



AMPP TR21522-2024
Approved October 3, 2024

Corrosion Testing for Additive Manufacturing

©2024 Association for Materials Protection and Performance (AMPP). All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means (electronic, mechanical, photocopying, recording, or otherwise) without the prior written permission of AMPP.

AMPP TR21522-2024

Corrosion Testing for Additive Manufacturing

This AMPP technical report represents a consensus of those individual members who have reviewed this document, its scope, and provisions. Its acceptance does not in any respect preclude anyone, whether he or she has adopted the technical report or not, from manufacturing, marketing, purchasing, or using products, processes, or procedures not in conformance with this technical report. Nothing contained in this AMPP technical report is to be construed as granting any right, by implication or otherwise, to manufacture, sell, or use in connection with any method, apparatus, or product covered by letters patent, or as indemnifying or protecting anyone against liability for infringement of letters patent. This technical report represents minimum requirements and should in no way be interpreted as a restriction on the use of better procedures or materials. Neither is this technical report intended to apply in all cases relating to the subject. Unpredictable circumstances may negate the usefulness of this technical report in specific instances. AMPP assumes no responsibility for the interpretation or use of this technical report by other parties and accepts responsibility for only those official AMPP interpretations issued by AMPP in accordance with its governing procedures and policies which preclude the issuance of interpretations by individual volunteers.

Users of this AMPP technical report are responsible for reviewing appropriate health, safety, environmental, and regulatory documents and for determining their applicability in relation to this technical report prior to its use. This AMPP technical report may not necessarily address all potential health and safety problems, or environmental hazards associated with the use of materials, equipment, and/or operations detailed or referred to within this technical report. Users of this AMPP technical report are also responsible for establishing appropriate health, safety, and environmental protection practices, in consultation with appropriate regulatory authorities, if necessary, to achieve compliance with any existing applicable regulatory requirements prior to the use of this technical report.

CAUTIONARY NOTICE: AMPP technical reports may be revised or withdrawn at any time in accordance with AMPP standards committee procedures. The user is cautioned to obtain the latest edition. Purchasers of AMPP technical reports may receive current information on all AMPP publications by contacting AMPP Customer Support, 15835 Park Ten Place, Houston, TX 77084-5145 (Tel: +1 281-228-6200, email: customersupport@ampp.org).

Document History:

2024-10-03: Approved by AMPP Standards Committee (SC) 08, Metallic Material Selection & Testing

AMPP values your input. To provide feedback on this standard, please contact: standards@ampp.org

Corrosion Testing for Additive Manufacturing

Foreword, Rationale	9
Referenced Standards and Other Consensus Documents	10
Section 1 Scope	14
Section 2 Introduction	14
Section 3 Terms and Abbreviations	15
Section 4 Additive Manufacturing and Corrosion Mechanisms	17
4.1 Introduction to AM and Corrosion Mechanisms	17
4.2 General and Localized Corrosion	17
4.3 Corrosion Fatigue	18
4.4 Hydrogen Related Mechanisms (HISC, HIC, SWC, SOHIC)	19
4.5 Environmentally Assisted Cracking (SCC and SSC)	21
4.6 High-Temperature Oxidation	22
Section 5 Additive Manufacturing – Corrosion by Alloy Type	23
5.1 Austenitic and Duplex Stainless Steels	23
5.2 Precipitation Hardened Stainless Steels	39
5.3 Nickel Alloys	41
5.4 Cobalt-Chromium Alloys	56
5.5 Titanium Alloys	59
5.6 Aluminum Alloys	80
Section 6 AM Process Details and Relation to Corrosion	102
6.1 Powder Bed Fusion (Laser and EB)	102
6.2 Directed Energy Deposition	123
6.3 Binder Jet Process	136
Section 7 AM Comparison with Conventional Processes with Respect to Corrosion	139
7.1 Overview	139
7.2 Microstructure/Heat Treatment	142
7.3 Surface Characteristics	143
7.4 Residual Stresses	144
Section 8 Assessing Corrosion Threats by Industry Segment Applications	144
8.1 Overview	144
8.2 Aerospace	145
8.3 Automotive	145
8.4 Biomedical	145
8.5 Defense/Military	146
8.6 Energy (Nuclear)	146

