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Standard Guide for Additive Manufacturing of Metals – Powder Bed Fusion – Guidelines for Feedstock Re-use and Sampling Strategies¹

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

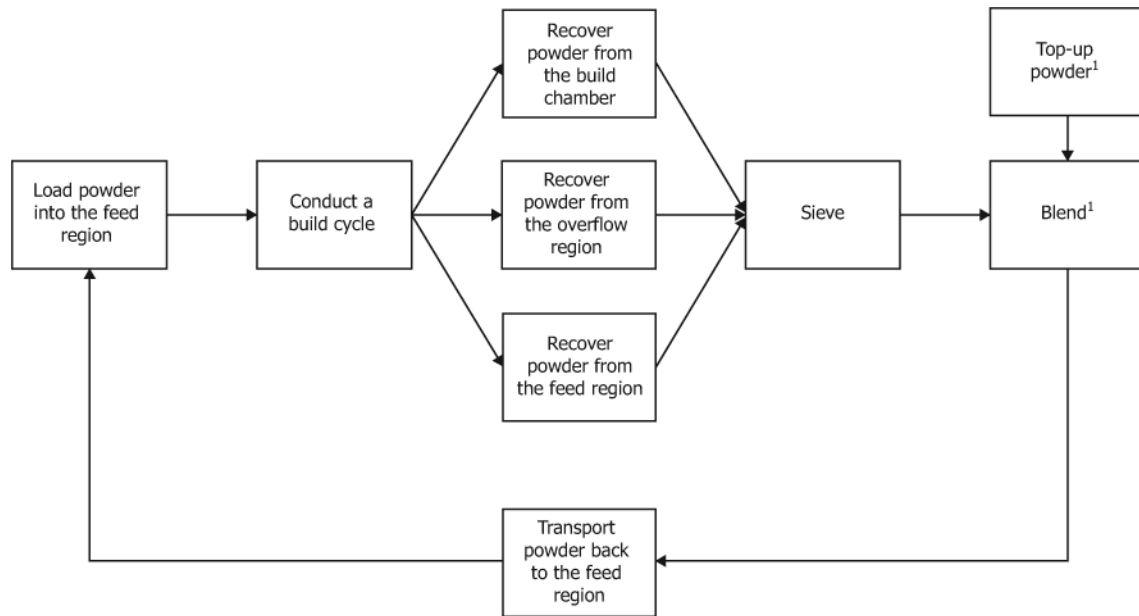
3.1 Powder metallurgy terms can be found in Terminology **B243** and AM processes and terms can be found in ISO/ASTM 52900. Terms used frequently in this document are given below.

3.2 *Definitions:*

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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,

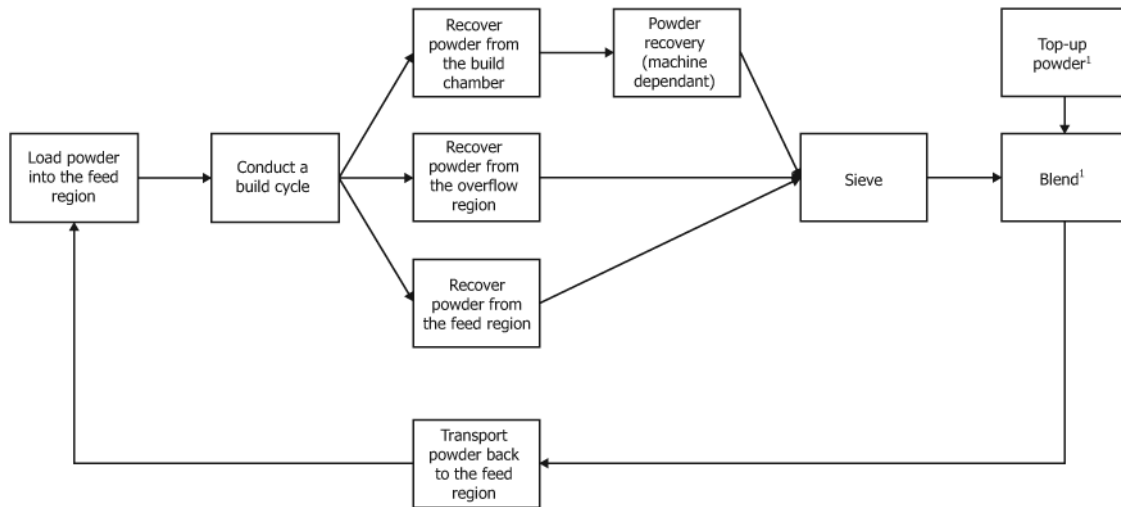
the virgin powder remains within specification and can be re-used in the PBF process. Furthermore, the business case for PBF manufacturing will typically require the remaining powder to be re-used. Powder re-use strategies have been developed to account for factors such as the type of feedstock material, 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>.



¹ Non-mandatory step

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 form 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 bed.

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 a way that

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.	–