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Galvanic anodes for cathodic protection in seawater and saline mud

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National foreword

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Galvanic anodes for cathodic protection in seawater and saline mud

Anodes galvaniques pour la protection cathodique dans l'eau de mer et les boues salines

Galvanische Anoden für den kathodischen Schutz in Seewasser und salzhaltigem Schlamm

This European Standard was approved by CEN on 25 April 2013.

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Foreword

This document (EN 12496:2013) has been prepared by Technical Committee CEN/TC 219 “Cathodic protection”, the secretariat of which is held by BSI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by December 2013, and conflicting national standards shall be withdrawn at the latest by December 2013.

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Introduction

The anticipated performance, including design life, of the cast galvanic anodes for use in sea water and saline mud is determined by their composition and the quality of their manufacture.

This European Standard specifies the minimum requirements for the galvanic anodes quality levels and verification procedures.

1 Scope

This European Standard specifies the minimum requirements and gives recommendations for the chemical composition, the electrochemical properties, the physical tolerances, and the test and inspection procedures for cast galvanic anodes of aluminium, magnesium and zinc based alloys for cathodic protection in sea water and saline mud.

This European Standard is applicable to the majority of galvanic anodes used for seawater and saline mud applications, i.e. cast anodes of trapezoidal, "D", or circular cross section and bracelet type anodes.

The general requirements and recommendations of this European Standard may also be applied to other anode shapes, e.g. half-spherical, button, etc., which are sometimes used for seawater applications.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 287-1, *Qualification test of welders — Fusion welding — Part 1: Steels*

EN 12473, *General principles of cathodic protection in sea water*

EN ISO 8044, *Corrosion of metals and alloys — Basic terms and definitions (ISO 8044)*

EN ISO 8501-1, *Preparation of steel substrates before application of paints and related products — Visual assessment of surface cleanliness — Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings (ISO 8501-1)*

EN ISO 15607, *Specification and qualification of welding procedures for metallic materials — General rules (ISO 15607)*

EN ISO 15609-1, *Specification and qualification of welding procedures for metallic materials — Welding procedure specification — Part 1: Arc welding (ISO 15609-1)*

ISO 10474:1991, *Steel and steel products — Inspection documents*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN ISO 8044 and EN 12473 and the following apply.

3.1

acidity

presence of an excess of hydrogen ions over hydroxyl ions (pH <7)

3.2

active surface

surface condition where corrosion occurs

3.3

anode consumption rate

mass consumption rate

amount of anode material consumed for a current output of one ampere during one year

Note 1 to entry: The anode consumption rate is expressed in kilograms per amp year (kg/A.y).

3.4

batch

charge

cast

unit that defines molten metal and identifies the anodes cast from it

3.5

bracelet anode

anode shaped as half- or part-rings to be positioned on tubular items

Note 1 to entry: Two or more part-ring anodes will have to fit together to become a bracelet anode.

3.6

calcareous deposit

layer consisting of a mixture of calcium carbonate and magnesium hydroxide deposited on surfaces being cathodically protected in seawater due to the increased pH adjacent to the protected surface

3.7

cast

see "batch"

3.8

charge

see "batch"

3.9

closed circuit potential

potential measured at the anode when a current is flowing in between the anode and the surface being protected

3.10

cold shut

horizontal surface discontinuity caused by solidification of a portion of a meniscus during the progressive filling of a mould, which is later covered with more solidifying metals as the molten metal level rises

Note 1 to entry: Cold shuts generally occur at corners remote from the point of pour.

3.11

core

see "insert"

3.12

crack

fracture of metal along a path producing a discontinuity similar to a ragged edge

Note 1 to entry: It can occur during the solidification of the anode (hot cracking), during the contraction of the anode after solidification, or under externally applied loads. Hot cracking can be associated with the shrinkage depression that can occur in open-topped moulds.

3.13

current capacity

total amount of electricity that is produced when one kilogram of anode material is consumed

Note 1 to entry: The current capacity is expressed in amp-hours per kilogram (A.h/kg).

3.14

driving voltage

voltage established between the operating potential of a galvanic anode and the protection potential of the structure

Note 1 to entry: This figure is used in the calculation of anode current output from the anode/electrolyte resistance.

3.15

electrochemical properties

properties of potential and current capacity that characterise a galvanic anode and can be assessed by quantitative tests

3.16

flush mounted anode

anode fitted to a structure with one face in contact with or very close to the structure

3.17

free running test

electrochemical test where potential and current are not controlled

3.18

gas hole

blow hole, channel or porosity produced by gas evolution during solidification

Note 1 to entry: Gas holes can indicate contamination of the mould or core prior to casting.

3.19

heat

product that is cast to a planned procedure in one melting operation in one furnace, without significant interruption

Note 1 to entry: If the casting sequence is interrupted, the anodes produced before, between, and after the interruptions constitute "batches".

3.20

insert

core form over which the anode is cast and which is used to connect the anode to the structure requiring protection

3.21

ladle sample

specimen taken from a molten metal stream

3.22

mass consumption rate

see "anode consumption rate"

3.23

non-metallic inclusions

particles of oxides and other refractory materials entrapped in liquid metal during the melting or casting sequences

3.24

passive surface

condition of low surface activity or resistance to corrosion of a metal, as a result of protective film formation

3.25

pit

localised corrosion resulting in pits, i.e. cavities extending from the surface into the metal

3.26

polarisation

change in the potential of an electrode as the result of current flow to or from that electrode

3.27

shrinkage depressions

natural concave surfaces produced when liquid metal is allowed to solidify in a container without the provision of extra liquid metal to compensate for the reduction in volume that occurs during the liquid-solid transformation

Note 1 to entry: The term also applies to the concave surfaces produced when liquid metal is solidified in a closed mould in such a manner that the area is not "fed" by the liquid metal provided by the mould design.

