

Application Note #563

Improving Additive Manufacturing with Accurate Surface Metrology

In the past few years, manufacturing has gone through a series of major evolutions. Standard formative techniques (molding, injecting, casting, stamping, forging) and subtractive processes (CNC milling and turning, drilling, cutting) have been challenged by new, rapidly growing disruptive technologies, such as additive manufacturing, 3D printing, and laser surface texturing, among others. This application note positions some of these new technologies versus legacy approaches to understand the underlying parameters and challenges. We also discuss how Bruker 3D optical profiling technologies fit into new and evolving manufacturing approaches. Finally, several case studies illustrate how optical profiling can contribute to the optimization of new manufacturing processes.

New Manufacturing Processes

While formative and subtractive techniques have already existed for a long time, requirements for flexibility in design, conception and customization have pushed manufacturing to seek innovative solutions. For instance, formative manufacturing requires the conception and manufacturing of molds or stamps, which do not allow any further customization or changes. On the other hand, it reduces cost for high-volume production. Likewise, in subtractive processes, advances in computing and 5-axis freedom, together with ultra-high speed machining, have

simultaneously boosted the usage and capability to produce complex parts. It has also, however, brought higher manufacturing costs due to the loss of material through subtractive techniques, starting from a large block and removing matter to design a part. Furthermore, some designs still remain unachievable, such as re-entrant or crossed features due to, for example, physical access limitations for a drilling bit.

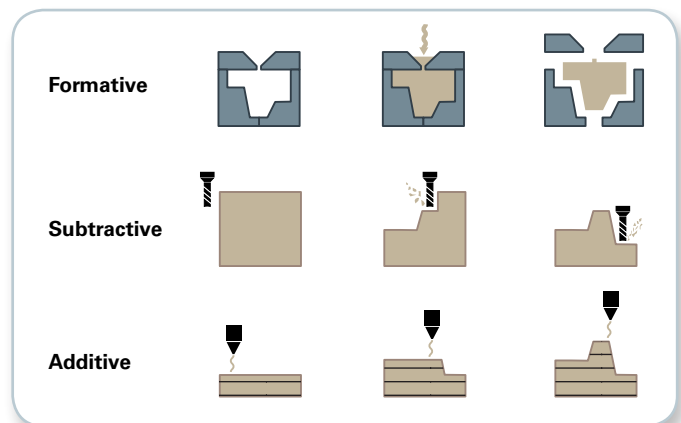


Figure 1. Illustrations of manufacturing principles.

Certain markets, such as automotive and aerospace, have triggered new manufacturing techniques requiring lighter, more mechanically resistant parts with inherent flexibility of

design or customization. Thus, techniques such as additive manufacturing, 3D printing, and laser texturing became new areas of industrial production. Additive manufacturing and 3D printing arise from the same idea of creating an object layer by layer directly from a CAD file (usually in STL format).

In more detail, additive manufacturing encompasses a process where metallic powder is set into a solid state through melting or sintering. Standard powders are made through the atomization process of pure metals, such as titanium, aluminum, nickel, copper, or alloys, such as steel, Inconel, and metallic ceramic. Most common melting techniques consist of scanning laser (direct metal laser sintering) or electron beam (EBM) on powder beds, which is refreshed after each pass. The technique is also known as powder bed fusion or LPBF.

3D printing arises from a slightly different principle. Material is directly deposited layer by layer through a nozzle via solid wire extrusion (fused deposition modeling) or binder (binder jetting). 3D printing is most often linked to polymer manufactured parts. A wide selection of polymers is applicable in 3D printing manufacturing, ranging from commodity polymers (PVC, ABS, PP, PE) to high-performance ones (PEEK, PEI).

