Deliverable D5.6
WP 5 Qualification

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Contents

1. Introduction

This document aims to outline a proposed roadmap for qualifying the WAAM process and the associated raw material (wire) used to manufacture a produced WAAM part. As WAAM manufacturing companies are more and more engaged in the development and refinement of this process, the establishment of robust qualification rules becomes imperative. Qualification rules provide the necessary framework to assess, validate, and ensure the reliability and consistency of the process.

As WAAM process technology is still in development from a standardization point of view and may lack the maturity necessary to define precise and definitive rules, this document is to be considered as a preliminary guide to expose recommendations and eventual qualification steps. It outlines a proposed roadmap for qualifying a part produced by WAAM, acknowledging the uncertainties inherent in its current state while providing a structured approach to its qualification steps. It implies that the qualification steps detailed in this deliverable only cover the qualification of a dedicated part, not the certification of the associated process and can't be applicable to a serial production.

Through collaboration, feedback, and iterative refinement with WAAM manufacturer and WAAM wire's manufacturer, BV aim to establish comprehensive qualification roadmap in line with current regulatory requirements but also align with industry best practices for this new manufacturing process.

2. Wire for WAAM process

2.1 Manufacturer quality system

The wire manufacturer should manage a quality system to be in accordance with internationally recognized quality standards. Associated documentation is to be maintained and should include:

- A summary of the organization including quality system management.
- List of manufacturing facilities, verification and testing means and devices.
- List of manufacturer's procedures and quality specifications.
- Manufacturing process flow chart.
- Testing/inspection methods during production.
- Identification/traceability methods during all manufacturing steps.
- incoming control, storage, and handling of raw material/finished product.
- pre-conditioning.

2.2 Material specification

2.2.1 Essential variables

The wire specification is to be linked to an internationally recognized industry standard. This specification is to include the essential parameters and associated ranges. Any change out of these ranges may lead to a new qualification. The essential parameters are as follow:

- Material grade.
- Type of the wire / applicable AM process.
- Size of the wire.
- Chemistry composition ranges.
- Guaranteed mechanical properties.
- Surface condition of the wire and tolerance.

2.2.2 Additional information

Other information should be indicated in the wire manufacturer's documentation for raw material control and traceability per batch/heat:

- Heat and/or batch reference No.
- Shielding gas to be used to obtain the guaranteed mechanical properties.
- Recommended deposit parameters, process parameters and limitations.
- Method/standard used for testing.
- Details for As-deposited properties versus PHT properties if applicable.

In addition, consideration should be given by wire user to other properties required by service/environment conditions such as corrosion, wear, fatigue resistance.

2.3 Qualification testing

2.3.1 Test coupon

A qualification testing campaign is to be carried out by wire manufacturer. The tests should be carried out using an additive manufacturing-built test coupons as proposed hereunder:

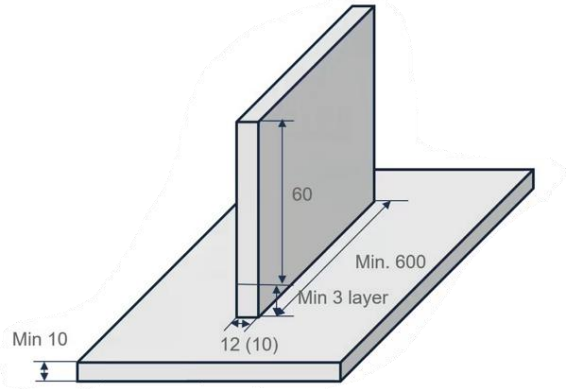

Figure 1: AM-built test coupons proposal from BV guideline NI662 (dimensions in mm.)

The base material should be similar to the deposited material used for the deposits. When the chemical composition of deposited metal is substantially different from the base material, an overlay may be carried out, as deemed necessary. The volume made of the first three layers over the base material should not be used to sample test specimens to avoid dilution effects.
Two test coupons may be produced with the maximal and minimal heat input recommended by the wire manufacturer to cover a larger range of qualified heat input. Those heat inputs will be obtained considering the deposit parameters included in the material specification (see §2.2). Post-process heat treatment of the type test samples is not allowed unless the wire is to be approved for the PHT condition.

