

Advisory Circular

CERTIFICATION, DESIGN AND PRODUCTION OF ARTICLES FABRICATED BY ADDITIVE MANUFACTURING

GENERAL.....	1
PURPOSE	1
APPLICABILITY	1
RELATED REGULATIONS	1
RELATED ADVISORY CIRCULARS	1
CANCELLATION.....	1
EFFECTIVE DATE.....	1
REFERENCES.....	2
1 INTRODUCTION	2
2 USE OF ADDITIVE MANUFACTURING	2
APPENDIX A - DESIGN ORGANISATION USING ADDITIVE MANUFACTURING.....	4
APPENDIX B - PRODUCTION ORGANISATION USING ADDITIVE MANUFACTURING.....	8

GENERAL

Advisory Circulars (ACs) are issued by the Director-General of Civil Aviation (DGCA) from time to time to provide practical guidance or certainty in respect of the statutory requirements for aviation safety. ACs contain information about standards, practices and procedures acceptable to CAAS. An AC may be used, in accordance with section 11 of the Air Navigation Act 1966 (ANA), to demonstrate compliance with a statutory requirement. The revision number of the AC is indicated in parenthesis in the suffix of the AC number.

PURPOSE

This AC provides information and guidance on the use of additive manufacturing in design activities and in the production of articles under Singapore Airworthiness Requirements (SAR) Part 21.

APPLICABILITY

This AC is applicable to applicants and holders of SAR Part 21 design and production organisation approvals.

RELATED REGULATIONS

This AC relates specifically to SAR Part 21.

RELATED ADVISORY CIRCULARS

- AC 21-1 Approval Requirements for Modifications and Repairs

CANCELLATION

This is the first AC issued on this subject.

EFFECTIVE DATE

This AC is effective from 26 May 2023.

REFERENCES

1. Singapore Airworthiness Requirements (SAR) Part 21, CAAS
2. 14 Code of Federal Regulations (CFR) Part 25, FAA
3. Certification Specifications (CS) Part 25, EASA
4. Recommended Guidance for Certification of AM Component, AIA Additive Manufacturing Group, February 2020 (RGCAMC)
5. Job Aid for Evaluating Additive Manufacturing at an MRO, FAA, December 2018
6. Certification Memorandum Additive Manufacturing, No. CM-S-008 Issue 3, EASA
7. Singapore Standard on Qualification of Parts Printed by Metal Additive Manufacturing, SS 666:2020, 27 November 2020
8. Technical Reference on Design Guidelines for Additive Manufactured Parts, TR 92:2021, 30 July 2021

1 INTRODUCTION

- 1.1 This AC provides guidance to design and production organisations who may be seeking CAAS' approval for the use of additive manufacturing (AM) in design and production of articles.
- 1.2 As AM involves a variety of machine, process and material options, the knowledge on common article defects or deficiencies associated with each AM technology may vary. The integrity and quality of the AM article to meet the design intent and requirements may be affected by many variables in the design and production processes. The significance of each variable may differ depending on the applications, processes, equipment, material and other resources used. Users of AM technology need to have a thorough understanding of the factors that can influence the integrity and quality of the article, develop and implement necessary controls in their design and production to meet their proposed use of AM. Different sets of tests, controls and inspections as part of design or production control, as compared to conventional manufacturing processes, may have to be developed to ensure robustness of the design or production control systems.

2 USE OF ADDITIVE MANUFACTURING

- 2.1 The Design Organisation Approval holder (DOA) and Production Organisation Approval holder (POA) should update their Exposition before incorporating, outsourcing or amending any design or production process involving the use of AM, including any update to the design and production controls (e.g. design control system needs to be updated due to a change of AM design capabilities, production control system needs to be updated due to a change to a production capability process).
- 2.2 The DOA and POA must submit proposed amendments to the Exposition for CAAS' approval. The submission should be made early, preferably at least 3 months ahead of the planned use of AM, and include information and appropriate justifications to enable CAAS to assess the proposed use of AM. Such information includes considerations on the safety impact and criticality of the article, maturity of the process, availability of reliable material data and the plans to obtain or establish the necessary specifications for the material, machine and process to be used. Areas that CAAS may consider in its assessment for DOA and POA are detailed in **Appendices A and B** respectively.