While both additive manufacturing and 3D printing bring required flexibility and rapid customization, they also share the same technical challenges. Inherent in the layer-to-layer process is anisotropic parts resistance due to columnar grain growth. To some extent, this is an advantage for specific applications where strain is mainly exerted in one specific direction. Strategies based on a crosshatch pattern for the laser scanning path or for proper overlapping between two laser paths have been proposed to improve isotropy. There is also layer-to-layer stress induced by successive heating/cooling cycles and subsequent thermal expansion/contraction for metals or recrystallization for polymers. Main consequences include crack propagation or limitation to sustain fatigue, as well as part deformation causing deviation from desired dimensional tolerances. Current solutions are based on post-process annealing phase or proper simulation of deformations to include them during the manufacturing process. Lastly, for any additive manufacturing processes based on powder bed fusion and, to a lesser extent, for material extrusion techniques, an optimum balance needs to be found between scanning speed, laser power (extrusion speed and temperature for wire) and bed thickness. Effects of laser power and scanning speed are illustrated in Figure 2. These parameters are crucial to ensure high mechanical performance. Poor process settings directly lead to porosity or voids formation, as well as non-cohesive material.

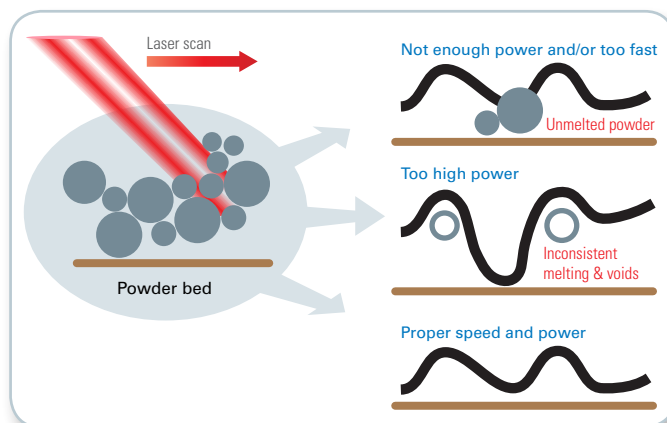


Figure 2. Illustration of the impact of laser power and scanning speed in laser selective melting on powder beds.

Characterization Techniques

As mentioned, additive and 3D printing technologies require proper manufacturing settings to be successful. Characterization techniques consequently play a role in driving process optimization by providing information on how the process went and identifying the root causes of failures. Bruker offers a unique suite of solutions with a wide range of applicable techniques:

- For particle chemistry, X-ray fluorescence provides elemental composition while combustion gas analysis and inert gas fusion mass spectrometry allows trace quantification of carbon, sulfur, argon, oxygen, nitrogen and hydrogen impacting mechanical properties.
- For grain texture and residual stress, X-ray diffraction provides global information while an EDX sensor on an electron microscope acquires local information.
- Mechanical properties can be characterized through nano (single particle/high-resolution mapping) or micro indentation (Vickers hardness). Tribology properties can also be assessed through wear (pin on disk, linear reciprocating) and fatigue testing.
- Surface and volume can be accessed via micro-computed tomography (μ CT) and optical profilometry. Critical dimensions (CD), void percentage, deviation from CAD models, waviness, and roughness are all important outputs.

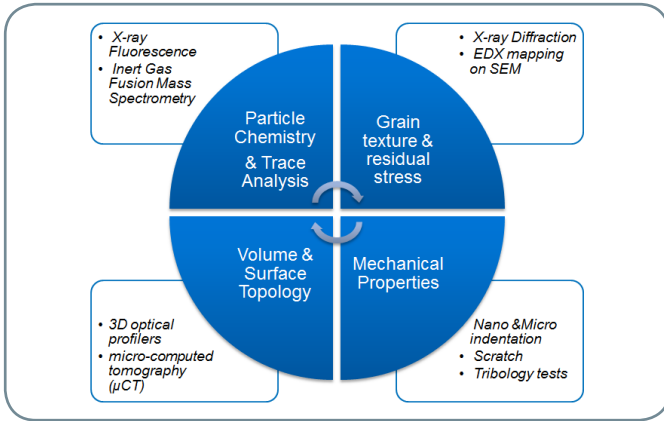


Figure 3. Summary of Bruker characterization techniques for additive manufacturing.

Here we concentrate on how 3D optical profilers turn topography measurements into quantified roughness parameters that directly link to the manufacturing process. Below are three case studies covering bed fusion additive manufacturing through selective laser melting (SLM) and polymer 3D printing.

