Designation: F3592 – 23

Standard Guide for Additive Manufacturing of Metals – Powder Bed Fusion – Guidelines for Feedstock Re-use and Sampling Strategies[1]

This standard is issued under the fixed designation F3592; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide:

1.1.1 Defines key powder re-use variables and factors affecting powder re-use strategies.

1.1.2 Outlines implications associated with implementation of powder re-use strategies based on selection of powder re-use variables and factors.

1.1.3 Provides guidance to AM users in selection of factors in powder re-use variables depending on considered material type, AM process type and end-use application.

1.1.4 Provides guidance on key process variables affecting powder properties, and considerations to mitigate their effects.

1.1.5 Identifies key powder properties that may be affected by powder re-use and provides AM users guidance on control measures that can be exploited to ensure quality of re-used powder.

1.1.6 Provides recommendations and guidance on factors to consider when implementing powder re-use strategies.

1.1.7 Provides information on how to design a powder re-use study to validate the selected re-use variables.

1.1.8 Summarizes sampling techniques and provides recommendations to AM users on sampling technique selection, and suitability of sampling techniques for powder re-use strategies.

1.1.9 Provides factors to consider when designing a powder sampling study to validate the selected sampling technique.

1.2 *Units*—The values stated in SI units are to be regarded as the standard units. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

B215 Practices for Sampling Metal Powders

B243 Terminology of Powder Metallurgy

F2924 Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium with Powder Bed Fusion

F3001 Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion

F3055 Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion

F3184 Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion

F3318 for Additive Manufacturing – Finished Part Properties – Specification for AlSi10Mg with Powder Bed Fusion – Laser Beam

F3456 Guide for Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications for Additive Manufacturing Feedstock Materials

2.2 *ISO/ASTM Standards:*[2]

ISO/ASTM FDIS 52900 Additive manufacturing — General principles — Fundamentals and vocabulary

ISO/ASTM PWI 52928 Additive manufacturing of metals — Feedstock materials — Powder life cycle management

ISO/ASTM 52907 Additive manufacturing — Feedstock materials — Methods to characterize metal powders

3. Terminology

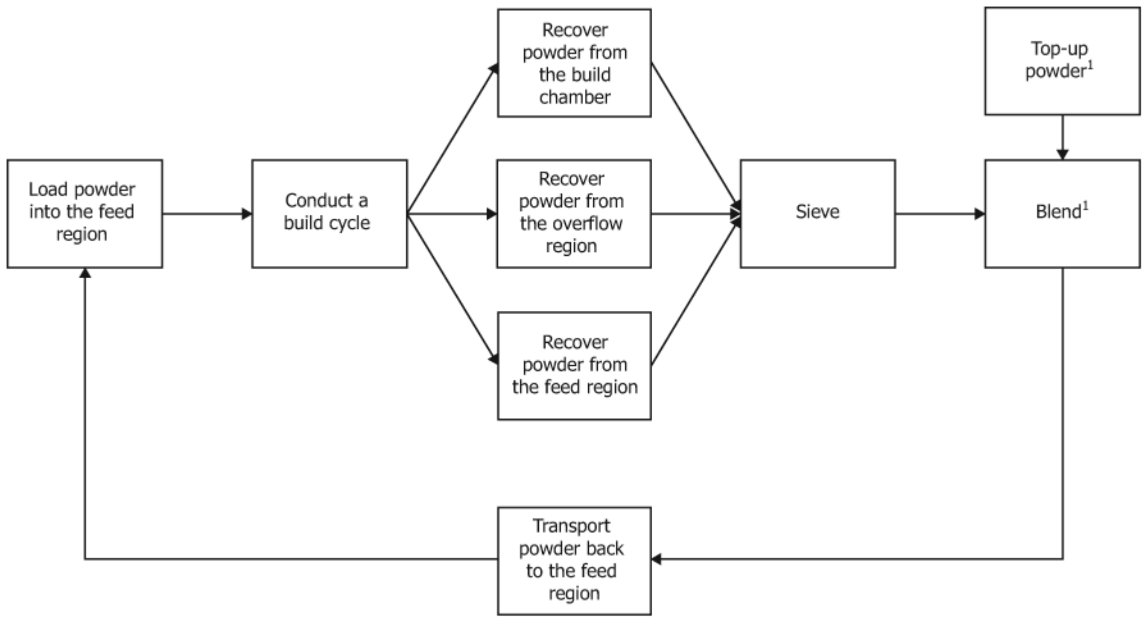
3.1 Powder metallurgy terms can be found in Terminology B243 and AM processes and terms can be found in ISO/ASTM 52900. Terms used frequently in this document are given below.

3.2 *Definitions:*

[1] This guide is under the jurisdiction of ASTM Committee F42 on Additive Manufacturing Technologies and is the direct responsibility of Subcommittee F42.05 on Materials and Processes.

