuring technology plays a central role in technical practice, as it remains a widely accepted method

in both industrial and research environments. While optical methods offer speed and non-contact advantages, they may suffer from reflectivity issues, limited depth penetration, or insufficient resolution on porous or semi-transparent materials like PA12. However, tactile profilometry is more sensitive to surface contamination and elastic deformation.

2. MATERIALS AND METHODS

The objective of the current research is to quantify the measurement uncertainty of surface roughness parameter Ra (arithmetic mean height) in accordance with ISO 21920:2021 [7] in case of a test specimen consisting of polyamide 12 (DuraForm ProX PA), manufactured by selective laser sintering (SLS) additive manufacturing at 167.5 °C with a layer thickness of 0.1 mm, using a powder blend of 40% virgin and 60% recycled material [8], using a Mitutoyo SurfTest SJ-301 stylus profilometer in metrologically controlled conditions ((20±1) °C, relative humidity between 40% and 60%).

The measurement protocol involves three measurements in the vertical and three in the horizontal direction relative to the orientation of the specimen, each measurement including five section lengths, all 2.5 mm long, with nesting indices $N_{ic} = 2.5$ mm and $N_{is} = 8$ μm, applying a Gaussian filter. Profilometric scans were acquired horizontally over an evaluation length of 12.5 mm. The instrument applied a stylus contact force of 7.5 mN. The stylus tip was made of diamond, with a 2 μm radius [9].

3. MEASUREMENT MODEL AND ITS UNCERTAINTIES

3.1 The Ra parameter

The formula for arithmetic mean height parameter based on ISO 21920:2021 [7] is

$$Ra = \frac{1}{l_e} \int_0^{l_e} |z(x)| dx \approx \frac{1}{l_e} \sum_{i=1}^n |z(x_i)| \Delta x = \frac{|z(x_1) + z(x_2) + \dots + z(x_n)|}{n}$$

The evaluation length l_e is approximated as $l_e = n \cdot \Delta x$, where Δx is the constant sampling interval, allowing the continuous integral of the surface profile $z(x)$ to be replaced by a discrete summation. Although the standard does not specify discretization, it is useful for practical calculations, with n treated as an exact, uncertainty-free parameter. However, since real measurements are influenced by inherent factors causing uncertainties, the resulting values are best modeled as random variables, requiring statistical methods for analysis.

3.2 Parameters affecting the measurement

The factors possibly causing deviations in the measurement data are mapped and identified using an Ishikawa diagram (Fig. 1.).

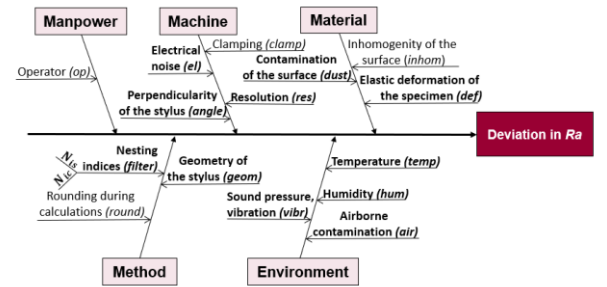


Fig. 1. Ishikawa diagram showing the influencing factors (the factors in bold referred to the vertical position of the stylus)

The diagram illustrates the potential causes of deviation in the Ra surface roughness value, organized into five main categories. Regarding the Material category, surface inhomogeneity and residual dust contamination was considered a primary source due to the nature of additive manufacturing. Specimens produced from PA12 exhibit also elastic behavior, resulting in significant deviation in surface roughness measurement.

Machine refers to the condition, maintenance, and operation of the equipment used. It is important to highlight factors not only manufacturer-defined limitations (resolution,

electrical noise), but operator-dependent deviations (clamping, perpendicularity of the stylus) as well.

Manpower relates to factors such as skill, experience, motivation, and overall performance of the operator during the measurement process, which also can affect the measurement.

Within the Method domain, parameters regarding the stylus and data processing are summarized, which influences how surface features are mechanically traced and resolved.

Finally, Environment relates to ambient conditions that can affect both the specimen significantly due to the hygroscopic property and not negligible thermal expansion coefficient of PA12, and the measuring device, while vibration impacts stylus stability during scanning. Other factors, such as air pressure and external electromagnetic noise are excluded based on prior studies and guidelines, that indicate their negligible influence under laboratory conditions.