- 2.3 CAAS may prescribe special conditions for an article to establish a level of safety equivalent to the airworthiness design standards specified in SAR 21.755. For example, when AM is used to manufacture an article as part of a modification or repair and it is determined that the airworthiness design standard used does not sufficiently address specific airworthiness design issues for the specific case, additional requirements will need to be specified in the special conditions for such an article.
- 2.4 A modification or a repair that utilises AM may involve usage of a different material or a different production process to manufacture the article. The design approval holders must follow the procedures defined in their approved Exposition or check with CAAS for the major or minor classification of the modification or repair.
- 2.5 The DOA and POA may utilise relevant industry standards (e.g. ASTM, ISO and SAE) for the design, materials, manufacture, testing, etc. of an AM article. Industry standards may be utilised to demonstrate compliance of the design to the applicable airworthiness requirements.

APPENDIX A - DESIGN ORGANISATION USING ADDITIVE MANUFACTURING

This Appendix details the typical areas that CAAS will consider when assessing whether a design organisation is ready to add AM capabilities into its work processes and system.

A1. Collaboration with Production Organisation

A1.1 The scope and responsibilities of the collaboration between the DOA and POA should be well-defined and include details on the transfer of technical information, advice on producibility of part designs, handling of continuing airworthiness issues and the materials review board (MRB) process to manage production deviations and article non-conformances. The following should be established between the DOA and POA:

- process to ensure timely and accurate transfer of technical information to the POA;
- factors and criteria on the acceptability of common production deviations (e.g. mixing of old/new material, number of times materials may be reused, requirements to requalify/recalibrate additive manufacturing machine after certain event), to ensure manufactured articles are of the desired quality;
- acceptance criteria of article non-conformances, which may be dependent on the type/criticality of article, to ensure that manufactured articles are of the desired quality;
- process to support MRB requests related to material issues;
- process to assist POA to evaluate production deviations; and
- process to assist POA to evaluate article non-conformances.

A1.2 The DOA should work closely with the POA, to ensure that the article design is sufficiently defined and had considered production limitations associated with the manufacturing process (e.g. use of suitable software file format, geometrical / manufacturing limitations of machine, tool / print head angle and access, proper placement of support material, etc.) to enable the POA to fabricate the article accurately.

A2. Design Controls

A2.1 The DOA should establish design controls at various design stages to ensure that the design can be consistently manufactured through a reliable production process.

Validation of Existing Material / Test Programme for New Material

A2.2 A test programme to collect material properties is necessary if there is no published technical data or specifications for the material to be used. Specifications and material information for existing material may be validated if it meets applicable airworthiness design requirements.

A2.3 The DOA may refer to industry standards or other internationally recognised specifications on the constituents of a material specification. Examples can be found in the following paragraphs of the RGCAMC:

- “Feedstock Material Specification” lists typical areas of a feedstock material specification.

- “Part Material Specification” lists the typical contents of a specification for a manufactured article.

A2.4 The DOA should determine the following when validating an existing material, or developing a test programme for a material:

- Application limitations of the material data (e.g. grain/material direction¹, machine-to-machine variability).
- Physical properties required of the feedstock material (e.g. powder particle size, morphology, surface and distribution, density (tap and apparent), flowability / pourability, ash content, and carbon content).
- Limitations for handling, and use of feedstock materials (e.g. number of times of re-use and mixing, proportion of mixture of new/old materials).
- Machine-to-machine variability when developing or compiling material data properties.
- Material properties data used in the design meets the applicable airworthiness design requirements such as mechanical strength, flammability requirements, statistical requirements (e.g. 14 CFR 2x.613 on “Material Strength Properties and Material Design Values”).
- Material test coupons to be used in the test programme are manufactured to an established production control process, to show that articles are consistently produced per the defined design and meets the applicable airworthiness design requirement (e.g. 14 CFR 2x.605 on “Fabrication Methods”).
- Any incompatibility of materials that are used for multi-material AM.

A2.5 A test programme to validate the material and manufacturing process for an AM article may consist of a series of progressive tests to screen the feedstock material, manufactured article and assembled component.