3.28

stand-off anode

anode which is offset a certain distance from the object on which it is positioned

3.29

surface lap

discontinuity caused by solidification of the meniscus of a partially cast anode as a result of interrupted flow of the casting stream

Note 1 to entry: The solidified meniscus is covered with metal when the flow resumes. Cold laps can occur along the length of an anode.

3.30

surface morphology

description of the features or structure of the anode surface

3.31

undercutting

cutting away metal from below, e.g. caused by pitting corrosion or inter-granular corrosion

4 Galvanic anode materials and their properties

4.1 General

Alloys used for galvanic anodes in seawater or saline mud shall be based on aluminium (Al), magnesium (Mg) and zinc (Zn). The performance, and therefore the suitability of a particular alloy for a specific application, will depend on the composition and characteristics of both the alloy and the electrolyte, temperature of operation and the anode current density.

The properties of an anode alloy may be obtained from the performance data in the given environmental conditions. The performance data shall include the current capacity in amp-hours per kilogram (A.h/kg), and the closed circuit potential of a working anode measured against a standard reference electrode.

Alloys shall be ordered either in compliance with a generic alloy composition, where required performance properties have been previously established or to meet a specific performance characteristic. In the latter case, the supplier should be required to provide confirmation of performance as demonstrated against defined test procedures (see 5.4).

4.2 Anode alloy composition

The chemical composition of any alloy used for galvanic anodes shall be specified by the supplier and the corresponding electrochemical properties shall be determined and documented.

The supplier shall provide supporting evidence for ensuring chemical composition according to 5.2.

The performance of an alloy is dependent on the specific alloy composition, resulting in variations in activation, resistance to passivation, current capacity and consumption morphology. In particular, some elements are known to have a detrimental effect on the anode performance and their content is normally subject to strict control.

The most common galvanic anode compositions for aluminium, magnesium and zinc based anode alloys are given in Annex B.

The required range of alloying elements will vary significantly, the tolerance on the composition changes with the range. For example, zinc content in aluminium based alloys can range from 2 % to 6 % (tolerance $\pm 0,5$ %), while indium content will typically be 0,01 % to 0,05 % (tolerance $\pm 0,005$ %).

4.3 Electrochemical properties

4.3.1 General

The performance of a galvanic anode material (alloy) is dependent on its actual chemical composition and homogeneity, current density and the environmental conditions in which it is exposed.

Since the method of cathodic protection is electrochemical in nature, the anode material's electrochemical properties shall be determined under the expected environmental operating conditions. These may include:

- potential;
- current capacity;
- anode consumption rate.

In addition, anode surface morphology affects the efficiency and shall also be determined.

These properties of the anode material shall be determined by appropriate tests (see 5.4).

Annex C describes the test methods that are most often used.

4.3.2 Potential

The selected anode alloy shall have a closed circuit potential more negative than the protection potential required for cathodic protection. The anode alloy operating potential shall be stable with time to ensure long-term performance and shall be documented by long-term testing for the particular operating environment.

Where long-term performance data relating to anode operating potential are not available for a specific alloy/environmental combination, additional tests should be carried out to determine the effect of current density, temperature and time on the operating potential in the particular environment and the various operating conditions of the anode.

Anode alloys will polarise, i.e. change potential, when current is passed. It is the potential of a working anode, i.e. the closed circuit potential, that is important. The potential of an anode material will also vary with the surrounding environment. The potential may change with time even when exposed to constant conditions due to corrosion products being formed on the anode surface and due to variations in the current demand.

The anode operating potential is generally more negative than -1,00 V measured with a Ag/AgCl/seawater reference electrode. However, where a low driving voltage is required either special anode compositions (with operating potential of -0,85 V vs. Ag/AgCl/seawater reference electrode) or anodes with a voltage controller (such as diode or resistive bond) between the anode and the structure can be used.

4.3.3 Current capacity

The current capacity for a galvanic anode alloy is expressed in ampere.hours per kilogram (A.h/kg) and is the total amount of electricity (A.h) that is produced in practice when one kilogram of the anode material is consumed for a given operating condition. The practical current capacity is different for anode materials exposed to different environmental conditions such as hot and cold seawater, seabed mud, etc.

The anode alloy practical current capacity shall be documented by long-term testing for the particular operating environment.

Where long-term performance data relating to anode capacity are not available for a specific alloy/environmental combination, then additional tests should be carried out to determine the effect of current density, temperature and time on the current capacity of the alloy in the particular environment and the various operating conditions of the anode.

NOTE Due to self-corrosion, all anode materials have a practical current capacity lower than that calculated by consideration of the theoretical electrical equivalence determined by Faraday's Law (i.e. some of the current produced by consumption of the anode is used for self-corrosion of the anode material and is not available for cathodic protection). It is the practical current capacity that is used in cathodic protection design. For example, the theoretical capacity of alloy M1 is approximately 2 220 A.h/kg whereas the practical capacity is only 1 200 A.h/kg.

