Introduction to “Guidelines for Additive Manufacturing (3D Printing)”

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1. INTRODUCTION

In recent years, the development of metallic products using additive manufacturing (AM) technologies, notably 3D printing, has spread rapidly, and in particular, this technology is used in fields such as automobiles, aerospace, medicine and industrial machinery. One reason for this rapid growth is the molding capability of AM, which makes it possible to produce shapes that were impossible with conventional technologies and is a distinctive feature of AM. Because this capability realizes molding of complex 3-dimensional shapes, grating structures and graded structures and makes it possible to manufacture highly designed products, additive manufacturing is expected to bring about a major revolution in manufacturing in the future.

Additive manufacturing has a long history, dating from the invention of optical modeling using ultraviolet rays and photosensitive resin in Japan at the beginning of the 1980s, and was subsequently commercialized by American and Japanese companies. Although the use of this technology initially concentrated in resin modeling, research on application to metal materials was also begun in the United States, and a large number of AM machines have been developed to date.

Recently, cost reduction and improved productivity have been strongly demanded in all manufacturing industries. AM technology has attracted considerable interest as a breakthrough solution to this problem, as it enables efficient manufacturing and is also a labor-saving process. Since the market scale of AM machines is also increasing by the year, a further expansion of the fields of product manufacturing utilizing AM technology is foreseen in the future, including application to the marine equipment field.

Against this backdrop, as an introduction to additive manufacturing technology, ClassNK prepared “Guidelines for Additive Manufacturing (3D Printing)”, which summarizes the terminology, types and characteristics of AM technology, together with the approval requirements for metallic marine equipment manufacturing using AM. The following introduces the content of the Guidelines.

2. INTRODUCTION TO THE GUIDELINES

2.1 Fundamental Knowledge of Additive Manufacturing (Part 1 of the ClassNK Guidelines)

2.1.1 Terminology

Because the terminology used in the Guidelines is the basic terminology of additive manufacturing (hereinafter called “AM”) technology, the terminology used in this documents is defined referring to international standards such as ISO and JIS or national standards. Specifically, the standards used as reference are as follows.

(1) ISO/ASTM 52900 : 2015 “Additive manufacturing – General principles – Terminology”

(2) JIS B 9441: 2020 “Additive manufacturing – General principles − Vocabulary and fundamental concepts”

2.1.2 Additive Manufacturing Technologies (AM Technologies)

The seven technologies listed in the following Table 1 have been defined as the basic types of AM technologies. Among these, the AM technologies which are mainly used in manufacturing metallic products are generally the powder bed diffusion (PBD) process and the direct energy deposition (DED) process. However, these Guidelines present the overview, feedstocks and process after lamination for all seven types of AM technology in Table 1. The categorization of the main AM technologies using each feedstock is also shown in Fig. 1.

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Table 1　Types of AM technologies

	Additive Manufacturing Technology
1	Binder Jetting：BJT
2	Material Jetting：MJT
3	Powder Bed Fusion：PBF
4	Directed Energy Deposition：DED
5	Sheet Lamination：SHL
6	Vat Photopolymerization：VPP
7	Material Extrusion：MEX