3.3 Measurement model

The model [10] in case of the surface roughness measurement can be expressed as

$$Ra_X = Ra_i + \delta z + \delta Ra = \frac{|z(x_1) + \delta z(x_1) + z(x_2) + \delta z(x_2) + \dots + z(x_n) + \delta z(x_n)|}{n} + \delta Ra = \frac{z(x_1) + z(x_2) + \dots + z(x_n) + n \cdot \delta z}{\frac{\sum_{i=1}^n z(x_i)}{n} + \delta z} + \delta Ra.$$

Here Ra_X is the unknown value of the arithmetic mean height of the R-profile, Ra_i is indicated value, δz denotes the correction of the (vertical) coordinate recorded and δRa the correction of the displayed Ra value, respectively.

It was assumed in the second step that the corrections of probing each surface point is approximately equal, i.e., $\delta z(x_1) = \delta z(x_2) = \dots = \delta z(x_n) = \delta z$, which allows the algebraic transformation in the last step.

The influencing factors related to the vertical position of the stylus (Fig. 1., highlighted in bold) and the Ra value are detailed below, following the sequence and separation of the factors in the Ishikawa diagram.

$$\delta z = \delta z_{res} + \delta z_{el} + \delta z_{angle} + \delta z_{def} + \delta z_{dust} + \delta z_{filterN_{ic}} + \delta z_{filterN_{is}} + \delta z_{geom} + \delta z_{vibr} + \delta z_{temp} + \delta z_{hum} + \delta z_{air},$$

and

$$\delta Ra = \delta Ra_{op} + \delta Ra_{clamp} + \delta Ra_{inhom} + \delta Ra_{round},$$

where

- δz_{res} is the correction for resolution,
- δz_{el} is the difference arising from electrical noise in the measurement unit,
- δz_{angle} is the difference resulting from angular misalignment of the stylus relative to the surface
- δz_{def} is the correction factor due to the elastic deformation of the specimen,
- δz_{dust} is for the difference caused by the contamination of the surface (residual dust from additive manufacturing, grease from touching the specimen),
- $\delta z_{filterN_{ic}}$ and $\delta z_{filterN_{is}}$ indicates the correction introduced by the Gaussian filtering of the profile,
- δz_{geom} is the correction due to stylus geometry and tip imperfections
- δz_{lin} is the component of change attributable to the linearity of the sensor,
- δz_{vibr} is the correction arising from mechanical vibrations during measurement,
- δz_{temp} is the correction due to temperature (thermal expansion),
- δz_{hum} is the correction for ambient humidity effects,
- δz_{air} is the difference for airborne contamination (dust, grease, others),
- δRa_{inhom} is the correction arising from surface inhomogeneity within the evaluation length,
- δRa_{round} is the change for numerical rounding,
- δRa_{op} is the correction related to operator influence or handling,
- δRa_{clamp} is the difference due to specimen fixation or clamping during measurement.

3.4 Measurement uncertainty contributions

In the model, error sources are categorized as systematic or random. Systematic effects—such as stylus misalignment, elastic deformation, filtering artifacts, and environmental influences—are considered repeatable and potentially correctable. Random contributions, including electrical noise, surface inhomogeneity, and external vibrations, are modeled as random variables with zero expected value and are quantified by standard uncertainty [11,12]. If a systematic bias cannot be reliably determined or corrected, its entire effect is incorporated into the standard uncertainty of the measurement result.

3.4.1 Resolution of the instrument

The resolution of the Mitutoyo SurfTest SJ-301 stylus profilometer [9] is 0.01 μm . Since the instrument uses a digital display, the readout is quantized. Assuming uniform distribution, the resulting standard uncertainty of $u_{\text{res}} = \frac{0.01}{\sqrt{12}} = 0.003 \mu\text{m}$.

3.4.2 Electrical noise

As recommended in DKD-R 4-2 Sheet 3 [13] and in [14], the typical electrical noise in the measurement signal is approximately 0.01 μm . Since the noise is considered to have normal distribution, the standard uncertainty is $u_{\text{el}} = \frac{0.01}{2} = 0.005 \mu\text{m}$.

