International Standard

ISO/ASTM 52945

First edition
2023-12

Additive manufacturing for automotive — Qualification principles — Generic machine evaluation and specification of key performance indicators for PBF-LB/M processes

Fabrication additive pour l'automobile — Principes de qualification — Évaluation générique de la machine et spécifications des indicateurs clefs de performance pour les procédés PBF-LB/M

Reference number
ISO/ASTM 52945:2023(en)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11

Email: copyright@iso.org
Website: www.iso.org

ASTM International
100 Barr Harbor Drive, PO Box C700
West Conshohocken, PA 19428-2959, USA
Phone: +610 832 9634
Fax: +610 832 9635
Email: khooper@astm.org
Website: www.astm.org

Published in Switzerland

Contents

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

ISO draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). ISO takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, ISO had not received notice of (a) patent(s) which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at www.iso.org/patents. ISO shall not be held responsible for identifying any or all such patent rights.

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 261, *Additive manufacturing technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on additive manufacturing, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, *Additive manufacturing,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document provides a methodology to evaluate PBF-LB/M AM-machines in the context of automotive on an objective basis. The need to provide a document standardizing this topic exists because in high-volume industrial production, the reproducibility of the produced component is crucial to meet production goals. Therefore, reproducibility and capability of the machines used for manufacturing need to be evaluated upfront. A methodology and performance characteristics are introduced to enable the evaluation on an objective and quantitative basis. The documentation resulting from the AM-machine evaluation is used to obtain a reliable orientation selection and evaluation of PBF-LB/M AM-machines.

Moreover, the document provides guidelines for machine production key performance indicators (KPIs) which can be used in procurement, production planning and production to improve the understanding between the machine manufacturer and user. The KPIs to be determined within the scope of this document help to systematically evaluate the performance of PBF-LB/M machines. However, this does not necessarily guarantee that the KPIs can always be used to select the most suitable machine for a specific application scenario. Since a large number of very specific influencing factors affect the selection of an optimal machine, situational, individual parameters must be included in the decision. However, the KPIs can form the basis for this decision.

The requirements regarding quality and planning of build jobs are specific for the automotive industry. The introduced generic approach can be expanded to other industries.

Additive manufacturing for automotive — Qualification principles — Generic machine evaluation and specification of key performance indicators for PBF-LB/M processes

1 Scope

This document specifies the methodology for generic AM-machine evaluation in automotive environment using objective test criteria and provides the framework for an objective AM-machine evaluation and comparison. This document finds application in benchmarks, in the preparation of purchase decisions, but also in AM-machine evaluation within the machine procurement, acceptance, and qualification processes. This document is specific to automotive, as it is related to existing series part requirements of various original equipment manufacturers, but the content can be transferred to other industries if necessary.

Furthermore, this document specifies machine KPIs in the context of machine procurement, production planning and production of PBF-LB/M components. It aims to reach a detailed understanding between machine supplier and machine user with respect to the acceptance criteria during the procurement process and evaluation of machine performance during running production. For using this document, all process parameters, such as scanning speed, laser power, etc., are fixed, since changing these parameters can affect the entire process performance and its stability. Therefore, variables are not changed any more during or after qualification. This document and the determination of the KPIs help in the evaluation of machine properties, but do not replace an application-specific approval process.

This document is applicable to the additive manufacturing technology PBF-LB/M.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3369, *Impermeable sintered metal materials and hardmetals — Determination of density*

ISO 4499-4, *Hardmetals — Metallographic determination of microstructure — Part 4: Characterisation of porosity, carbon defects and eta-phase content*

ISO 6892-1, *Metallic materials — Tensile testing — Part 1: Method of test at room temperature*

ISO 25178 (all parts), *Geometrical product specifications (GPS) — Surface texture: Areal*

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

ISO/ASTM 52902, *Additive manufacturing — Test artifacts — Geometric capability assessment of additive manufacturing systems*

ISO/ASTM 52928, *Additive manufacturing — Feedstock materials — Powder life cycle management*

ASTM E8M, *Standard test methods for tension testing of metallic materials*

3 Terms and definitions

For the purposes of this document, the terms and definitions of ISO/ASTM 52900 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
performance characteristics
defined characteristics which are measured in a defined framework (in this document based on generic build jobs and produced specimens) and can be used to evaluate machines on an objective basis

3.2
machine KPIs
machine key performance indicators (KPIs) measure the relevant output of a production machine in a defined framework, e.g. timeframe, defined production lots

Note 1 to entry: Throughout this document, various such KPIs are introduced and their meaning, as well as how to measure them, is explained in detail.

EXAMPLE Overall equipment effectiveness.

3.3
quality level
defined ranges of values for a specified set of quality parameters such as relative density, surface roughness, mechanical properties, etc.

3.4
specimen package
set of different specimens

Note 1 to entry: Examples of different specimens are shown in Table 1.

4 Methodology for generic machine evaluation

4.1 Specification of use-cases

4.1.1 General

This clause introduces the methodology of generic machine evaluation. The generic machine evaluation shall be used to carry out an assessment to evaluate the performance of a PBF-LB/M machine on a defined objective basis.

The methodology of generic machine evaluation introduced here is not intended to define and verify compliance of target metrics but should instead be used to generate information and efficiency metrics to enable machine assessment and comparison. Further details of the machine acceptance process are shown in ISO/ASTM TS 52930. For this document it is mandatory that consistent handling sequences can be achieved through a good operator's expertise, since it is important on AM systems for a stable component quality (see ISO/ASTM 52926 series).

The generic machine evaluation shall be used to generate a sufficient, neutral, and documented evaluation basis for two different use-cases, which are described in 4.1.2 and 4.1.3.