The electrochemical properties of galvanic anodes are temperature dependent and should be known for the design of cathodic protection systems for risers and submarine pipelines transporting commodity at elevated temperature. The practical current capacity decreases with increasing temperature both in seawater and in marine sediments.

The practical current capacity increases with increasing anode current density. At extremely low current densities, self-corrosion may be more pronounced and can give a significant reduction in the practical current capacity.

4.3.4 Anode consumption rate

The anode consumption rate for a galvanic alloy anode is expressed in kilograms per ampere.year (kg/A.y) and is the total amount of anode material consumed in practice for a current output of one ampere during one year. Like current capacity (see 5.3), all anode materials have a practical consumption rate different from their theoretical consumption rate. In this case, the consumption rate is higher than that calculated by Faraday's Law.

The anode consumption rate and the current capacity are related by:

$$E \cdot Q = 8\,760$$

where

E is anode consumption rate (kg/A.y);

Q is current capacity (A.h/kg);

8 760 is number of hours in one year.

5 Anode design and acceptance criteria

5.1 General

The anodes, including cores and supports, shall be designed in such a way as to give the specified performance during fabrication, transport, installation and operation. The dimensions and shape of the anodes, steel core and attachments shall be designed to withstand the mechanical forces that may act on the anodes, for example waves, currents, pile driving or vibration. For all anodes, the anode and anode core dimensions shall be designed for the proposed fitting requirements. Any special provisions needed to make the core compatible with the attachment to the protected structure shall take preference over other requirements.

In subsea areas where divers or remote operated vehicles are likely to operate, stand-off type anodes should be provided so that the support cores protrude through the end-faces of the anode, in order to reduce the danger of entangling wires, ropes, umbilical cables, etc.

Over-pouring to fill shrinkage depressions shall be kept to a minimum. All pouring of molten anode alloy shall be finished before the surface of the cast anode solidifies. The surface of the anode may be kept in a liquid state for a while by applying heat, i.e. from gas burners, but once solidified, no re-melting shall be allowed, not even to fill shrinkage depressions.

The exposed (external) surfaces of the anode shall not be subject to any coating, except for flush mounted and bracelet anodes where the anode surface facing, immediately adjacent, to the structure surface to be protected may be coated.

Physical tolerances of anodes shall be confirmed in accordance with the requirements of Annex A.

NOTE Further information for inspection of anodes is given in NACE SP0492-2006 and NACE SP0387-2006.

5.2 Chemical composition

Galvanic anode material performance is related to the chemical composition. Therefore, strict control of the alloy chemical composition, both alloying elements and impurities, is essential.

All samples shall be identified with the cast number. All anodes should be similarly identified with the cast number.

The samples shall be analysed to prove compliance with the agreed chemical composition limits of the alloy being produced. Additional sample(s) may be taken and stored for future determination of chemical composition.

Two samples from each heat shall be taken for chemical analysis. The samples shall be taken in the beginning and at the end of casting from the pouring stream. For smaller alloying furnaces (max. 500 kg), one sample per heat may be sufficient. The sample shall be taken at the beginning of the first heat and at the end of the second heat, then in the beginning of the third heat and so on. The samples shall be analysed to verify the required chemical composition.

Anodes from heats whose chemical composition do not meet the required chemical composition shall be rejected.

For alloys where heat treatment forms part of the specification, details of the heat treatment history for each furnace charge shall be recorded. The chemical analysis and the temperature sensing and recording equipment shall be suitably calibrated.

5.3 Physical properties

The physical and dimensional tolerances determined by the anode design shall be complied with.

No anode or its steel core shall have any defect either on its surface or within its body that will affect the transportation, installation and future performance of the anode. Tolerances defined in Annex A shall be respected.

5.4 Electrochemical testing

Where there are no reliable historical or laboratory data relating to the performance of a specific anode alloy in a particular environment, electrochemical testing shall be carried out to confirm the relevant anode operating potential and anode capacity. The same kind of testing shall also be performed on any field proven alloy composition when manufactured by a supplier that has not been qualified for this composition.

The laboratory test procedure shall be selected to provide best representation of the expected operating conditions (including electrolyte, temperature and anode current density).

The three main electrochemical techniques used for anode testing are: free running, galvanostatic (constant current) and potentiostatic (constant potential) methods. Each of these test methods emphasises different

aspects of the anode performance. It is therefore important when choosing a test method that the relevant factors of the anode performance will be revealed by that technique.

Galvanostatic tests (as described in C.2) should only be used as a quality assurance test to confirm the performance of known alloy type in a known environment. Where a new alloy is to be used or where an alloy is to be used in a different environment (e.g. salinity, temperature) where there are no documented historical field performance data or previous laboratory data, then long-term (free running) tests (as described in C.1) should be used. This is mandatory for applications where the long-term performance of the installed anodes is essential, e.g. offshore pipelines and structures.

The long-term testing procedure and the resulting test data can be useful for design purposes. These laboratory tests will produce anode performance data, which ranks the materials on a relative scale. For more reliable data for design purposes, field-testing should be carried out. The number of tests should be selected to give statistically significant information.

Where performance tests are to be used to determine anode alloy performance properties for design purposes they should be conducted or witnessed and assessed by an independent inspection authority.

Samples for electrochemical testing should be representative of the specified alloy composition range, the process route, and typical of the target chemical analysis.

The anode material dissolution morphology following laboratory testing should be examined as the corrosion pattern can indicate whether active or passive behaviour is likely and it will also indicate any tendency to undercutting.