2.3.2 Type of tests

Each test coupon is to be tested to evaluate the wire properties when deposited in wall configuration. The tests to be considered should be as follow:

- Visual inspection: no visible defect is to be identified like crack, surface porosity, poor forming, collapse, …
- Dimension inspection: the AM-built test coupons are to be within tolerance of AM-built test coupons drawing validated prior deposit steps.
- Chemical analysis: composition is to be in range of chemical elements as per material specification.
- Microstructure examination: results and photographic documentation should detail the typical metallurgical phase.
- Tensile tests: Rp0,2, Rm, A%, Z% and failure type/location are to be detailed.
- Charpy V-notch impact tests, if applicable: each test should be performed on a set of three test specimens and a temperature of test is to be defined.
- Hardness: test at the interface substrate/weld deposit should be performed to evaluate the hardness evolution and get information regarding the dilution phenomena.
- Other tests: other tests may be performed if properties required by service/environment conditions such as corrosion, wear, fatigue resistance have been specified by manufacturer.

2.3.3 Sampling

Both ends of the deposited wall should be removed as particular phenomena may occur in these areas implying results with too much variability without involvement of the wire quality.
As previously stated in §2.3.2, an hardness test at the interface substrate/weld deposit should be performed. Minimum three layers should be tested to get the evolution of hardness linked to the dilution. These values are to confirm other test specimens have been extracted from an area without dilution phenomena between substrate and weld deposit.
Impact and tensile tests should be extracted from both main directions of the well deposit. Indeed, mechanical properties variation may occur when direction changes. Three set of each test and for each direction are to be extracted to get an average value for each mechanical property. The location of test specimens should be distributed to cover the entire wall deposit, voiding the dilution area (see §2.3.1).
A sampling map is to be used to extract the test specimens for each test. The sampling map should be as follows:

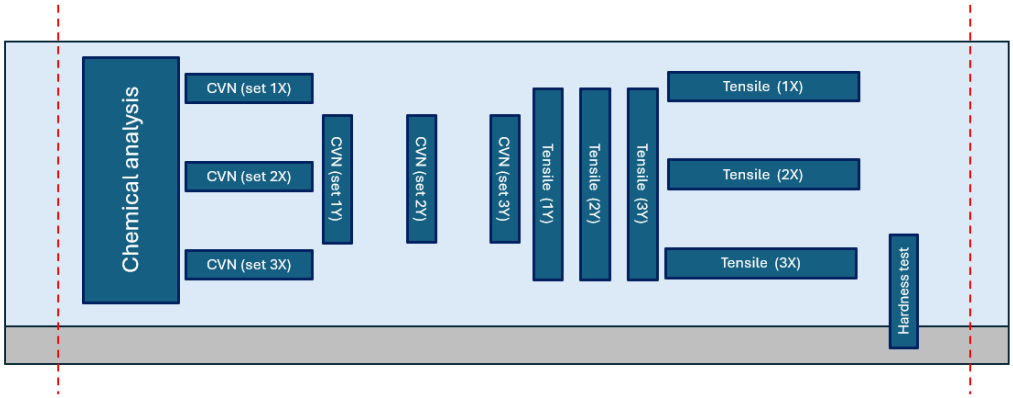

Figure 2: Test specimen location in AM-built test coupon

2.4 Survey

2.4.1 Initial survey

At the initial stage of the qualification request, a survey should be conducted to assess the wire manufacturer's quality system and associated production methods:

- The manufacturing process should be outlined through internal specification and procedures detailing each step of the wire quality process including manufacturing, traceability, handling, sampling, inspection, and testing documentation.
- An inspection of the wire production should be conducted including a review of calibration certificates of production and testing equipment. The maintenance of this equipment should be verified to ensure correspondence with previous quality system survey.

2.4.2 Annual survey

The workshop where the initial survey was conducted may be subject to annual test, or other timing as deemed necessary. The annual survey should include a plan to demonstrate the essential parameters are followed by production test coupon and wire produced as per documentation reviewed at the time of qualification.
During this survey, full or partial approval test campaign may be requested based on the performance of the annual production record.

3 Part produced by WAAM process

3.1 Criticality

3.1.1 Risk assessment

The level of criticality for AM parts can be established based on their service environment and the potential consequences of part failure. The risk assessment and associated level of criticality is defined by the part designer or manufacturer and must be approved by the customer. The criticality may be defined with two categories:

- Non-critical: A part whose failure would not impact the system's operation/personnel safety.
- Critical: A part whose failure could implies serious risks to personnel or create a significant operational hazard.