Case Study: Process Influence for Stainless Steel Parts

The additive manufacturing process leaves different surface roughness than standard subtractive techniques. This case study illustrates how 3D optical profiling can assess roughness differences between processes and allow quantification of post-process efficiency. Multiple stainless steel bars for mechanical testing were manufactured with different processes, from regular turning machine up to additive manufacturing. Additive manufacturing was performed via an EOSIn M270 machine together with EOS Stainless Steel GP1 powder along two different directions (longitudinal or transversal from bar direction). Topography was captured by a white light interferometry (WLI) 3D optical profiler with a 20x objective along a 1mm² area to emphasize differences. The different processes are summarized in Figure 4.

Processes	Turned machined	Vertically printed by DLSM	Horizontally printed by DLSM	Post-processed AM
Aspects				
Building path				

Figure 4. Summary tab for processes and visual aspects for metallic bars. Samples courtesy University of Sydney, Australia.

The 3D topographies shown in Figure 5 indeed confirm topology differences with respect to process type. A turning machined surface results in the lowest roughness while raw additive manufactured surfaces exhibit a large vertical range. Post-process lies in between and clearly shows that

it has successfully reduced overall roughness.

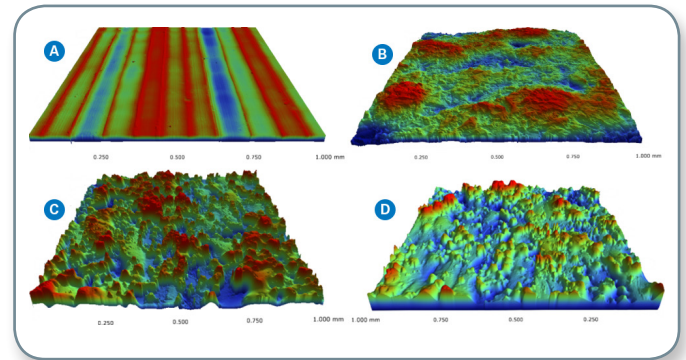


Figure 5. Topography results from the four different processes. Area and vertical scales are identical for comparison (1 mm² and [-60 μm, +80 μm] respectively). Turning machined is represented in A while post-processed AM bar is shown in B. C and D show vertical and horizontal grown bars, respectively.

The effectiveness and efficiency of roughness reduction can easily be gauged by the mean roughness parameter Sa (see Figure 6). It is a convenient and well-accepted parameter that can rank different post-processes to find the most cost-effective one.

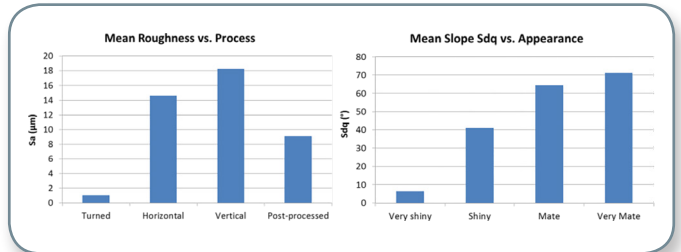


Figure 6. Graphic summary of mean roughness versus processes (left) and appearance versus shininess (right).

Each bar also had very different aspects, varying from shiny to matte surfaces. Depending on the market served by manufacturing, aesthetics may play a significant role in customer perception, making it a critical concern in final quality checks. This control is most often manual and is solely based on the visual perception of the operator. To reduce operator time and achieve higher consistency for the production line, the mean slope parameter Sdq can be one possible selection. As illustrated in Figure 7, there is nice correlation and strong dependence between shininess and the mean slope.

Finally, additive manufactured parts usually require a second step process to optimize surface functionality performance, such as mechanical and wear resistance or the ability to strongly anchor coating/paint. Thus, additive manufacturing requires dedicated parameters that are able to rank how good the initial manufactured surface is and how much post-processing improves it. For this purpose, functional areal roughness parameters easily work out initial volume of matter in contact (Sm) that can inversely link with abrasion resistance and porosity volume (Sv) to impact

lubricant/paint retention or mechanical strength with a high probability of cracks.

