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Corrosion Testing for Additive Manufacturing

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Foreword

This report was assembled as a critical technical resource for engineers, scientists, and technical personnel responsible for, or interested in, the corrosion performance of additively manufactured components intended for use in industrial applications. This rapidly evolving field of manufacturing has a long history in development but has only found a foothold in widespread applications relatively recently. The expansion of the variety of additive manufacturing methods into new applications and new industries will rely on the ability to demonstrate the performance of additively manufactured parts relative to the wrought forms of material they are intended to replace.

While decades of collective industrial experience informed the specification framework governing testing and acceptance of wrought materials, unique aspects of additive manufacturing processes raise questions about the applicability of specifications developed using conventional methods. The list of potentially applicable standards is much too long to present here, but this report seeks to address some of those questions through a review of the technical literature and the collective knowledge and experience of the project team. To that end, this report highlights the myriad of additive-manufacturing-specific features that may be of interest from the corrosion perspective, ranging from microstructure to surface finish, build parameters to post-processing, alloy composition to powder morphology. Technical personnel tasked with creating part specifications or quality assurance staff responsible for ensuring part compliance will benefit from this report's assessment of the current state-of-the-art knowledge of critical features that can influence the corrosion performance of additively manufactured parts.

The gap analysis presented at the end of this report is much less a conclusion than a call to action. Recognition of the limitations of current understanding highlights the need for further research, modification of current standards, and/or the development of new ones. Definition of the unknown is a springboard to finding solutions; to that end, this document will be an invaluable reference for those evaluating and modifying existing industrial standards to address corrosion testing and evaluation of additively manufactured parts.

Finally, this report includes information for professionals in a wide variety of industries including but not limited to, aerospace, automotive, biomedical, military, nuclear energy, and oil and gas. As additive manufacturing expands to new applications and new industries, this report is intended to be a helpful reference to facilitate the integration of this technology with engineering confidence in part quality and corrosion performance.

Rationale

The variables that affect the corrosion behavior of additive manufactured metallic materials are important to understand in order to successfully fabricate functional AM components. Issues such as the type of AM process, AM build parameters, microstructure, surface condition, specimen geometry, post-processing heat treatments, etc. all affect the finished product. The literature to date does not have sufficient single source papers that cover all of these variables and the variables that are assessed are usually limited to one or two classes of metal alloy systems. Also, though standardized corrosion testing methods are typically appropriate for AM products, the selection and treatment of the test samples used have not been adequately addressed. This technical report was created in order to provide a summary of the current state of knowledge of each of the variables that affect the corrosion, cracking, fatigue, and oxidation behavior of AM fabricated parts, including test methodologies. In addition, this report also highlights the limits of the current industry understanding of AM corrosion issues by including a gap analysis.

Referenced Standards and Other Consensus Documents

Unless specifically dated, the latest edition, revision, or amendment of the documents listed in the table below shall apply.

AMPP/NACE/SSPC, www.ampp.org:

NACE/ASTM G193	Standard Terminology and Acronyms Relating to Corrosion
ANSI/NACE MR0175/ISO 15156	Petroleum and Natural Gas Industries-Materials for Use in H_2S-Containing Environments in Oil and Gas Production
ANSI/NACE MR0103/ISO 17945	Petroleum, Petrochemical and Natural Gas Industries — Metallic Materials Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Environments
NACE TM0177	Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H_2S Environments
NACE TM0198	Slow Strain Rate Test Method for Screening Corrosion-Resistant Alloys for Stress Corrosion Cracking in Sour Oilfield Service
NACE TM0284	Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen-Induced Cracking
NACE TM0316	Four-Point Bend Testing of Materials for Oil and Gas Applications

American Petroleum Institute (API), www.api.org:

API Standard 6ACRA	Age-Hardened Nickel-based Alloys for Oil and Gas Drilling and Production Equipment
API Standard 20S	Additively Manufactured Metallic Components for Use in the Petroleum and Natural Gas Industries

American Welding Society (AWS), www.aws.org:

AWS A5.16	Specification for Titanium and Titanium-Alloy Welding Electrodes and Rods
AWS D20.1	Standard for Fabrication of Metal Components using Additive Manufacturing

ASTM International, www.astm.org:

ASTM B26	Standard Specification for Aluminum-Alloy Sand Castings
ASTM B85	Standard Specification for Aluminum-Alloy Die Castings
ASTM B381	Standard Specification for Titanium and Titanium Alloy Forgings
ASTM E466	Standard Practice for Conducting Force Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials
ASTM E606	Standard Test Method for Strain-Controlled Fatigue Testing