Deep and undercut pits may develop due to an acidic environment formed within the pit because of a restricted electrolyte access. This may lead to increased self-corrosion inside the pits and consequently a loss in capacity. In addition, the pitting can lead to undercutting with loss of anode material and reduced anode life.

Inter-granular (or inter-crystalline) corrosion can lead to a rapid disintegration of the anode material and consequently to a greatly reduced anode life. Metallographic evidence of any tendency of inter-granular corrosion may be a cause for rejection of the anode material.

As a part of the quality control programme, short-term high current density tests as described in C.2 and C.4 shall be carried out at a frequency of at least one test per 15 t. These tests shall prove compliance with the agreed electrochemical properties of the alloy being produced. Additional sample(s) may be taken and stored for future electrochemical testing.

Data from such quality control tests should not be relied on for system design.

5.5 Anode core materials

Anode cores shall be fabricated from weldable structural steel plate/sections according to a recognised standard such as EN 10025 (all parts) or similar. Anode core materials to be welded to the structure shall be compatible with the steel of the structure or structural elements to which it is attached, and the carbon equivalent (CE) shall not exceed the CE value of the steel on which it will be welded. The CE value shall be calculated using Formula (1):

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15} \quad (1)$$

If the full chemical composition is not reported, the alternative CE Formula (2) may be used.

$$CE = \%C + \frac{\%Mn}{6} + 0,04 \quad (2)$$

In all cases, CE shall be no more than 0,45.

The material certificate for the anode cores shall meet at least the requirements of ISO 10474:1991, 2.1 b).

For all fabrication welding of steel anode cores, welding procedures shall be in accordance with relevant requirements of EN ISO 15607 and EN ISO 15609-1 or any equivalent standard.

NOTE 1 AWS D1.1/D1.1M constitutes an acceptable equivalent.

Welds shall be performed by welders qualified according to EN 287-1.

NOTE 2 AWS D1.1/D1.1M constitutes an acceptable equivalent.

100 % visual inspection of the cores shall be carried out prior to casting.

For zinc or magnesium anodes, the steel cores may be bare steel or hot dip galvanised steel. In this case, hot dip galvanising shall be in accordance with EN ISO 1461.

Zinc electroplated coatings according to EN ISO 2081 will not provide a true steel-zinc inter-metallic bond and should be used with caution.

Visible surface contamination of the blast cleaned or zinc coated surface shall not be permitted. When bare steel core are used, they shall be blast cleaned to the grade Sa 2½ defined in EN ISO 8501-1.

For aluminium anodes, the steel core shall be blast cleaned at a minimum to the grade Sa 2½ defined in EN ISO 8501-1 before casting. Galvanised or zinc electroplated cores shall not be used.

NOTE 3 A zinc coating on the insert would give only a mechanical bond and would be dissolved during casting with possible modification of the alloy chemical composition.

Rust discoloration and/or visible surface contamination of the cores shall not be accepted.

5.6 Cable connections

Where anodes are to be connected to the structure or pipeline using cables, as opposed to direct welding of the core to the structure, the cable shall be selected to provide a robust connection. The cable shall be multi-stranded with minimum cable size of 10 mm² cross section area.

Cable shall be connected to the anode using a suitably sized and fixed cable lug. The cable shall be fixed to the lug by both mechanically crimping and welding or brazing. The cable lug shall be connected to the anode core by either mechanical (i.e. bolted connected) or direct welding. The contact point should be protected using a suitable coating.

A suitable coating may be an epoxy or equivalent.

Where connection is by cable, consideration should be given to utilising multiple cables to provide a degree of redundancy in case of cable damage.

The method of cable attachment to the structure should be selected to provide both a mechanically secure and a low electrical resistance connection, such as pin brazing, thermit welding or by use of "volcano" bolts or serrated washers and use of lock nuts as appropriate.

Annex A (normative)

Physical tolerances for galvanic anodes

A.1 Anode mass

Individual anode castings with total net mass above 50 kg shall have a net mass within $\pm 3\%$ of the nominal net mass. For castings with nominal net mass below 50 kg, the tolerances shall be $\pm 5\%$. Net mass is the casting mass determined from the gross as-weighed mass after deduction of the average insert (core) mass.

Castings may be weighed either individually or in batches. Sample weighing may be undertaken but in any case a minimum of 10 % of the total number of castings shall be weighed.

The total net mass of anode castings shall not be less than the nominal value and should be no more than 2 % above.

A.2 Anode dimensions and straightness

a) Stand-off and flush mounting anodes

Dimensions shall conform to the following:

- 1) Anode mean length should be $\pm 3\%$ of nominal length or ± 25 mm, whichever is smaller.
- 2) Anode mean width should be $\pm 5\%$ of nominal mean width.
- 3) Anode depth should be $\pm 10\%$ of nominal mean depth.
- 4) The diameter of cylindrical anodes should be $\pm 2,5\%$ of nominal diameter.

The straightness of the anode shall not deviate more than 2 % of the anode nominal length from the longitudinal axis of the anode.

At least 10 % of the total number of anodes shall be checked to confirm compliance with these requirements.

b) Bracelet anodes

Dimensions shall conform to the following:

- 1) The mean length of the anode casting should be $\pm 3\%$ of nominal length or ± 25 mm, whichever is smaller.
- 2) The anode internal diameter shall conform to the following dimensional tolerances:
 - i) $-0 / + 4$ mm for pipeline diameters ≤ 300 mm;
 - ii) $-0 / + 6$ mm for pipeline diameters > 300 mm and ≤ 610 mm;
 - iii) $-0 / + 1\%$ for pipeline diameters > 610 mm.
- 3) The dimensional tolerances on the anode thickness shall be ± 3 mm.