Current edition approved July 15, 2023. Published September 2023. DOI: 10.1520/F3592-23.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.



[1] Non-mandatory step

FIG. 1 Flow Diagram of Generalized Powder Handling Processes in PBF-LB

3.2.1 *batch, n*—description can be found in ISO/ASTM 52900.

3.2.2 *heat affected zone (HAZ), n*—unmelted powder affected by heating due to the proximity of the powder to melted powder.

3.2.3 *lot, n*—description can be found in ISO/ASTM 52900.

3.2.4 *powder re-use, n*—the process of returning used and virgin powder that is within specification, to be re-used in the PBF build process.

3.2.5 *refreshed powder batch, n*—description can be found in Guide F3456.

3.2.6 *used powder, n*—definition can be found in ISO/ ASTM 52900.

3.2.7 *virgin powder, n*—same definition as 'virgin' feedstock found in ISO/ASTM 52900.

4. Significance and Use

4.1 The overall aim of this guide is to support AM users with the selection of the optimum re-use strategy for their AM process and end-use application, and provide guidance on how to implement re-use strategies in their organization.

4.2 This guide suggests possible control measures that AM users can use to maintain powder quality, and factors to consider when validating selected re-use strategies, including guidance on sampling techniques.

4.3 This guide is intended for metal powders used in Powder Bed Fusion processes.

5. Background

5.1 A relatively small fraction of powder feedstock used in Powder Bed Fusion (PBF) Additive Manufacturing (AM) machines is turned into the final part. In the majority of cases, the virgin powder remains within specification and can be re-used in the PBF process. Furthermore, the business case for PBF manufacturing will typically require the remaining powder to be re-used. Powder re-use strategies have been developed to account for factors such as the type of feedstock material, the design of the PBF machine and most importantly, the criticality of the end-use application. This guide aims to define common powder re-use variables upon which the powder re-use strategy is based, that can be commonly applied in PBF for metal powders.

5.2 Powder Bed Fusion (PBF) is one of seven AM process categories defined by ASTM/ISO 52900 and the process where powder re-use is most critical. Metal PBF processes use an energy source, either a laser beam or an electron beam, to melt metal particles together. The two main metal-based PBF processes: laser PBF (PBF-LB/M) and electron beam PBF (PBF-EB/M).[3] The generalized powder handling operations that occur during the PBF-LB and PBF-EB process chains are shown in Fig. 1 and Fig. 2, respectively. The main difference between the two process flow diagrams is the addition of the powder recovery step in the PBF-EB process chain, which is a designed to break-up the semi-sintered powder bed.

5.3 The powder handling operations shown in the figures above may not be required for all AM platforms, and partly depend on the implemented powder re-use strategy. The typical stages of powder re-use in PBF include the following stages.[3]

5.3.1 *Loading Powder into the Feed Region*—Regardless of machine platform, loading powder into the PBF machine requires some form of decanting, whether this is decanting into

[3] MTC. Metal Powder Bed Fusion Processes – Overview. Additive Manufacturing Knowledge Hub. [Online] 2021. http://knowledgehub.the-mtc.org/documents/#/folder/66.

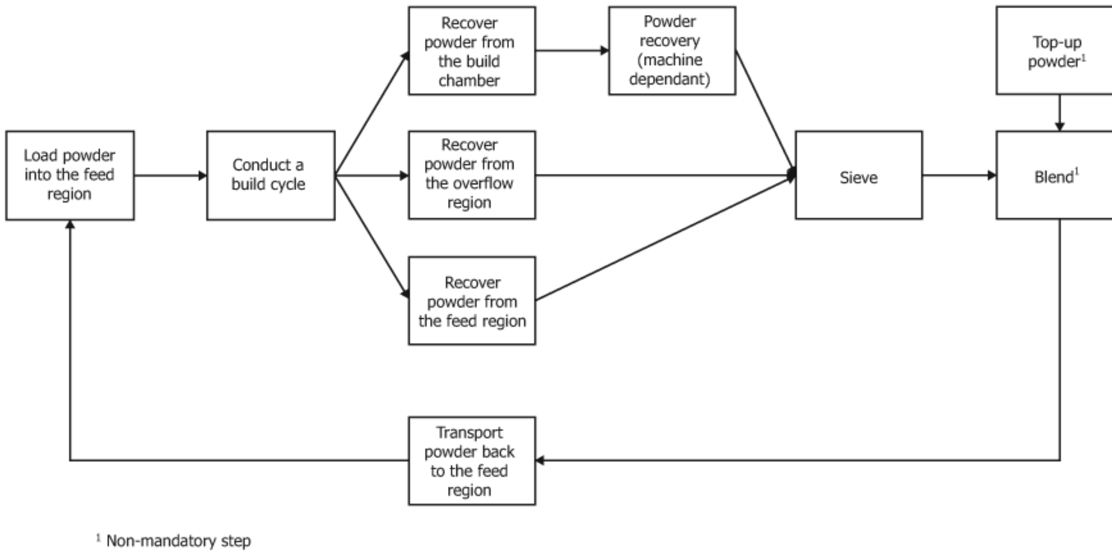


FIG. 2 Flow Diagram of Generalized Powder Handling Processes in PBF-EB

machine specific hoppers from original powder packaging, or hand pouring powder directly into the AM machine itself. The decanting operation has the potential to expose the powder to the environment and expose the AM operator to the powder dust, which may become airborne during handling. To minimize exposure, best practice for powder loading should involve sealed decanting solutions such as sleeves and pneumatic conveyors.