4.1.2 Use-case 1 – Benchmarking of machines

The framework and methodology introduced in 4.3.1 shall be used in the context of benchmarking of machines. Therefore, a minimum of 1 run of the described build jobs according to 4.2.2 shall be produced and tested in the described way. To strengthen the statistical significance of the benchmark, production and evaluation of additional build jobs shall be necessary. This is an option at the discretion of the machine manufacturer or the user.

4.1.3 Use-case 2 – Generic evaluation in factory/site acceptance test

The framework and methodology introduced in 4.3.1 shall furthermore be used in the machinery procurement process, more specific in the factory and site acceptance test. Before using the methodology, the specific target values for the performance indicators shall be agreed on between user and machine manufacturer. During factory and site acceptance test, at least one build job run is mandatory.

This methodology can also be used to evaluate build job-to-build job performance. For a better evaluation of the machine, further evaluations of build jobs with specific relevant part designs can be taken into consideration. The frame conditions for such specific build jobs can be derived from the framework of the expected (future) build jobs or be pre-arranged by agreement between machine manufacturer and user.

4.2 Specification of specimen and build job design

4.2.1 Specification of generic specimen and testing standards

In the following, the test specimens used in the generic construction jobs and for the evaluation of these construction jobs as well as the associated tests are defined. This clause gives an overview of the relevant use cases for the generic machine evaluation and introduces the framework for the data generation (specimens used, test methods, build job design and quality requirements).

Specimen geometries to be used throughout the generic build job are described in Table 1.

Part, as well as build job powder removal methods cannot be changed, in order to maintain consistent mechanical and surface quality of the specimen. The surface measurement shall be performed prior to the porosity measurement.

The introduced methodology is applied to quasi-static mechanical properties, relative density, and surface characteristics. Further properties (e.g. dynamic, and cyclic properties) are excluded on purpose and can be included in individually designed build jobs following this methodology or individual agreements between user and machine manufacturer.

Table 1 — Specification of specimen for measurement of surface roughness, relative density, and tensile strength

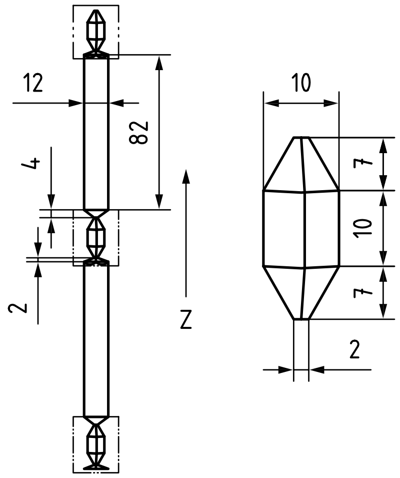
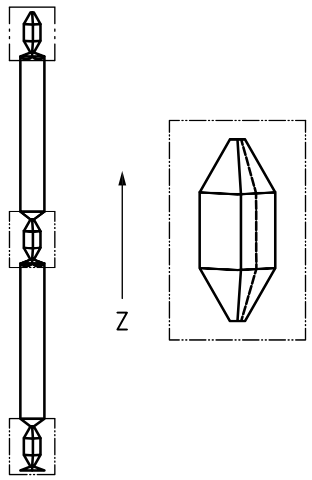
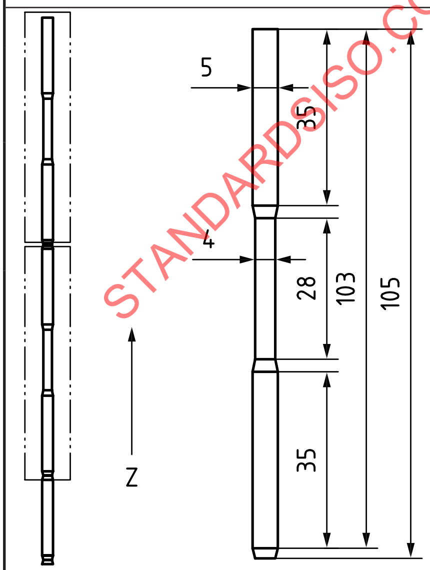
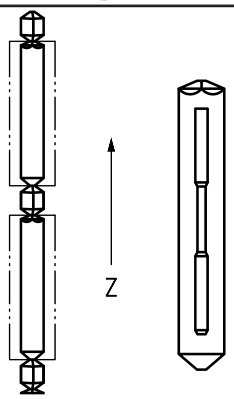
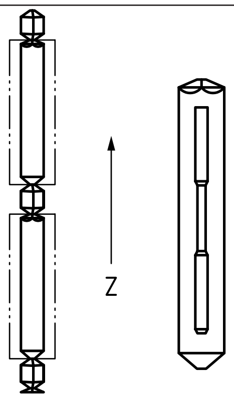
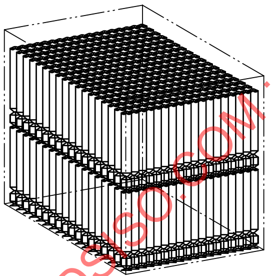
Test specimen	Test standard, purpose and description	Test procedure and criteria
	Surface measurement: — Test standard: ISO 25178 (all parts) — Test specimen:10 mm × 10 mm × 10 mm diamond surface/density specimen — Test purpose: Measurement of surface roughness on: — 45° — 90° and — 135° surfaces — Test specimen surface: powder removed with pressured gas (no surface modification)	— Measurement (in accordance with ISO/ASTM 52902) of S_z, S_a, S_{sk} and S_{ku}, on each of the 4 surfaces for 45°, 90°, 135° angle against the build plate — Determination of mean value and quantiles for each cube — Area of measurement shall be the complete area that is available in each direction — Typically used measurement filters in accordance with ISO/ASTM 52902
	Porosity measurement: — Test standard: — Preparation: ISO 4499-4 — Porosity measurement: ISO 4499-4 — Test specimen: 10 mm × 10 mm × 10 mm diamond surface/density specimen — Test purpose: measurement relative density in cross section — A testing with the Archimedes method in accordance with ISO 3369 can be added	— Cross section cut through the diamond specimen — Preparation of the cross section cut according to the test standard — Measurement of the relative density according to the test standard in 25 x magnification
	Tensile test (as-built surface): — Test standard: ISO 6892-1 — Test specimen: Near net shape tensile specimen (in accordance with ASTM E8M, the requirement regarding surface roughness may be waived) — Tensile testing near net shape with as-built surface (no post processing) — Enabling tensile strength trend analysis over height	— Testing according to test standard and measurement of R_m, $R_{p0,2}$ and A