At least 10 % of the total number of anodes shall be checked to confirm compliance with these requirements.

Anodes shall be free from excessive bowing or twisting. This shall be verified on a completely assembled bracelet by fitting to a full-length former or by any other agreed method. The external diameter should at no point exceed the summation of the tolerances given above.

A.3 Steel core

The cross section dimensions of the anode core shall comply with the appropriate specification.

The tolerances for the position of the core for bracelet and flush mounting anodes shall be ± 5 mm and for stand-off type anodes ± 10 % of anode material thickness covering the core. Anode core protrusions and any other specified critical dimensions shall be measured on samples of all anodes of each type and shall conform to specified requirements.

A.4 Anode surface irregularities

All anodes shall be inspected visually to confirm compliance with the following requirements.

Shrinkage depressions shall not exceed 10 % of the nominal thickness or depth of the anode, as measured from the uppermost corner to the bottom of the depression.

Shrinkage depressions that expose the anode core are not acceptable.

In the topping up area the maximum shrinkage shall not be more than 10 mm depth measured from a straight edge across the topping up face and not more than 0,5 % of the gross anode volume. Any additional topping up materials or casting surface irregularities shall be fully bonded with the bulk anode material.

Cold shuts shall not exceed a depth of 10 mm and/or extend over a total length of more than 3 times the width of the anode (for stand-off and flush mounting anodes) or more than 150 mm (for bracelet anodes).

All protrusions that are hazardous to personnel during handling shall be removed.

A.5 Cracks in cast anodic material

A.5.1 General

All anodes shall be inspected visually to confirm compliance with the following requirements.

Even with good foundry practice, particular anode alloy composition (notably aluminium based) may suffer a degree of cracking. Cracks may occur while cooling during the casting of galvanic anodes because of the different coefficients of expansion of the anode and the core. These cracks are not detrimental, provided they do not converge in a manner to allow loss of anode material. A small amount of warpage is acceptable if it does not adversely affect the anode installation.

No treatment shall be applied to grind, peen, or in any other manner dress cracks before inspection and checks.

Zinc and magnesium anodes shall be free from cracking visible without the aid of magnification.

Small cracks in the anodes can be accepted in aluminium anodes provided the cracks would not cause any mechanical failure during installation, transportation or service of the anode. The combination of cracks and lack of bond to the core is detrimental.

- Visible cracks in the area where the anode material is not internally supported by the core shall not be accepted.
- Cracks penetrating to the steel core or penetrating through the anode are not permitted.

A.5.2 Stand-off and flush mounting anodes

For transverse cracks within the section of an anode wholly supported by the core, the following acceptance criteria shall be applied:

- Cracks within the section of an anode supported by the core are not acceptable if the length is more than 100 mm and/or the width is more than 1 mm.
- Maximum 10 cracks per anode.

Cracks which follow the longitudinal direction of long slender anodes shall not be accepted.

A.5.3 Bracelet anodes

Cracks with a length of more than 100 mm or 50 % of the anode length (whichever is greater) and/or cracks with a width greater than 3 mm are not acceptable.

Provided the above is satisfied, the following cracks are acceptable in transverse direction:

- A maximum number of two cracks is acceptable if they do not exceed the following criteria.
- Cracks with a length of less than 50 mm or less than 20 % of the anode diameter, whichever is less, and width less than 3 mm.
- Cracks with a length between 50 mm and 200 mm or between 20 % and 50 % of the anode diameter, whichever is less, and width less than 1 mm.
- Cracks with a length between 50 mm and 200 mm shall be limited to 2 per half bracelet or 4 per anode.
- Cracks which follow the longitudinal direction of the anodes shall not exceed 100 mm or 20 % of anode length, whichever is less, and/or 1 mm in width.

Acceptance criteria for other sizes of cracks would be dependent upon core and anode design.

A.6 Internal defects and destructive testing

The number and method of selection of anodes to be destructively tested (sectioned) within each anode type/size shall take into account anode design, and the total number of anodes.

If the anode does not meet the requirements below, an additional anode shall be subjected to destructive testing. If this does not satisfy specified requirements, the whole anode lot should be rejected or other actions taken as agreed prior to fabrication.

Slender and flush mounting anodes selected for examination shall be sectioned transversely by single cuts at 25 %, 50 %, and 75 % of nominal length, or at other agreed locations for a particular anode design.

Bracelet anodes selected for examination shall be sectioned transversely by single cuts at 25 % and 50 % of nominal length, or at other agreed locations for a particular anode design.

The cut faces, when examined visually without magnification, shall conform to the following criteria:

- Gas holes and porosities shall be limited to maximum 2 % of the total cut surface areas, and maximum 5 % of any individual cut surface area; no cavity shall exceed 1 cm² for the cross-sectional area in the transverse section.
- Non-metallic inclusions shall be limited to maximum 1 % of the total cut surface areas and maximum 2 % of any individual cut surface area; no non-metallic inclusion shall exceed 1 cm².

- Lack of bond (voids adjacent to the core) shall be limited to maximum 10 % of the total anode core perimeter and maximum 20 % of the perimeter for any individual cut.

For non-tubular cores where prevention of voids may be particularly difficult, the limits may be otherwise agreed between the manufacturer and the purchaser.