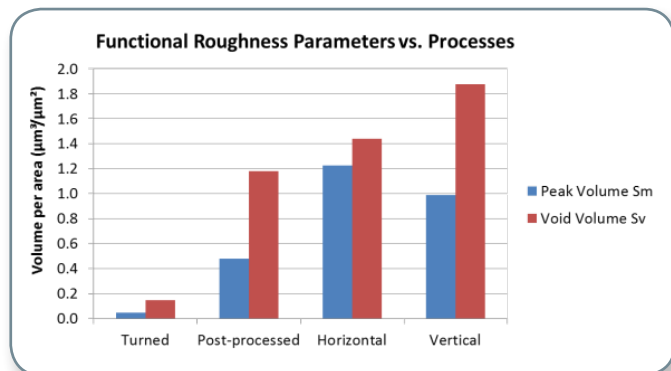


Figure 7. Summary of peak material and void densities for various processes.

In the present study, the subtractive process leaves a smooth surface with a high load capability and low surface porosity, as shown by both low peak and void volume parameters. Meanwhile, the same parameters nicely differentiate additive manufacturing paths: vertical manufacturing gets less peak volume but higher porosity volume than horizontal manufacturing. Mechanical strength, as well as wear resistance, would certainly be highly impacted in the vertical, which leads to a preference for horizontal layer growth. As this value is user-independent and quantified, it becomes possible to use it and other such parameters to gauge the effectiveness of different building strategies. Lastly, functional parameters emphasize how post-process operates by reducing porosity and peak volumes for better bearing and higher mechanical strength. One can therefore rank the effectiveness of different post-processing methods and provide background on inherent reasons for failures and/or under-performing products.

In this study, non-contact 3D profiling has clearly differentiated each process and is in the position to deliver quantified normative values linked to functionalities. These parameters can serve both in the development phase and in production line quality control.

Case Study: Powder Influence for Aluminum Alloy Parts

All bed fusion-based additive manufacturing processes are sensitive to powder selection to such an extent that changing powder actually requires the fine tuning of production parameters. This case study illustrated the impact of changing Inconel 718 to pure aluminum powder to build the exact same part. Effects were quantified through recording topography with a focus variation-based 3D optical profiler. A 20x objective was used to achieve best balance between lateral/vertical resolutions and field of view to capture key characteristics of both parts. Besides its ability to operate on very rough surfaces, the focus variation technique provides a color image at the focus point for every pixel, on top of topography. The

color adds extra information about possible oxidation or alloy formation. Figure 8 shows an example for both aluminum- and Inconel-based surfaces.

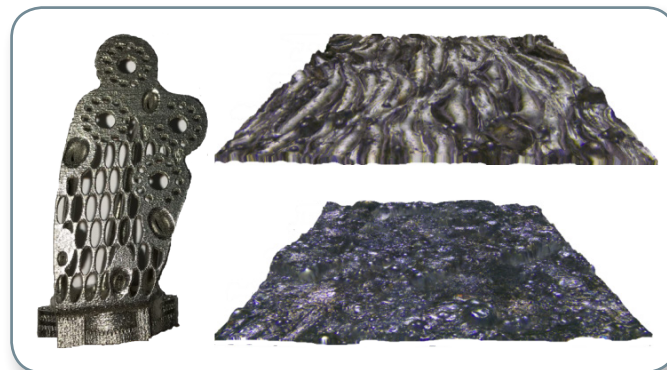


Figure 8. True color image of a manufactured metal part (left), courtesy of Volum-E, France; and 3D rendering of topographies ($0.7 \times 0.7 \text{ mm}^2$) with color map overlays of an aluminum powder (top right) and an Inconel powder (bottom right).

Systematic measurements were performed at identical locations (see Figure 9). At first glance, parts manufactured with aluminum clearly exhibit higher corrugation, together with a presence of round particles or aggregates. In contrast, the Inconel-based process left a smoother surface that revealed the typical ridges left by the movement of the melting front. In some occasions, we found round particles that were smaller and well spread apart compared to the aluminum powder. Based on this study, production parameters seem more suited for the Inconel powder, with less spatter and better fusion completeness. However at certain locations, laser speed appears to be too fast, as porosity can be observed (see Figure 9 bottom row).

