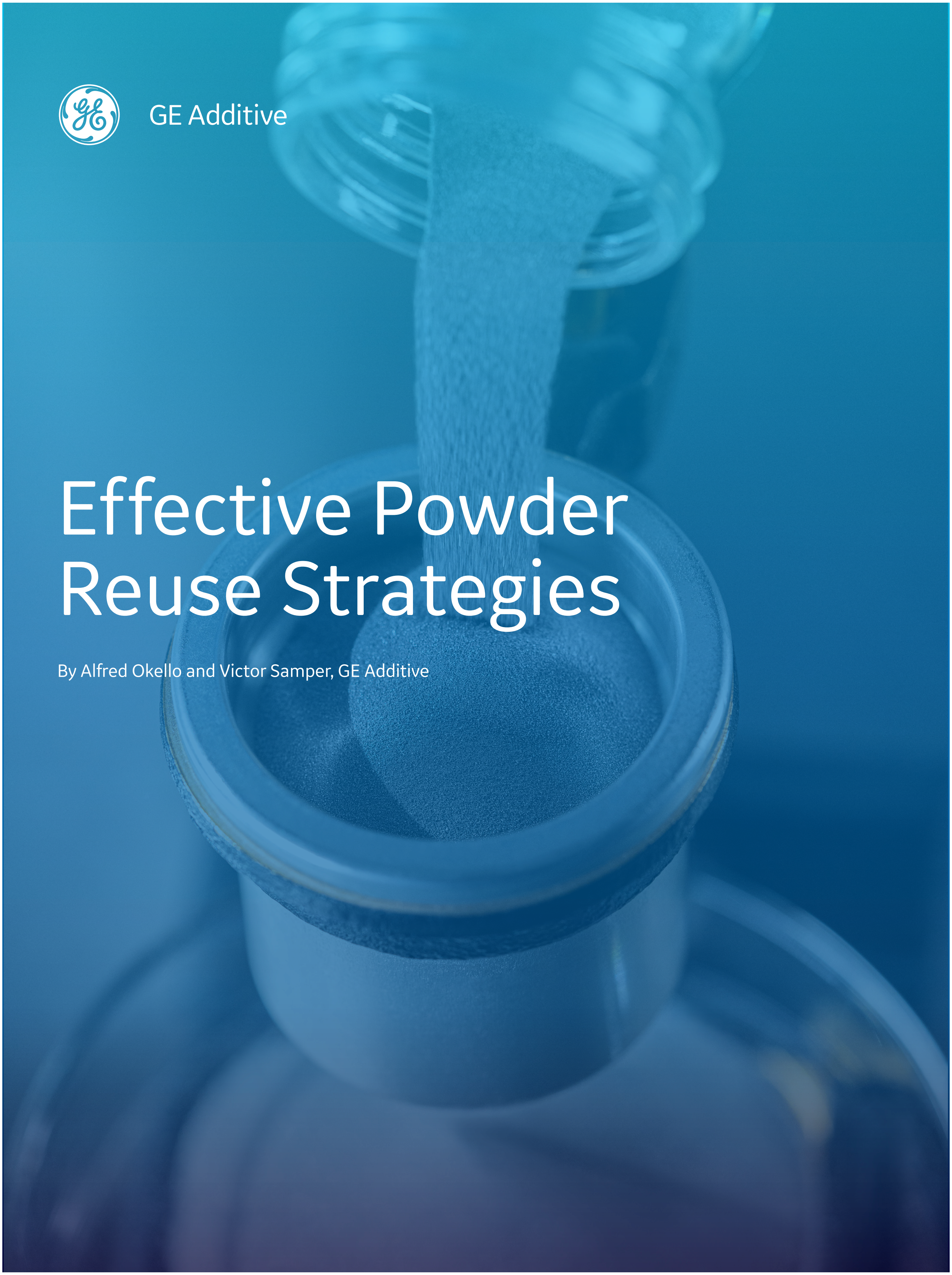

GE Additive

Effective Powder Reuse Strategies

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GE Additive

Effective Powder Reuse Strategies

INTRODUCTION

Additive manufacturing continues to disrupt conventional fabrication methods with the advantages of designing complex shapes and waste management (simplified operations). While there is less material waste compared to conventional methods, the production of powder may be an expensive process that could translate to process and part costs [1], [2].