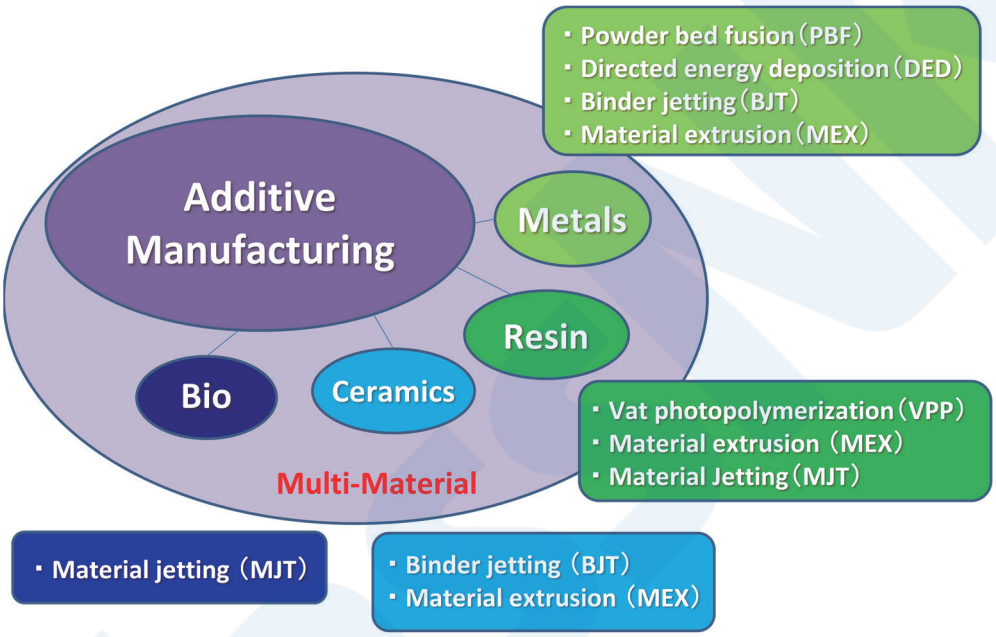

Fig. 1　Categorization of main AM technologies used for feedstocks

2.2　Handling of Metallic Marine Equipment Manufactured with AM (Part 2 of ClassNK Guidelines)

2.2.1　General

(1) Application

ClassNK (hereinafter, also referred to as the Society) regards AM technology as an alternative to casting technology and assumes that there will be cases in which products and parts that have been manufactured using casting technology until now will be manufactured using AM technology in the near future. Accordingly, products which are cast products used in ships and require the approval of the Society are considered to be the objects of application of these Guidelines. The specific targets of application are assumed to be the metallic products mentioned in Chapter 3, Part 1 of Guidance for the Approval and Type Approval of Materials and Equipment for Marine Use (in case NK approval materials are used), as shown in the following Table 2. A separate approval scheme has been prepared to respond to requests for approval of metallic products other than those in Table 2 (called “not NK approval material” in the table), and its content is introduced in section 2.2.5 below.

Table 2　Examples of products subject to application of the Guidelines

Material classification		Product classification
Castings	Carbon steel castings*	(1) Component parts for hull (Examples : stern frames, rudder frames, rudder stocks, etc.) (2) Component parts for Diesel engines (Examples : connecting rods, piston rods, piston crowns, cylinder covers, etc.) (3) Crankshafts (4) Component parts for shafting (Examples : thrust shafts, intermediate shafts, propeller shafts, etc.) (5) Component parts for power transmission gears (Examples : reduction gears, reduction gear shafts, etc.) (6) Component parts for steam turbines (Examples : turbine rotors, turbine discs, turbine blades, etc.) (7) Component parts for piping (Examples : valves, pipe fittings, etc.) (8) Component parts for cargo gears (Examples : gooseneck pins, gooseneck brackets, etc.) (9) Component parts for boilers and pressure vessels (except those for low temperature service.) (10) Component parts for ships carrying liquefied gases in bulk
	Low-alloy steel castings	
	Stainless steel castings	
	Steel castings for low temperature services	
	Spheroidal graphite iron castings	
	Grey iron castings	
Forgings	Carbon steel forgings*	
	Low-alloy steel forgings	
	Stainless steel forgings	
	Steel forgings for low temperature services	

(2) Approval flow

The approval flow in these Guidelines is shown in Fig. 2. As mentioned in the above (1), when products that fall under Table 2 are to be manufactured using AM technology, the flow denoted by "NK approval material" in Fig. 2 is applied. In case an applicant wishes to obtain approval on a voluntary basis for a metallic product which is not included in Table 2 (i.e., use a not NK approved material), the flow denoted by "Not NK approval material" is applicable. The detailed contents of the items in the flow shown in Fig. 2 are described in 2.2.2 "Type Approval of Feedstocks," 2.2.3 "Approval of Manufacturing Process," 2.2.4 "Test and Inspection of Products" and 2.2.5 "Preliminary Examination of Products to be Manufactured."