	8.7	Energy (Oil & Gas).....	146
	8.8	Other Market Segments.....	147
Section 9		Corrosion/Environmental Cracking Testing of AM Products.....	147
	9.1	Overview.....	147
	9.2	Common Tests by Corrosion Mechanism.....	147
	9.3	AM Related Variables by Corrosion Mechanism.....	148
Section 10		Discussion and Gap Analysis.....	150
	10.1	Overview.....	150
	10.2	Primary AM Variables for Corrosion Performance.....	151
	10.3	Test Performance as a Predictor of Part Performance.....	151
	10.4	Critical AM Test Specimen Attributes.....	152
	10.5	Limitations of Part Inspection Technology.....	153
	10.6	AM Part Response to Static, Cyclic, Dynamic Loading.....	153
	10.7	Testing Statistics and Representativeness.....	153
	10.8	Test Result Interpretation.....	154
	10.9	Linking Test Protocols with Application Requirements.....	154
	10.10	Lack of Existing Scientific Data.....	154
Section 11		Conclusions.....	155
	11.1	AM Process versus Corrosion Mechanism.....	155
	11.2	AM versus Conventional Materials.....	157
Section 12		Direction Forward.....	158
		Other Referenced Documents.....	159

TABLES

Table 1	Corrosion Testing on AM Austenitic Stainless Steels.....	24
Table 2	Corrosion Testing on AM 17-4PH.....	39
Table 3	Corrosion Testing on AM Nickel Alloys.....	41
Table 4	Corrosion Testing on AM UNS N07718 Sorted by Corrosion Mechanisms.....	43
Table 5	Additive Manufactured Other Nickel Alloys and Corrosion Mechanisms.....	54
Table 6	Additive Manufactured CoCr Alloys and Corrosion Mechanisms.....	57
Table 7	Additive Manufactured Titanium Alloys and Corrosion Mechanisms.....	60
Table 8	Corrosion Comparison Between EB PBF and Wrought Ti-6Al-4V.....	64
Table 9	Corrosion Resistance of LPBF Ti-6Al-4V by Build Plane Orientation.....	65
Table 10	Corrosion Resistance of EB PBF Ti-6Al-4V by Build Plane Orientation.....	65
Table 11	Corrosion Comparison of LPBF Ti and TiB Composite.....	67
Table 12	Corrosion Comparison of LPBF Ti-6Al-4V as a Function of Heat Treatment.....	68
Table 13	Effect of Heat Treat Temperature on Corrosion per Dai et al., 2017.....	69
Table 14	Effect of Heat Treat Temperature on Corrosion per Ettefagh et al., 2019.....	69
Table 15	Effect of Heat Treat Temperature on Corrosion of LPBF Ti-6Al-4V.....	69
Table 16	Comparison of Thermal Desorption Behavior of Hydrogenated EBM and Wrought Ti-6Al-4V.....	72