Article Design

A2.6 The DOA should consider the following when designing the article:

- Intended or worst-case operating environment of the article to determine the limits for the material used, as required by applicable airworthiness requirement e.g. 14 CFR 2x.603 on “Materials”.
- Damage-tolerance, static and fatigue strength requirements of the article, depending on the application, as required by applicable airworthiness requirement e.g. 14 CFR 2x.571 on “Damage Tolerance and Fatigue Evaluation of Structures”.
- Expected characteristics and limitations of the manufactured article for the selected AM process and machine.
- Dimensional and material limitations due to the AM machine and apply geometry and dimensional corrections / tolerances on the manufactured article design to account for deviations (e.g. thermal distortion) that may be encountered during production.
- Effect of support structure, print position, and manufacturing orientation on material testing.

¹ The paragraph on “Material Allowables and Design Values Development” in the RGCAMC provides examples of application limits of materials.

- Inspections² to verify that the produced articles are in accordance with the approved design (e.g. first article inspection, sampling rate, production parameters to monitor, test material which follows every production batch, types of inspections and tests, etc).

Modelling and Analysis

A2.7 The DOA should consider the following for the modelling and analysis of the article design:

- Geometry corrections for the model where necessary (e.g. certain AM processes could result in deviation in geometry).
- Document the steps for modelling of the article, such as if there is a need to convert surface models to solid volumes before performing polygonization / triangulation.
- Placement of support material as there is possibility of surface damage when removing support material. Some software may place support material automatically and such automated placement of support material should be evaluated.
- Correction factors to the analysis where the finite element models do not account for certain article features or characteristics e.g. grain growth, manufacturing temperature, surface finish.
- Software to be used to access the electronic file.

Additive Manufacturing Process Control

A2.10 The DOA should work with the POA to determine the production control process required for the fabricated AM parts, which should include the setting of Key Process Variables (KPVs)³ and acceptable tolerance of production parameter to ensure that the article meets the required form, fit and function of the design.

Post Additive Manufacturing Processes

A2.11 Post AM processes are an integral part of the manufacturing process, and the DOA should work with the POA to define the required processes to fabricate the AM article designed, and should include:

- where the same article may be produced by more than one type of manufacturing process, AM articles should be marked such that it is clear that the article has been manufactured by AM;
- verification / sampling tests requirements at production to ensure that the produced articles have been manufactured in accordance with the design; and
- the removal of support / excess material (that may cause result in stress concentrations or microstructural changes), if such post AM process is necessary.

² Refer to the chapter on “inspection” in the RGCAMC for possible inspection techniques.

³ The chapter “Development Process” in the RGCAMC provides a guide on defining KPVs.

A3. Personnel Training

- A3.1 The DOA should ensure that the article design is performed by personnel who has undergone sufficient training, to enable the proper execution of tasks assigned. Training requirements should be set and planned as necessary.
- A3.2 The DOA should develop a training programme that consists of initial and recurrent training to equip designers, DOA Design Signatories and other relevant personnel with sufficient knowledge to perform their respective tasks effectively. The training programme should include:
- Training of relevant personnel to be proficient in calling out critical dimensions for inspection of first article and subsequent articles, procedures for installation of AM article (if any), special process treatment of the AM article, or important parameters to note during manufacturing of the article (i.e. chamber temperature; article build direction); and
 - Training of relevant personnel to be proficient in identifying and rectifying errors/limitations in the process of obtaining the required additive manufacturing file format.
- A3.3 The DOA should regularly review its personnel training programme and align with its current and future AM activities.

APPENDIX B - PRODUCTION ORGANISATION USING ADDITIVE MANUFACTURING

This Appendix details the typical areas that CAAS will consider when assessing whether a production organisation is ready to add AM capabilities into its work processes and system.