The core position within the anode should be confirmed by measurement on the cut faces.

Annex B (informative)

Composition and performance properties for galvanic anodes

B.1 Aluminium alloys

B.1.1 Anode material

Aluminium alloys for use in seawater and saline mud normally contain zinc together with small amounts of indium as an activator; however, there are a wide range of alloy compositions available. Some alloys are non-proprietary; some are proprietary and are covered by national and/or international patents. The different compositions are aimed at modifying the properties of the anodes either to optimise manufacture of specific anode shapes or to optimise specific performance properties.

Compositions for the common aluminium anode alloys are given in Table B.1, aluminium being the balance.

Table B.1 —Chemical composition for aluminium anodes given as mass fraction in %

Elements	Alloy A 1	Alloy A 2	Alloy A 3	Alloy A 4
Zn	2,0 – 6,0	3,0 – 5,5	4,75 – 5,75	0,15 max.
In	0,010 – 0,030	0,016 - 0,040	0,016 – 0,020	0,005 max.
Ga	-	-	-	0,092 - 0,110
Fe	0,12 max.	0,09 max.	0,06 max.	0,08 max.
Si	0,12 max.	0,10 max.	0,08 – 0,12	0,10 max.
Cu	0,006 max.	0,005 max.	0,003 max.	0,005 max.
Cd	0,002 max.	0,002 max.	0,002 max.	-
Other Impurities (each)	0,02 max.	0,02 max.	0,02 max.	0,02 max.
Other Impurities (total)	0,1 max.	0,1 max.	0,05 max.	0,05 max.
Al	remainder	remainder	remainder	remainder

NOTE 1 Alloy A 1 is generally used for marine applications.

Alloy A 2 is normally used for offshore applications.

Alloy A 3 is normally used for deepwater and cold water applications.

Alloy A 4 is an alloy used for low driving voltage applications.

Alloy manufacturers can produce anode alloys within categories A1 to A4 to tighter composition limits than shown in Table B.1.

NOTE 2 Alloy A 4 is a recently developed alloy designed for low driving voltage applications (e.g. for use with high strength steels) and has not been widely used. This alloy is proprietary and is subject to international patents (see [14], [15] and [16] for more information on this alloy).

The aluminium-zinc-indium anode alloys (A 1, A 2 and A 3) are generally the most frequently used. There are many individual specifications for this generic alloy; however, the zinc content is usually in the range 2,5 % and 5,0 % and the indium content around 0,02 %. Residual impurities, such as iron and copper should be kept to a minimum, but due to production methods the iron content is the most difficult to control. For long-term applications the iron content shall be less than 0,09 %.

Alternative alloys based on aluminium-zinc-indium-magnesium (Al-Zn-In-Mg) alloys may suffer from age hardening and cracking in certain circumstances, these are no longer commonly used.

Alternative alloys based on aluminium-zinc-tin (Al-Zn-Sn) require heat treatment to achieve effective activation, and may suffer inter-granular corrosion and slow activation at low temperatures (i.e. 5 °C). Al-Zn-Sn alloys are no longer commonly used.

Alternative alloys based on aluminium-zinc-mercury (Al-Zn-Hg) are no longer used due to environmental restrictions.

Historically anode alloys other than those in Table B.1 have been found to passivate (i.e. form a stable protective film on the anode surface) which prevents further anode dissolution and hence provision of current for cathodic protection.

The indium activated aluminium anode alloy (A1, A2 & A3) have proved to be applicable in marine sediments, i.e. covered with mud.

Aluminium alloys are only applicable for environments with salinity of greater than 5 g/kg (mass fraction 0,5 %), i.e. typically in seawater / brackish water environments with resistivity of less than 2 Ω m.

B.1.2 Electrochemical properties

The electrochemical properties for aluminium based alloys vary depending on the specific alloy composition, operating temperature, operating anodic current density and the operating environment.

The actual properties for an alloy / operational condition should be determined and documented by testing in accordance with Annex C. Indicative values for typical alloy compositions as shown in Table B.1 are given in Table B.2 for normal operation (ambient temperature, normal seawater, anodic current density higher than 1 A/m²). More detailed recommendations are given in each of the specific EN standards relative to application of cathodic protection in seawater environments.

Table B.2 — Typical properties of aluminium anodes in normal operation conditions

Alloy type	Environment	Closed circuit potential Ag/AgCl/seawater reference electrode	Current capacity	Anode consumption rate
		V	A.h/kg	kg/A.y
Alloy A 1	Seawater	-1,09	2 500	3,5
	Marine sediments	-1,05	2 000	4,4
Alloy A 2	Seawater	-1,09	2 500	3,5
	Marine sediments	-1,05	2 000	4,4
Alloy A 3	Seawater	-1,09	2 500	3,5
	Marine sediments	-1,05	2 000	4,4
Alloy A 4	Seawater	-0,83	1 500	5,8

NOTE 1 The typical closed circuit potential, capacity and anode consumption rate shown are based on normal operating conditions of anode current density, temperature and environment.

NOTE 2 The current capacity values shown are the practical current capacity values for aluminium alloys and incorporate an allowance for self-corrosion of the alloy. No further efficiency allowance is necessary.

NOTE 3 There are no reported performance data for Alloy A 4 in marine sediments.

The practical current capacity for a specific Al-Zn-In alloy should be confirmed based on either long-term performance tests of at least 12 months duration or from long-term practical experience. Short-term tests are likely to give higher capacity values (i.e. will indicate a higher current capacity close to the theoretical Faraday capacity) due to the higher current density applied to the anode alloy test sample compared to anodes in service. Where long-term performance data are not available, caution should be exercised in selecting values for design purposes.