5.3.2 *Conducting a Build Cycle*—The AM process itself involves dosing powder from the feed region, followed by spreading the powder across the build chamber. The spread layer is then subjected to melting through the use of a laser or electron beam. It is during the preheating and melt events that most of the degradation of the powder is likely to occur since the powder will be more susceptible to oxidation at higher temperatures.

5.3.3 *Powder Recovery*—Recovering the used powder following completion of a build is typically performed manually by an operator. Whilst it does depend on machine platform and the type of re-use strategy being used, generally there are three locations where powder would be collected from, these are:

(1) Surrounding build volume powder from the build chamber (always required). This powder should be considered used powder.

(2) Powder which has been collected in an overflow region (machine dependent). This powder has been in the build chamber and should be considered used powder.

(3) Powder which has not been dosed from the feed region (machine dependent). This powder has not been in the build chamber and, dependent on the requirements for the final application, could still be considered as virgin powder.

5.3.3.1 Powder recovery is usually performed using a conveying system to collect the powder, using equipment rated as Ex per IEC 60079 Explosive Atmospheres, Part 0: General Requirements.

5.3.4 *Powder Recovery (PBF-EB)*—During some PBF-EB processes it is most commonly necessary to sinter the powder in the powder bed. This pre-sintering operation creates a loosely bound powder mass, which needs to be broken up before it can be reused. This requires the use of a powder recovery system which is effectively a shot blasting unit, which uses the same metal powder as the feedstock as blasting media. As the sintered mass is broken down into individual powder particles, these particles also for part of the metal powder blasting media. The powder recovery system also has a cyclone removal system, which is capable of removing fine particles. Certain PBF-EB systems can operate without pre-sintering, hence shot blasting during powder recovery is dependent on machine model, and is therefore an optional operation. Shot blasting operations with metal powder should be conducted in an inert atmosphere with an oxygen sensor. Please note that recovered powder is often more combustible than the feedstock powder because of possible partial removal of the oxide surface layer, as well as possible size reduction.

5.3.5 *Sieving*—It is most commonly required or highly recommended, that the powder is sieved prior to reusing it. Sieving is effectively passing the powder through a fine wire or nylon mesh, usually by mechanical action. This enables the removal of any oversized particles that may have been created during the AM process.

5.3.6 *Top-up*—If the specific re-use strategy being used involves topping-up the powder batch after a build cycle, then generally top-up powder would be added after the sieving stage and prior to the blending stage (if blending is being performed). Customers may require non-blending of raw material lots and therefore can only be topped up with the same lot of material.

5.3.7 *Blending*—Blending is an optional process step, which is not always carried out. It is a useful process to ensure that the powder being returned to the machine is homogenous, on receipt from decanting individual containers or on significant top-up. Homogeneity in this sense can refer to particle size distribution (i.e. to eliminate any segregation that may have occurred) or to chemical composition (i.e. used powder may have a higher oxygen content than top-up powder). Blending will help achieve bulk scale homogeneity in the powder batch, although it is important to remember that inhomogeneity at the particle level will still remain. Customers may require non-blending of raw material lots and therefore can only be blended with the same lot of material.

5.4 There are many powder bed AM machines available commercially, which have slightly different set-ups and parameters. Additionally, there are AM systems featuring automated powder re-use in a fully sealed environment under an inert gas atmosphere. These systems feature on-board sieving but do not allow for powder blending. AM systems with sufficient internal powder handling capabilities may minimize the risk of powder cross-contamination and powder exposure to oxidizing atmospheres. Additionally, these AM systems improve health and safety in the workplace by mitigating operator exposure to hazardous substances during powder handling.

6. Definitions of Re-use Variables

6.1 This section identifies key powder re-use variables and factors for each variable. A number of assumptions were made when defining these variables, and these are as follows:

6.1.1 A powder that is used in the first build cycle is sieved and blended before it is loaded into the feed region.

6.1.2 A powder used in a first build cycle will be:

6.1.2.1 A virgin powder;

6.1.2.2 A used powder that is formed by loading virgin powder into the build chamber and heating the build chamber to the build temperature, without building any parts. This practice is in Guide F3456.