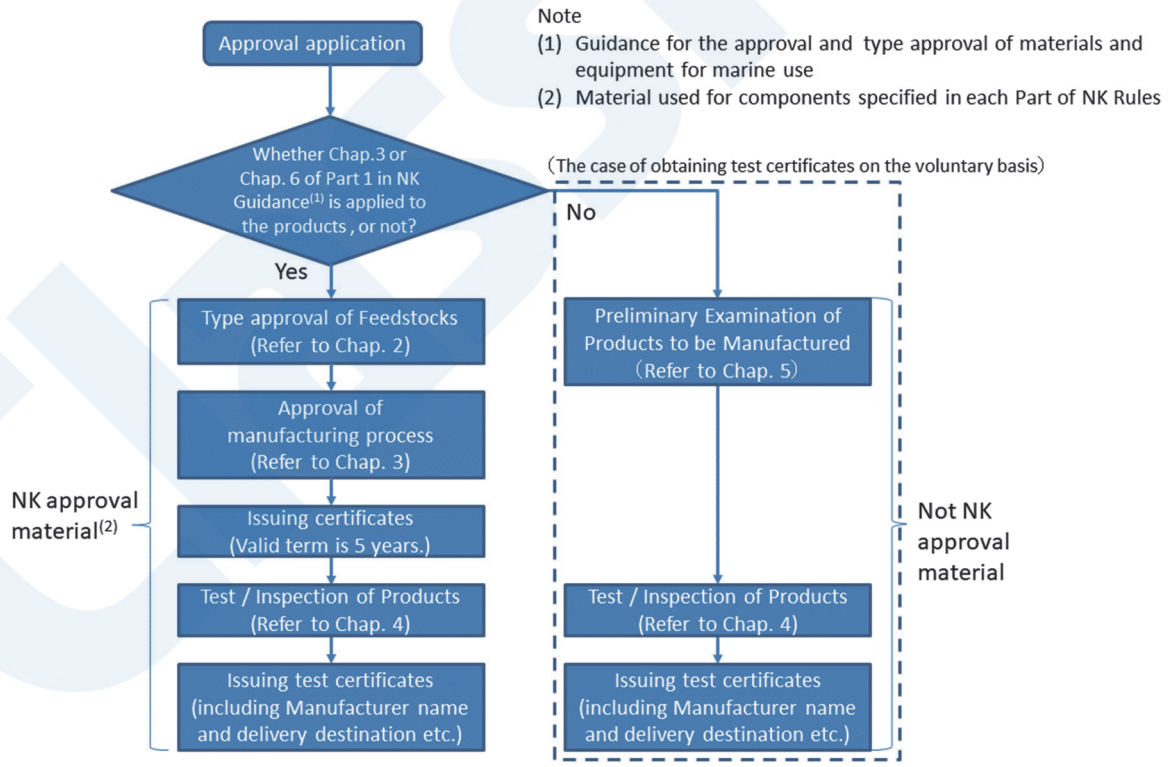

Fig. 2　Approval flow

(3) Feedstocks and product material symbols

For the symbols of AM feedstocks and products, the symbols defined in public standards such as Part K of the Society's Rules for the Survey and Construction of Steel Ships or international or national standards (e.g., JIS, ISO, etc.) recognized as appropriate by the Society are to the used.

For feedstocks for AM, the designation -F-AM is to be added after the material symbol of the feedstock, and is to be followed

by the symbols indicating the type of heat treatment, as described below (Table 3) and the material symbol for the type of AM (Table 4). When necessary, the symbols for the hydrogen content (-H5, -H10, -H15) defined in Chapter 6, Part M of Rules for the Survey and Construction of Steel Ships may also be used.

For products manufactured by AM, the designation -AM, the symbols indicating the type of heat treatment in Table 3 and the material symbols indicating the type of AM technology used in Table 4 are to be added after the material symbol of the material.