Table 1 *(continued)*

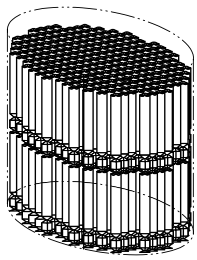
Test specimen	Test standard, purpose and description	Test procedure and criteria
	Tensile test (machined surface): — Test standard: ISO 6892-1 — Test specimen: Machined tensile/packing density specimen (in accordance with ASTM E8M) (optional) — Enabling density & surface trend analysis over height in multiple layers — Creation of packing density	— Machining of the cylinder in accordance with ASTM E8M — Testing according to test standard and measurement of R_m, $R_{p0,2}$ and A
	Specimen package: — Test specimen: combined diamond surface/density, near net shape tensile and machined tensile/packing density specimen — This combination of specimen is named specimen package and should be used in the following for build job design considerations — The specimen package has a height of 112 mm	— Test procedure according to the description for the individual components of the specimen package (see above)

4.2.2 Build job design

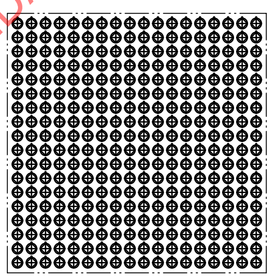
In Figure 1, the representation of the generic build job for two different kinds of machines (in this example 400 mm cubic/cylindrical build envelope) is shown.



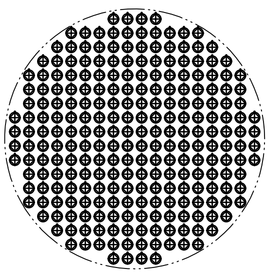
a) Isometric view: cubic build envelope



b) Isometric view: cylindrical build envelope



c) Top view cubic build envelope



d) Top view cylindrical build envelope

Figure 1 — Examples of build job design

The requirements for the generic build job are:

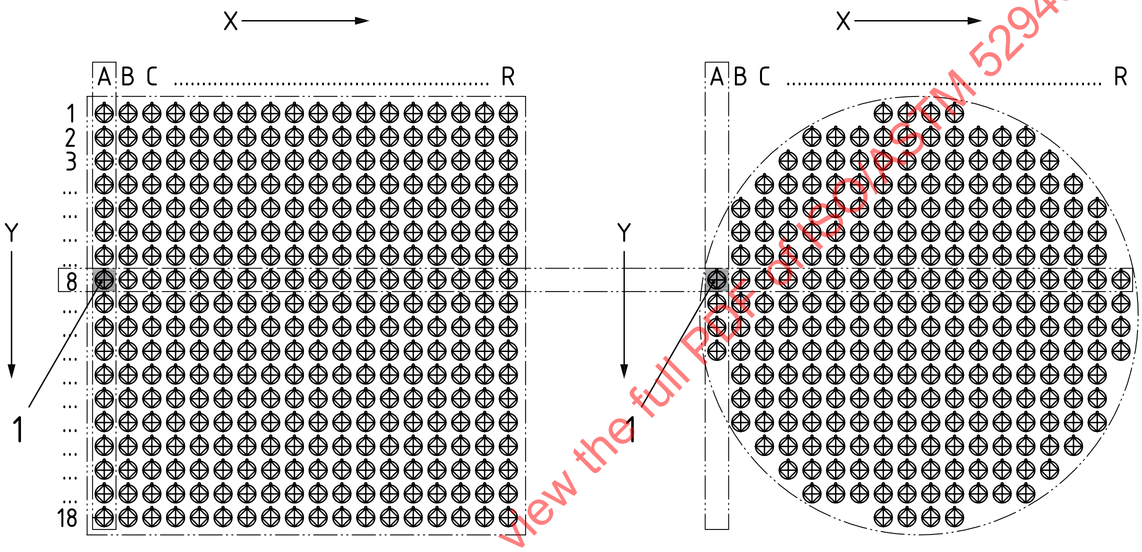
— The specimen packages shall be stacked in Z for the maximum Z-height possible within the present machine design (e.g. for a 400 mm Z-height shall be 3 layers of specimen packages, 112 mm each);

— The specimen packages shall be distributed homogeneously and with equal distances;

— The build job shall contain a packing density of approximately 30 % containing specimen packages and measured from the volume in the bounding box of the full build envelope in X-Y and the height of the build job (Z);

— The machine manufacturer shall provide the exact packing density and spacing used for the assessment as part of the documentation.

For further testing and evaluation of the specimen packages and single specimen from the specimen packages, distinctive naming shall be assigned. The distinctive naming is described in Figure 2 and Figure 3.