6.1.3 Powder sieving is performed after each use in a build cycle. The powder from a part cake, an overflow region and a build chamber is subjected to the sieving process. The sieving process enables removal of any oversized particles that may have been created during the AM process (spatter particles, agglomerates, oversized particles).

6.1.4 Powder blending is an optional process step ensuring that the powder that is loaded back into the feed region is homogeneous in terms of particle size distribution (for example, to eliminate any segregation that may have occurred) or chemical composition (for example, to ensure consistency of the chemical composition within the powder), or both. Therefore blending is identified as a powder re-use variable. The powder that is subjected to blending can come from different sources such as the feed region, the overflow region, the build chamber, the part cake (sintered mass of powder in the build chamber) and top-up. Blending multiple batches can compromise material traceability.

6.1.5 Powder recovery systems can be used to allow removal of loose powder and the powder cake from parts, and recover the powder under an inert gas atmosphere.

6.2 A summary of key powder re-use variables and factors for each variable is given in Table 1. A graphical representation of re-use variables is shown in Fig. 3.

7. Overview of Re-use Variables

7.1 This section provides the summary of benefits and limitations associated with implementation of each re-use strategy based on selection of key powder re-use variables.

7.2 Descriptions of key criteria considered for each powder re-use factor are outlined in Table 2. A summary of advantages and disadvantages associated with different powder factors is outlined in Table 3 and key (shown below table).

8. Classification

8.1 The selection of the appropriate factors in the defined powder re-use variables depends on several considerations. Section 7 outlines the pros and cons of selecting the defined factors for given powder re-use variables, however it is also important to consider the scenarios where the factors are most applicable. Guidance on the suitability of the factors can be assessed by considering different parts of the AM process chain in turn, to help end-users to determine when the selected powder re-use factors should be applied. The recommendations are summarized in Table 4 (and the key shown below the table). The AM process chain scenarios that could be considered are:

8.2 *Material Type:*

8.2.1 *Reactive Material*—More easily forms oxides or nitrides in high temperature and humidity environments (such as aluminium and titanium alloys).

8.2.2 *Non-reactive*—Less easily forms oxides or nitrides in high temperature and humidity environments (such as stainless steel and nickel alloys).

8.3 *End-Use Application:*

8.3.1 *Critical*—Failure of the part built using the AM process is considered a critical part by the end user.

8.3.2 *Non-critical*—Failure of the part built using the AM process is considered a non-critical by the end user.

9. Key Process Variables

9.1 This section provides a description of key process variables affecting powder re-use, and considerations that end-users should consider during implementation of the powder re-use strategy. End users should establish values, tolerances, and measurement frequencies for all relevant key process variables. A summary of key process variables affecting powder re-use is given in Table 5.

10. Key Powder Variables and Control Measures

10.1 This section identifies key powder properties likely to be affected by powder re-use and control measures enabling mitigation or elimination of change of a powder property induced by powder re-use. The key powder properties and control measures are outlined in Table 6.

11. Recommendations on Powder Re-use

11.1 This section provides recommendations and guidelines associated with key powder handling operations during the powder re-use. A summary of key powder handling operations is outlined in Table 7 alongside technology options used for particular operations and recommendations.

11.2 Any powder handling operations carried out during powder re-use should account not only for the quality of re-used powder and the application of the final AM components, but also should be carried out in such a way to

TABLE 1 Descriptions of Key Powder Re-use Variables and Factors Defining the Powder Re-use Strategies

