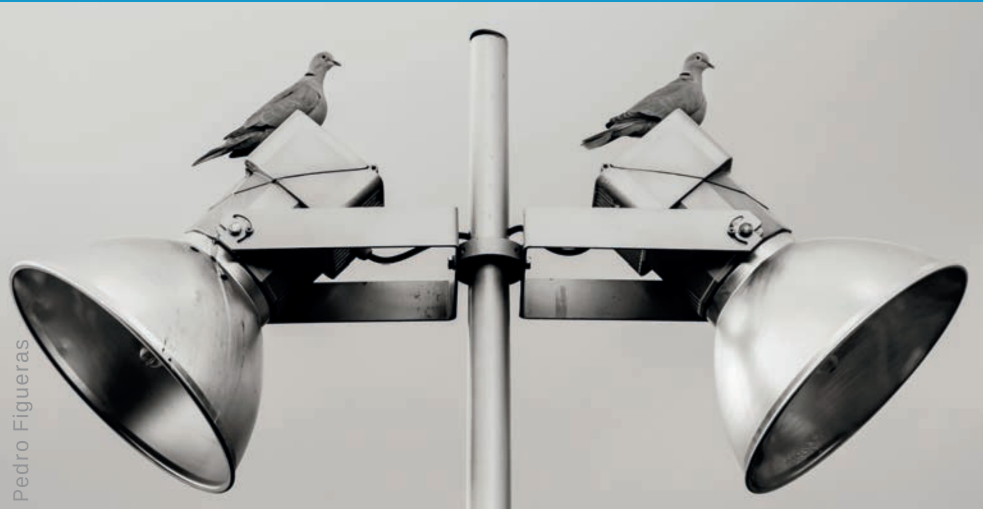
Guide to Handle Variability in Additive Manufacturing



Guide to handle variability in AM

Printing products is easy. This statement is both true and false.

Compared to conventional machining, operators do not need to read technical drawings and translate them into numerical code. However, there are several steps in the printing process, where product quality can vary. This happens even if the operator does everything right.

This guide describes the sources of variability that exist when printing in different places, on different machines, with different materials. Whether printing all batches on the same machine or spreading production ovcross several machines, this guide gives you an insight into the most critical parameters and how to handle them.

Talk to us. We are there to help.

Daniel Straub

Variability

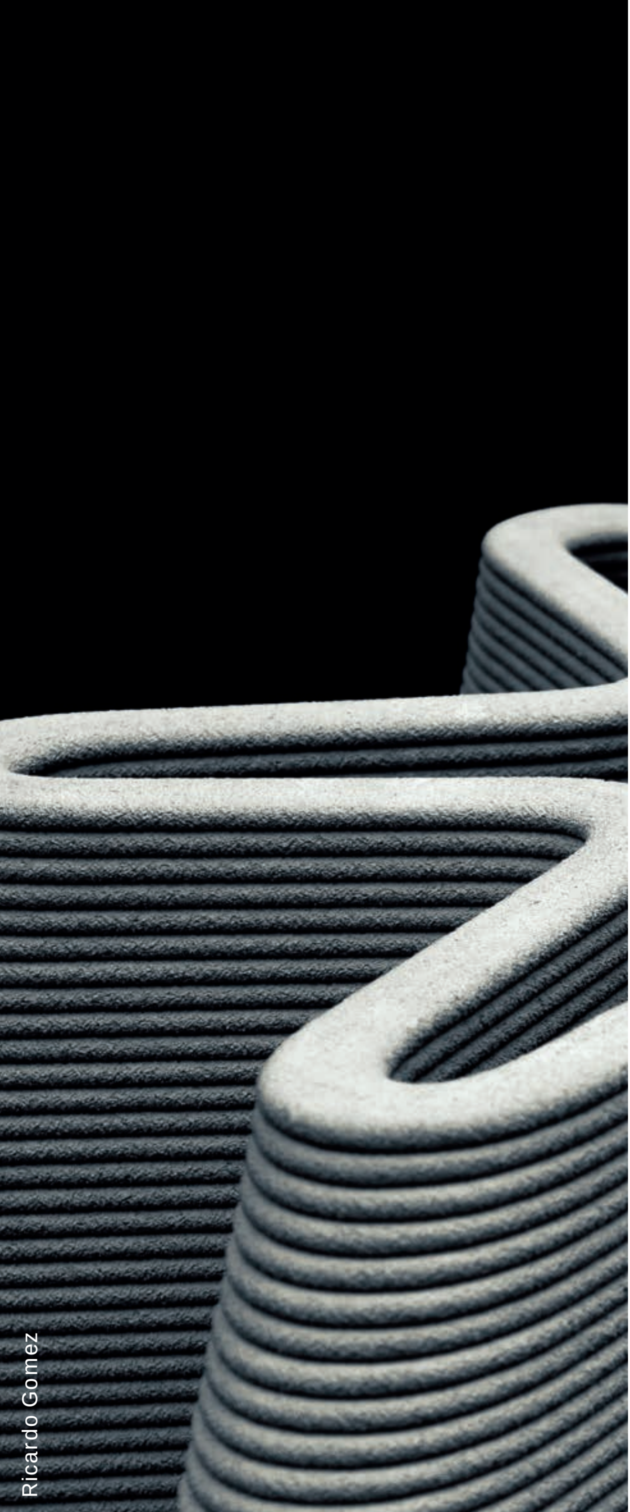
Whether you print a component in-house or send it to a 3DP bureau, there are several process steps that will occur for the component design (i.e. the CAD model) to become a finished component. Each step can introduce variability in the quality of the finished component Figure 1 shows the primary steps where variability is introduced:

During design you already need to address variability in printing.

- Variability in the conversion process from the CAD model of the component that is to be printed to the “build model”
- Variability in the condition of the feedstock used for printing
- Process parameters used for the particular geometry that is to be printed
- Properties of the printing system which may fluctuate between one machine and another of the same make and model
- Variability in the support removal process and other post-processing steps

Beyond an introduction into the topic, this guide describes the main parameters for variability in each of these steps and which ones the customer can control to minimise their effect on the product’s final quality.

This guide finished with an introduction to concepts of repeatability and reproducibility, which are both useful when tracking variability within a production facility and between separate production facilities.

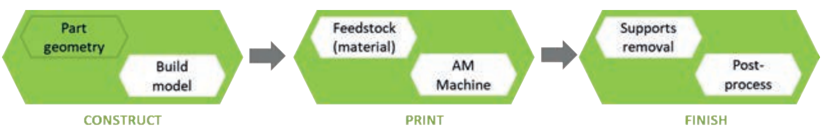


Ricardo Gomez

AM Process Stages

Build Model Generation

The first step of nearly every additive manufacturing process is the conversion of a CAD model of the component into a 'build model'. The build model shows the component in a virtual build chamber of the chosen AM machine. This is the stage where the component is orientated for buildability and supports are added if required by the AM process. The build model is then converted into a 'slice file'. The slice file is the definition of each 'slice' or 'layer' of the build and is the information that the AM machine receives and replicates in the physical build chamber.



Main steps in the additive manufacturing process chain of powder bed technologies where variability accurs

There are certain variables when it comes to prepare the model for the print job that can affect the physical part that you will receive. The primary ones are

CAD model conversion:

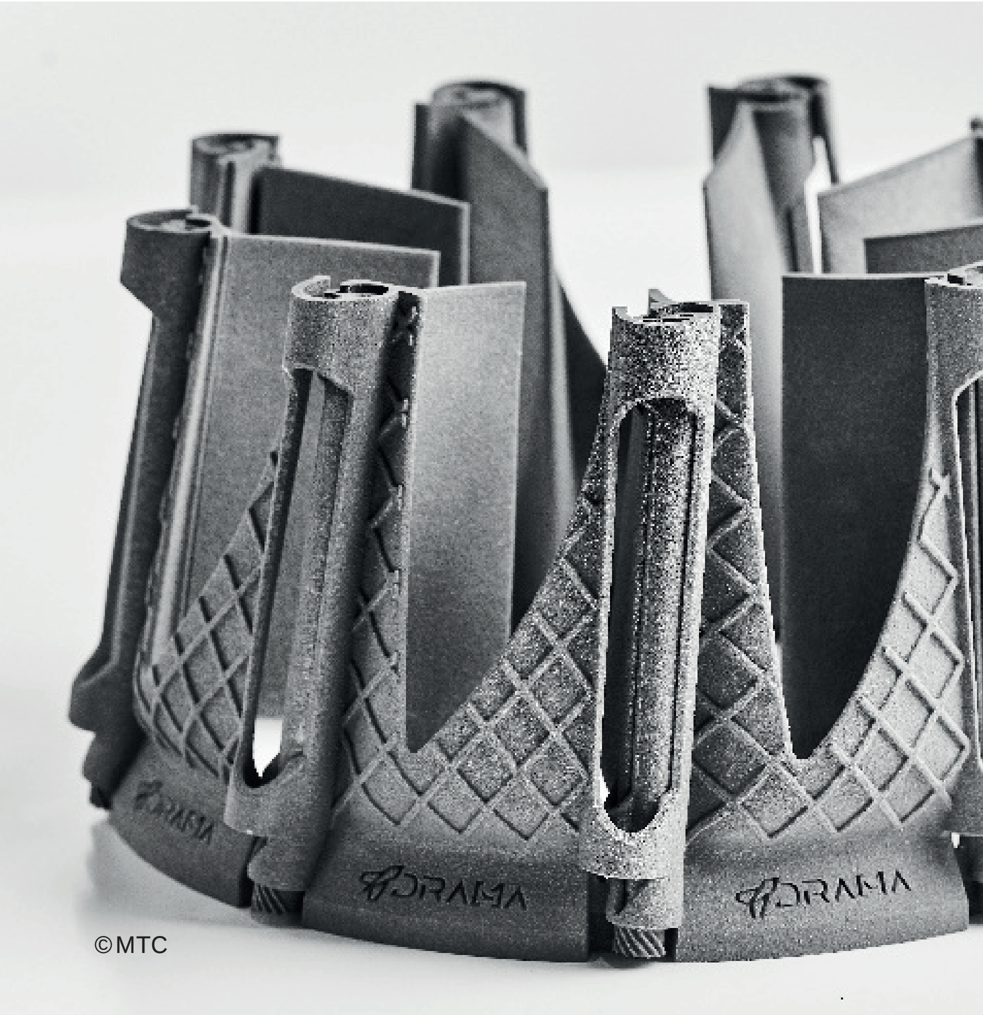
- The CAD model needs to be converted to an .stl, .3mf or .amf file, all of which represent the geometry of the component using a triangulated mesh. The accuracy of this conversion is controlled during export of the model from the CAD software package. There is a trade-off between a high resolution file that is very large (hundreds of megabytes) and a low resolution one that may lack definition, especially of curved features.

– Control: we suggest either to send the triangulated mesh file to the printing bureau or process engineer directly. If sending the native CAD file - due to file size limitations for example - including specific conversion parameters that you have tried yourself and are satisfied with.

The build chamber is where powder-bed based technologies encounter variability.

Build plate:

• Position and orientation of components
  – The orientation of the component is



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important as it dictates the direction of the layering in the built component, the surface texture around the component and the need for supports to be added (see section 2.4).
  - For metal AM processes, the location of the component in the machine's build volume can change the microstructure of the built component.
  - Control: we suggest using an engineering drawing or other document to specify the location and orientation of the component and where supports are permitted

- Size of build plate (how many components can fit in one build and their proximity to each other)
  - For some AM processes, heat dissipation during the build may affect the characteristics of the final material. For traceability and repeatability, we suggest asking for a screenshot of the build file, or a copy of the file itself.