3.4.3 Angular error (non-perpendicular stylus)

If the stylus is not perfectly perpendicular to the surface, the measured profile may slightly differ due to cosine (second-order) error. In this setup, an angular error of $\pm 1.5^\circ$ is considered [9]. For an assumed profile height of 20 μm , the error due to the tilt of the stylus, assuming uniform distribution, is calculated as $u_{\text{angle}} = \frac{20 \cdot (1 - \cos(1.5^\circ))}{\sqrt{3}} = 0.004 \mu\text{m}$.

3.4.4 Elastic deformation

The elastic deformation caused by the stylus pressing into the sample surface can be estimated using Hertzian contact model [15]:

$\delta = \left(\frac{3F}{4E^* \sqrt{R}} \right)^{\frac{2}{3}}$ with effective Young modulus $\frac{1}{E^*} = \frac{1-\nu_p^2}{E_p} + \frac{1-\nu_s^2}{E_s}$. The indentation depth δ is calculated using known material parameters:

stylus radius $R = 2 \mu\text{m}$, applied force $F = 7.5 \text{ mN}$, and elastic moduli $E_p = 1050 \text{ GPa}$ (pin) and $E_s = 1 \text{ GPa}$ (specimen) with Poisson's ratios of 0.18 and 0.4, respectively. The resulting indentation is $\delta = 0.0366 \mu\text{m}$. Assuming a triangular distribution, the standard uncertainty is $u_{\text{def}} = \frac{0.0366}{\sqrt{6}} = 0.015 \mu\text{m}$. Due to the high stiffness of the diamond stylus, its deformation can be neglected.

3.4.5 Surface contamination

After SLS printing, glass bead blasting with 70–110 μm diameter particles at 2.3 bar is used to remove residual powder [8] with grain size 50–100 μm [16]. Despite cleaning, fine powder particles may remain on the surface, potentially causing deviations of up to $\pm 0.5 \mu\text{m}$. Based on this estimation and assuming a uniform distribution, the associated uncertainty is $u_{\text{dust}} = \frac{0.5}{\sqrt{3}} = 0.288 \mu\text{m}$.

3.4.6 Filtering (nesting indices)

The values of the nesting indices of the applied Gaussian filters values used in surface roughness measurements can introduce uncertainty as well. In [17], the estimation applies to milling and turning, which generate regular, periodic surface textures. However, in the case of SLS-manufactured specimens, irregular and granular microtopography may lead to greater deviations in nesting index values, resulting in slightly increased uncertainty. Based on these considerations, nesting index-related uncertainties are estimated as $u_{N_{\text{ic}}} = 0.080 \mu\text{m}$ for the profile L-filter and $u_{N_{\text{is}}} = 0.010 \mu\text{m}$ for the profile S-filter.

3.4.7 Stylus geometry

The nominal stylus tip radius is given as $(2 \pm 0.2) \mu\text{m}$ [9]. Although the stylus is made from diamond and thus highly wear-resistant, manufacturing tolerances still introduces uncertainty. Variations in tip radius can reduce profiling accuracy, as a cannot access fine surface features. Using a triangular distribution to model this variation, the standard uncertainty is estimated as $u_{\text{geom}} = \frac{0.2}{\sqrt{6}} = 0.082 \mu\text{m}$.

3.4.8 External vibration

External mechanical vibrations – such as low frequency sound pressure – can also impact surface roughness measurements. As indicated

in [18], such effects may cause over 15% deviation in Ra values in cases of steel alloys, especially on the higher end of the domain (80-100 Hz). However, PA12 is a much softer, more flexible material, so it dampens vibrations better. Besides, the use of a granite base during measurements, the aforementioned influence is reduced. Estimating the impact as 2.5% of the average 20 μm Ra value, and assuming a uniform distribution, a standard uncertainty of $u_{\text{vibr}} = \frac{0.5 \mu\text{m}}{\sqrt{12}} = 0.144 \mu\text{m}$ is obtained.

3.4.9 Thermal expansion

Temperature fluctuations can cause dimensional changes due to thermal expansion. For a profile height of $z_0 = 20 \mu\text{m}$ (rounded) and a temperature change of $\Delta T = \pm 1^\circ\text{C}$, which is the allowed deviation from the standardized temperature of dimensional measurements, the expansion can be calculated using the formula $\Delta z = z_0 \cdot \alpha \cdot \Delta T$, where $\alpha = 15 \cdot 10^{-5} \frac{1}{\text{K}}$ [19]. This yields a change of 0.003 μm . Assuming a uniform distribution, the standard uncertainty is $u_{\text{temp}} = \frac{0.003}{\sqrt{3}} = 0.002 \mu\text{m}$.