3.1.2 Qualification requirements

The risk assessment should be used to define the procedures to be prepared by manufacturer about the different aspects of the part manufactured by WAAM process. Such production and associated quality should consider the design requirements, material specification, manufacturing procedure and control of associated essential parameters including pre-deposition, deposition and post-deposition steps. The below table summarize assessment task to be performed and which can be adopted as part of the qualification process of WAAM part considering level of risk.

Type of document/task	Non-critical	Critical
Design review	To be reviewed	To be reviewed
Software survey		To be reviewed
Material specification	To be reviewed	To be reviewed
Manufacturer approval		To be reviewed
Inspection equipment	To be reviewed	To be reviewed
Manufacturing procedure	To be reviewed	To be reviewed
Prototype test piece	Coupon	Representative

3.2 Design review

3.2.1 General

The manufacturer should issue manufacturing procedures in accordance with the customer specifications and applicable conditions of use:

- Applicable standards or manufacturer’s specifications.
- Risk assessment
- Drawing of the part to be built and the associated CAD model
- Material/wire specification (see §2.2) with acceptance criteria of each property to be tested
- Design analysis report, if customer requires/defines it.

3.2.2 Drawing model

The drawing model to produce the AM produced part should define all the dimensions of the part and the associated tolerances. These inputs are to be linked to a recognized standard. If a design optimization is planned, the part produced with WAAM process is to be at least equivalent to traditionally manufactured part regarding integrity and associated functionalities.
The review of the drawing model should take into consideration:

- The customer requirements and functional application, including load calculations.
- The building strategy including clamping method.
- The part orientation and bound box.
- Verification that design enables machining/inspection steps.

The drawing model revision should be considered as an essential variable of the qualification. The revision is to be included in the AM approval documentation and update should be reviewed to evaluate the impact of the modification.

3.3 Software survey

The software survey, when required, should be carried out together with the design review to consolidate the verification of the model and the manufacturing simulation. It may include the following checks:

- Software version and patches
- Traceability of file format and revision
- Compatibility between file format and machine software
- Proper manufacturing steps completion without gap/overlap during deposit steps or potential collision between machine part/environment.

The data flow from part need definition to produced part should be as detailed in Figure 1 - ISO/ASTM 52950:2021. Concerns about data formats and preparation are also included in this standard and may be used as a survey support.

3.4 Material specification

The quality of a part is evaluated by comparing its characteristics against a predefined set of requirements. The material specification should outline all acceptance criteria related to the material properties in its final delivery condition, including any applicable heat treatments. These requirements must be explicitly defined in the purchase specification. The chosen materials should be appropriate for the expected load conditions, functionality, and operating environment. Inspection and testing of the part and corresponding test specimens are performed to verify compliance with these requirements.

The following properties should be included in the material specification for final delivered condition:

- Material type and grade
- WAAM process
- PDHT if applicable
- Chemical composition range
- Mechanical properties (e.g., tensile, impact, hardness) including test condition in line with operating environment
- Specific properties if applicable (e.g., fatigue, fracture mechanics properties, corrosion, wear resistance) including test condition in line with part functionality
- NDT acceptance criteria

3.5 Manufacturer approval

3.5.1 Manufacturer quality system

The WAAM manufacturer should manage a quality system to be in accordance with internationally recognized quality standards. The machine, technical documentation and personnel should be framed by written procedures, up to date and applied during the manufacturing process. The quality management system should maintain and include the following technical documentation:

- A summary of the organization, quality department and AM production historic data.
- List of manufacturing/testing equipment and associated capacities.
- List of manufacturer's procedures and quality specifications.
- Manufacturing process flow chart.
- Post printing treatment documentation including heat treatment
- Management of qualification specification (process, operator)
- Quality document dedicated to the management of the files used to print products and to record manufacturing data (model of software, 3D print file and records format).
- Feedstock and gas handling, traceability and storage procedures
- Testing/inspection methods during production.
- Identification/traceability methods during all manufacturing steps.
- incoming control, storage and handling of raw material/finished product.
- pre-conditioning.