Table 17	TDS Spectra in the XY and XZ Orientations for SLM Ti-6Al-4V	72
Table 18	Activation Energy Associated with Hydrogen Charging	73
Table 19	Fatigue Strengths Determined by Staircase Method at 2M Cycles and Surface Roughness Parameters	74
Table 20	Geometric Effects.....	76
Table 21	Wrought and Machined Properties are Used as Baseline to Compute K_f for All Other Conditions	79
Table 22	Summary of Fatigue Properties and K_f per Equation	79
Table 23	Mechanical Properties (Fatigue R = -1) of Heat Treated LPBF Ti-6Al-4V171.....	80
Table 24	Additive Manufactured Al Alloys and Corrosion Mechanisms	81
Table 25	Hardness and Mechanical Properties for LPBF AlSi10Mg by Heat Treat Condition	84
Table 26	Mechanical Properties of LPBF AlSi10Mg as a Function of Direction and Heat Treatment	84
Table 27	Residual Stress and Mechanical Properties for LPBF AlSi10Mg as a Function of Stress Relieve	85
Table 28	Elongation and Toughness with Mechanical Properties as a Function of Heat Treatment	87
Table 29	Process Variables and Resulting Native Oxide Film Thickness and E_{corr}	87
Table 30	Corrosion as a Function of Surface Finish and Porosity for LPBF AlSi10Mg	88
Table 31	Tensile Properties and Fracture Toughness for LPBF AlSi10Mg as a Function of Heat Treatment	95
Table 32	Fatigue Performance of AP and Heat-Treated LPBF AlSi10Mg.....	96
Table 33	Tensile and Fatigue Properties of LPBF AlSi10Mg at Various Heat-Treated Conditions	96
Table 34	Properties Associated with the Preheat and Stress Relief Conditions.....	98
Table 35	Test Parameters and Resulting Average Fatigue Lives (N_f , Ratios Calculated Using ID #12 as Baseline) at Stress Amplitude (S_a) of 120 MPa (R = -1, 30 Hz) (M-Milled, AP-As-printed).....	99
Table 36	Test Parameters and Porosity Results (Area Fraction and Average Diameter) and Fatigue Strengths (HT-500 °C/1 h)	99
Table 37	Comparison of the Rotating Bending Fatigue Test Results of LPBF AlSi10Mg after T6 Heat Treat- ment (Different Solution Temperatures Shown, Same Artificial Aging at 160 °C/6 h) and Different Surface Treatments Using Smooth or Notched Bar Specimens	100
Table 38	E_{corr} and I_{corr} Electrochemical Results as a Function of Powder Condition and Orientation for 316L SLM in 6.0 wt.% FeCl ₃ Solution at 25 °C	113
Table 39	Microstructural and Mechanical Effects as a Function of Post Build Heat Treatment	124
Table 40	Effect of Heat Treatment on the Corrosion Resistance of WAAM Duplex SS.....	127
Table 41	Fatigue Study Test Conditions	130
Table 42	Tensile and FCGR of L-DED 718 as a Function of Heat Treatment.....	134
Table 43	L-DED Process Parameters Referenced for Alloy 718 (Specific Energy = Power / [Speed*Spot dia.]	135
Table 44	L-DED Process Parameters Referenced for Ti-6Al-4V	136
Table 45	Chemical Composition and Volume Fraction of Phases in L-DED Ti-6Al-4V (R-Retained, T-Trans- formed; SR-650 °C/1 h FC; Annealed (A)-550 °C/4 h FC; STA-920 °C/2 h, AC, 550 °C/5 h, FC)	136
Table 46	Comparison of AM Processes for Cemented Tungsten Carbides.....	139
Table 47	Comparisons of Additive Manufactured Alloys with Conventionally Manufactured Alloys	140
Table 48	Summary of Standards and Test Methods Used for Quantifying AM Alloy Corrosion Resistance	149

FIGURES

Figure 1 CPT, CCT Determination by Corrosion Rate for 316L.....28

Figure 2 Distribution of Corrosion Studies as of 2021 by Stainless Steel Alloy, Process, and Environment.....29

Figure 3 (a) Effect of High-temperature Annealing Conditions on MnS Precipitate Populations for SLM 316L and (b) Average Breakdown Potentials and Standard Deviation for the Same Material along with Wrought 316L in 0.6 M NaCl at 25 °C29

Figure 4 (a) Global Polarization Curves (3.5% NaCl AT 25 °C, 1 Mv s-1) of the Different Samples after Surface Preparation. (b) Relationship between Pitting Potential Derived from Global Polarization Curves and PREN for Different Austenitic Alloys31

Figure 5 Potentiodynamic Scans Performed at 1 Mv/s in Deaerated 0.1 M HCl versus an Ag/AgCl Reference. The Trends from the Wrought and PBF-L 316L Samples are Identified Accordingly, where the Latter Exhibited Reduced Passivity and an Increased Anodic Current Density31

