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A QUALITY ASSURANCE FRAMEWORK FOR METAL ADDITIVE MANUFACTURING

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***Abstract**: From a defense perspective, Additive Manufacturing (AM) has evolved from a rapid prototyping technology into a strategic capability and has become one of the key enablers of military modernization. Its applications include replenishing spare-part inventories for legacy platforms, enhancing supply chain agility, supporting forward operational logistics through on-site production of spare parts and rapid repairs, and improving overall operational readiness. Original Equipment Manufacturers (OEMs) and defense industries must rapidly adapt to AM technologies and comply with a comprehensive set of qualification and certification requirements to become qualified AM producers capable of manufacturing and delivering critical spare parts.*
*The qualification of AM processes and parts is a highly challenging and demanding task, primarily defined by **ISO/ASTM 52920:2023**, the international standard for quality assurance in additive manufacturing. Within the Quality Assurance (QA) framework, certification and qualification serve as essential tools for verifying and validating that manufacturing processes, parts and personnel comply with established standards and specified requirements.*
This paper provides a brief overview of the certification and qualification process for AM processes and components. Furthermore, it discusses the key challenges associated with conventional and AM-specific qualification approaches, as well as a novel qualification methodology currently being developed by the U.S. National Institute of Standards and Technology (NIST). Finally, the paper presents a basic framework for the qualification of AM parts intended for use in the armament and military equipment of the Serbian Armed Forces (SAF).

***Keywords:** Quality Assurance, Additive Manufacturing, Qualification, Certification.*

1. INTRODUCTION

Quality standards, in the broadest sense, are established to ensure the consistent quality of industrial products over an extended period. When machine parts are manufactured using additive manufacturing (AM) technologies, it is essential to verify that they meet all specified technical and quality requirements. This requires that every stage of the production chain (Figure 1) be designed and controlled to ensure the consistent and repeatable quality of manufactured parts.

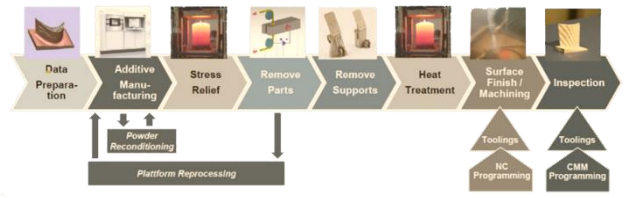


Figure 1. AM operations flow diagram

Quality Assurance (QA) is a comprehensive and systematic approach aimed at preventing defects and ensuring that a product or service fully complies with specified standards and user requirements before it reaches the end user.

Unlike Quality Control (QC), which focuses on detecting defects in finished products, QA encompasses the entire manufacturing process. It ensures process quality and stability during machine operation (in-process QA), as well as throughout the pre-process phase (input material verification and process preparation) and the post-process phase (inspection and testing of the finished part).

Quality Assurance (QA) uses Certification and Qualification as key tools to ensure and validate that processes meet set standards. The certification process is to assure the compliance with qualified parameters and standards. The qualification process is to demonstrate the ability to fulfil specified metal AM requirements, [1].

A specific aspect of quality assurance in additive manufacturing concerns production facilities and infrastructure, which must comply with stringent environmental control requirements. In addition, personnel involved in AM processes must possess appropriate qualifications and competencies.

The rapid adoption of metal additive manufacturing has introduced numerous technical challenges related to

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ensuring product quality and confidence in component performance. Despite significant technological advances, concerns remain regarding whether metal AM parts can reliably replace components manufactured using conventional production methods, particularly in safety-critical applications. Nevertheless, additive manufacturing technologies are steadily becoming an integral part of modern manufacturing alongside conventional production technologies.

To achieve reliable and continuous quality management in industrial AM production, manufacturing equipment must be qualified in accordance with ISO/ASTM 52920:2023 [2], while programmers and machine operators must be qualified in accordance with the applicable personnel qualification standards [3,4]. Both qualifications are mandatory prerequisites for the certification of metal AM parts. Only after successful certification manufactured components (particularly those intended for load-bearing or mission-critical applications) can be integrated into military equipment.

Additive manufacturing is transforming defense procurement, from rapid prototyping and field repair to the production and deployment of qualified end-use components. Armed forces increasingly employ AM to enhance operational readiness by reducing supply chain vulnerabilities and enabling agile, on-demand, and localized manufacturing.