3.5.2 Manufacturing equipment

The main equipment for WAAM part production is a robotized welding machine. The manufacturer should issue and maintain documentation proving the process equipment and auxiliary systems are capable of functioning within defined limits and tolerances. The calibration of the welding machine and the robotic arm should be performed at regular and reasonable frequency.
The machine documentation should at least include the following information:

- Machine reference and manufacturer
- Serial number
- Associated software, power source
- Capacity of welding room and substrate positioner
- Calibration records

3.5.3 Personnel

The operators who are responsible for manufacturing a part by WAAM process should be competent with documented knowledge and regular practical training. Theoretical training and testing should cover all the AM aspects (process, quality, safety, machine, maintenance). Practical training should demonstrate necessary manufacturing steps are well executed following a WAAMPS (see §3.7). The personnel training record should be traceable and managed by the quality management system. Qualification principles dedicated to WAAM should be follow as defined in recognized standard such as ISO/ASTM 52926-5:2023.

3.6 Inspection equipment

The inspection equipment should be used to ensure the printed parts are in accordance with acceptance criteria and customer requirements (see §3.4). This equipment may be use during all the manufacturing phase (pre-deposition, deposition, post-deposition) and results obtain should be recordable. The equipment may be used to inspect directly the printed part:

- Visual examination
- Surface/volume examinations (NDT methods such as PT or UT)
- Dimensional measurements

The calibration of the inspection equipment should be performed at regular and reasonable frequency.

3.7 WAAM procedures

Manufacturing steps are to be executed following procedures to monitor essential and non-essential variables that may impact the quality of the final printed part. The parameters should remain in range of approval defined from approval test and protype part testing. The input included in the manufacturing procedure should be recorded for each part production.

3.7.1 Pre-Build procedure

The pre-build procedure should define the preparation steps and variables involved before the machine starts the metal deposition phase. This procedure should identify:

- The part location orientation and bound box.
- Support/clamping position and orientation.
- Cleaning steps for positioner/substrate.
- Identification of equipment to be used during deposit steps.

3.7.2 Deposition procedure (WAAMPS)

The WAAMPS should include all the essential parameters to be defined for the deposition phase. For Grade 2XL project, a pWAAMPS template has been issued by BV and used by WAAM manufacturers (see deliverable D1.7 for applicable case). These parameters should be monitored during the deposition as per the following categories:

- WAAM Process:
    - Robot, power source serial numbers
    - Torch diameter
    - Torch/part/positioner orientations
    - Frequency of the contact tip change
    - Specific technique such as weaving, multi-wires or pulse for wire
    - Pulse frequency when applicable
    - Weaving amplitude when applicable
    - Wire specification
    - Shielding gas composition and flow rate
- Substrate specification
- Deposition pattern design
    - N° of layers n°, direction, thickness
    - Start and stop location, clamp position
- WAMM Process parameters
    - Electrical parameters (Amps, Volt)
    - Contact-tip to work piece distance (CTWD)
    - Travel speed
    - Heat input range
    - Inter-pass temperature
    - Post-process heat treatment (see §3.7.3)
    - Inter-pass cleaning method, if applicable
    - Environment condition (temperature, moisture)

Sketches to show the part orientation and to detail these parameters should be provided for each main steps of the deposition. The range of qualified essential parameters should be stated in the WAAMPS. These ranges are defined from the approval test campaign conducted prior production (see §3.8).

3.7.3 Post deposit procedure

The post-build procedure should define the steps of part's manufacturing that occurred after the deposition phase to provide the final delivered part, if applicable. This procedure should identify:

- The Post Deposition Heat Treatment. The parameters such as temperatures, heating rates, soaking time, cooling time should be specified with tolerances. These parameters are to be recorded. The timing of such heat treatment should be detailed and notify if it is applied before or after the support/clamping removal.
- The shot peening/polishing/machining steps. The surface finish should be detailed by manufacturer's specification.
- Support removal from positioner/build platform. The parameters such as part temperature and timing when the support/clamping are planned to be removed.
- The Non-Destructive Testing. The dimensions, surface and/or volume of the final part should be inspected with NDT techniques. The NDT timing should be defined. The extent of NDT, applicable standard and associated acceptance criteria should be in accordance with the inspection plan.