Powder Re-use Variable	Factors			Description	Related Standard
1 Feedstock source	1.1 Single lot	1.1.1 Single batch		Quantity of feedstock produced under traceable controlled conditions from a single manufacturing process cycle. The size of the feedstock lot is determined by the feedstock supplier. A single powder lot is used as feedstock in build cycles.	ASTM/ISO DIS 52900
		1.1.2 Multiple batches		Quantity of feedstock produced under traceable controlled conditions from a single manufacturing process cycle. The remaining feedstock of insufficient quantity to complete the build cycle that has been used in multiple AM machines is combined, blended and used to finish the powder lot.	–
	1.2 Multiple lots			More than one powder lot are used as feedstock in build cycles. Multiple lots are usually blended before being loaded into the feed region.	–
2 Top-up	2.1 No top-up			No addition of top-up powder to the feedstock during powder re-use.	–
	2.2 Top-up	2.2.1 From the same powder lot		Addition of virgin powder from a single powder lot, added to used feedstock from the same original lot as the used powder, during powder re-use. If powder properties change during the process (size, morphology, or chemistry), adding virgin powder to used powder may create chemical composition differences in the powder batch and resultant as-built material, depending on powder blending technique efficacy.	–
		2.2.2 From a different powder lot		Addition of virgin powder from a different powder lot, added to the feedstock during powder re-use. Blending powder from different lots may result in chemical composition differences in the powder batch and resultant as-built material, depending on powder blending technique efficacy. Blending multiple batches can compromise material traceability.	–
3 Top-up regularity	3.1 Regular			Top-up occurs to maintain a constant feedstock mass in the feed region. Top-up occurrence is fixed, for example after every build cycle or after every N number of build cycles.	–
	3.2 Irregular			Top-up occurs when a particular powder variable reaches a specification limit or set point (such as powder mass in the re-use process, or oxygen content). Top-up occurrence is variable and depends on measurement data in relation to pre-determined specified limits.	–
4 Powder blending	4.1 No powder blending			The blending operation does not occur between build cycles. Any recovered powder from the overflow region and the build chamber are loaded directly into the feed region and placed on top of the virgin powder remaining in the feed region.	–
	4.2 Powder blending	4.2.1 Powder recovered from a single batch	4.2.1.1 From all sources	The blending operation occurs between build cycles. The blended powder comes from the feed region, the build chamber, the overflow region and includes the powder used for the top-up if the top-up occurs during powder re-use.	–
			4.2.1.2 From selected sources	The blending operation occurs between build cycles. The blended powder comes from the build chamber and may include the top-up powder, if the top-up occurs during powder re-use. The blended powder does not include the powder remaining in the feed or overflow regions which are considered as virgin powder. Recovered overflow powder is normally added to the top of the virgin powder remaining in the feed region. The blended build chamber/top-up powder can be placed on top of the virgin powder remaining in the feed region or blended with it.	–
			4.2.1.3 In-process stored	Powder recovered from the build chamber that is stored. Once the entire powder batch has been through the build chamber, all in-process stored powder is blended and re-introduced to the machine. Storing will minimize differences (size/morphology as well as chemical composition) in the powder batch. As such, top-up is not normally utilized with storing in-process powder.	–
		4.2.2 Multiple batches		The blended powder includes the remaining feedstock of insufficient quantity to complete a build cycle that has been used in multiple AM machines. Mixing of multiple machine batches with different virgin size ranges shall not be permitted.	–

TABLE 1 *Continued*

Powder Re-use Variable	Factors		Description	Related Standard
5 Powder handling	5.1 Internal	5.1.1 Controlled atmosphere	Automated recycling or storage of used powder inside AM machines, or both, in a fully sealed powder environment in an inert gas or vacuum atmosphere, limiting exposure to the external environmental conditions.	–
		5.1.2 Uncontrolled atmosphere	Automated recycling or storage of used powder inside AM machines, or both, in a fully sealed powder environment under an ambient atmosphere.	–
	5.2 External		Manual handling of used powder performed in powder handling operations external to the AM machine, increasing potential exposure of the powder to the external environment.	–

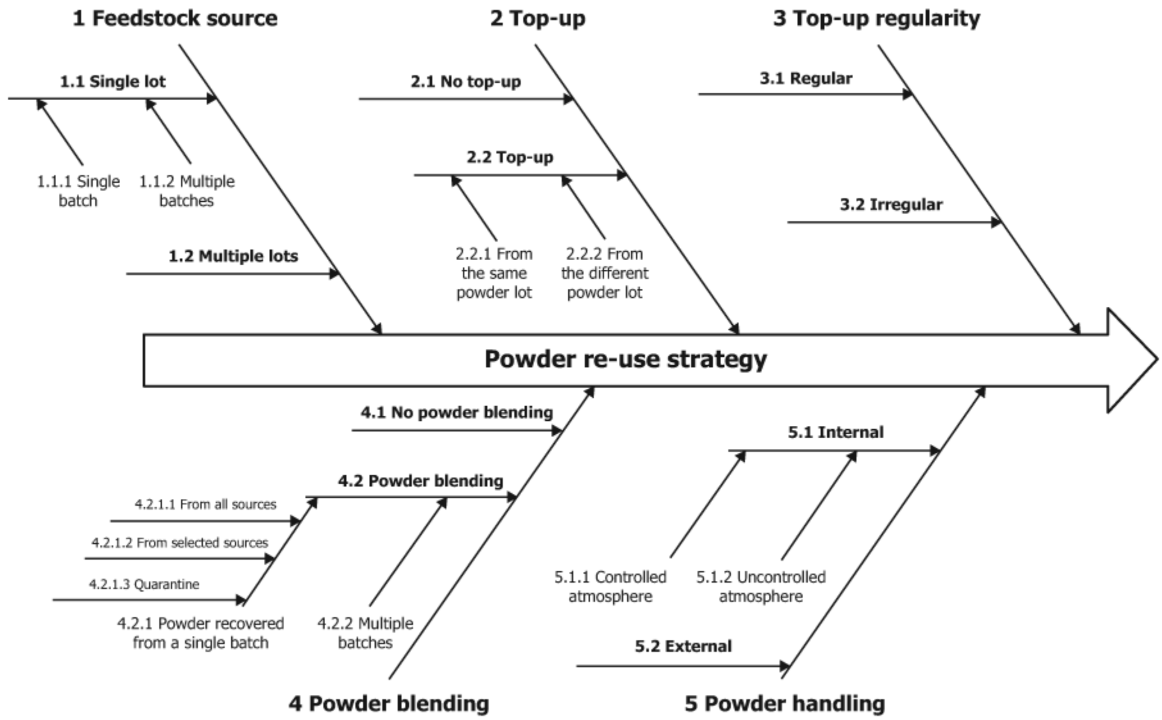


FIG. 3 Graphical Representation of the Key Powder Re-use Variables and Factors Defining the Powder Re-use Strategies