- Whether any test coupons, carrier specimens or other artefacts should be included.
  - These artefacts can be useful for evaluating material properties and for traceability and repeatability across builds and between different machines. The process engineer may include some by default, but the customer can specify which ones they want

Slicing

- Layer thickness
  - Many AM process can build in several different layer thicknesses. The choice of layer thickness is a trade-off between speed and resolution and can affect material properties.
  - Control: we suggest asking for the available layer thicknesses, checking the geometry resolution against the thickness of a slice and specifying the

required thickness to be used.

Hatching is key in getting complex structures built to specifications. Only a few software packages allow you to control hatching.

- Hatching of solid areas on each layer (for metal, raster based processes)
  - The way large areas are filled in, or 'hatched' can affect final microstructure of the component, which in turn affects the achievable material properties and machine manufacturers may provide multiple options for the process engineer to choose from.
  - Control: Whilst this cannot be controlled by the customer, we suggest a discussion with the process engineer to understand the impact on the customer's geometry

- Software version and parameter set used
  - Each component geometry has different types of features (for example thin walls, sharp edges, overhanging surfaces) and the slicing software uses algorithms to calculate the best way to consolidate the material for these features to give good interlayer adhesion, good external surface quality etc. From one software version to the next, changes in these algorithms could give a different result for the same component geometry, resulting in a variation of part quality. In addition, there may be different parameter sets available in the software for the process engineer to choose from (for example "high quality", "fast" etc)
  - Control: We suggest asking the process engineer to record the software version and the parameter set that were used.

Feedstock (Raw Material)

Most AM processes use feedstock in one of three forms: powder, liquid (resin) and filament/wire. In each case, the condition of the feedstock links to the quality of the parts produced. For production in-house, the material acceptance criteria and storage conditions are important to control component quality. If outsourcing production, then assurance should be requested from the supplier.

Powder

Many stories about powder are out there. Make sure, you follow the right instructions.

Powder for AM needs to have a specific range of particle sizes (the 'Particle Size Distribution') and particle shapes (the morphology) in order to flow and spread correctly in the AM process. It also has to be of a specific chemical composition corresponding to that of the bulk material it is made of. These characteristics may be altered by:

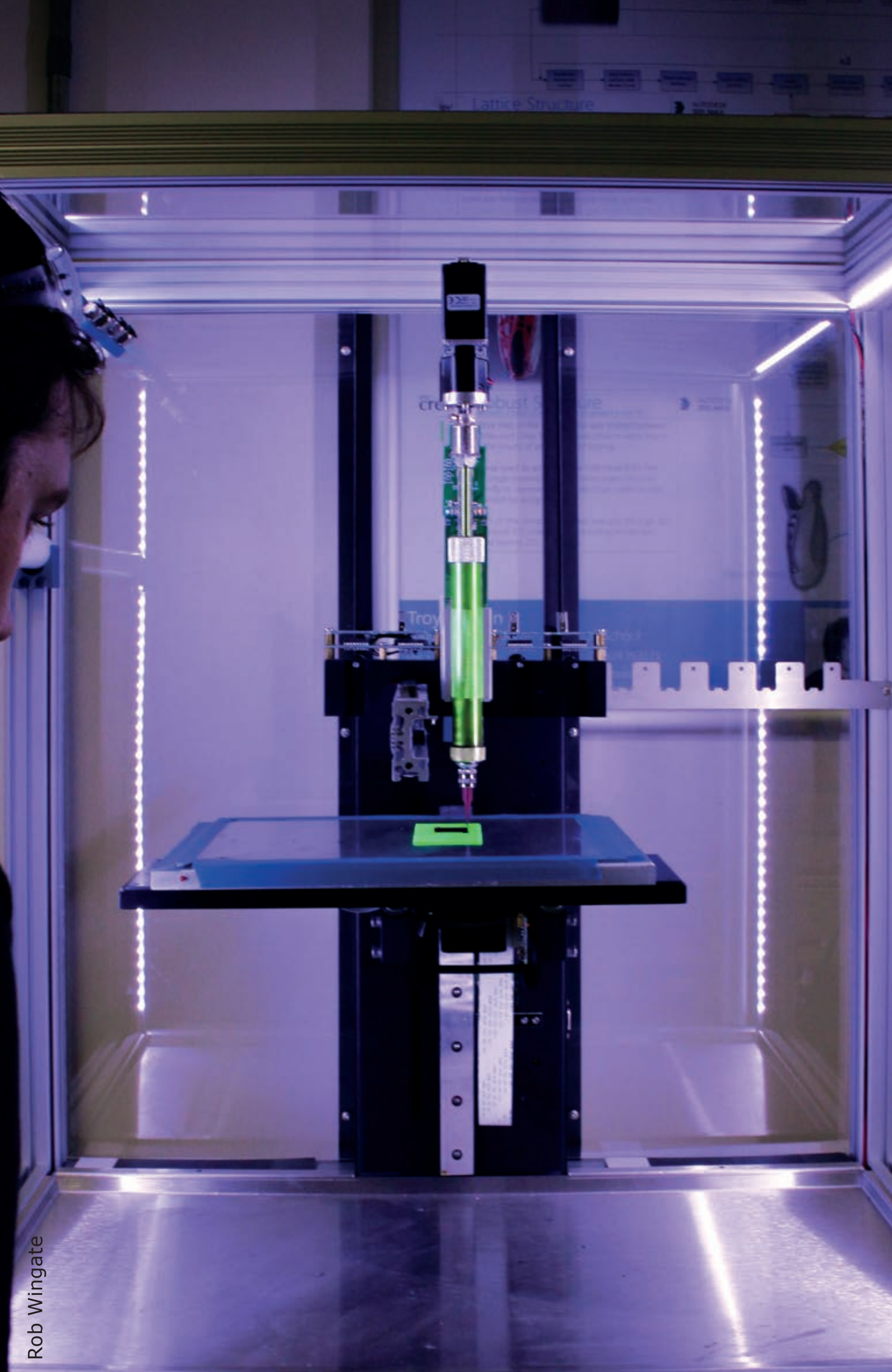
- Recycling of powder – reusing unconsolidated powder from builds reduces material cost, but the trade-off is that the morphology of the powder can change, affecting the way it flows and spreads, as can the chemical composition. The manufactured part may then contain internal defects and altered microstructure. The policy of using recycled powder should therefore be agreed with the producer of the AM component.
- Storage and handling conditions – some materials pick up oxygen or other elements, including atmospheric moisture, which changes the final component material property. This can occur during builds (see above) or due to the conditions that they are kept in. They therefore need to be stored and handled correctly in temperature and humidity-controlled environments.

Consider the factors that really impact your part quality.

Resin

AM processes that use resins require a material with:

- A specific viscosity, so that it flows predictably
- A specific chemical composition, so that it reacts predictably to the curing



Rob Wingate

processes, (ie heat and/or UV light) as well as having nominal material properties when cured.
- In addition, loaded resins (ie resins that carry solid particles of filler such as glass fibre) require the filler to be uniformly distributed in suspension in the resin.

To ensure consistent quality from resin-based processes, the user just needs to:

- Store the material in a controlled environment (as specified by the material manufacturer)
- Observe the shelf life of the material
- If necessary, pre-mix or agitate the material (again as specified by the manufacturer)

Filament/wire

Impact of variability in all technologies and materials.

There are two main factors for filament or wire that can cause variability in the components quality:

- Filament/wire diameter - fluctuating diameter will cause the material deposition rate to fluctuate leading to uneven material deposition. This in turn affects surface texture and intralayer/interlayer adhesion. The feedstock manufacturing process determines the consistency of diameter , so as a user this can be measured upon receipt of the material but not controlled
- Moisture – some filament materials will absorb moisture which is then ejected during melting, interfering with the printing process. Filaments should therefore be stored under controlled conditions

AM machine

AM Machine is not AM Machine. Even if both are yours.