Anode capacity for all aluminium-based alloys will be significantly lower at higher operating temperatures. For example, anode capacity for alloys A 1 and A 2 will drop essentially linearly from 2 500 A.h/kg at 25 °C to 500 A.h/kg at 80 °C. (Equivalent to a change in anode consumption rate of 3,5 kg/Ay at 25 °C to 17,5 kg/Ay at 80 °C). In saline mud, at elevated temperatures, the capacity values will be lower than those indicated for seawater (see references [18] and [19]).

Environments such as brines, seawater of varying salinity or marine sediments, with or without hydrogen sulphide (H₂S), result in variations in aluminium anode alloy performance properties.

B.2 Magnesium alloy

B.2.1 Anode material

Magnesium based anodes are not normally required for use in seawater due to the naturally low seawater resistivity which ensures sufficient current is provided by aluminium or zinc alloys. However, they may be required in brackish or fresh water where their high driving voltage is required to provide practical current output, or in seawater where rapid polarisation is desired.

There are two generic groups of magnesium alloys used in cathodic protection as shown in Table B.2, magnesium being the balance.

Table B.3 — Chemical composition for magnesium alloy anodes given as mass fraction in %

Elements	Alloy M 1	Alloy M 2
Mn	0,15 - 0,7	0,5 – 1,5
Al	5-7	0,05 max.
Zn	2-4	0,03 max.
Fe	0,005 max.	0,03 max.
Cu	0,08 max.	0,02 max.
Si	0,3 max.	0,05 max.
Pb	0,03 max.	0,01 max.
Ni	0,003 max.	0,002 max.
Others	Total: 0,30 max.	Each: 0,05 max.
Mg	remainder	remainder

NOTE Alloy M 1 is normally supplied in accordance with ASTM B843-93.

In both cases, residual impurities naturally occur in the magnesium need to be controlled to limit polarisation and self-corrosion. Manganese is added to sequester iron impurities and make the anode potential more negative.

Magnesium based anodes are generally only applicable where frequent replacement is practicable. However, magnesium anodes may be designed for long-term use in seawater, if the anode shape, anode resistance, total circuit resistance and the anode / structure spacing are specifically selected for such applications.

B.2.2 Electrochemical properties

Magnesium based alloys have a high operating voltage (typically -1,5 or -1,7 V Ag/AgCl/seawater) but have a low current capacity (high consumption rate) due to self corrosion.

Table B.4 — Typical electrochemical properties of magnesium anodes at ambient temperatures (5 °C – 25 °C)

Alloy type	Environment	Closed circuit potential Ag/AgCl/seawater reference electrode V	Current capacity A.h/kg	Anode Consumption Rate kg/A.y
Alloy M 1	Seawater	-1,50	1 200	7,3
Alloy M 2	Seawater	-1,70	1 200	7,3

NOTE The current capacity values shown are the practical current capacity values for magnesium alloys and incorporate the high self-corrosion (corresponding to approx 50 %) of the alloy. No further efficiency allowance is necessary.

The practical capacity may be considerably lower when operating at low current densities or over extended operating periods.

It is reported that magnesium anode electrochemical properties cannot be accurately predicted from composition alone; documented short-term potential and capacity determinations should be considered for each batch or series of batches of anodes having the same minor impurities and microstructure (see references [20], [21] and [22]).

B.3 Zinc alloy

B.3.1 Anode material

Zinc based anodes are widely used for shipping applications, they are also used for offshore structures but their higher density can lead to weight limitations. Zinc anodes do not require a chloride environment to operate and can be used in brackish and fresh water applications. There is a wide range of alloy compositions available. Most are non-proprietary, however some are proprietary or the subject of National and/or International Patents. The different compositions are intended to optimise specific performance properties.

Pure zinc can only be used if the iron impurity content is less than 0,001 4 %; however, with the addition of aluminium this level of acceptable iron impurity can be slightly increased, and further additions of cadmium promote the formation of a soft, non-adherent corrosion product on the anode. Some alloy compositions are proprietary to specific manufacture and/or subject to international patents.

Chemical compositions of typical zinc anode alloys given in Table B.5, zinc being the balance.

Table B.5 — Chemical composition for zinc anodes in % of weight

Elements	Alloy Z 1	Alloy Z 2	Alloy Z 3	Alloy Z 4
Al	0,1-0,5	0,005 max.	0,10 – 0,20	0,10 – 0,25
Cd	0,025 – 0,07	0,003 max.	0,04 – 0,06	0,001 max.
Fe	0,005 max.	0,0014 max.	0,001 4 max.	0,002 max.
Cu	0,005 max.	0,002 max.	0,005 max.	0,001 max.
Pb	0,006 max.	0,003 max.	0,006 max.	0,006 max.
Sn	-	-	0,01 max.	-
Mg	-	-	0,5 max.	0,05 – 0,15
Others	0,10 max.	0,005 max.	0,1 max.	0,1 max.
Zn	99,314 min.	99,99 min.	remainder	remainder

NOTE 1 Alloy Z 1 is normally supplied in accordance with U.S. MIL-A-18001-K (1993) or to ASTM B418, Type I.

NOTE 2 Alloy Z 2 is of term “high purity zinc” and is normally supplied in accordance with ASTM B418, Type II.