B1. Collaboration with Design Organisation

B1.1 The scope and responsibilities of the collaboration between the design and production organisations should be well-defined. The responsibilities to be defined should include transfer of technical information, assistance to manage production issues, handling of continuing airworthiness issues and details of the materials review board (MRB) process to manage production deviations and article non-conformances. The following should be established between the DOA and the POA:

- process to ensure timely and accurate transfer for technical information from DOA;
- Well-defined incoming, in-process and post-process/final inspection requirements, including the process to manage production deviations;
- in-process monitoring procedures to cater to possible causes of defects;
- criteria on the acceptability of common production deviations (e.g. mixing of old/new material, number of times materials may be reused, exceedance of typical production parameter ranges, requirements to requalify/recalibrate AM machine after certain event);
- acceptance criteria of article non-conformances, which may be dependent on the type/criticality of the article. The acceptance criteria should be aligned with the DOA's expectations on the quality of manufactured articles;
- MRB process and DOA's involvement in the MRB on material issues;
- process to evaluate production deviations and DOA's involvement;
- process for DOA to provide assistance on evaluation of non-conformances articles.

B1.2 The POA should obtain technical advice from the DOA on AM matters that may affect the quality of the manufactured article.

B2. Production Control

B2.1 The POA should establish production controls at various stages to ensure articles are being manufactured in accordance with a documented process for consistency.

Additive Manufacturing Process

B2.2 The POA should incorporate the following production controls in the fabrication of AM articles:

- production control procedures that document the AM process and include the areas listed under "Process Specification" in the RGCAMC;
- a quality control plan to control and monitor critical material properties and key features dimension in every batch, which should also establish the acceptance criteria for any necessary process monitoring inspection(s) and test(s);
- procedures for handling, mixing of raw materials (such as number of times of mixing, proportion of mixture of new/old materials);

- measures to ensure that the previous feedstock material has been fully purged / removed from the machine;
- procedures for the operator to start-up, check, operate, monitor, pause / shutdown the machine;
- process to manage build interruptions;
- acceptable tolerance range of operating parameters for the machine;
- records of the actual manufacturing parameters;
- production parameters (e.g. operating environment, AM build chamber) should be controlled or checked against during / after manufacturing.

Post AM Process

- B2.3 The POA should incorporate controls for post processing of AM articles, such as removal of build plate and support material to minimise any negative effects on the material or article produced. The POA may refer to the RGCAMC for more details on “Post-Process Plans”.

Other Production Aspects

- B2.4 The POA should work with the DOA to establish a process to manage production deviations. Certain production deviations from the established production process may affect the quality of the produced article and require requalification of the process and machine / equipment. The POA should refer to the RGCAMC for scenarios which may require requalification of the machine / equipment / process.
- B2.5 The POA should work with the DOA to determine the record keeping requirements. The production records of feedstock material used should provide sufficient traceability on the material for troubleshooting or investigation into defects of produced articles. For example, the records kept should include the material records from the manufacturer / supplier, new/used material mixture proportion, number of times which the material has been reused, date which material was used and the material expiry date. The POA may refer to the RGCAMC on the records that should be kept for AM articles.
- B2.6 Statistical process control may be employed to monitor production parameters which may be used as part of an inspection programme. The POA should refer to the RGCAMC to identify areas of post processes to pay attention to, and for guidance on the use of Statistical Process Control methodology.

B3. Personnel Training

- B3.1 The POA should ensure that the various stages of production, including handling of design data, incoming material inspections, in-process monitoring, post-processing, assembly and other processes required to fabricate the article, are performed by personnel who has undergone sufficient training, to enable the proper execution of tasks assigned.
- B3.2 The POA should develop a training programme that consists of initial and recurrent training to equip machine / equipment operators, POA Certifying Staff and other relevant personnel with sufficient knowledge to perform the specific tasks effectively. The POA may refer to the RGCAMC for a list of topics that may be included in the

training curriculum. The training programme should ensure that relevant personnel are trained to:

- be proficient in interpreting drawing requirements of the DOA and convert them to manufacturing instructions and other documents / files necessary for production.
- be proficient in the usage of AM software, which may be different depending on the AM process and software used by DOA.
- be proficient in using the AM machine and other equipment that form part of the entire production process. The relevant personnel should attend all the necessary training, such as those provided by the OEM / supplier of the equipment.
- understand the storage and handling of the raw materials and effectively perform their required roles.

B3.3 The POA should regularly review its personnel training programme and align with its current and future AM production activities.