3.4.10 Humidity

Although specific data on the effect of the hygroscopic properties of PA12 on surface roughness are lacking, studies on PA6G indicate an average Ra increase of 0.4 μm under humid conditions in case of workpieces produced from PA6G [20]. Unfortunately, specific humidity values were not provided. Given that PA12 absorbs significantly less moisture (0.7–0.8%) [21,22], a more conservative estimate of $\Delta z_{\text{hum}} = \pm 0.2 \mu\text{m}$ is used. Assuming uniform distribution, this leads to a standard uncertainty of $u_{\text{hum}} = \frac{0.2}{\sqrt{3}} = 0.115 \mu\text{m}$.

3.4.11 Airborne contamination (dust, grease)

Airborne dust particles are categorized according to their size [23]. In a typical metrology lab environment, the only airborne particles present are fine dust ($\leq 1 \mu\text{m}$ in diameter), which are generally loose and easily displaced. Additionally, surface grease can sometimes decrease the measured roughness. Therefore, estimating the total potential deviation as $\pm 0.1 \mu\text{m}$ and assuming a uniform

distribution, the uncertainty is $u_{\text{air}} = \frac{0.1}{\sqrt{12}} = 0.029 \mu\text{m}$.

3.4.12 Operator

The operator's influence in case of surface roughness measurements is shown to be statistically insignificant [24]. As such, the uncertainty contribution is considered $u_{\text{op}} = 0 \mu\text{m}$.

3.4.13 Clamping

Improper clamping can cause the specimen to move during measurement and introduce significant error. Nevertheless, through the use of stable and reliable fixturing, this factor has been eliminated, thus its contribution to the uncertainty is considered $u_{\text{clamp}} = 0 \mu\text{m}$.

3.4.14 Surface inhomogeneity (stylus location)

Surface roughness can vary depending on the location of the measurement on the specimen's surface. The Ra of 50 mass-produced 3D-printed components were measured six times on one side of each workpiece, and analyzed statistically in terms of mean and standard deviation [25]. Based on this dataset, the pooled standard deviation was calculated to be 1.85 μm , which characterizes the variability observed in repeated measurements. Thus, this value is used to estimate the standard uncertainty due to inhomogeneity, $u_{\text{inhom}} = 1.850 \mu\text{m}$.

3.4.15 Rounding

Rounding errors arise when numerical results are rounded to fewer digits. In this analysis, such effects are deemed negligible and are therefore assumed to cause no uncertainty, i.e., $u_{\text{round}} = 0 \mu\text{m}$.

3.5 Expanded uncertainty

Ra_X serves as the output quantity (Y), while all other variables are considered as input quantities (X_i) [11]. Assuming no correlation between inputs, the combined standard uncertainty is calculated according to the GUM [10] as:

$$u_c(Ra_X) = \sqrt{\sum_{i=1}^{16} \left(\frac{\partial Ra}{\partial x_i} \right)^2 u^2(x_i)},$$

where x_i 's are the input estimates with standard uncertainties. The expanded uncertainty at

approximately 95% confidence level (coverage factor $k = 2$ [11]) is:

$$U = 2 \cdot u_c(Ra_X).$$

Following the EA-4/02 M:2022 guideline [4], the uncertainty budget is summarized in Table 1. The evaluated combined standard uncertainty is $u(Ra_X) = 0.632 \mu\text{m}$, resulting in an expanded uncertainty of $U = 2 \cdot 1.885 = 3.770 \mu\text{m}$. Therefore, the final measurement result is reported as:

$$Ra_X = 18.4 \pm 3.8 \mu\text{m}.$$

It can be observed that the expanded uncertainty is $\pm 20.6\%$ in this case, where the measured surface corresponds to an additively manufactured part.

3.6 Pareto analysis

A Pareto analysis in Fig. 2. illustrates the relative contributions of various uncertainty sources to the combined standard uncertainty $u_c(Ra_X)$ in AM parts. Surface inhomogeneity has the greatest impact, followed by surface contamination (residual dust) and mechanical vibrations. Inhomogeneity results from local microstructural variations due to the layered structure or porosity typical of additive manufacturing. Residual dust is especially relevant in SLS, as unsintered powder can remain embedded in surface pores or adhere electrostatically, even after cleaning, leading to higher Ra values and greater measurement variability.