The primary AM technologies currently used in defense applications include, [5]:

- Polymer AM**,** particularly Material Extrusion (MEX) systems, which are widely adopted because of their relatively low acquisition cost, compact size, ease of operation, and plug-and-play capability.
- Metal Additive Manufacturing (MAM) technologies, including Laser Powder Bed Fusion (L-PBF), Directed Energy Deposition (DED), and Cold Spray. Although these technologies require significantly more complex infrastructure and logistics, they are rapidly advancing and are becoming increasingly important for the production of high-performance metal components.

The remainder of this paper is organized as follows. Section 2 provides an overview of the primary standards governing additive manufacturing. Section 3 reviews the conventional qualification process for parts manufactured using traditional production technologies and proposes a qualification new framework for AM components intended for military applications. Section 5 discusses personnel qualification requirements for Metal Additive Manufacturing. Finally, Section 6 outlines the infrastructure requirements for AM facilities and addresses the health and safety (H&S) aspects associated with metal additive manufacturing.

2. AM RELATED STANDARDS

ISO/TC 261 (International Organization for Standardization – Technical Committee) classifies AM standards into three levels, [6]: 1) *General standards:* which define general concepts, common requirements, or provisions applicable to most AM materials, processes, and applications, 2) *Category standards:* which specify requirements applicable to a particular material category (e.g., metal powders) or process category (e.g., Powder Bed Fusion), 3) *Specialized standards:* which define requirements for specific materials (e.g., aluminum alloy powders), specific processes (e.g., Material Extrusion using ABS), or application-specific sectors (e.g., aerospace, medical, or automotive industries).

To date, ISO/TC 261 has published 27 international standards**,** while 32 additional standards are currently under development, [7]**.** The large number of standards reflects the complexity and rapidly evolving nature of additive manufacturing technologies. As AM continues to mature and expand into new industrial sectors, further standardization activities are expected.

The development of AM standards is carried out jointly by ISO and ASTM International (formerly the American Society for Testing and Materials) through close cooperation between their respective technical committees. Such collaboration is essential to ensure that multidisciplinary expertise is incorporated into internationally recognized standards and to promote harmonized industrial practices worldwide.

The ISO/ASTM 52920:2023 standard establishes a comprehensive quality assurance framework that integrates system qualification, process monitoring, and part verification throughout the additive manufacturing process, Figure 2.

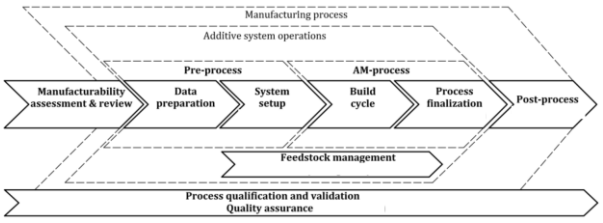


Figure 2. Overview of AM relevant processes in an AM production site

Furthermore, the standard defines the AM-related processes performed within an AM production facility and specifies the corresponding quality requirements for each process. The framework is organized into the following core technical areas, [2]: 1) Infrastructure of the part manufacturer; Manufacturability assessment and review; 2) Qualification of additive manufacturing system operations**,** focusing on machine qualification and risk assessment; 3) Quality-relevant process steps**,** addressing the control of production operations and material management; 4) Quality assurance**,** including personnel competence, final part verification, and the management of nonconforming products.

The minimum requirements for a Quality Management

System (QMS) are specified in ISO 9001. However, several industrial sectors have established sector-specific quality management standards that include additional requirements reflecting their particular regulatory and operational needs.

The most widely recognized examples include IATF 16949 for the automotive industry, ISO 13485 for medical devices, and EN/AS 9100 for the aerospace and defense industries. For organizations intending to supply AM components to the aerospace industry, certification according to EN/AS 9100 is generally considered a mandatory prerequisite, [8].

Based on the principles of ISO 9001, the EN/AS 9100 standard introduces additional requirements that are particularly relevant to aerospace and defense applications. For components manufactured using additive manufacturing technologies, these include: 1) Configuration management and process parameter control, 2) Complete material traceability throughout the manufacturing process, 3) Comprehensive risk management, 4) First Article Inspection (FAI), 5) Supplier qualification and control.

3. CERTIFICATION PROCESS DESCRIPTION AND PROPOSED FRAMEWORK

The certification of Metal Additive Manufacturing (MAM) parts is a complex and multidisciplinary process that typically involves several organizations and institutions. Outsourcing specific qualification activities to pre-qualified organizations can significantly reduce both the time and cost required for part certification while ensuring compliance with applicable standards.