AM is a relatively new manufacturing process and as such AM machines are still evolving, in terms of their design and production but also in terms of the associated maintenance procedures, ease of use and of detecting machine errors. For this reason, when sending components for manufacture, the variability introduced by the actual AM machine itself is an important consideration and has several manifestations:

Variability between machines from different manufacturers

Variability can arise in the same category of AM processes, for example between SLA machines from different manufacturers

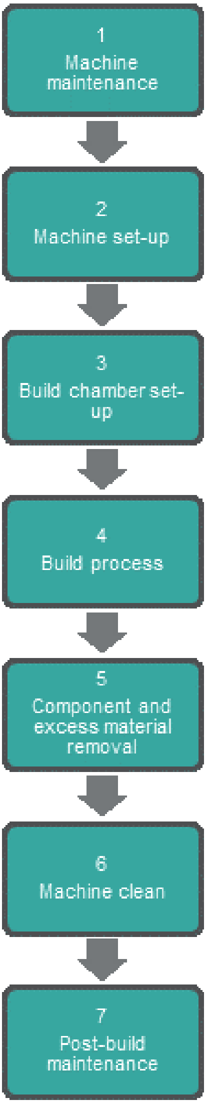
- Due to different implementations of the technology, some examples being:
  – the laser source diameter and power
  – number of lasers
  – type of recoater used
  – rastering hardware
  – inert gas circulation
  – software etc

- In general, machines from different vendors cannot be used in a batch production situation

Variability between multiple machines from the same manufacturer

Variability can even arise between multiple machines that are of the same manufacturer and model number, even at the same site

- Due to the machine manufacturing process, the machine setup process at the facility or the process engineer or machine operator.



Generic AM Machine process flow

Variability between subsequent builds

- Due to the individual machine operator or machine service condition, variability can occur from machine setup, material preparation or environmental conditions.

To minimise the effects of the above variabilities, it is common practice in highly regulated industries such as the aerospace sector to consider each specific material-machine pair as a "printer system". Each individual printer system is then treated as a separate goods supplier, with its own process documentation, and quality control procedures.

For less demanding applications, the user should consider being able to specify or control of all the process steps that are shown in Figure 1, in accordance with the manufacturer's advice.

Support Removal & Powder Removal

When the build is completed, most of the times there is still a number of tasks that need to be completed before having the finalised component. One of them is to remove the excess feedstock (for powder or resin-based processes) from the build area and then remove any support material attached to the components. Depending on the AM processes used, the supports may be easy to remove (e.g. soluble supports) or difficult (e.g. with metal powder bed processes). In all processes however, support removal is a manual process and therefore introduces sources of variability:

- The order of removal of the supports depending on their location, as this is different for every design
- Supports design and access – can they be snapped off with the hands or dissolved away or are tools required?

- Type of tools or equipment used for this tasks eg pliers, bandsaw, grinder.
- Baseplate separation method – wire-EDM, bandsaw
- Operator skill

These processes are hard to control when outsourcing to a subcontractor and therefore best kept in-house if possible to maximise consistency.

Other post-processing

It may be the case that further post-processing is required to achieve the required component specification. These post-build processes often include:

Post-build curing (for UV-based polymer processes) or sintering (for metal binder processes)

- The components are removed from the build and placed in a secondary process, which must go through a predetermined cycle. Machine maintenance and correct operation are the factors that require monitoring.

Thermal treatment

- Many metal-based processes make use of thermal treatment to:
  - Relax residual stresses out of the component
  - Alter the mechanical properties of the ally
  - Close any pores or voids in the component

- Again for all of these treatments, a certified service provider will be needed to ensure consistency

Machining

- Interfaces with other components will normally require machining to achieve

required tolerances. Machining is a well know process but AM parts can introduce challenges such as:
  - Cutting forces on thin and complex features
  - Components coming out of the AM build with (thermal) distortion
  - Datuming organic forms
  - Fixturing of complex geometries. In this case a 3DP fixture or jig is useful to ensure consistent results

Surface finishing

- Surface finishing is commonly used on metal AM parts to improve surface texture. The methods used to achieve this are based on conventional abrasive, chemical or thermal processes and as such, the physics of the processes are well understood. The variability when using the processes arises from:
  - The complex geometry, which affects access for media in abrasive processes, and may remove varying amounts of material from the component
  - The initial surface roughness variation over the surface of the component , which in turn will leave a varying residual surface roughness
  - For surface finishing process that are manual, the method of application of the finishing process

- These factors are usually addressed using tests to establish the finishing process parameters, which are then applied and monitored during production runs


FT4

How to evaluate variability?
A case study on how-to and how difficult it is.