Different materials have different concerns depending on requirements. For instance, titanium powders are expensive to produce and are prone to picking up oxygen with an increasing number of build cycles. Therefore their use is limited by the amount of this pickup in the final parts [3], as seen in effects on ductility and strength.

A different alloy, like Nickel Alloy 718, can go through several cycles without significant change in chemistry or powder characteristics [3].

On the other hand, different additive technology modalities have different process needs. The electron beam melting (EBM) environment, for instance, offers high temperature processing capability under vacuum where pickup of contamination depends on moisture on the surfaces inside the machine and oxygen level reached by the vacuum evacuation. With direct metal laser melting (DMLM), inert gas flow is used to reduce oxygen levels and maintain the environment in the chamber.

There is a strong business case for using non-virgin powder to produce affordable parts that will still meet the technical requirements: conforming material properties with tracked powder characteristics that meet user specifications.

A successful powder reuse campaign will foster the long-term viability and industrialization of additive technologies.

This paper considers the choice of powder reuse strategies in the industry which will drive cost, ease of implementation and quality. It also intends to provide insight on the basics and factors affecting a successful powder reuse study – from highlighting the complexity of answering a recurring question asked by customers on how many times powder can be reused, to the justification/business case of reusing powder several times for part production, to an overview of the reuse strategies that are typically encountered.

A case-study of the consolidation of a titanium alloy (Ti-6Al-4V) via GE Additive Arcam EBM machines is included with lessons learned from the study and conclusions.

How Many Times Can I Reuse My Powder?

This common question is often met with responses such as "that's an interesting question," or "it depends." Why is it so difficult to give a number? As simple as it sounds, the question implies that someone, somewhere, has a formula that tells us how many times we can reuse powder before the results of our additive build won't meet our quality requirements.

But what are the quality requirements, and is it accurate to believe that the number of reuses provides enough information to predict performance?

To answer the powder reuse question, we must first understand and characterize our processes, and define the line between a build that is a "fail" and one that is a "success."

Processes include the melting of powder inside the 3D printer, the filling and emptying of powder from the printer, storing powder, vacuuming and unpacking the build, sieving used powder, and blending new powder. Each of these processes has the potential to change the physical and chemical properties of the powder.

Different use cases for additive drive the selection of one material over another and define the target material properties that lead to success.
In metal additive we are very often discussing use cases with structural parts, leading to the generalization that mechanical properties such as tensile or fatigue limits are the most important.

While this may cover most cases for some users, it's worth remembering that there are also applications that depend on very different materials and requirements.

Copper for hardening steel with induction coils is one such example. In the case of copper, electrical conductivity would be the main property that defines success.

Accepting for a moment the possibility that a property can deteriorate with powder reuse, but also acknowledging that higher powder reuse reduces waste material, where is the line that defines "good enough," and what level of confidence in part quality do we need to substantiate?

Figure 1 shows a summary of the points that need to be defined before the powder reuse question can be answered.