Table 3　Symbols indicating type of heat treatment

-A	As printed
-SR	Stress relieve heat treated
-SA	Solution annealed / e.g., for homogenization
-HIP	Hot isostatic pressed
-HPHT	High pressure heat treatment
-X	Other heat treatment

Table 4　Symbols indicating type of AM technology

MJT	Material jetting
PBF-LB	Powder bed fusion for laser beam melting
PBF-EB	Powder bed fusion for electron beam melting
PBF-SL	Powder bed fusion for selective laser melting
LMD	Laser metal deposition
WAAM	Wire arc additive manufacturing
Other AM	Must be recognized as appropriate by the Society

Examples of the description of material symbols are shown below.

KSCA45-F-AM-A-WAAM:

Feedstock for low-alloy steel castings KSCA45 as-printed by wire arc additive manufacturing

KFCD45-AM-A-PBF-LB:

AM product of spherical cast graphite cast iron KFCD45 as-printed by powder bed fusion for selective laser melting

2.2.2　Type Approval of Feedstocks

(1) Flow of type approval

The flow of type approval of feedstocks is shown in Fig. 3. Here, as the “Application,” it is assumed that the application for type approval is submitted by the material supplier. The details of the respective items are shown below in (2) and the following sections. Materials approved by the Society are required to be used in main structures such as the hull structure, engine, etc. in ships which are registered as ClassNK ships. The same concept is also applied to materials for metallic marine equipment, etc. which is manufactured by AM.

Fig. 3　Flow of type approval of feedstocks

(2) Submitted documents

Table 5 shows the minimum level of the documentation which is to be submitted when applying for type approval. Some of the submitted documents may be omitted in case the feedstock has already received type approval by the Society and these documents would duplicate those submitted in the previous application.

Table 5 Documents to be submitted for type approval of feedstocks

	Submitted documents
①	Application for type approval of feedstocks
②	Type approval test plan (including acceptance criteria)
③	Outline of manufacturing plant (a) Name and location of plant (b) History (c) Organization and number of employees
④	Documents for manufacturing processes (a) Manufacturing processes (including the flowchart of each of the main processes) (b) Outline of the main manufacturing facilities
⑤	Documents for feedstocks (including information such as the names and locations of material suppliers) (a) Manufacturing process and type of feedstocks (b) Feedstock characteristics (e.g., in the case of powders, flowability and fillability) ● Wire type: Documents concerning the type of core wire, chemical composition, acceptance procedure, wire drawing, rust prevention and wire diameter ● Powder type: Documents concerning the main composition, density, surface area, particle size distribution, flow property, uniformity/equivalence, morphological characteristics, inter-particle friction, particle agglomeration, etc. (c) Characteristics of products manufactured by AM (tensile strength range, etc. for each AM technology) (d) Management method in AM site (e) Reuse criteria and methods (if applicable)
⑥	Documents for quality management of feedstocks (a) Quality management system and criteria (b) In-house inspection standards and inspection facilities (c) In-house inspection department and complaint handling department (d) Example of shipping certificate
⑦	Documents for past manufacturing record for main feedstocks
⑧	Documents for chemical composition of feedstocks
⑨	Documents for heat treatment (if performed)
⑩	Documents for storage methods and storage periods before and after unsealing (if performed)
⑪	Documents for packaging, shipping marking and traceability
⑫	Documents for the use method and additive manufacturing technology to be applied (including recommended conditions)
⑬	Other documents as deemed necessary by the Society

(3) Confirmation of manufacturing and quality control procedure (confirmation survey)

The purpose of this survey is to confirm that the applicant has the capability (facilities, technology, quality management and in-house inspection department) to consistently manufacture the feedstock which is the object of certification at the same level or exceeding the level of the feedstock used in the type approval test with uniform and continuous quality. In conducting the survey, mainly the following items are confirmed.

- Manufacturing processes
- In-house inspection and complaint handling department
- Manufacturing facilities and inspection facilities
- Company standards, work standards, the quality management system and their implementation status

(4) Type approval test

Tests in connection with the following items (Table 6) are to be conducted in accordance with the test plan approved by the Society. The purpose of these tests is to confirm the soundness of the material.