Laser Powder Bed Fusion (L-PBF) is currently the most extensively researched additive manufacturing technology for aerospace applications and is therefore at the forefront of qualification and certification activities.

The National Aerospace and Defense Contractors Accreditation Program (Nadcap) was among the first certification bodies to establish a dedicated audit and accreditation program for Powder Bed Fusion technologies for the application in aviation, defense, and space programs. The Nadcap AM audit evaluates powder management, machine calibration, process control, and part qualification.

3.1 Certification procedure within the Serbian Ministry of Defense of the Republic of Serbia

Within the Serbian Ministry of Defense (MoD), the certification procedure for parts manufactured by the Original Equipment Manufacturer (OEM) is governed by the Regulation on Conformity Assessment in the Production of Armament and Military Equipment (AME) together with the corresponding Implementation Instructions, which provide detailed guidance for the execution of the conformity assessment procedure.

The conformity assessment is performed according to an approved Test Plan and Test Program by the relevant national institutions, including the Overhauling Facility Čačak, the Aeronautical Institute "Moma Stanojlović", the Technical Test Center (TTC), the Military Technical Institute (MTI), and, where appropriate, the relevant OEMs from the Serbian defence industry.

Upon successful completion of the certification activities, the OEM submits the required documentation to the Department for Defense Technology, including the test report, conformity assessment report, and evidence of compliance with applicable management system requirements, primarily the Quality Management System (QMS). Following a technical review of the submitted documentation, the Department issues the final Certificate of Conformity together with the approval for serial production.

3.2 Proposed framework for the certification of AM parts

The proposed framework is intended to optimize the qualification effort throughout the certification process while incorporating internationally recognized best practices for the industrial implementation of Additive Manufacturing.

At present, Serbia does not have a dedicated certification body accredited for the qualification of metal AM components. The institutions from MoD with the highest level of competence in this field are the Technical Test Center (TTC) and the Military Technical Institute (MTI). The proposed certification framework therefore should assume close cooperation between these two institutions. Although neither of these institutions individually possesses the competencies required to perform the complete qualification process, together they can provide comprehensive coverage of the required activities.

For additively manufactured components, conventional qualification procedures originally developed for traditional manufacturing technologies cannot be directly applied without modification. Consequently, a new qualification framework should clearly distinguish part verification from process and production-site qualification, including facility qualification.

The proposed qualification methodology consists of four sequential stages, Figure 3: 1) Process qualification, 2) Part qualification, 3) Functional testing under operational conditions, 4) Issuance of the Certificate of Conformity and production approval.

Process qualification verifies that materials, equipment, manufacturing parameters, and production workflows consistently produce components that satisfy the specified technical and quality requirements. The qualification methodology follows the internationally accepted three-stage approach consisting of Installation Qualification (IQ), Operational Qualification (OQ), and Performance Qualification (PQ), [9].

IQ confirms that the AM machine, software, auxiliary equipment, and supporting infrastructure are installed, calibrated, and maintained in accordance with the OEM's

specifications. This stage also verifies that environmental conditions, including temperature, humidity, ventilation, and safety systems, satisfy the required operating conditions.

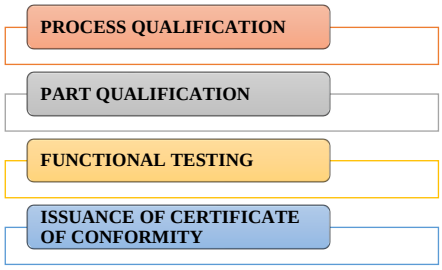


Figure 3. Framework proposal for am part qualification

OQ evaluates the critical process parameters, including laser power, scanning speed, layer thickness, hatch spacing, and other process variables. Qualification specimens are manufactured and tested to verify material properties, process capability, and manufacturing repeatability.

PQ demonstrates that the complete manufacturing process—from design and feedstock preparation to printing, post-processing, and inspection—can repeatedly produce conforming parts over multiple production runs. Qualification specimens are subjected to dimensional inspection, non-destructive testing (NDT), destructive testing, and mechanical property evaluation.

Regardless of the selected production model, whether components are manufactured in-house or supplied by an external supplier, the manufacturing organization must comply with the requirements of ISO/ASTM 52920:2023**.** These requirements are independent of the material system, manufacturing route, or final application. Major OEMs increasingly use this standard as the basis for auditing and approving contract manufacturers.