3.8 Approval test piece

3.8.1 General

To prove manufacturer can produce a WAAM produced part that meet the associated quality requirement, a part/coupon should be produced to allow destructive/non-destructive tests and verify all the requirements are satisfactory. The manufacturing of such test part/coupon are to be carried out following the procedure to be qualified. The qualification records dedicated to approval manufacturing by procedures with revision and essential parameters will be fixed for production purpose, if the qualification is validated.
Two options for approval test piece may be considered, depending on the criticality of the final part to produce (see §3.1):

- If the part is considered as “Critical”, the approval test piece should be a prototype of the final part with the requested material and geometry.
- If the part is considered as “Non-critical”, the approval test piece should be a test coupon built with the same deposit condition/material interface than final part. The coupon may be built as a prolongated part of the final part or an independent one representing a part section thickness. The characteristics of the coupon (location, orientation, bound box) should be included in the WAAMPS. Representative PDHT should be applied to the independent coupon to obtain the same heat effect than the final part.

3.8.2 Type of test

The following tests are to be carried out on test piece:

- Non-destructive tests:
    - Visual examination
    - Surface examination
    - Volume examination
- Destructive tests:
    - Chemical composition analysis
    - Microstructure
    - Tensile test
    - Impact test
    - Bend test
    - Hardness test

These tests should be conducted according to recognized standards, such as the guidelines in ISO/ASTM 52905:2023 for non-destructive tests and ISO/ASTM 52927:2024 for destructive tests. Acceptance criteria and extent of testing are to be in line with test categories defined according to the application and the type of material and agreed between manufacturer and customer.
Other tests such as function test may be applicable depending on final part application and should be defined by customer.

3.8.3 Sampling

As each part may imply different configuration for sampling and properties to check, an inspection plan should be agreed on a case-by-case basis. Due to the complex geometry of parts produced by WAAM, defining sampling can be challenging. A standard like ISO/ASTM 52909:2024 can be used for guidance. The mechanical tests are to be extracted in all the directions, if applicable, and at different height of the approval test piece and for each deposited material in case of multi-material part.
Chemical composition and microstructure should be checked at several points of the approval test piece, in particular at material interface.

Hardness test should be carried out also at material interface or substrate interface to check the dilution transition phenomena between two deposited material or the presence of substrate in the first layers of deposition.

3.8.4 Range of qualification

The range of qualification should be the essential variables used to produce the approval test piece:

- Drawing model with reference and revision.
- WAAM machine and power source (serial number)
- Material specification (wire manufacturer)
- Manufacturing specification (pre-deposit/deposit/post-deposit)

As each part produce by WAAM may imply different manufacturing process, the part-by-part qualification philosophy should remain the option to qualify a new part and should be approved through a new qualification campaign dedicated to the part.
A family of part may be qualified through a same qualification. However, this range should be study on a case-by-case basis and manufacturer should identify the change of manufacturing steps and prove it does not impact the repeatability of the qualified manufacturing process previously guaranteed. In this case, additional test may be performed to expand the range of approval.

3.9 Survey

3.8.1 Initial survey

At the initial stage of the qualification request, a survey should be conducted to assess the WAAM manufacturer's quality system and associated production methods:

- The manufacturing process should be outlined through internal specification and procedures detailing each step of the WAAM quality process including manufacturing, traceability, sampling, inspection, and testing documentation.
- An inspection of the plant should be conducted including a review of calibration certificates of production and testing equipment. The maintenance of this equipment should be verified to ensure correspondence with previous quality system survey.

3.9.2 Annual survey

The workshop where the initial survey was conducted may be subject to annual test, or other timing as deemed necessary. The annual survey should include a plan to demonstrate the essential parameters are followed by production test coupon and produced as per documentation reviewed at the time of qualification.
During this survey, full or partial approval test campaign may be requested based on the performance of the annual production record.

4 Annexes

Glossary

PHT	Post-process Heat Treatment
PDHT	Post Deposit Heat Treatment
AM	Additive Manufacturing
WAAM	Wire Arc Additive Manufacturing
(p)-WAAMPS	(preliminary)-WAAM Procedure Specification
Rp0.2	Proof stress (yield strength) at which total extension is equal to 0.2%, in N/mm²
Rm	Tensile strength, in N/mm²
A%	Percentage elongation after fracture
Z%	Percentage reduction of area
Kv	Average of Charpy V-Notch impact energy (J)
NDT	Non-Destructive Testing
PT	Penetrant testing
UT	Ultrasonic testing

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