Table 6　Type approval test

Test item	Content of test
Analysis of chemical composition	The analysis of the chemical composition is to be conducted by a method, such as JIS G 0321, which is recognized as appropriate by the Society to confirm that the analysis result is the same as the value shown in the document (Submitted documents (8)) submitted previously.
Tensile test	The tensile test is to be conducted using a test piece prepared at the same time as the product (certified maximum dimensions) manufactured using the feedstock to confirm that the test result conforms to the acceptance criteria described in the test method approved in advance. For tensile test pieces, considering the anisotropy of the structure due to rapid melting and solidification, at least 3 test pieces are to be prepared for each of the test angles as shown in Fig. 4 to Fig. 6.
Structure observation	The structure of the test pieces is to be observed in cross sections in each of the directions x, y and z to confirm that the structure is continuous and contains no defects (cavities, lack of fusion, etc.) that could possibly cause failure.
Other tests (if recognized as necessary by the Society)	Additional tests may also be required, such as the hardness test, bending test, impact test, surface roughness test, brittle fracture test, fatigue test, corrosion test, hydrogen test, powder reuse test, particle size distribution test, particle morphology test, metal powder flow test, repose angle test, shearing strength test and compressive strength test.

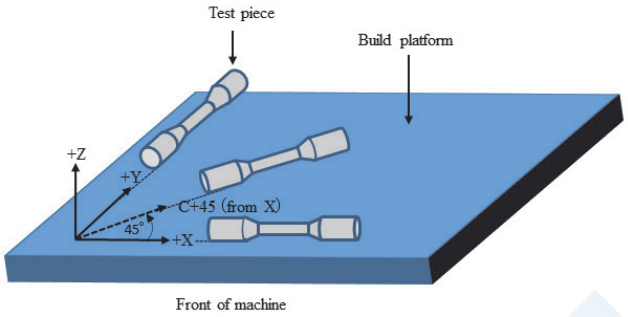

Fig. 4　Tensile test piece [0 degrees]

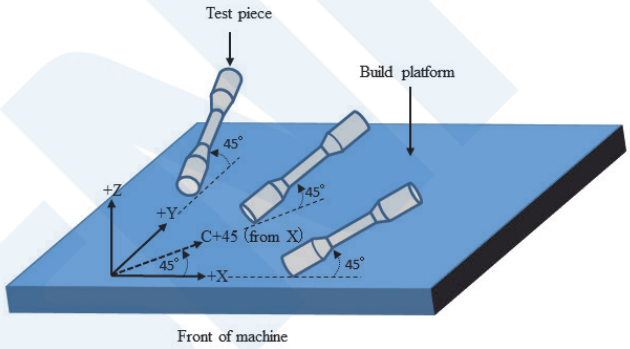

Fig. 5　Tensile test piece [45 degrees]

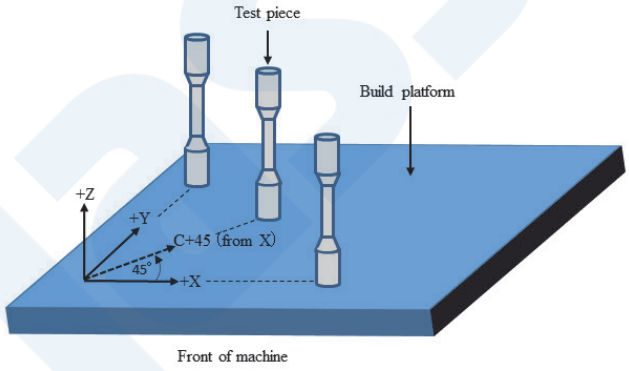

Fig. 6　Tensile test piece [90 degrees]

(5) Acceptance criteria

The acceptance criteria are to be determined by the applicant with reference to public standards such as Part K of Rules for the Survey and Construction of Steel Ships or international standards or national standard (e.g., JIS or ISO) recognized as appropriate by the Society.

(6) Notification of type approval

The Society issues a type approval certificate for each brand for feedstocks recognized as appropriate in accordance with the documentary examination, confirmation of the manufacturing and quality control procedure and test report. The validity period of the type approval certificate is to be one year from the date of issuance.