eliminate the health and safety risks where possible or reduce them as low as reasonably practicable. There are different hazards associated with each operation, therefore, it is essential to identify hazards associated with all powder handling operations during powder re-use and comply with appropriate health and safety legislation. This document is not intended to provide guidance on health and safety aspects of powder re-use.

11.3 Guidance and advice should be sought in relevant national legislation, materials safety data sheets, equipment manuals and internal company policies. AM users have to ensure that they are aware and comply with legislation applicable to them. Risk assessments must be carried out by AM users prior to all powder handling operations during powder re-use to identify additional safety measures mitigating the risks associated with powder handling operations.

12. Powder Re-use Study Design

12.1 This section provides suggestions on how to conduct a powder re-use study in order to validate the effectiveness of the selected re-use strategy. Top-level considerations for AM end-users when validating the re-use strategy selected, are outlined in Table 8.

13. Sampling Techniques

13.1 This section provides guidance to AM users on sampling techniques suitable for AM metal powders. Powder sampling is required to collect a powder test specimens for powder qualification. Powder sampling in the powder re-use process is critical to ensure that measured properties of the obtained sample are representative of the entire powder batch used in the PBF process. The list of sampling techniques used in AM is given in Table 9 alongside definitions, sampling locations and their suitability for use depending on powder re-use variables. The discussed sampling techniques include the procedures in Practices B215 and ISO 3954 as well as non-standardized sampling techniques implemented in AM.

14. Recommendations on Powder Sampling

14.1 The overview of each sampling technique and recommended guidelines are outlined in Table 10.

14.2 The general recommendations on powder sampling are as follows:

14.2.1 The powder should be sampled after it is sieved to remove coarse material;

14.2.2 The sampling procedure should not alter the material;

14.2.3 The obtained increments are combined into the composite sample and blended by rotating for 15 revolutions at relatively low rotational speed.

14.2.4 The powder should not be shaken during blending. The composite sample can be blended manually or using the blender.

14.2.5 Sufficient powder should be sampled from each powder batch or lot to perform all required tests at least twice.

14.3 Usually, the obtained powder sample requires further sub-dividing into smaller test specimens. It is recommended to follow the splitting procedures in Practices B215.

14.4 A spinning riffler is the preferred method for splitting fine AM powders into small test portions and should be used if available. A chute splitter does not provide as representative test portions as the spinning riffler and is manually intensive and, therefore, is not the preferred method of splitting AM powders.

TABLE 2 Descriptions of Criteria Considered in Assessing Powder Re-use Variables and Factors

Criteria	Criteria Description
Powder feedstock utilization	The remaining amount of powder feedstock after the build process is completed.
Storage space required	A designated storage space required for storing virgin and used powder feedstock in accordance with specified requirements.
Up-front investment	The up-front cost of feedstock or AM machine procurement.
Ease of implementation	This factor accounts for the number and complexity of powder handling operations occurring during powder re-use.
Labor requirements	Labor requirements determine the amount of manual handling carried out by an operator. High labor requirements can increase operational costs and potential health and safety risk to operators.
Inherent safety	The potential for explosive atmospheres to occur during powder handling operations
Risk of deterioration of powder (and part properties)	The potential for deterioration of powder and part properties due to powder degradation because of powder re-use.
Risk of powder contamination	Powder contamination that may occur due to powder exposure to external environments and contamination during powder handling.
In-batch powder history traceability	Maintaining in-batch powder traceability enables tracking of a powder lot and the number of its reuses in build cycles, for all parts made in a specific build cycle.
Variability of powder properties within the build cycle	Similar powder properties within a build cycle is a factor that will contribute to greater consistency of properties of parts produced in the same build cycle, and therefore greater predictability of build cycle outcomes.

14.5 Larger amounts of powders can be split multiple times using the spinning riffler, then recombined and split further, however, this approach is more laborious and less representative.

15. Powder Sampling Study Design

15.1 This section provides guidance on how to conduct a powder sampling study in order to validate the effectiveness of the selected powder sampling strategy.

15.2 It is critical to ensure that the sampling technique results in a representative powder sample for the test ensuring obtained results are not affected by the sampling technique.

15.3 The following recommendations are provided on the effectiveness of the powder sampling method:

15.3.1 The sample should always be taken from a homogeneous powder batch. It is assumed that the analysed powder batch exhibits uniform distribution of powder properties in terms of size and chemistry.