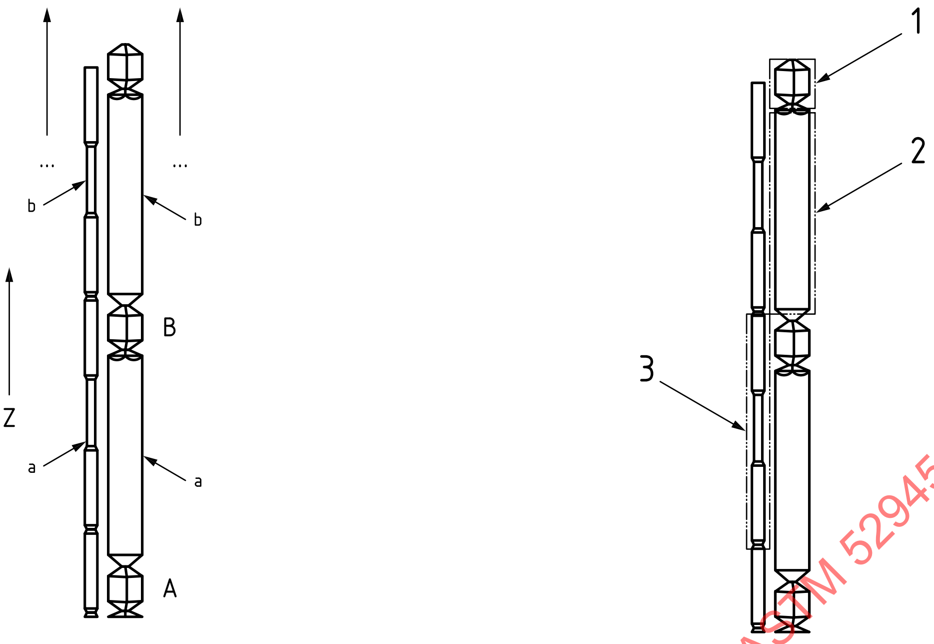
Key

X X-axis

Y Y-axis

1 example specimen label A8

Figure 2 — Build job labelling X-Y-directions



Key

Z Z-axis
A A-level of density/surface specimen
B B-level of density/surface specimen
a A-level of tensile specimen as built.
b B-level of tensile specimen as built.

1 example A8_C
2 example A8_2_m
3 example A8_1_ap

Figure 3 — Build job labelling Z-direction and specimen differentiation

For the machine evaluation, a representative number of each specimen package layer shall be tested. Due to the different ability of machines to realize full field laser exposure, the build envelope is divided in 4 equal areas (quadrants, which are labelled 1, 2, 3, 4, see Figure 4). From these areas, a minimum of 21 specimens per layer (for cylindrical build envelopes), or a minimum of 25 specimens per layer (for cubic build envelopes), shall be taken for evaluation. Upon agreement, a different number of specimens can be considered. The specimens to be considered (21 specimens for cylindrical build envelopes, 25 specimens for cubic build envelopes) should be evenly distributed on the build platform, see Figure 4, in dark grey. The positions of the geometries are for the cubic arrangement: A1, A5, A9, A13, A18, B1, B5, B9, B13, B18 and so on. For the cylindrical build, the arrangement is: A9, B5, B13, E2, E5, E9, E13, E17 and so on. The arrangement is always such that the outer edges of the construction space are considered, and the interior of the building space is scanned at regular intervals.

In case the build envelope is restricted due to screw holes the specimen package that need to be taken into consideration, it shall be shifted accordingly. The numbers and letters on the sides of the building field shown in Figure 4 from above determine the specific position through rows and columns of the respective sample geometry. They serve a simple and quickly understandable specimen naming.

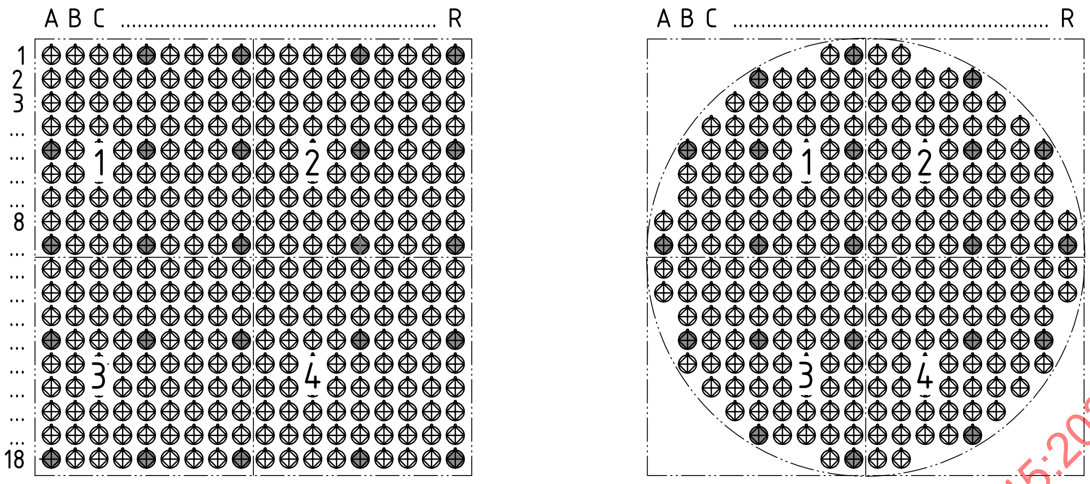


Figure 4 — Definition of specimen selection for cubic and cylindrical build envelopes

4.3 Machine performance characteristics

4.3.1 Input data and framework

To be able to calculate the machine performance characteristics following the generic build job production, data input shall be provided and recorded. The data input shall be divided into three areas:

a) Technical data from the machine data sheet (see Table 2)

Table 2 — Data input from technical machine data sheet

Characteristic	Unit
Available laser power	W
Number of lasers	—
Beam diameter (adjustable from ... to ...)	µm
Laser Working mode (e.g. continuous mode, pulsed mode)	—
Preheating temperature (max.)	°C
Build space [*x*-*y*-*z*[a]]	mm × mm × mm
Required floor space for installation	m^2
Mass of machine	kg
[a] Less build plate thickness.	

b) Technical data describing the PBF-LB/M process for generating the generic build job (see Table 3).