NOTE 3 Alloy Z 4 is a proprietary alloy that has been developed for use at elevated temperatures.

B.3.2 Electrochemical properties

The electrochemical properties for zinc based alloys will vary depending on the specific alloy composition and the operating environment. Generally, zinc alloys are only applicable at temperatures up to 50 °C. Above this temperature, zinc alloys Z 1 and Z 3 can suffer from inter-granular corrosion, especially when buried in saline mud. Some proprietary alloys have been developed that can operate successfully at higher temperatures up to 85 °C. At higher temperatures (> 70 °C) zinc anodes in low chloride environments can exhibit potential reversal with steel (see references [13], [23] and [24]).

The actual properties for an alloy/operational condition should be determined by testing in accordance with Annex C. Typical values of electrochemical properties for alloy compositions shown in Table B.5 are given in Table B.6.

Table B.6 — Typical electrochemical properties of zinc anodes at ambient temperatures (5 °C – 25 °C)

Alloy type	Environment	Closed circuit potential Ag/AgCl/seawater reference electrode V	Current capacity A.h/kg	Anode consumption rate kg/A.y
Alloy Z 1	Seawater	-1,03	780	11,2
	Marine sediment	-0,99	750	11,8
Alloy Z 2	Seawater	-1,00	760	11,5
Alloy Z 3	Seawater	-1,03	780	11,2
Alloy Z 4	Seawater	-1,03	780	11,2
	Marine sediment	-0,98	710	12,3

NOTE 1 The current capacity values shown are the practical capacity values for zinc alloys and incorporate an allowance for self-corrosion of the alloy. No further efficiency allowance is necessary.

Alloys Z 1 and Z 3 should not be used at temperatures above 50 °C in sediments.

NOTE 2 Alloy Z 4 is a proprietary alloy that has been developed for use at elevated temperatures. It is claimed that at 60 °C to 80 °C the practical capacity in seawater is 690 A.h/kg, anode consumption rate of 12,7 kg/Ay and the claimed operating potential is -0,97 V vs. Ag/AgCl/seawater.

NOTE 3 In marine sediment the proprietary alloy Z 4 at 50 °C is claimed to have a practical capacity of 710 A.h/kg, anode consumption rate of 12,3 kg/A.y and operating potential of -0,95 V vs. Ag/AgCl/seawater. At 85 °C the claimed practical capacity is 430 A.h/kg, anode consumption rate of 20,4 kg/A.y and the claimed operating potential is -0,94 V vs. Ag/AgCl/seawater.

Annex C (informative)

Description of various electrochemical tests

C.1 Free running test

In this test, the galvanic anode is connected to a steel cathode and the polarisation behaviour is produced by the galvanostatic effect under given conditions. The free running test represents a simulation of the galvanic anode in some practical situations. During the test exposure, the current and the anode potential should be recorded. After the exposure, the anode capacity can be calculated. This test will give data on practical current capacity and anode potential. The anode potential can give information on passivity. The cell arrangements and exposure conditions can be critical in free-running tests. An important factor is to avoid the anode current being controlled by the cathodic polarisation current (e.g. if the area of the cathode sample is too small or if calcareous deposits reduce the cathodic current to a too low value, the anodic current will be reduced to near zero).

With adapted cell arrangements, the free running test can be used as a screening test to give data on current capacity, anode potential and also on tendencies to passivity.

NOTE A method currently used for long-term testing is given in Det norske Veritas RP-B401 and detailed in its Annex C [1].

C.2 Galvanostatic test

In this test, the galvanic anode is exposed to a given defined constant current density. During the exposure the anode potential is recorded and after the exposure the anode capacity is calculated. The exposure to a constant current density on the anode does not represent a real life situation for a galvanic anode where the anode current density may vary greatly during the service life. Passivation effects can therefore not be studied in this test. In order to provide an indication of likely anode performance the galvanostatic test can be performed at different current densities (0,003 A/m² to 10 A/m²). It is important to take into account that the anode capacity will increase with increasing current density.

It is also important to note that at low current densities, significant scatter may be obtained which may invalidate the results.

NOTE 1 Examples of galvanostatic test procedures are NACE TM0190-98 [5] for aluminium and zinc based anode alloys and ASTM G97 [22] for magnesium anode alloys.

NOTE 2 These short-term tests do not provide a definitive measure of long-term anode performance and are generally only used as part of a quality control procedure (as described in C.4) or as a pre-screening procedure.

C.3 Potentiostatic test

In this test, the anode is exposed at a given defined value of potential. For a practical situation an anode will operate with a relative stable potential, while the current can be expected to vary significantly. However, for testing purposes the operating potential may not be sufficiently known and the set potential may give an unrealistic current output. Therefore, for potentiostatic testing carried out to determine the capacity it would require experience or detailed knowledge of the operating potential.

Tests performed over a range of potentials represent the preferred approach.

The potentiostatic test is suited for establishing tendencies to passivity. Such tendencies may be observed in a free-running test, but not with a galvanostatic test.

NOTE Details of potentiostatic test procedures are given in ASTM G5-94 [9].

C.4 Quality control testing

Short-term testing for quality control purposes may be requested to be carried out to confirm operational performance of individual anode alloy batches. Short-term testing does not provide reliable data regarding long-term anode material capacity or operating potential. The results from such tests should not be used for design purposes.

NOTE Methods currently used are described by Det norske Veritas RP-B401 Annex B [1] and NACE TM 0190-98 [5].

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