The certification of the manufacturing process and the qualification of an individual AM component are closely interconnected and cannot be treated as independent activities. An additively manufactured component cannot be qualified unless the complete manufacturing process has first been successfully qualified. Consequently, part qualification represents the final stage of the certified manufacturing process.

According to ISO/ASTM 52920:2023, part qualification includes the following key activities: 1) verification of the manufactured geometry against the approved CAD model, 2) strict configuration and change management to preserve the qualified ("frozen") manufacturing process, 3) validation through co-built witness coupons and First Article Inspection (FAI), including dimensional inspection, non-destructive testing, destructive testing, and mechanical property evaluation. The standard further requires requalification whenever any significant change is introduced into the manufacturing process, equipment, materials, or process parameters.

Upon completion of the qualification activities, the component is subjected to functional testing under representative operating conditions in accordance with the approved Test Plan and Test Program. Only after successful completion of all qualification and testing activities the Certificate of Conformity and the approval for production can be issued.

3.3 Future trends in C&Q

One of the major challenges facing Metal Additive Manufacturing (MAM) is achieving consistent process repeatability. Components manufactured on different machines (even when using the same process parameters and feedstock) may reveal variations in microstructure, mechanical properties, and dimensional accuracy. This lack of reproducibility significantly complicates and prolongs the qualification and certification process.

Another major challenge is the continued reliance on conventional qualification methodologies based primarily on extensive experimental testing. Although these approaches have proven effective for conventionally manufactured components, they are often unsuitable for additive manufacturing because they require large numbers of physical test specimens, resulting in high qualification costs and lengthy development cycles, particularly in highly regulated sectors such as the aerospace and defense industries.

To address these challenges, new qualification methodologies are currently being developed. One of the most significant initiatives is the Computational Materials for Qualification and Certification (CM4QC) program led by the National Institute of Standards and Technology (NIST), U.S. Department of Commerce**.** The objective of this program is to integrate validated computational models into the qualification process, enabling the prediction of component properties and performance while substantially reducing the dependence on costly physical testing, [10].

This model-based qualification approach relies on high-fidelity numerical simulations capable of predicting the influence of manufacturing parameters on the final characteristics of additively manufactured components. For such simulations to be accepted by certification authorities, their predictive capability must first be experimentally validated. To support this objective, NIST has established the Additive Manufacturing Benchmark Test Series (AM-Bench)**,** an internationally recognized benchmark platform for validating computational models. AM-Bench consists of carefully designed experiments performed under strictly controlled conditions, generating high-quality reference datasets that enable researchers to evaluate and compare the accuracy of simulation tools worldwide.

Consequently, the AM-Bench datasets constitute the scientific foundation for establishing confidence in computational models and are expected to play a key role in the future implementation of model-based qualification and certification of additively manufactured components for aerospace, defense, and other safety-critical industries.

4. MAM PERSONNEL QUALIFICATION

Qualified personnel represent one of the most critical resources in additive manufacturing (AM), as in all advanced manufacturing technologies. Similar to other industrial fields, such as welding, the qualification of AM designers and machine operators requires a structured combination of theoretical education and practical training. Practical training is conducted under the supervision of qualified personnel and is followed by a formal qualification assessment consisting of written, oral, and practical examinations. Successful candidates receive certification authorizing them to perform specific AM-related tasks.

In addition to machine operation, other activities associated with additive manufacturing (including post-processing, machining, destructive testing, and non-destructive testing (NDT)) also require appropriately qualified personnel in accordance with the applicable qualification standards, [3].

4.1 Qualification of Operators for PBF-LB

The qualification of operators for Laser Powder Bed Fusion (PBF-LB) systems shall be performed in accordance with a documented qualification procedure or manufacturing plan. Prior to qualification, candidates shall complete the prescribed theoretical and practical training specified by the relevant qualification standard, [4].

The practical examination demonstrates that the operator possesses the knowledge and practical skills required to independently perform all manufacturing activities associated with a specific production task.

Upon successful completion of the qualification process, the operator shall be competent to understand and perform the following activities: 1) principles and operational aspects of the selected AM technology, 2) feedstock handling, storage, and material management, 3) AM system setup, calibration, and preparation, 4) build preparation, process monitoring, and manufacturing operations, 5) post-processing activities, including part removal, cleaning, and inspection.

4.2 Tasks and Competencies of the AM Designer

An **AM Designer** is a professional who applies knowledge of additive manufacturing process capabilities to develop optimized geometrical, functional, and manufacturing-oriented component designs for metal additive manufacturing, without necessarily being responsible for the execution of the manufacturing process [3].