Once a set of measures are chosen for a given set of process steps, they can be used to track variability across a production process by assessing:

- Repeatability of process step results: Based on the overall results, how repeatable can you expect results within that process to be?
- Reproducibility of process step results: Based on the overall results, how reproducible can you expect results to be between different production facilities?

These indicators allowed the evaluation of two metrics; Production facility consistency (intra-facility) and under the question how consistent are the results within a facility, relative to the expected repeatability? Overall consistency (inter-facility). How far do the results from this facility deviate from the average between facilities?

The relationship to the results can be thought of as follows:

- If repeatability is poor, you would expect variable results from any one facility.
- If reproducibility is poor, you would expect different results from two different facilities.

The following case study is an example of evaluating variability of metal powder feedstock. For this type of feedstock, it is important to characterise the physical and chemical aspects of the powder since variation affects build quality, as described above. The study investigated the reliability and reproducibility of three key powder characteristics that were measured at different laboratories. The characteristics were particle size distribution (PSD), rheometry and chemical composition.
The powder characterisation test used to assess the material were a combination of automated and manual tests:

- Particle Size distribution (PSD):
  - This is an automated test process that uses laser diffraction

- Powder rheology (flowability):
  - This test (Freeman FT4) measures the dynamic flow of the powder material and is a manual test that requires operator skill to obtain consistent results

- Bulk alloy chemistry:
  - An automated test using Inductively Coupled Plasma spectroscopy (ICP) to obtain composition by mass percent
  - The operator uses chooses where in the sample to measure compositions

In the study, the results showed that laboratory performance was generally good and no individual laboratory showed consistently poor repeatability. This was true irrespective of whether test methods were automated or manual. However, several test methods showed low reproducibility across labs, despite good repeatability within labs and acceptable consistency statistics:

- Variable Flow Rate testing using Freeman FT4 showed poor repeatability and reproducibility for one powder characteristic only (BFE). This was thought to be due to conditioning or environmental control and highlights the importance of maintaining consistent conditions between facilities.

	Test	Ti-6Al-4V		Inconel-718	
		Parameter	Value (%)	Parameter	Value (%)
Highest $\%s_r$ (Lowest Repeatability)	PSD	D90	1.50	D10	2.71
	FT4	SE	5.93	BFE	13.9
	ICP	Fe	1.95	B	10.6
	ONH/CS	H	8.2	S	14.9
Highest $\%s_R$ (Lowest Reproducibility)	PSD	D10	1.26	D10	3.71
	FT4	BFE	18.8	BFE	32.3
	ICP	Fe	13.5	P	49.8
	ONH/CS	H	28.7	S	32.5

- The bulk alloy chemistry showed poor reproducibility for specific alloying elements tested in Inconel-718 (elements Co, B, P, Si and S). This may have been associated with the low absolute values recorded for the elements.

An overall conclusion is that process steps which include manual skills are not necessarily a source of inconsistency, but environmental factors and choosing a parameter that is consistently measurable is more important.

neonbrand

Resume

Additive manufacturing is around for years. And many success stories have been published. From the first major story "Print me a Stradivarius" that the Economist published in 2011 to the latest desktop and industrial machines. Innovation has evolved in this field. Still, varibility is one of the key challenges of this technology. In this guide,

we touch a few things that are relevant to the topic. However, variability is always closely connected to the manufacturing challenge that you face. And it is specific to your environment. So, watch out and take care. Wanna know more?

Talk to us. We support you.

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