Powder	First layer - Bottom	First layer - Top	Last layer - Bottom	Last layer - Top
Al				
Inconel 718				

Figure 9. Summary table showing topographies for both powders and different locations on sample. All topographies are displayed with same area and same vertical scale ($0.7 \text{ by } 0.7 \text{ mm}^2$, Z scale $[-140 \mu\text{m}; +140 \mu\text{m}]$ respectively).

While 3D topography provides qualitative information on how well a process went, areal roughness can add the quantitative data necessary for proper feedback to production and the fine tuning of manufacturing parameters. In our case study, the presence of spatter and/or remaining un-sintered particles can be emphasized through invert of mean summit radius and appropriate spatial filtering to

reveal the particles (see Figure 10). Under these conditions, significant difference appears between Inconel- and aluminum-based parts that can be used as key check parameters to either fine tune the process or control quality.

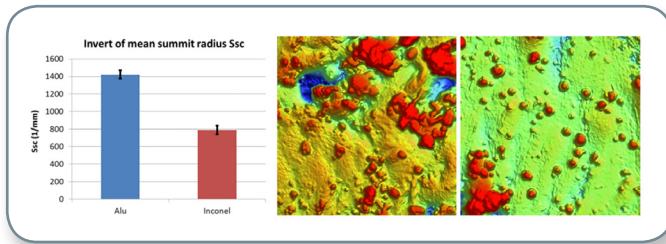


Figure 10. Differentiation between aluminum-based and Inconel-based parts through roughness parameters. Graph on left shows average value (solid bars) with 1 σ dispersion (vertical lines). Topographies (aluminum-middle; Inconel-right) are shown after high-pass robust Gaussian, 2nd order and 0.25 mm cut-off. Vertical scales are optimized for particle rendering.

Further quantification of the number and size of the particles can be worked out through adequate segmentation. This strengthens initial analysis by giving a clear indication of the average diameter of particles and indicates possible root causes of failure through comparison to native particle diameters. Figure 11 provides an example where particles are ranked from largest to smallest average diameter.

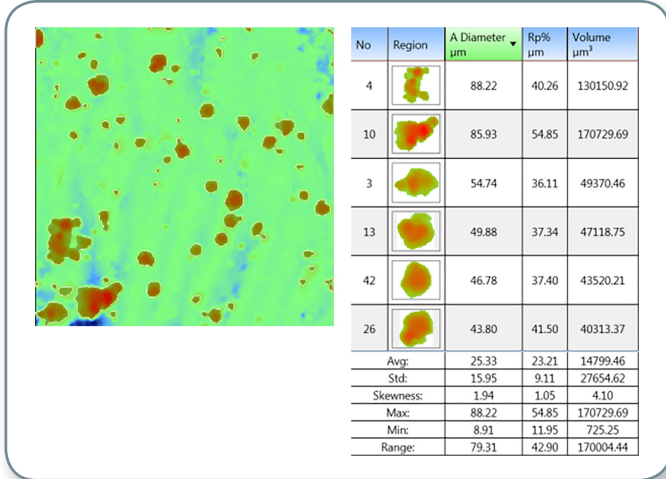


Figure 11. Left, automatic segmentation of filtered topography image from Inconel part. Right, summary of all detected particle with average diameter, total height (Rp%), and volume.

This study clearly illustrates that a 3D optical profiler utilizing focus variation can reliably inform on the impact of

powder type on the additive manufacturing process. This technique also captures such key information as presence of spatter and/or remaining particle, which can be used to further improve and track manufacturing processes.