Mechanical vibrations contribute significantly to uncertainty, as insufficient vibration isolation can cause the profilometer to misinterpret environmental vibrations as surface features, resulting in an overestimation of Ra . Together, these three factors represent only 17.6% of all considered sources but account for approximately 75% of the total uncertainty. Other sources, such as ambient humidity—which is important for hygroscopic materials—and the uncertainty in stylus tip geometry, also contribute, especially on finely textured surfaces where the probe cannot access narrow valleys, causing underestimation of surface features. The effect of the nesting index (N_{ic}) is minimal.

Although the magnitude of these effects depend on material properties and

manufacturing processes The results emphasize the importance of environmental control and standardized measurement procedures in reducing uncertainty.

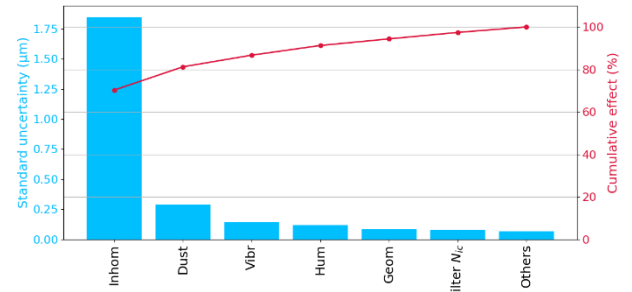


Fig. 2. Pareto analysis on the effect of the uncertainty contributors

4. SUMMARY

In this paper, a detailed analysis of measurement uncertainty is presented for surface roughness evaluation of an additively manufactured specimen using a contact-type stylus profilometer. The analysis follows the framework of the GUM and includes a comprehensive uncertainty budget accounting for 16 distinct contributors. These encompass instrumental, environmental, and surface-related factors, such as resolution, sensor linearity, residual surface contamination, and material inhomogeneity.

As a result, it can be stated that surface roughness measurements on additively manufactured parts are significantly influenced by surface inhomogeneity, residual contamination and external mechanical vibrations. These three factors alone contribute to approximately 75% of the total measurement uncertainty. The findings underscore the need for controlled measurement environments and standardized procedures to ensure reliable and repeatable roughness evaluations in AM applications.

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APPENDIX A

Table 1. The uncertainty budget of contact-type surface roughness measurement on AM specimen

quantity X_i	estimate x_i (μm)	standard uncertainty $u(x_i)$ (μm)	probability distribution	sensitivity coefficient c_i	contribution to the standard uncertainty $u_i(y)$ (μm)
Indicated R_a value	18.43	0	normal	1	0
Resolution of the instrument (res)	0	0.003	uniform	1	0.003
Electrical noise (el)	0	0.005	normal	1	0.005
Angular error ($angle$)	0	0.004	uniform	1	0.004
Elastic deformation of the specimen (def)	0	0.015	triangular	1	0.015
Contamination of the surface ($dust$)	0	0.288	uniform	1	0.288
Deviation in N_{ic} ($filter\ N_{ic}$)	0	0.080	normal	1	0.080
Deviation in N_{is} ($filter\ N_{is}$)	0	0.010	normal	1	0.010
Geometry of the stylus tip ($geom$)	0	0.082	triangular	1	0.082
Vibration ($vibr$)	0	0.144	uniform	1	0.144
Thermal expansion of the specimen ($temp$)	0	0.002	uniform	1	0.002
Humidity (hum)	0	0.115	uniform	1	0.115
Contamination in the air (air)	0	0.029	uniform	1	0.029
Inhomogeneity of the surface ($inhom$)	0	1.850	uniform	1	1.850
Y	18.43 μm				1.885 μm

Áron Lóránd, PhD student & assistant lecturer, Obuda University, Institute of Mechanical Engineering and Technology, lorand.aron@bgk.uni-obuda.hu, 1081 Budapest, Csokonai utca 3. (Hungary), +36-30-658-1342

Ágota Drégelyi-Kiss, PhD, associate professor, Obuda University, Institute of Mechanical Engineering and Technology, dregelyi.agota@bgk.uni-obuda.hu, 1081 Budapest, Csokonai utca 3. (Hungary), +36-70-611-5361