Table 3 — Minimum data input from PBF-LB/M process

Characteristic	Unit
Number of lasers used	—
Laser power used (hatch)	W
Layer thickness (hatch)	µm
Scanning speed (hatch)	mm/s
Hatch distance (hatch)	µm
Laser power used (contour)	W
Layer thickness (contour)	µm

Table 3 *(continued)*

Characteristic	Unit
Scanning speed (contour)	mm/s
Volume build job (V_{BJ})	cm^3
Duration build job (t_{BJ})	h

The data input shown in Table 3 is the minimum amount of data required to generate an understanding of the process used by the machine manufacturer to produce the generic build job. In addition to that, the machine manufacturer should provide data that helps the user to further understand the machine and the process used. An explanation of which parameters were used can be added using ASTM F2791-13.

c) Technical data describing the raw material used in the PBF-LB/M process.

The alloy used in the PBF-LB/M process may be chosen by the machine manufacturer. Feedstock data used throughout the methodology shall be provided in a material data sheet in accordance with ISO/ASTM 52928. In the use-case factory and side acceptance test, the alloy used may be individually agreed on between user and machine manufacturer.

4.3.2 Definition of the machine performance characteristics

The machine performance characteristics introduced here are metrics for efficiency measurement and information about a certain machine. As such, they shall be determined as the result from the generic build job generation for benchmarking reasons. They can then be used as informative support in the context of a procurement process.

There are two main machine performance characteristics which shall be used for visualization and comparison of different machines. These are:

a) Productivity indicator K_P [cm^3/h]

$$K_P = \frac{V_{BJ}}{t_{BJ}} \quad (1)$$

where:

V_{BJ} Volume of the generic build job adjusted to the specific machine [cm^3]

t_{BJ} Necessary build time of completion of the generic build job [h]

b) Reproducibility indicator K_{rep} [-]

For the calculation of the reproducibility indicators, a reference shall be defined upfront. The reference used for this document is shown in Table 4:

Table 4 — Introduction of evaluation reference $E_{r,c}$ ($R_{p0,2}$, R_{m}, A in accordance with VDI 3405-2.1, 2.4)

Evaluation reference $E_{r,c}$	Unit	Target
Relative density, ρ_{rel}	%	>99,2
Surface roughness, S_a	µm	<10
Yield strength, $R_{p0,2}$	MPa	— AlSi10Mg: 210 to 295 — Ti-6Al-4V: 1 026 to 1 178
Tensile strength, R_m	MPa	— AlSi10Mg: 353 to 482 — Ti-6Al-4V: 1 222 to 1 334
Elongation, A	%	— AlSi10Mg: 2 to 7 — Ti-6Al-4V: 2,9 to 9,3

Other values can be agreed between manufacturer and user.

If the mechanical properties of the material that are evaluated are not defined within VDI 3405 (all parts), other suitable standards should be used upon agreement between machine manufacturer and user. Note that during the factory and site acceptance tests, a different reference may be used upon agreement between user and machine manufacturer.

Since the aim of the generic machine evaluation is to determine the minimum capable quality (minimum capable specification) in the present methodology, the reproducible quality Q_{rep} is introduced for further calculations. Q_{rep} defines the quality which, based on the given characteristic (R_m, $R_{p0,2}$, A, ρ_{rel}, S_a), can be produced in a reproducible way. Based on Q_{rep}, a specification for resulting quality for the evaluated machine and the evaluated characteristic can be derived and compared to results from different PBF-LB/M machines.

In Formulae (2) and (3), the calculation of the capability indicator are shown:

$$K_{rep,c} = \frac{Q_{rep,c}}{E_{r,c}} \text{ (valid for characteristic } R_{p0,2};\ R_m;\ A;\ \rho_{rel}) \qquad (2)$$

$$K_{rep,Sa} = \frac{E_{r,c}}{Q_{rep,C}} \text{ (valid for characteristic } S_a) \qquad (3)$$

where

$Q_{rep,c} = u_c - (u - U_p) \times C_{mk}$ (valid for characteristics $R_{p0,2}$; R_m; A; ρ_{rel})

$Q_{rep,Sa} = u_{Sa} - (u_{Sa} - U_{p,Sa}) \times C_{mk}$ (valid for characteristic S_a)

C_{mk}: machine capability indicator = 1,67 by requirement

O_p: 99,865 % quantile

U_p: 0,135 % quantile

u: mean value

For evaluation purposes, the detailed results from relative density, surface roughness, yield strength, tensile strength and elongation shall be documented so that additional calculations such as the determination of the absolute reproducible quality can be performed.

5 Definition of overall equipment effectiveness (OEE) for AM-machines

5.1 General

Major aspects of the automotive development process are planning, sourcing, setting-up and launching production facilities and machines. During these phases of the development process, continuous monitoring of the key performance indicator "overall equipment effectiveness (OEE)" ensures transparency with respect to root causes of down time losses, speed losses and quality losses. The common understanding shall be used as the basis for product requirement sheets and machine acceptance processes.

The stated OEE definitions and monitoring procedures shall be used for performance-definition and -loss-analysis in one single system. This approach is not applicable for the comparison of different machines/systems.

For the evaluation, the following items shall be agreed between machine manufacturer and user in form of a product requirement sheet before the start of the procurement process:

a) time period for evaluation;

b) build job design (generic or specific part designs);

c) target quality;

d) target quantity.

Generic build jobs (see Clause 4) and defined customer parts can be used for the stated OEE definition and monitoring procedures. In both cases, defined quality and build job times which produce the required quality shall be known and defined upfront to determine targets and framework of the OEE monitoring.