Figure 6 Secondary Electron Images of the Typical Pit Morphologies Resulting from Cyclic Polarization in 0.6M NaCl for the (a) Wrought, (b) HP, and (c) LP 304L. Higher Magnification of the Boxed Area in (c) Shows Residual δ-ferrite Spanning the Pit Mouth (d)32

Figure 7 Typical DLEPR Polarization Curves for the Wrought and DED Specimens in Quiescent 0.5M H₂SO₄ + 0.005M KSCN (a), with Scan Direction and Activation (IA) and Reactivation (IR) Current Labeled for the LP Scan. The Average IR/IA Ratio is Plotted against Measured Delta Ferrite Content in (b). Error Bars Represent One Standard Deviation33

Figure 8 CPT Values of Cross Sections at Different Build Heights for Different Post-processing Heat Treatments with Max/min Values Indicated by Error Bars.....34

Figure 9 Volta Potential of Ferrite (α), Austenite (γ), and Sigma Phase (σ) for Different Post-processing Treatments Demonstrating the Influence of the Presence of σ.....34

Figure 10 Cyclic Potentiodynamic Polarization Curves of As-received Cold-rolled and Annealed Reference Alloy 2205, as-SLM-processed DSS 2205, and SLM-processed DSS 2205 with Post-heat Treatment in Neutral 0.6 M NaCl Solution at Room Temperature, Respectively. The Arrows Indicate the Polarization Direction35

Figure 11 Representative Engineering Stress-strain Curves at a Strain Rate of 10⁻⁴ s⁻¹ of CM316L and As-built AM316L with and without 7 Days of Hydrogen Precharging36

Figure 12 Typical Engineering Stress-engineering Strain Curves of the (a) LPBF, (b) CA, and (c) CA-TMT Samples with and without H. The Insets Show the SEM Images of the Surface of Samples after Tensile Testing at the Region of Fracture. (d) Quantification of HE Susceptibility for Each Condition. Error Bars Represent the Standard Deviations of the ε_{f,H}/ε_{f,0} Values Obtained from Several Stress-strain Curves. Note that Tensile Loading Direction is Parallel to the Y Direction in Figures 2 and 3. (LPBF: Laser Powder-bed Fusion, CA: Casting plus Annealing, TMT: Thermomechanical Treatment)37

Figure 13 H Desorption Curves of the 5 Days H-charged Samples at a Heating Rate of 26 °C/min. The Inset Shows the Variation in H Desorption Curve with H-charging Time for the LPBF Sample. (LPBF: Laser Powder-bed Fusion, CA: Casting plus Annealing, TMT: Thermomechanical Treatment)37

Figure 14 Cyclic Polarization Curves of Wrought 718 and AM718 in 2.25M Cl-Solution at 88 °C47

Figure 15 Comparison of SSC Resistance from Three Different Providers49

Figure 16 Stress-strain Curves of Both Wrought 718 and AM 718 in Air and 3.5% NaCl+CP51

Figure 17 (a) Stress-strain Curves of AM 718 with and without Hydrogen Charging: HP-Horizontal Plane; VP-Vertical Plane; HU-hydrogen Uncharged; HC: Hydrogen Charged. (b) Illustrated Mechanisms of Hydrogen-assisted Crack Initiation, Growth, and Propagation of AM 718 Samples52

Figure 18 Comparison of Tensile Behavior due to Hydrogen Effect of Wrought 718 and AM 71853