ASTM E647	Standard Test Method for Measurement of Fatigue Crack Growth Rates
ASTM E1457	Standard Test Method for Measurement of Creep Crack Growth Times in Metals
ASTM E1820	Standard Test Method for Measurement of Fracture Toughness
ASTM E1823	Standard Terminology Relating to Fatigue and Fracture Testing
ASTM F2624	Standard Test Method for Static, Dynamic, and Wear Assessment of Extra-Discal Single Level Spinal Constructs
ASTM F3001	Standard Specification for Additive Manufacturing Titanium-6 Aluminum-4 Vanadium ELI (Extra Low Interstitial) with Powder Bed Fusion
ASTM F3055	Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion
ASTM F3318	Standard for Additive Manufacturing – Finished Part Properties – Specification for AlSi10Mg with Powder Bed Fusion – Laser Beam
ASTM G5	Standard Reference Test Method for Making Potentiodynamic Anodic Polarization Measurements
ASTM G28	Standard Test Methods for Detecting Susceptibility to Intergranular Corrosion in Wrought, Nickel-Rich, Chromium-Bearing Alloys
ASTM G30	Standard Practice for Making and Using U-Bend Stress-Corrosion Test Specimens
ASTM G36	Standard Practice for Evaluating Stress-Corrosion-Cracking Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution
ASTM G38	Standard Practice for Making and Using C-Ring Stress-Corrosion Test Specimens
ASTM G39	Standard Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test Specimens
ASTM G48	Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution
ASTM G49	Standard Practice for Preparation and Use of Direct Tension Stress-Corrosion Test Specimens
ASTM G59	Standard Test Method for Conducting Potentiodynamic Polarization Resistance Measurements
ASTM G61	Standard Test Method for Conducting Cyclic Potentiodynamic Polarization Measurements for Localized Corrosion Susceptibility of Iron-, Nickel-, or Cobalt-Based Alloys
ASTM G67	Standard Test Method for Determining the Susceptibility to Intergranular Corrosion of 5XXX Series Aluminum Alloys by Mass Loss After Exposure to Nitric Acid (NAMLT Test)
ASTM G76	Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets

ASTM G78	Standard Guide for Crevice Corrosion Testing of Iron-Base and Nickel-Base Stainless Alloys in Seawater and Other Chloride-Containing Aqueous Environments
ASTM G102	Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements
ASTM G111	Standard Guide for Corrosion Tests in High Temperature or High Pressure Environment, or Both
ASTM G123	Standard Test Method for Evaluating Stress-Corrosion Cracking of Stainless Alloys with Different Nickel Content in Boiling Acidified Sodium Chloride Solution
ASTM G129	Standard Practice for Slow Strain Rate Testing to Evaluate the Susceptibility of Metallic Materials to Environmentally Assisted Cracking
ASTM G134	Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet
ASTM G142	Standard Test Method for Determination of Susceptibility of Metals to Embrittlement in Hydrogen Containing Environments at High Pressure, High Temperature, or Both
ASTM G148	Standard Practice for Evaluation of Hydrogen Uptake, Permeation, and Transport in Metals by an Electrochemical Technique
ASTM G150	Standard Test Method for Electrochemical Critical Pitting Temperature Testing of Stainless Steels and Related Alloys
ASTM G168	Standard Practice for Making and Using Precracked Double Beam Stress Corrosion Specimens
ASTM G170	Standard Guide for Evaluating and Qualifying Oilfield and Refinery Corrosion Inhibitors in the Laboratory
ASTM G184	Standard Practice for Evaluating and Qualifying Oil Field and Refinery Corrosion Inhibitors Using Rotating Cage
ASTM G185	Standard Practice for Evaluating and Qualifying Oil Field and Refinery Corrosion Inhibitors Using the Rotating Cylinder Electrode
ASTM G192	Standard Test Method for Determining the Crevice Repassivation Potential of Corrosion-Resistant Alloys Using a Potentiodynamic-Galvanostatic-Potentiostatic Technique
ASTM G199	Standard Guide for Electrochemical Noise Measurement
ASTM G202	Standard Test Method for Using Atmospheric Pressure Rotating Cage
ASTM/ISO 52900	Additive manufacturing — General principles — Fundamentals and vocabulary

European Committee for Standardization (CEN), www.cencenelec.eu:

EN 1706	Aluminium and aluminium alloys - Castings - Chemical composition and mechanical properties

International Organization for Standardization (ISO), www.iso.org:

ISO 1099	Metallic materials — Fatigue testing — Axial force-controlled method
ISO 7539-2	Corrosion of metals and alloys - Stress corrosion testing - Part 2: Preparation and use of bent-beam specimens
ISO 7539-3	Corrosion of metals and alloys - Stress corrosion testing - Part 3: Preparation and use of U-bend specimens
ISO 7539-4	Corrosion of metals and alloys - Stress corrosion testing - Part 4: Preparation and use of uniaxially loaded tension specimens
ISO 7539-5	Corrosion of metals and alloys - Stress corrosion testing - Part 5: Preparation and use of C-ring specimens
ISO 7539-7	Corrosion of metals and alloys - Stress corrosion testing - Part 7: Method for slow strain rate testing
ISO 7539-9	Corrosion of metals and alloys - Stress corrosion testing - Part 9: Preparation and use of pre-cracked specimens for tests under rising load or rising displacement
ISO 7539-11	Corrosion of metals and alloys - Stress corrosion testing - Part 11: Guidelines for testing the resistance of metals and alloys to hydrogen embrittlement and hydrogen-assisted cracking
ISO 8044	Corrosion of metals and alloys — Vocabulary
ISO 11846	Corrosion of metals and alloys — Determination of resistance to intergranular corrosion of solution heat-treatable aluminium alloys
ISO 12106	Metallic materials — Fatigue testing — Axial-strain-controlled method
ISO 12108	Metallic materials — Fatigue testing — Fatigue crack growth method
ISO 16773	Electrochemical impedance spectroscopy (EIS) on coated and uncoated metallic specimens