Case Study: Temperature Influence on 3D Printing of PEEK Material

PEEK is an important material with notable inert behavior over a wide range of environments. It is a material of choice for the pharmaceutical industry to deliver aerosol drugs without anchorage of foreign particles (cleanness), and with an adequate mixing of drug components. For this case study, we focused on designing a mixer via hot extrusion 3D printing. This consisted of continuous melting of a PEEK filament, which was pushed out a scanning nozzle to build the mixer layer by layer. The main aim was to check the influence of extrusion temperatures on inner channel topology. For that purpose, two samples were prepared: one under proper temperature and the another under too high a temperature. After building, the parts were cleaved to access the inner channel for 3D optical measurement. Micro-computed tomography would have served as another non-destructive solution.

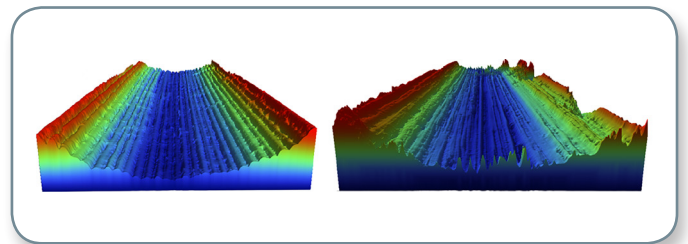


Figure 12. Channel topography measured with a 10x objective and stitching: channel with proper temperature (6.9x3.5x0.7 mm³) on left; channel with inappropriate temperature (9.0x2.4x0.6 mm³) on right. The mean roughness (Sa) was 7.8 μm and 7.5 μm , respectively, after a high-pass Gaussian regression filter, 1st order, 0.25 mm cut-off. Samples courtesy of I-Form, Dublin, Ireland.

The impact of temperature is clearly emphasized by the 3D topography measurement. Too high of a temperature triggered pores/depressions that created reservoirs of fluid along the channel. This implies possible contamination and/or a mixing issue that excludes such structures for demanding pharmaceutical applications. The mean roughness parameter (Sa) cannot, however, act as a pass/fail criteria since, surprisingly, the defective channel design has a smoother appearance aside from the pores (see Figure 12). It also does not provide any indication of the reason of failure, nor does it serve as an indicator of what to do to drive process improvement.

Since 3D printing leaves a well-defined layer-to-layer pattern, an areal roughness parameter from the spatial section is

a better indicator. For instance, the auto-correlation length (Sal) nicely differentiates processes, as shown in Figure 13. Besides differentiation, Sal also provides direct information on layer-to-layer periodicity, which directly relates to the manufacturing process. It provides a major advantage since it simultaneously checks the agreement between expected layer spacing and actual results. In a proper process, Sal reaches 89 μm , which corresponds to the nozzle spacing between layers, while for defective parts, Sal is smaller, indicating a merging/mixing between layers. The Sal roughness parameter thus becomes a key feedback parameter while changing extrusion temperature. A higher or lower value versus the expected layer spacing directly implies a defective process. In this way, a user can quickly and reliably converge toward the best set of parameters for optimum production.

actionable assessments on how good a manufacturing process is. 3D optical profiling has thus become a key characterization technique for the support of the development and fine tuning of 3D printing and additive manufacturing techniques.

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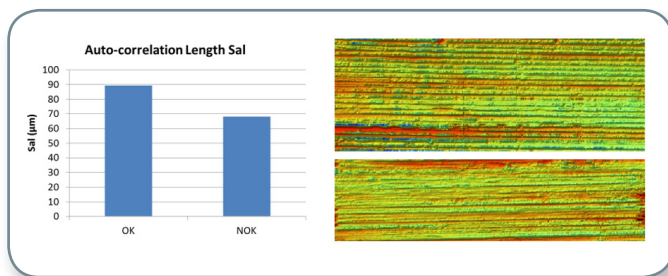


Figure 13. Graph showing auto-correlation length differences between parts that will work and ones that will not (left). The topography after shape removal and masking on smooth areas of the properly processed part (top right) is shown versus the topography of the defective parts (bottom right).

Conclusions

This application note has demonstrated how valuable 3D optical profiling can be for failure analysis, process optimization, and quality control in additive manufacturing. Across different processes, different powders, or different temperatures, the vertical and lateral accuracy of optical profiler metrology, combined with non-contact and areal measurements, leads to reliable diagnostics and