Figure 19 Tribo-corrosion Behavior of AM 718 and Wrought 71854

Figure 20	SSRT Results of AM 625 in SOW under Cathodic Protection after Hydrogen Pre-charging: UT – Untreated; HT – Heat Treated.....	56
Figure 21	Cooling Path and Critical Cooling Rates for Ti-6Al-4V Microstructure Formation in EBM Process with a Chamber Temperature of 650 °C. Microstructural Transformations Happening in Each Stage Are Also Noted.....	61
Figure 22	Schematic Illustrations of Phase Transformation Mechanisms during Continuous Cooling of Ti-6Al-4V from Temperatures above β–transus. Gray Regions are β Phase, White Regions are α Phase in (a)–(e), the Grain in (f) with Thin, Orthogonal Lines Denotes a Fully Martensitic Grain (can be α' or α''), while the Black Lines are β Grain Boundaries. Note that Only the Phase Transformation Activity in the Center Grain is Depicted in Each Sub-figure for Simplicity, although the Surrounding Grains Experience the Same Phenomena.....	62
Figure 23	Relationship between Baseline Current Density at 0.1V SCE (ibase) and Re-establishment Time Following a Single Mechanical Scratching Event in MEM (Minimum Essential Media) at 37 °C.....	66
Figure 24	The Polarization Curves of CP-Ti and Ti-TiB2 Samples Produced by LPBF Immersed in Aerated Hank's Solution at Body Temperature.....	67
Figure 25	Correlation between Effective Stress and Crack Initiation Site (CIS) Size for Different CIS Types: LOFs, Spherical Pores, and α-colonies/prior-β grains. Effective Stress is Used to Compensate for Different R Ratios (-1, 0.1), by Using $\sigma_{\text{eff}} = \sigma_{\text{max}} \left(\frac{1-R}{2} \right)^{0.28}$. (d) is the Project Defect Area.....	75
Figure 26	Comparison of Fatigue Lifetime Obtained for Both SLM and EBM Processes with More Classical Casting and Wrought Processes (Tendencies Extracted from M.J. Donachie, Titanium: A Technical Guide [2nd ed.], ASM Int'l, 2000176) with a Common Denominator of Max Stress.....	78
Figure 27	Gravity Cast AlSi10Mg (Left) and LPBF (Right) AlSi10Mg.....	82
Figure 28	Microstructures of the LPBF AlSi10Mg Alloy: (a) As-built State, (b) Annealed at 160 °C/5 h, (c) Stress-relieved at 300 °C/2 h, (d) after T6 Heat Treatment (510 °C/6 h, WQ, 170 °C/4 h).....	86
Figure 29	Mechanism Showing the Corrosion Evolution for 2 Separate Cases: One for when there is a Connected Silicon Network (a) to (d) and Another for when the Silicon Forms Separate Precipitates (e) to (h). Green is Used to Denote the Aluminum Phase and Black is Used for the Silicon Phase. The Images Represent Cross-sections of Corroded Specimens, with the Top of the Figures Corresponding to the Corroded Surface.....	89
Figure 30	Effect of Heat Treatment Temperature on the Cumulate Frequency of the Pitting Potentials (16 Specimens, XY and XZ Combined) (or OCP for the Pitting was Initiated during the Equilibration Time) in 0.02 M NaCl Solution at 23 °C. UT: As-printed.....	90
Figure 31	Potentiodynamic Polarization Response of Wrought and LPBF (SLM) AA7075 (with Different Heat Treatment) in De-aerated 0.1 M NaCl. The Plots Presented are Comprised of a Unique Anodic and Unique Cathodic Scan for Each of the Specimen Conditions.....	93
Figure 32	Cross-sectional Fracture Surfaces of the High-cycle Fatigue Experienced by the (a, d) As-built, (b, e) T6, and (c, f) Direct Aged Samples.....	97
Figure 33	Comparison of Fatigue Strength in Early High Cycle to Very High Cycle Fatigue a) AlSi12 (A-B from Table 34) and b) AlSi10Mg (C-D from Table 34).....	98
Figure 34	An Overall Comparison of the Sole Effects of Each Post-treatment on Microstructural and Mechanical Characteristics Compared to the As-built State (HT not Placed in the CRS Column, as It is More Relaxing the Tensile Stresses Rather than Inducing CRS).....	101
Figure 35	SEM Image of the Alloy Powders Manufactured by (a) PREP (b) RA and (c) GA Process. Comparison of Shape of Powders Fabricated by (d) GA and (e) WA Process. A 718 Component Fabricated Using (f) GA and (g) PREP Powder.....	104
Figure 36	(a) SE Image of Gas Atomized 316L Powder and (b) BSE Image of the Same Powder in Cross section with Gas Pores (Black Circles) Visible within Some Particles.....	105