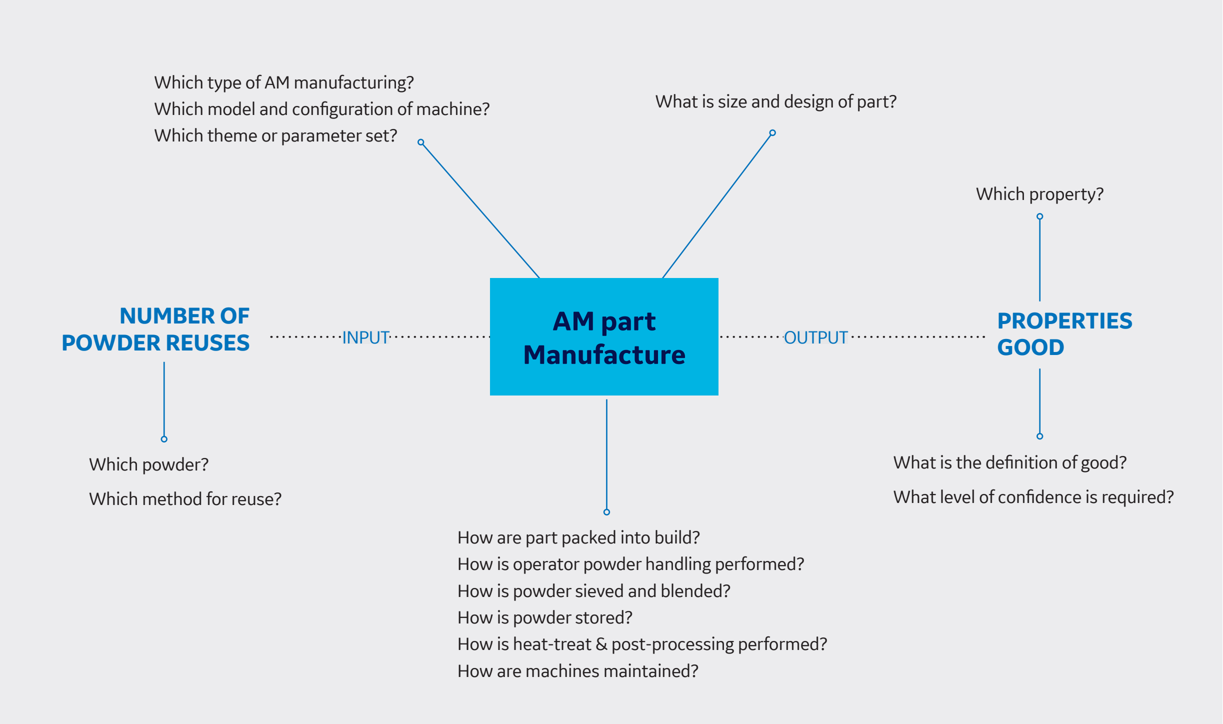

Figure 1: The AM Powder Reuse Transfer Function

The Business Case for Powder Reuse

Additive technologies continue to unlock new possibilities in applications through increased freedom of design, especially in parts where weight is important.

The efficient use of raw material also helps the economic viability of materials otherwise considered as exotic, such as titanium alloys.

Titanium powders are examples of high-cost raw materials often used in specialty aerospace and medical applications, where the number of times a powder can be reused is a key component in governing their affordability [4].

Figure 2 shows that both freedom of design and the strength of a business case have a strong dependency on the number of times powder can be reused.

LIGHTWEIGHT PARTS

The freedom additive brings to part design unlocks new approaches to improve the use of material in satisfying part requirements, often leading to open strut-like structures with large enclosing volumes related to their weight.

However, reuse studies come at a price that affects both the design and the business case. A powder reuse campaign can be costly, especially when it involves several reuse cycles. This cost is associated with the raw material to be used and the effort to conduct the study.

If the study is conducted in parallel during production of parts, an additional cost is attributed to the time lost while waiting for the results of the study in order to make decisions. During this time the shipping of the manufactured products might be delayed.