OEE monitoring always constitutes a comparison between target and actual times. The following sub-clauses define these time blocks.

5.2 Overview

The time blocks are introduced in Figure 5.

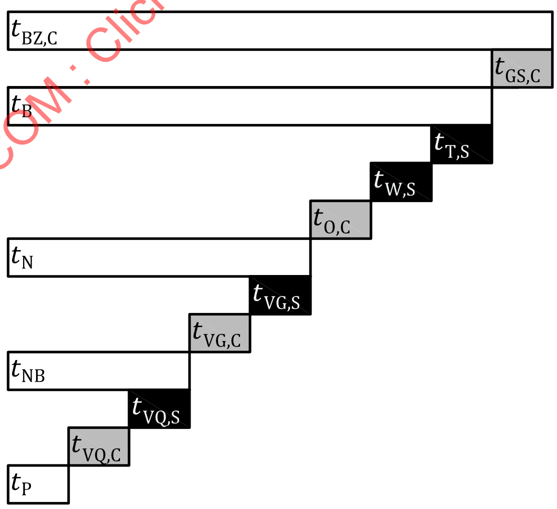


Figure 5 — Overview of time blocks contributing to OEE calculation

Figure 5 depicts the time blocks which contribute to the calculation of an OEE (see VDI 3423). In the following, a company that offers a PBF-LB/M systems for sale or provides manufacturing capacity on such a plant is designated as a supplier. The potential buyer/purchaser of these goods (automotive OEM or also a tier supplier) is referred to as the customer. The planned production time can be calculated according to Formula (4):

$$t_B = t_{BZ,C} - t_{GS,C} \quad (4)$$

where

$t_{BZ,C}$ considered plant operating time for OEE monitoring. The customer responsible for its definition;

$t_{GS,C}$ time loss from planned shutdown. The customer responsible for its definition;

t_B planned production time.

The operating time can be calculated according to Formula (5):

$$t_N = t_B - t_{T,S} - t_{W,S} - t_{O,C} \quad (5)$$

where

$t_{T,S}$ time loss from equipment failures (technical down time). The supplier is responsible for its definition;

$t_{W,S}$ time loss from planned supplier-maintenance and inspection (preventive maintenance time). The supplier is responsible for its definition;

$t_{O,C}$ time loss from set-up/adjustments/customer-maintenance/cleaning (organisational down time). The customer is responsible for its definition;

t_N operating time.

The net operating time can be calculated according to Formula (6):

$$t_{NB} = t_N - t_{VG,S} - t_{VG,C} \quad (6)$$

where

$t_{VG,S}$ time loss from reduced speed (includes minor stoppage), due to supplier issues. The supplier is responsible for its definition;

$t_{VG,C}$ time loss from reduced speed (includes minor stoppage), due to customer issues. The customer is responsible for its definition;

t_{NB} net operating time.

The fully productive time can be calculated according to Formula (7):

$$t_P = t_{NB} - t_{VQ,S} - t_{VQ,C} \quad (7)$$

where

$t_{VQ,S}$ time loss from rejected pieces that do not meet quality requirements, due to supplier issues. The supplier is responsible for its definition;

$t_{VQ,C}$ time loss from rejected pieces that do not meet quality requirements, due to customer issues. The customer is responsible for its definition;

t_P fully productive time.

5.3 Considered plant operating time for OEE monitoring

A fundamental requirement for OEE definition and monitoring is the existence of a production plan. Thus, OEE monitoring is always a comparison between predefined target times and measured actual times. Depending on the phase in which the OEE monitoring is conducted, the production plan shall be:

— the plan for the factory acceptance test (FAT) of the machine on the supplier's premises,

— the plan for the site acceptance test (SAT) of the machine on the customers premises, or

— the production plan for a defined time span (e.g. one full week/month/year).

To be able to clearly measure whether a machine is performing according to the specifications agreed on in the product requirements sheet, the machine supplier and machine customer shall agree on a detailed plan for the FAT and SAT. An example for an SAT plan is given in Annex A. The product requirements sheet of an AM-machine shall clearly quantify the maximum accepted values for time losses which lie in the responsibility of the machine supplier. The following sub-clauses categorize these time losses.

5.4 Availability rate

The availability rate R_A takes into account down time loss, which includes all events that stop planned production for an appreciable length of time (usually several minutes). Examples include equipment failures, material shortages, and changeover time. Changeover time is included in OEE analysis since it is a form of down time. While it is usually not possible to eliminate changeover time, in most cases it can be reduced (the basis of SMED (Single Minute Exchange of Die) programs). The remaining time is called operating time. The availability rate is the ratio of operating time t_N to planned production time t_B. It shall be calculated according to Formula (8):

$$R_A = \frac{t_N}{t_B} = \frac{t_B - t_{T,S} - t_{W,S} - t_{O,C}}{t_B} \tag{8}$$

The three categories ($t_{T,S}$, $t_{W,S}$ $t_{O,C}$) of down time loss are assigned through VDI 3423.

5.5 Performance rate

The performance rate R_P takes into account speed loss, which includes all factors that cause a process to operate at less than the maximum possible speed when running. Examples include machine wear, substandard materials, misfeeds, and operator inefficiency. The remaining time is called net operating time. The performance rate is the ratio of net operating t_{NB} time to operating time t_N. It shall be calculated according to Formula (9):

$$R_P = \frac{t_{NB}}{t_N} = \frac{t_N - t_{VG,S} - t_{VG,C}}{t_N} \tag{9}$$

Table 6 assigns different events which can occur during production to the two categories ($t_{VG,S}$, $t_{VG,C}$) of speed loss.