2.2.3　Approval of Manufacturing Process

(1) Flow of approval

The approval of the manufacturing process means that it is proven that the manufacturing process can be judged appropriate

for the product in question by conducting the examinations, tests and inspections of the product, based on prior confirmation of the manufacturing process and quality management for a representative product, premised on uniformity of product quality. The flow of this approval procedure is shown in Fig. 7. Here, it is assumed that the "Application" is submitted by the owner who controls the entirety of the AM system.

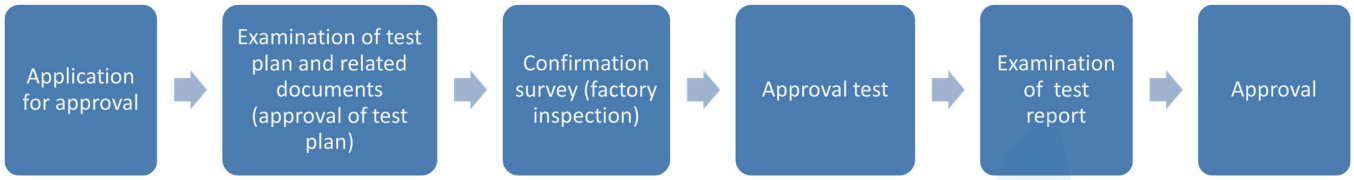

Fig. 7　Flow of approval of manufacturing process

(2) Submitted documents

Table 7 shows the minimum level of documentation which is to be submitted when applying for approval of the manufacturing process. Some of the submitted documents may be omitted in case the product has already received the approval of the Society and these documents would duplicate those submitted in the previous application process.

Table 7　Documents to be submitted for approval of manufacturing process

	Submitted documents
①	Application form for approval of the manufacturing process
②	Approval test plan (including acceptance criteria)
③	Outline of the manufacturing plant (a) Name and location (b) History (c) Organization and number of employees
④	Documents for the additive manufacturing machine to be used (including the maximum dimensions and maximum thickness)
⑤	Documents for manufacturing processes (including documents describing the deposition rate and topology optimization)
⑥	Documents for feedstocks (including information such as the names and locations of material suppliers) (a) Manufacturing process (b) Feedstock characteristics (e.g., flowability and fillability in the case of powders) (c) Management method (d) Criteria and method of reuse (if applicable) (e) Quality management
⑦	Documents for quality management of products (including testing machines, etc.) (a) Quality management system and management criteria (b) In-house inspection standards and inspection equipment (c) In-house inspection department and complaint handling department (d) Example of shipping certificate
⑧	Documents for heat treatment methods (if applicable) (a) Heat treatment furnaces (types, dimensions, locations of heat source and thermocouples, etc.) (b) Heat treatment conditions (temperature, holding time, cooling medium, etc.) (c) Heat treatment record-keeping method
⑨	Documents for nondestructive testing (including employee list)
⑩	Documents for production records of main products
⑪	Documents for the chemical composition and mechanical properties of products
⑫	Documents for the weldability of products (if applicable)
⑬	Documents for the surface state (roughness, finishing state, etc.)
⑭	Documents for repair procedures (including the allowable condition of flaws)
⑮	Other documents as deemed necessary by the Society

(3) Confirmation survey (factory inspection)

The factory inspection is conducted to confirm that the applicant possesses the facilities, processes, quality management and other capabilities necessary to manufacture the product with uniform quality. This inspection is conducted at an appropriate time

so that the actual AM system, manufacturing process, etc. can be surveyed.

(4) Approval test

The applicant is to conduct tests of the following items (Table 8) in accordance with the approved test plan. The purpose of this test is to confirm the appropriateness of the said manufacturing process using products manufactured based on the predetermined manufacturing process.