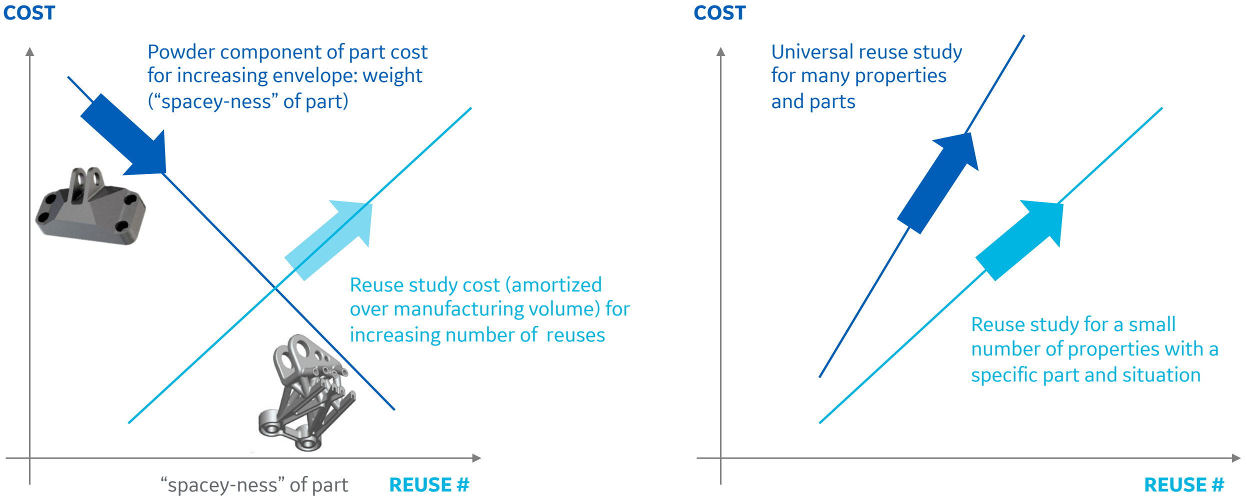

Figure 2: Graphs showing effect of the number of times a powder can be reused and the freedom of part design and business case. Image credit: GE Additive.

Making Process and Science work for the Business Case

An evaluation of metal additive manufacturing as a replacement for a conventional process chain was carried out at one of GE Aviation's sites to determine the minimum number of powder reuses needed for a viable business case.

And in the case, the LEAP fuel nozzle manufactured via DMLM using CoCr material, a minimum powder reuse threshold was also set for a viable business case.

In both examples, the business case set the target for powder reuse before the engineers knew how to achieve this.

When the business case and cost define the finish line, the question becomes: "what can materials science and the manufacturing process do to make it possible to reach the cost target?"
Regardless of the modality, as powder makes its way around a powder reuse loop (as shown in Figure 3), there are multiple opportunities for the powder to be contaminated, pick up interstitials, and have its physical and chemical attributes altered. For this reason, it is important to assess and control each process in the powder reuse loop prior to engaging in a powder reuse study and data collection campaign.

If we now point the spotlight on Ti-6Al-4V EBM process, the mechanical properties of Ti-6Al-4V are known to be sensitive to interstitial elements, with reduced quantities of oxygen and nitrogen improving ductility and toughness but degrading stiffness and strength. Additional oxygen in the powder not only comes from the air, but also from humidity.

The high temperatures of the additive process increase the rate of oxygen pick-up and it is important when planning the unpacking of an EBM build to remember that the material in the center of the bed can be significantly hotter than the powder at the surface due to the poor thermal conductivity of powder beds.

The importance of this consideration depends on the build size.

Physical classifications, such as the powder size distribution (PSD), can be affected at all stages of powder reuse cycle. Over-loading the sieving element is a simple way to accidentally shift the PSD, which consequently impacts powder spreadability and melting in the printing process.

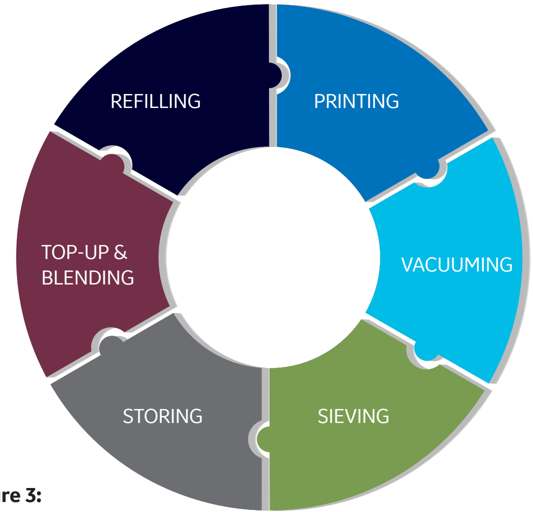

Figure 3:
Powder reuse loop

Is over-loading a sieve possible in your process? Are there other process steps that impact your PSD?

The Human Factor

Variation is part of life, and with operators being critical in today's metal additive manufacturing processes, they represent a potential source of significant variation.