Table 6 — Assignment of production events to speed loss categories

Speed loss category	Production event (including example)
$t_{VG,S}$	Actual build time is longer than reference build time (e.g. longer recoating time necessary to process defined material)
$t_{VG,C}$	Actual build time is longer than reference build time (e.g. extra data collection by customer during build results in longer job time)

5.6 Quality rate

The quality rate R_Q takes into account quality loss, which factors out produced pieces that do not meet quality requirements, including pieces that require rework. The remaining time is called fully productive time. The quality rate is the ratio of fully productive time t_P to net operating time t_{NB}. It shall be calculated according to Formula (10):

$$R_Q = \frac{t_P}{t_{NB}} = \frac{t_{NB} - t_{VQ,S} - t_{VQ,C}}{t_{NB}} \qquad (10)$$

Table 7 assigns different events which can occur during production to the two categories ($t_{VQ,S}$, $t_{VQ,C}$) of quality loss.

Table 7 — Assignment of production events to quality loss categories

Quality loss category	Production event (including example)
$t_{VQ,S}$	Time fraction during build time spent producing inferior quality parts, due to machine related issues (e.g. unplanned loss of laser power resulting in higher part porosity)
$t_{VQ,C}$	Time fraction during build time spent producing inferior quality parts, due to operating related issues (e.g. uncleaned laser window resulting in weaker energy deposition and higher part porosity)

5.7 OEE calculation

The OEE takes into account all three factors and is the ratio of fully productive time t_P to planned production time t_B. It shall be calculated according to Formula (11):

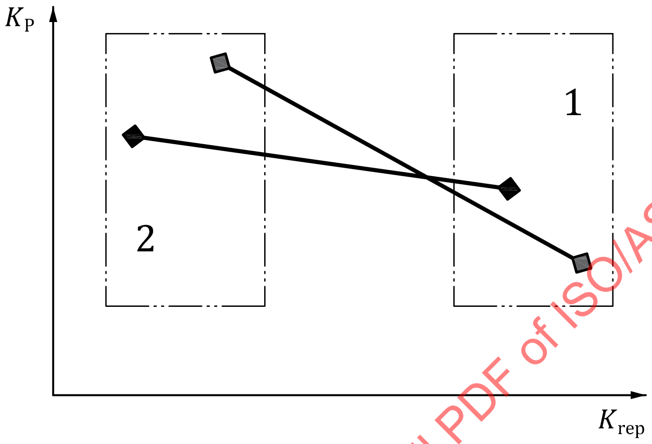
$$O_{EE} = \frac{t_P}{t_B} = R_A \cdot R_P \qquad (11)$$

The OEE represents the fraction of production time spent making good pieces (no quality loss), as fast as possible (no speed loss), without interruption (no down time loss).

Annex A
(informative)

Examples for Clauses 4 and 5

A.1 Examples for Clause 4: Example visualization of machine performance characteristics



Key

K_p machine performance characteristics productivity

K_{rep} machine performance characteristics reproducibility

1 machine 1

2 machine 2

Figure A.1 — Visualization of machine performance (Productivity over reproducibility)

The previously determined machine performance characteristics productivity (K_P) and reproducibility (K_{rep}) are used to create a performance map of the machine as shown in the diagram above. From this map, the performance of the machine can be determined for at least two data points based on quality premises 1 (determined as reference in 4.3.2) and an additional quality level (here named as level 2 – which is optional and based on voluntary provision by the machine manufacturer). Additionally, a comparison of different machines can also be carried out and visualized. The machine manufacturer can provide data for machine evaluation based on different quality level to describe the evaluated machine. The machine manufacturer can perform the introduced methodology for other parameter sets he offers on a voluntary basis to improve the data basis for customer decisions. For the user, this can help to understand the machine performance in different working modes and draw the right conclusions regarding the individual application area.

A.2 Examples for Clause 5: Calculation example for OEE during SAT

Table A.1 gives an example for a SAT plan consisting of

— Generic build job 1 (consisting of 30 test specimens, build time 1 875 min.) performed 2 times;

— Generic build job 2 (consisting of 40 test specimens, build time 2 100 min.) performed 2 times;

— Serial build job 1 (consisting of 24 parts, build time 2 000 min.) performed 6 times;

— Serial build job 2 (consisting of 100 parts, build time 1 950 min.) performed 2 times;

— one maintenance interval and

— setup times of 1 hour prior to every single job.

In this example the SAT is planned for 30 days resulting in a considered plant operating of 720 h. The time loss from planned shutdown is given with 305,5 h resulting in a planned production time of 414,5 h.

Table A.1 — Number example of SAT OEE Plan with generic and serial build jobs planned during one month