Table 8　Approval test of manufacturing process

Test item	Content of test
Tensile test	The tensile test is to be conducted using test pieces prepared at the same time as the product to confirm that the test result conforms to the acceptance criteria described in the test method approved in advance. For tensile test pieces, as in the type approval test of the feedstock, at least 3 test pieces are to be prepared for each test angle, as shown in Fig. 4 to Fig. 6.
Structure observation	The structure of the test pieces is to be observed in cross sections in each of the directions x, y and z to confirm that the structure is continuous and contains no defects (cavities, lack of fusion, etc.) that could possibly cause failure.
Nondestructive test	The nondestructive test of the product is to be conducted by a method which is capable of detecting internal defects and surface defects considered detrimental in use to determine whether the said product contains internal or surface defects that would be detrimental in use.
Visual inspection	A visual inspection of the external appearance of the product is to be conducted to determine whether defects considered detrimental in use are present on the product surface.
Analysis of chemical composition	The analysis of the chemical composition is to be conducted by a method, such as JIS G 0321, which is recognized as appropriate by the Society to confirm that the analysis result is the same as the value shown in the document (Submitted documents ⑪) submitted previously.
Other tests (if recognized as necessary by the Society)	Additional tests may also be required, such as the hardness test, bending test, impact test, surface roughness test, brittle fracture test, fatigue test, corrosion test, shearing strength test, compressive strength test, weldability test, etc.

(5) Acceptance criteria

The acceptance criteria are to be determined by the applicant with reference to public standards such as Part K of Rules for the Survey and Construction of Steel Ships or international standards or national standard (e.g., JIS or ISO) recognized as appropriate by the Society.

(6) Approval certificate

The Society approves the manufacturing process for the product using an AM system which the Society recognizes as appropriate in accordance with the documentary examination, factory inspection and test report and issues a Certificate of Approval. The validity period of the Certificate of Approval is to be 5 years from the date of approval.

2.2.4　Test and Inspection of Products

(1) Flow of test and inspection of products

The flow of the test and inspection procedure conducted prior to shipment of the product is shown in Fig. 8. Here, it is assumed that the “Application” is submitted by the owner of the AM system or the owner of the AM system who contracted to perform this test and inspection work.

Fig. 8　Flow of test and inspection of product

(2) Submitted documents

Prior to conducting the test and inspection of a product, the applicant is required to submit the test and inspection plan to the Society. The acceptance criteria for the tests and inspections are also to be included in this plan.

(3) Test and inspection

The applicant is to conduct the tests and inspections for the following items (Table 9) in accordance with the approved test and inspection plan. The purpose of these tests is to confirm the soundness of the product by using a representative product.

Table 9 Approval tests of product

Test item	Content of test
Mechanical test	The following tests are to be conducted to confirm that the product conforms to the acceptance criteria described in the approved test and inspection method. (1) Tensile test (see Table 6) (2) Hardness test (3) Impact test * (*The Society may allow omission of this test in some cases, depending on the feedstock used.)
Structure observation	The structure of the test pieces is to be observed in cross sections in each of the directions x, y and z to confirm that the structure is continuous and contains no defects (cavities, lack of fusion, etc.) that could possibly cause failure.
Nondestructive test	The nondestructive test of the product is to be conducted by a method which is capable of detecting internal defects and surface defects considered detrimental in use to determine whether the said product contains internal or surface defects that would be detrimental in use.
Visual inspection	A visual inspection of the external appearance of the product is to be conducted to determine whether defects considered detrimental in use are present on the product surface.
Dimension measurement	Dimensional measurement of the product is to be conducted to determine whether the dimensions are as designed.
Analysis of chemical composition	The analysis of the chemical composition is to be conducted by a method, such as JIS G 0321, which is recognized as appropriate by the Society to confirm that the analysis result is the same as the value shown in the document (Submitted documents (11)) submitted previously.
Other tests (if recognized as necessary by the Society)	Additional tests may also be required, such as the bending test, surface roughness test, brittle fracture test, fatigue test, corrosion test, shearing strength test, compressive strength test, etc.

(4) Acceptance criteria

The acceptance criteria are to be determined by the applicant with reference to public standards such as Part K of Rules for the Survey and Construction of Steel Ships or international standards or national standards (e.g., JIS or ISO) recognized as appropriate by the Society.

(5) Marking of the product

Products which pass the test and inspection procedure are to be stamped with the stamp of the Society. In cases where stamping would not be appropriate, the indication may be provided by another appropriate method, such as imprinting a seal, etc.