Fortunately, this source can be controlled. It requires meticulous attention to documenting standard working procedures, not only for the additive machine operation and maintenance, but at every stage of the powder cycle.

It is good to aim for the process that has the best mean result, but in the language of Six Sigma, "customers feel variance, not the mean."

Figure 4 shows the process of transforming powder to a part during manufacturing and highlights potential variations that can potentially impact the overall outcome of the process.

The variations are described as random; non-random from unknown factors, such as the packing of re-coated powder layers; and variation from machine performance such as laser power, residual oxygen, gas flow rates and scan rates.

There is another significant source of variation that comes from the human interaction (operators) with the powder reuse process during powder handling, packaging, contamination from cleaning of the machine or preparation of machine parts (for example the re-coater blade).

One of the objectives of implementing lean principles is to eliminate waste during the process.

Additive technologies already show an inherent reduction in material waste compared to subtractive manufacturing. Earlier in this paper, it was shown how waste can be reintroduced in the technology if delays are experienced during waiting of reuse results prior to shipping of parts.

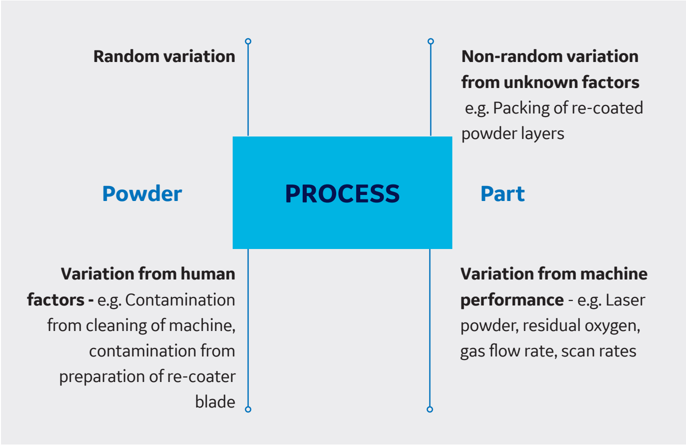

Figure 4: Printing process showing the transformation of powder to a part with examples of sources of variation.

Powder Reuse Strategies

There are various approaches to powder reuse. The choice impacts cost, quality, and ease of implementation.

The table shown in Figure 5 summarizes and compares the following three broad classifications of powder reuse strategy, against a “no reuse” powder strategy. The following comparisons discuss the reuse number of powder for example, “1 use.” Reuse number is defined by the number of cycles around the powder reuse loop of Figure 3, and not the age of the powder in units of time. For illustration, if powder sits in a dose supply chamber for multiple build cycles, but does not cross the build plate, its reuse number would not change.

In GE Additive’s EBM and DMLM machines, the dose hopper in EBM is a FIFO (first-in first-out) arrangement, and the dose chamber in DMLM is a FILO (first-in last out) arrangement. A consequence of this difference is that DMLM powder can, depending on the details of a powder reuse strategy, potentially remain in the dose chamber for multiple builds. The reuse number of this powder would remain unchanged until it crossed the build plate, and any risks associated with powder storage inside the machine need to be addressed elsewhere.

2-bin

Virgin powder from a single powder batch is loaded into the additive manufacturing (AM) machine and the print is executed. At the end of the process, overflow powder and unconsolidated powder from the powder bed is unloaded from the AM machine and stored in a container labeled as “1 use”. The AM machine supply of powder is topped up with more virgin powder from the same batch and the process is repeated until there is no virgin powder left to top up the machine. At this point, the remaining powder is unloaded from the machine, transferred to the “1 reuse” container, the powder in the “1 reuse” container is sieved, and the cycle is repeated with “1 reuse” powder instead of virgin powder. Overflow and powder bed powder is now stored in a container labeled as “2 reuse”. This cycle repeats until a designated maximum number of reuses is reached, or there is insufficient powder for the build.