15.3.2 Multiple increments are taken using a particular sampling technique. The number of increments depends on statistics selected. Three increments sampled from the same location are the minimum recommended number.

15.3.3 Selection of the data quality indicators evaluating the sampling effectiveness should account for the variability of the particular powder characterisation technique. It is recommended to use powder characterisation techniques exhibiting high repeatability in order to validate the effectiveness of the sampling technique. An indication of the levels of variability that can be obtained from different powder characterisation techniques can be found in ISO/ASTM 52907.

15.3.4 The quantity/volume of each increment should be equal.

15.3.5 Table 11 provides the recommended minimum quantities of powder sample required for full powder characterization (for one measurement repetition). The minimum quantities required for the full powder characterisation can be found in ISO/ASTM 52907.

15.3.6 It is recommended that sampling is conducted in humidity and temperature controlled environment if possible.

15.3.7 Ensure the sampling equipment is clean and fully dried before use.

16. Keywords

16.1 additive manufacturing; AM; metal powder; metal powder recycling; PBF; PBF-EB; PBF-LB; powder bed fusion; powder re-use variables; powder variables; process variables; re-use; re-use schema; re-use strategies; sampling schema; sampling techniques

TABLE 3 The Summary of Advantages and Disadvantages of Key Powder Re-use Variables and Factors

Powder re-use variable	Factors			Criteria: Powder feedstock utilization	Storage space required	Up-front investment	Ease of implementation	Labor requirements	Inherent safety	Risk of deterioration of powder properties (and parts)	Risk of cross-contamination of powder	In-batch powder history traceability	Variability of powder properties within the build cycle
1 Feedstock source	1.1 Single lot	1.1.1 Single batch		L	H	H	H	L	N/A	N/A	L	H	L
		1.1.2 Multiple batches		M	M	H	M	M	N/A	N/A	M	M	M
	1.2 Multiple lots			H	L	L	L	M	N/A	N/A	H	L	H
2 Top-up	2.1 No top-up			L	H	H	H	L	N/A	H	L	H	L
	2.2 Top-up	2.2.1 Top-up from the same lot		M	M	M	M	M	N/A	L	M	M	M
		2.2.2 Top-up from different lots		H	L	L	L	M	N/A	L	M	L	H
3 Top-up regularity	3.1 Regular			N/A	N/A	N/A	M	H	N/A	L	H	M	M
	3.2 Irregular			N/A	N/A	N/A	L	M	N/A	M	M	L	H
4 Powder blending	4.1 No powder blending			N/A	N/A	N/A	H	L	N/A	H	L	N/A	H
	4.2 Powder blending	4.2.1 Powder recovered from a single batch	4.2.1.1 From all sources	N/A	N/A	N/A	M	H	N/A	M	H	N/A	M
			4.2.1.2 From selected sources	N/A	N/A	N/A	M	M	N/A	M	M	N/A	M
			4.2.1.3 In-process stored	H	H	H	M	H	N/A	L	L	N/A	L
		4.2.2 Multiple batches		N/A	N/A	N/A	L	H	N/A	L	H	N/A	M
5 Powder handling (machine)	5.1 Internal	5.1.1 Controlled atmosphere		N/A	N/A	H	M	L	H	L	L	N/A	H
		5.1.2 Uncontrolled atmosphere		N/A	N/A	H	M	L	M	M	L	N/A	H
	5.2 External			N/A	N/A	L	L	H	L	L	H	N/A	L

Key:
L = Low
M = Medium
H = High
N/A = Not relevant – does not have an impact on powder re-use

TABLE 4 Recommendations on Selection of Factors in the Powder Re-use Variables Accounting for the AM Process Chain Scenarios

Powder Re-use Variable	Factors			Material Type: Reactive	Material Type: Non-reactive	End-use Application: Critical	End-use Application: Non-critical
1 Feedstock source	1.1 Single lot	1.1.1 Single batch		R	–	R	–
		1.1.2 Multiple batches		–	–	R	–
	1.2 Multiple lots			–	–	N	–
2 Top-up	2.1 No top-up			N[A]	–	R[A]	–
	2.2 Top-up	2.2.1 From the same powder lot		R	R	R	–
		2.2.2 From a different powder lot		–	–	N	–
3 Top-up regularity	3.1 Regular			R	–	–	–
	3.2 Irregular			-	–	–	–
4 Powder blending	4.1 No powder blending			N	–	–	–
	4.2 Powder blending	4.2.1 Powder recovered from a single batch	4.2.1.1 From all sources	-	–	–	–
			4.2.1.2 From selected sources	R	R	R	R
			4.2.1.3 In-process stored	R	–	R	–
		4.2.2 Multiple batches		–	–	R	–
5 Powder handling (machine)	5.1 Internal	5.1.1 Controlled atmosphere		R	–	R	–
		5.1.2 Uncontrolled atmosphere		–	–	–	–
	5.2 External			–	–	–	–

[A] For the case of 'reactive' material types and 'critical' end-use applications, 'no top-up' are both recommended and not recommended for different reasons. Reactive materials tend to degrade more readily; hence top-up will allow the overall chemical composition content of the powder to be controlled. Critical components will benefit from the improved traceability offered by not topping up. It is for the user to decide which aspect takes precedent.