(6) Test and inspection certificate

In addition to the above (5), the Society issues a "Test and Inspection Certificate" for products which pass the test and inspection procedure. This certificate is not indicated a validity period and only certifies the fact of the inspection.

2.2.5 Preliminary Examination of Products to Be Manufactured

(1) Flow of examination

This examination is a requirement in case the applicant wishes to obtain approval on a voluntary basis for a metallic product other than those in Table 2 (i.e., use a not NK approval material). The flow of the approval is shown in Fig. 9. Here, it is assumed that the "Application" is submitted by the owner of the AM system.

Fig. 9 Flow of preliminary examination of products to be manufactured

(2) Submitted documents

In order to confirm the appropriateness of the application of these Guidelines to the product which is scheduled to be

manufactured using the AM system, it is necessary to submit the documents listed in Table 10 when requesting the examination. If no particular problems in the application of these Guidelines are confirmed as a result of the examination, the Society notifies the applicant to submit a test and inspection application as defined above in 2.2.4.

Table 10　Documents to be submitted for preliminary examination of products to be manufactured

	Submitted document
①	Detailed documents for the product to be manufactured (e.g., structural drawing, material supplier, brand of feedstock, laminated structure, internal structure, etc.)
②	Specification of AMmachine to be used
③	Documents for AM processes for the product to be manufactured (including documentation showing that it is possible to perform AM with uniform quality at any position in the build chamber or on the build platform)
④	Documents for quality management (including the acceptance criteria for feedstocks)
⑤	Documents for the chemical composition and mechanical properties of the product
⑥	Other documents recognized as necessary by the Society

(3) Test and inspection

The soundness of the product is to be confirmed by conducting the tests and inspections defined in the requirements of the above 2.2.4. Prior to conducting the said tests and inspections, a test and inspection plan, including the acceptance criteria, is to be prepared and submitted to the Society. In preparing the acceptance criteria, the acceptance criteria are to be determined in accordance with public standards such as Part K of Rules for the Survey and Construction of Steel Ships or international standards or national standards (e.g., JIS or ISO) recognized as appropriate by the Society.

(4) Marking of the product

As in the above 2.2.4, products which pass the test and inspection procedure are to be stamped with the stamp of the Society. In cases where stamping would not be appropriate, the indication may be provided by another appropriate method, such as imprinting a seal, etc.

(5) Test and inspection certificate

As in the above 2.2.4, the Society issues a “Test and Inspection Certificate” for products which pass the test and inspection procedure.

2.3　Characteristics of Metal Powder (Appendix 1 of the Society’s Guidelines)

Focusing on metal powders, which are important in the manufacture of metallic products with AM technology, Appendix 1 summarizes the basic items in connection with the characteristics, storage and management methods for metal powders and measures and response in case of unforeseen accidents. The overview of each item is as shown below (Table 11).

Table 11　Content described in Appendix 1 (overview)

Characteristics of metal powders：	✓ Flowability, spreadability and fillability are important characteristics of the metal powders required in AM. ✓ The typical particle diameters of powders used in AM technologies are as follows: ・Laser beam powder bed method: 20 to 45 μm ・Electron beam powder bed method: 45 to 105 μm ・Deposition method: 45 to 105 μm
Storage and management methods：	✓ Powders are not to be stored in excessively humid areas, and must be stored in a cool, dark place. ✓ The powder management method should be described in a manual. ✓ Before using powder, the moisture content (hygroscopicity) in the powder must be measured using a hygrometer and is to be controlled to less than the threshold value determined by the user company. ✓ For recycled powder, the powder shape and oxygen content are to be measured periodically and controlled.
Measures and response to unforeseen accidents：	✓ In combustion of metal powders, ignition is caused by the combination of (1) a combustible material, (2) oxygen and (3) an ignition source. Therefore, any one of these three elements must be removed. ✓ If ignition occurs during work, the supply of oxygen is to be blocked by using a fire extinguisher for metal powder fires and drying sand. Foam-type fire extinguishers are not to be used, and fire-fighting using water is also strictly prohibited because hydrogen may be generated.

REFERENCES

1) ClassNK, Guidelines for Additive Manufacturing (3D Printing), (2021)