Virgin Blend

Another common approach is to rejuvenate used powder with virgin powder of the same type, or even to rejuvenate with a different powder to compensate for depletion of an element or maintain a desired chemistry in the presence of an unwanted element uptake. Once again, using Ti-6Al-4V as an example, rejuvenating used grade 5 powder with grade 23 helps extend the time it takes to exceed the critical oxygen threshold of 0.2%. If rejuvenating with virgin powder, the process begins with a supply of virgin powder from a single powder batch that is split into 2 fractions. One fraction is kept aside and labeled as “top-up” to rejuvenate used powder. The other fraction of virgin is the “main supply.” Initially, virgin powder from the main supply is loaded into the AM machine and the print is executed. At the end of the process, overflow powder and unconsolidated powder from the powder bed is unloaded from the AM machine and stored in a container labeled as “1 use”. The AM machine supply of powder is topped up with more virgin powder from the “main supply” and the process is repeated until there is no “main supply” left to top up the machine. At this point the powder in the “1 reuse” container is blended with a pre-determined fraction of “top-up” and sieved. This blended “1 reuse” powder is considered rejuvenated. The powder cycle repeats until a designated maximum number of reuses is reached, there is insufficient powder for the build, or there is insufficient “top-up” powder for rejuvenation.

Top-up Newest

A hybrid approach of the “2-bin” and “rejuvenate” strategies. Used powder is rejuvenated, however, instead of blending with virgin powder, any powder with a lower number of reuses can be used.

There are many additional powder reuse variations than as described above in the comparison table. Should all unused powder in the AM machine be completely unloaded after each print cycle? Further considerations in a powder reuse strategy are batch management, which stage in the powder cycle to add additional powder, and storage conditions.

The rules used for generation of the summary comparison table in Figure 5 are:

Cost

Lowest cost means the greatest number of prints from a fixed starting volume of powder before crossing a threshold of a maximum number of reuses

Simplicity

- No blending is easier than blending
- No topping up is easier than topping up a measured volume
- Less tracking is easier than more tracking
- Not emptying dose hoppers is easier than emptying dose hoppers
- Fewer storage silos are easier than more silos
- Ordering powder and disposing of powder is neglected

Quality

- The more unknowns in the overall process, the higher the risk of variation

- The more often there is a human touch point, the higher the risk of contamination or variation
- Combining powders in dose hoppers runs risks with stratification
- The more often blending is required, the higher the risk of variation from blending

The simplest reuse method is “no reuse”. It defines the upper boundary on quality, but it is essential to factor the resale price of the unused powder bed into the cost model, as well as having a plan for storage of used powder and what to do with different powder batches when remaining virgin powder from a batch is insufficient for a build.

	Cost	Simplicity	Quality
No Reuse	-	+	++
2 Bin	++	O	+
Virgin Blend	O	-	O
Top-up Newest	O	++	-

O (Neutral), - (worse), and + (Better)

Figure 5: Summary comparison table

Any reuse strategy brings its own mixture of strengths and weaknesses. Before electing a reuse strategy, it is essential to understand the requirements of the application, the performance of all the processes in the powder reuse loop, and the quality management capabilities of the organization.

In space and aerospace applications, quality is the priority, while automotive applications need to find the balance between cost and quality.

What is important for you? This is a question you and your team need to answer before selecting a reuse strategy.

CASE STUDY

EBM Ti-6Al-4V

In preparation for running a re-use study, we found it helpful to verify the baseline performance of the machine and process, agree on one reuse strategy, define the objectives and end point of the study, prioritize the material properties + test conditions + process window to explore, and plan with, sample sizes that achieve the desired confidence level.

In general, a process map (as shown in Figure 6) that describes the powder cycle in detail, including sample collection, storage, and evaluation, can be used as a tool to identify potential sources of variation, including human factors to be addressed with Standard Operating Procedures (SOPs).

Continuing with the spotlight on EBM Ti-6Al-4V, powder reuse has been investigated for the GE Additive Arcam EBM Q10plus and GE Additive Arcam EBM Q20plus systems.

The reuse strategy consisted of loading the hoppers with virgin powder, running a test build job, collecting the unused powder from the hoppers and build, passing the used powder through the powder recovery system (PRS), sieving, and then reloading this sieved powder back into the hoppers to run through the loop again.