Standards Norway, www.standard.no:

NORSOK M-630	Material data sheets and element data sheets for piping

AMPP technical reports are intended to convey technical information or state-of-the-art knowledge regarding corrosion. In many cases, they discuss specific applications of corrosion mitigation technology, whether considered successful or not. Statements used to convey this information are factual and are provided to the reader as input and guidance for consideration when applying this technology in the future. However, these statements are not intended to be recommendations for general application of this technology and must not be construed as such.

Section 1: Scope

This technical report presents the current state of knowledge and gap analyses on corrosion testing of metallic materials produced using additive manufacturing (AM) technologies in environments relevant to several industrial applications. The discussed materials were produced primarily via laser powder bed fusion (LPBF), directed energy deposition (DED), and specifically the wire arc additive manufacturing (WAAM) form of DED. Many variables may not be sufficiently detailed in the rapidly evolving state of the art at the time of publication for the assessment of the performance of AM products; some variables such as microstructure, post-build processing, surface condition, residual stress, physical defects, and selection of representative test specimens (size and/or geometry) for a finished product are addressed. This report contains approaches for corrosion and environmental cracking assessment of AM materials, including test details that are relevant to the AM processes for some specific cases. The technical report provides the foundation for the preparation of test standard(s) that apply to AM products.

Section 2: Introduction

2.1 Additive manufacturing (AM) is a technology that has made significant advances in terms of its number of applications in diverse industrial sectors over the past decade. While the technology itself has been in existence for nearly 30 years,[1,2] improved understanding of the science underpinning this manufacturing approach has led to higher quality levels while simultaneously making strides to be more cost-competitive. AM, as defined by ASTM/ISO 52900, is "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies." The potential uses of AM technology have captured the attention of the global manufacturing, scientific, and engineering communities.

2.2 However, for any manufactured component to be considered fit for service, acceptance testing criteria must be met – in many cases corrosion-related. This is particularly true for applications in industrial sectors such as energy, food and chemical industries, medical applications, transportation, and critical infrastructure. In July 2021, this AMPP TR21522 project team was formed to create a technical report that presents the current state of knowledge and gap analysis on corrosion testing for products that are manufactured using AM processes. The membership of this team is comprised of about 35 subject matter experts in AM, materials, and corrosion. The project team organized their efforts in stages to produce the report. These were assessing the state of the art through a literature search, capturing the relevant knowledge with respect to corrosion and testing, and finally preparing the report that includes a gap analysis and recommendations regarding the applicability of testing methods and acceptance criteria intended for products manufactured by conventional means and those made through the AM production route. A variety of corrosion mechanisms were considered and investigated in this report, reflecting both the content of the technical literature and the collective experience and expertise of the project team.

2.3 To facilitate the broad-scale review of the existing technical literature, the project team established categories by corrosion mechanism, materials, and specific AM process. The corrosion mechanism categories were (1) general and localized corrosion, (2) high-temperature oxidation, (3) stress corrosion cracking (SCC) and sulfide stress cracking (SSC), (4) corrosion fatigue, and (5) hydrogen-induced stress cracking (HISC). The materials were classified as nickel alloys, titanium alloys, austenitic stainless steels, precipitation-hardening stainless steels, cobalt-chromium alloys, carbon and low-alloy steels, and aluminum alloys. The additive manufacturing processes were powder bed fusion (laser and electron beam), directed energy deposition (wire arc, laser wire, and laser powder), and binder jet. It should be noted that these categories were selected to capture the diversity of the literature as it currently exists; the absence of some categories that the reader might consider as "missing" is merely a reflection of the lack of published corrosion-related research at the time of publication.

2.4 While performing the literature assessment, thousands of citations were examined and about 450 of those were found to be relevant to one or more of the corrosion mechanisms for the purposes of this report. Our task was made easier by review papers such as those of Sander et al.,[3] Ko et al.,[4] Schindelholz et al.,[5] Hamza et al.,[1] Revilla et al.,[6] Chen et al.,[7] Ettefagh et al.,[8] and Renner et al.[9] With the exception of Sander et al.,[3] most of the review papers were focused on specific classes of materials such as aluminum alloys or stainless steels.

2.5 The literature review also resulted in identifying the variables from the AM processes that have a role in