An AM designer should possess both general manufacturing knowledge and specialized expertise in additive manufacturing technologies. In addition, the designer should be proficient in Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and the software tools required to support the complete AM workflow.

The wide variety of engineering challenges associated with metal additive manufacturing directly influences the competencies required of an AM designer. These include occupational health and safety (OH&S) considerations, material behavior, process limitations, geometric inspection, qualification testing, post-processing, and manufacturing economics.

Since Metal Additive Manufacturing (MAM) technologies differ significantly in terms of process characteristics and manufacturing constraints, the designer must understand how these differences influence component design. Typical design considerations include machining allowances for post-processing, build orientation, support structure design, residual stress mitigation, and the selection, location, and orientation of qualification specimens.

An AM designer should be able to understand and perform the following tasks: 1) understand the fundamentals of additive manufacturing technologies and their operating principles, 2) apply Design for Additive Manufacturing (DfAM) principles, 3) develop component designs optimized for additive manufacturing, 4) perform pre-processing and build data preparation, 5) define process control requirements during manufacturing, 6) identify appropriate post-processing methods based on functional requirements, 7) evaluate manufacturing costs while considering technical and quality requirements, according to [3].

5. INFRASTRUCTURE AND OH&S CHALLENGES

5.1 Infrastructure challenges

The highest level of qualification for an organization involved in Additive Manufacturing (AM) extends beyond the qualification of manufacturing processes and includes the organization's overall quality infrastructure. The scope of qualification depends on the company's activities and production portfolio.

For example, the MTI has implemented an Integrated Quality Management System (IQMS) comprising certification according to several internationally recognized standards, including ISO 9001 (Quality Management System), ISO 14001 (Environmental Management System), ISO 45001 (Occupational Health and Safety Management System - OH&S), ISO/IEC 27001 (Information Security Management System), and accreditation of testing laboratories in accordance with ISO/IEC 17025**.**

In addition to implementing an Integrated Quality Management System, the introduction of advanced Metal Additive Manufacturing technologies, such as Laser Powder Bed Fusion (PBF-LB/M), requires additional qualification procedures. In particular, qualification of the production facility in which the AM equipment is installed is mandatory.

A qualified AM production facility should include dedicated areas for design and engineering activities, production, metrology, post-processing, material handling and storage, quality inspection, and supporting activities

required throughout the AM workflow illustrated in Figure 1.

Ultimately, a qualified AM production facility consists of qualified personnel, qualified equipment, and qualified manufacturing processes operating within an integrated quality management framework to consistently produce components that satisfy all specified requirements, [9].

5.2 OH&S challenges

The use of metallic powders in additive manufacturing introduces a number of new occupational health and safety challenges. Although many metallic alloys employed in AM present relatively low health risks, fine aluminum and titanium powders represent significant fire and explosion hazards because of their high reactivity and large specific surface area. As metal additive manufacturing continues to expand across industrial sectors, organizations must identify, assess, and mitigate these hazards through systematic risk management.

Risk mitigation should follow the internationally accepted **Hierarchy of Controls**, which consists of five levels: 1) Elimination, 2) Substitution, 3) Engineering Controls, 4) Administrative Controls, 5) Personal Protective Equipment (PPE).

Before implementing Metal Additive Manufacturing technologies, organizations should perform a comprehensive occupational health and safety assessment covering all stages of powder handling, machine operation, post-processing, maintenance, waste management, and emergency response procedures, [11].

6. CONCLUSION

The qualification and certification of metal components manufactured by AM represent a new and strategically important field for the Republic of Serbia, particularly in the context of defence applications. The implementation of internationally recognized qualification principles is essential for ensuring the reliability, repeatability, and traceability of AM processes and for enabling the safe integration of additively manufactured components into military equipment.

This paper has presented an overview of the qualification and certification requirements for Metal Additive Manufacturing (MAM), with particular emphasis on the requirements defined in ISO/ASTM 52920:2023**.** The proposed framework aligns the requirements of international AM standards with the existing national conformity assessment system and identifies the complementary roles of the Technical Test Center (TTC) and the Military Technical Institute (MTI) in establishing a future national certification capability.

The paper also discussed the differences between conventional and additive manufacturing qualification approaches and highlighted emerging trends, including model-based qualification initiatives currently being developed by NIST.

Future research will focus on validating the proposed qualification framework through representative case studies, establishing standardized testing procedures for AM components intended for military applications, and supporting the development of an accredited national certification capability.

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