This process was repeated if there was enough powder to complete the build. With the Arcam EBM Q10plus a maximum of six builds could be completed, and with the Arcam EBM Q20plus a maximum of seven builds could be completed.

Upon completion of the sixth or seventh builds, a variety of tests mechanical (tensile and fatigue), chemical, metallographic, and powder evaluations were performed to compare virgin powder and test parts with final build powder and test parts.

Samples for fatigue were evaluated in a machined and as-built state, with and without hot isostatic press treatment. The objective of all evaluations was to determine the significance of powder reuse.

The EBM Ti-6Al-4V results demonstrated virgin and sixth and seventh powder reuses result in consolidated material that complies with ASTM F3001 tensile properties. There were measurable differences in PSD and powder oxygen content, however they remained within specification. Low and high cycle fatigue results showed no apparent effect of powder reuse as shown in Figure 7.

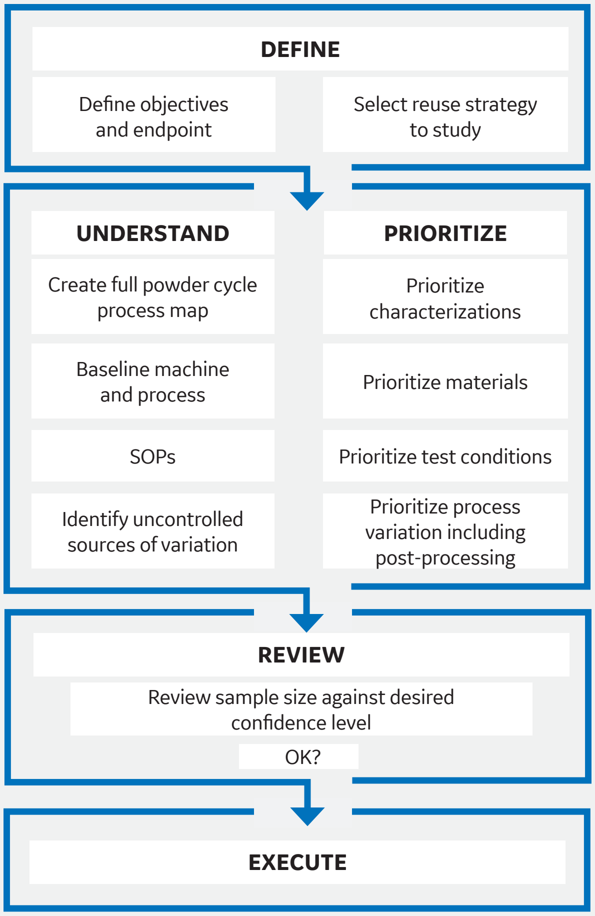

Figure 6: Process map describing the steps and decisions towards a successful powder reuse campaign. Image credit: GE Additive.