Key:
R = Recommended for consideration
– = No recommendation (user to decide)
N = Not recommended for consideration

TABLE 5 Summary of Key Process Variables

Key Process Variables	Effect on Powder Properties	Considerations
Build Chamber Environment		
Humidity	Increased humidity can result in moisture pick-up which may affect powder flowability and powder spreading behavior, as well as increasing the potential for powder oxidation. May result in increased hydrogen porosity in certain alloys.	• Humidity control in powder handling operations; • Appropriate powder storage practices, such as using fully sealed and impervious storage containers; • Internal powder handling solutions minimizing powder exposure to atmosphere.
Nitrogen level in atmosphere	Metallic materials can form nitrides at elevated temperature, and can increase the strength and decrease elongation of titanium alloys.	• Maintaining a low nitrogen level in the build chamber; • Internal powder handling solutions minimizing powder exposure to atmosphere.
Oxygen level in atmosphere	Metallic materials tend to oxidize at elevated temperature, and can increase the strength and decrease elongation of alloys, particularly titanium alloys.	• Maintaining a low oxygen level in the build chamber; • Stopping the build cycle if the oxygen level in the build chamber exceeds a Limiting oxygen concentration for the combination of powder and inert gas; • Internal powder handling solutions minimizing powder exposure to atmosphere.
AM Platform		
Electron beam/laser power / L-PBF temperature	Laser power affects the temperature in the build chamber, which may affect the energy dissipated in to the heat-affected zone, causing high local powder oxidation. Higher build temperatures increase reactivity of the powder surfaces, increasing susceptibility of the powder to evaporation of elemental species and adsorption of gases. Interaction between the laser and powder can result in powder contamination, which increase when the laser power is increased, including particle agglomeration, partial fusing, oxidation, metal vapour condensate and spatter generation.	• Selection of the optimized scanning strategy minimizing the total power input; • Selecting the lowest possible energy source accounting for the processing material, particle size range, part complexity, internal cavities, and layer thickness.
Shielding gas flow rate/regime	Shielding gas removes the process by-products such as spatter and welding fumes from the build area. Ineffective removal or inhomogeneous gas flow distribution can increase interactions between the power source and process by-products resulting in attenuation of the laser spot and re-deposition of process by-products on the powder bed.[A]	• Higher shielding gas velocities in the laminar flow regime typically enhance the removal of process by-products and prevents redeposition of by-products; • Homogenous gas flow directed over the entire build surface and constant gas flow velocity ensures the effective removal of process by-products; • Selection of the most suitable scan strategy may enhance removal of process by-products from the process zone. • Reduction of flow separation and turbulence in upward direction decreases possibility of disturbance of the laser beam path by process by-products.[A]
Shielding gas purity	Shielding gas purity may be an additional source of atmospheric contaminants leading to oxidation and nitridation.	• Mitigation techniques include gettering to improve the purity of shielding gas. • PBF-EB processes that bleed a significant amount of inert gas into the build chamber during the build to maintain a 'controlled vacuum'.
Operational		
Part design	The complexity of the part affects the powder exposure to the laser/electron beam in the heat affected zone (HAZ).	• Reducing overhang surfaces reduces powder partial sintering below the overhang; • Applying supports mitigates the residual stresses in the build, dissipates heat and reduces powder exposure to high temperatures.
Component packing (Volume of metal melted)	The number of parts affects the powder exposure to the laser/electron beam in the HAZ.	• Optimal part orientation on the build plate ensuring there is enough space between parts may reduce powder exposure to the HAZ; • Reducing part density by reducing the number of parts per build must be balanced to meet the part quality and business / cost model
Number of builds	The number of builds affects the total powder exposure to the laser/electron beam and other contamination sources.	• Select the total number of builds for the recycling and re-use strategy, to reduce the level to which the powder will degrade.
Contamination	Contamination may occur due to wear of equipment surfaces; bad housekeeping practices; and poor powder management (storage and handling). Contamination can affect the material phases and cause defects in parts (gas porosity, inclusions).	• Dedicated equipment for a specific alloy type preventing cross-contamination from one powder type to another. If this is not possible then, thorough and documented machine cleaning process must exist. • Dedicated areas for powder handling; • Regular inspection and maintenance of equipment; • Good housekeeping practices.

[A] Influence of the shielding gas flow on the removal of process by-products in the selecive laser melting process. Ladewig, A., et al. s.l. : Additive Manufacturing, 2019, Vol. 10.