	Day	Planned operation	Jobstart	$t_{BZ,C}$ min	$t_{GS,C}$ min	t_B min	t_{TS} min	$t_{W,S}$ min	$t_{O,C}$ min	t_M min	$t_{VG,S}$ min	$t_{VG,C}$ min	t_{MB} min	$t_{VO,S}$ min	$t_{VO,C}$ min	t_P min
1	Mo	Generic build job 1 (1 875 min)	08:00	1 440	420	1 020			60	960			960			960
2	Tue			1 440	525	915				915			915			915
3	Wed	Serial build job 1 (2 000 min)	08:00	1 440	420	1 020			60	960			960			960
4	Thu			1 440	400	1 040				1 040			1 040			1 040
5	Fri	Generic build job 2 (2 100 min)	08:00	1 440	420	1 020			60	960			960			960
6	Sat			1 440	300	1 140			1 140			1 140				1 140
7	Sun			1 440	1 440	0				0						
8	Mo	Serial build job 2 (1 950 min)	08:00	1 440	420	1 020			60	960			960			960
9	Tue			1 440	450	990				990			990			990
10	Wed	Serial build job 1 (2 000 min)	08:00	1 440	420	1 020			60	960			960			960
11	Thu			1 440	400	1 040				10 400			1 040			1 040
12	Fri	Serial build job 1 (2 000 min)	08:00	1 440	420	1 020			60	960			960			960
13	Sat			1 440	400	1 040				1 040			1 040			1 040
14	Sun			1 440	1 440	0				0						
15	Mo	Serial build job 1 (1 875 min)	08:00	1 440	420	1 020			60	960			960			960
16	Tue			1 440	5 255	915				915			915			915
17	Wed	Maintenance (300 min)		1 440	1 140	300		300		0						
18	Thu	Serial build job 1 (2 000 min)	08:00	1 440	420	1 020			60	960			960			960
19	Fri			1 440	400	1 040				1 040			1 040			1 040
20	Sat			1 440	1 440	0				0						
21	Sun			1 440	1 440	0				0						
22	Mo	Serial build job 2 (2 100 min)	08:00	1 440	420	1 020			60	960			960			960
23	Tue			1 440	300	1 140				990			990			990
24	Wed	Serial build job 1 (2 000 min)	08:00	1 440	420	1 020			60	960			960			960
25	Thu			1 440	400	1 040				1 040			1 040			1 040
26	Fri	Serial build job 2 (1 950 min)	08:00	1 440	420	1 020			60	960			960			960
27	Sat			1 440	450	990				990			990			990
28	Sun			1 440	1 440	0				0						
29	Mo	Serial build job 1 (2 000 min)	08:00	1 440	420	1 020			60	960			960			960
30	Tue			1 440	400	1 040				1 040			1 040			1 040
		Total [h] =		**720**	**305,5**	**414,5**	**0**	**5**	**12**	**397,5**	**0**	**0**	**397,5**	**0**	**0**	**397,5**

Prior to the SAT, the table is filled with the known job times and planned maintenance and setup times. In order to base OEE calculation on the correct planned production time, it is important to define the exact starting time of every job. The resulting OEE calculation of the number-example shown in Table A.1 is given in Figure A.2.

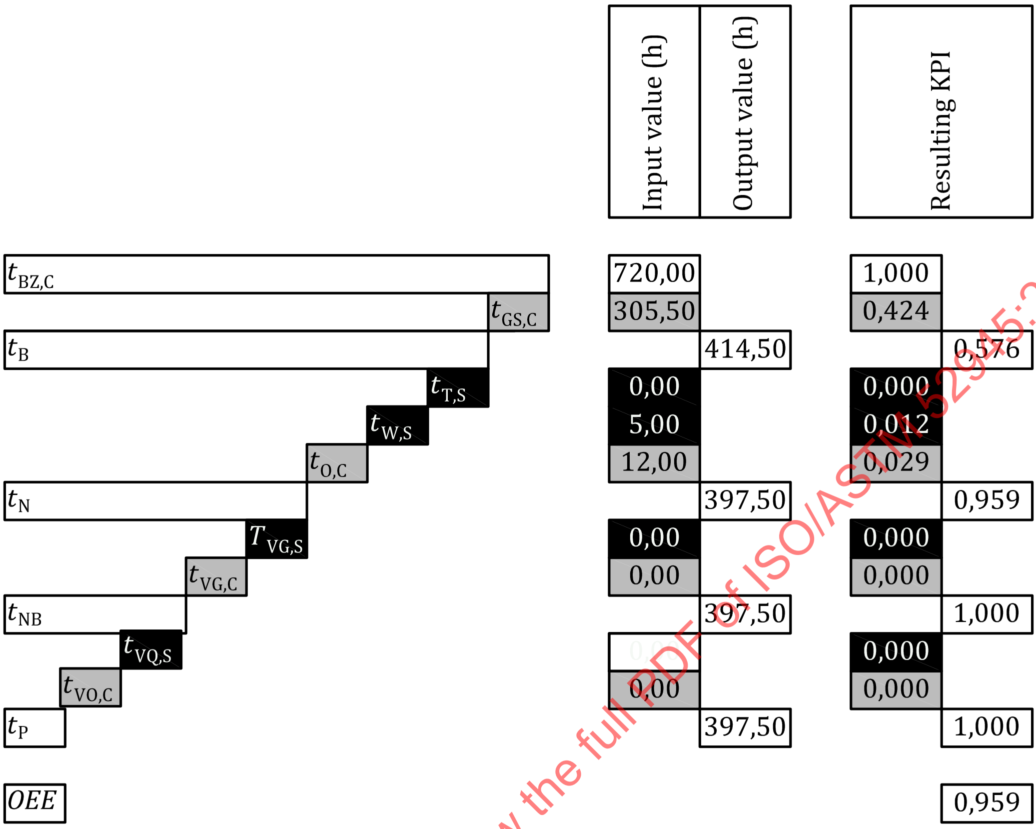


Figure A.2 — Calculation example of a SAT OEE Plan

In the calculation example shown in Figure A.2, the following limit values for down time, speed and quality losses during SAT are defined by supplier and customer:

$t_{T,S}$ = 0 h (no time loss due to equipment failures is allowed during SAT)

$t_{W,S}$ ≤5 h (max. time loss due to planned supplier-maintenance and inspection)

$t_{O,C}$ ≤13,2 h (max. time loss due to set-up/adjustments/customer-maintenance/cleaning)

$t_{VG,S}$ ≤1 h (max. time loss due to reduced speed caused by supplier issues)

$t_{VG,C}$ ≤3 h (max. time loss from reduced speed caused by customer issues)

$t_{VQ,S}$ ≤35 h (max. time loss from pieces/specimens that do not meet quality requirements, due to supplier issues)

$t_{VQ,C}$ ≤5 h (max. time loss from pieces/specimens that do not meet quality requirements, due to customer issues)