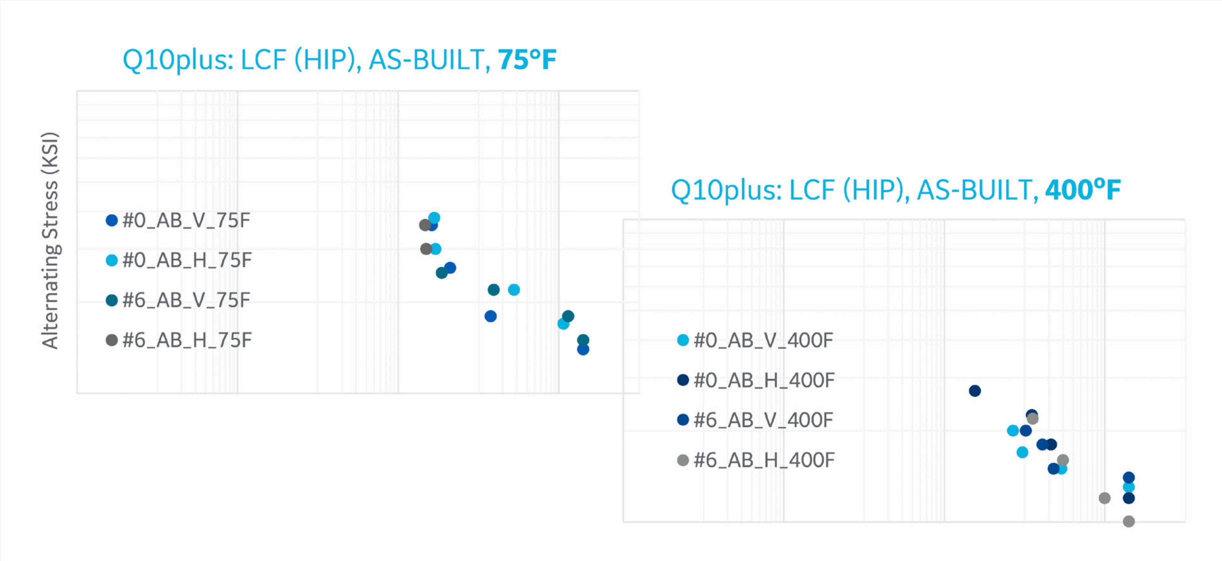

Figure 7: Fatigue of Ti-6Al-4V fabricated with new and used powder in Arcam EBM Q10plus. The legend represents virgin (#0) and 6x use powder (#6) in the as-built condition (AB) for horizontal (H) and vertical (V) orientations.

Lessons Learned

Powder reuse studies can be expensive and time consuming to perform because of the large number of potential variables to explore.

The simple question “how many times can I reuse my powder?” unfolds with multiple parameters that can make it challenging to obtain statistically strong sample sizes.

In the EBM Ti-6Al-4V case study, despite the large number of specimens, a typical sample size for a set of unique conditions was rarely more than three. At the end of our study, we felt that WHAT-WHY-HOW approach up front in the planning phase would have led to a better outcome (as illustrated in Figure 8).

In the EBM Ti-6Al-4V investigation, we felt we could not over-stress the risk that a powder reuse study can be open-ended. In some cases, it is possible to plan for an open-ended reuse investigation, but in all cases the objectives need to be clearly defined before the investigations begin.

An objective could be to demonstrate that parts produced with 5x reused powder and a strategy perform adequately for the application.

Alternatively, one could investigate “how many times powder can be reused”, as the question is so often posed, however this is a multi-factorial question that can be prohibitively costly to answer for the general case.

Conclusion

Powder reuse studies may be expensive endeavors and without careful definition and planning, they can ruin an otherwise viable AM business case.

While it's clear that reuse study costs are incurred from the consumables used to perform the study, and the assessments made on the test parts, it's sometimes not as easy to quantify the cost of delaying a full transition to production while a pre-manufacturing study is performed, or the cost of holding back release of multiple batches of manufactured parts until confidence in quality is established.

Conversations about powder reuse often begin with an aspiration to perform an all-encompassing design-of-experiment that reveals everything about powder re-use.

Unfortunately, in our experience, this path is not practical in a business setting. We have found that the scope of the reuse study needs to be tightly defined and limited as much as possible, especially when all sources of potential variation are considered.

When narrowing the scope of the study, we find it helpful to make sure the team is prepared to answer "what is the study out to determine?", "why is the study cost high?", and "how do we mitigate challenges early?" - the three questions shown in Figure 8.

Working collaboratively with others is an easy way to share costs and working together with someone who has been on the reuse journey before is an easy way to reduce the chance of repeating avoidable mistakes.

The AddWorks team at GE Additive with its vast experience and expertise can help you on your reuse journey.

WHAT QUESTIONS TO ASK FOR THE STUDY

- How many times I can reuse my powder
- What is the statistically significant sample size

WHY THE STUDY CAN BE EXPENSIVE

(Huge experimental parameter space)

Observed parameters:

- Machine type, heat treatment recipe, build orientation, etc.

Unobserved parameters:

- Sieving performance, humidity of storage conditions, etc.

HOW TO MITIGATE THE CHALLENGES EARLY

(Reducing the number of independent parameters)

- Identify critical factors for study
- Define SOPs to reduce human error in operation
- Involve technicians and operations prior to study

Figure 8: What-why-how questions to ask in the planning phase of a powder reuse study?

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