Figure 37	(a) Corrosion Potential and (b) Passive Current Density as a Function of Printing Speed for the L-PBF 316L Specimens. Measurement Ranges for Wrought 316L (Grey Rectangles) are Included for Reference with a Magnified Region around this Range for the Passive Current Density Shown in the Inset in (b)	107
Figure 38	(a) Pitting and (b) Repassivation Potential Measurements as a Function of Printing Speed for the AM L-PBF 316L Specimens. Measurement Ranges for Wrought 316L (Grey Rectangles) are Included for Reference.....	107
Figure 39	Relationship between the Pitting Potential and the Amount of Cr and Mo (Pitting Index) Measured in Dendrite Cores of SLM SS 904L. The Relationship between Core Composition and Scan Speed (v) during Laser Remelting is Indicated by the Arrow.....	108
Figure 40	(a) Anodic Polarization Behavior and (b) Breakdown Potentials of Different SLM 316L As-printed Surface Orientations, a Mechanically Ground SLM 316L Surface, and Wrought 316L	108
Figure 41	Relationship between Breakdown Potential of SLM 316L and Average Surface Roughness (S_a) in 3.5 wt% NaCl at 25 °C for a Variety of Surface Finish Treatments. Breakdown Potential for Ground Wrought 316L is Also Shown	109
Figure 42	Anodic Linear Polarization Resistance Plot for Wrought and Additive Manufactured UNS 30403 in (a) As-built Condition and Heat Treated at (b) 700 °C and (c) 800 °C for 250 Hours.....	110
Figure 43	Anodic Tafel Plot for Wrought and Additive Manufactured UNS 30403 in (a) As-built Condition and Heat Treated at (b) 700 °C and (c) 800 °C for 250 Hours.....	111
Figure 44	Cyclic Potentiodynamic Polarization Plot for Wrought and Additive Manufactured UNS 30403 in (a) As-built Condition and Heat Treated at (b) 700 °C and (c) 800 °C for 250 Hours	111
Figure 45	Cyclic Potentiodynamic Polarization for AM and Wrought 316L Stainless Steels.....	112
Figure 46	Optical Images of (a) Etched, As-built SLM 316L and (b) through (d) the Same Material Subjected to Annealing at Different Temperatures for 2 h Followed by Water Quenching.....	114
Figure 47	Relationship between Pitting Potential of SLM 316L and Annealing Time in 3.5 wt% NaCl at Room Temperature	115
Figure 48	(a) Effect of High-temperature Annealing Conditions on MnS Precipitate Populations for SLM 316L and (b) Average Breakdown Potentials and Standard Deviation for the Same Material along with Wrought 316L (Commercial) in 0.6 M NaCl at 25 °C	116
Figure 49	Fatigue Crack Growth Rate (FCGR) Data of AM 304L (d(l)-ts) and Forged 304L for Conditions: Hydrogen-precharged Tested in Air (Internal H), Non-charged Tested in 103 MPa Hydrogen Gas (External H), Non-charged Tested in Air (Ambient). FCGR Based on International Institute of Welding (IIW) Recommendation for Steel Provided for Context.....	117
Figure 50	Comparison of da/dN vs. ΔK between Cold-worked and Non-cold-worked AM 316L SS with Different Heat Treatments and Crack Orientations	118
Figure 51	Comparison of SCC Growth Behavior of Unrecrystallized (650 °C Stress-relieved), Partially-recrystallized (955 °C Heat-treated), and Fully-recrystallized (HIP+SA) AM 316L SS. All Materials were Tested in the X-Z Orientation with No Additional Cold Work	119
Figure 52	A Comparison of Charpy Impact Toughness Values at Room Temperature between AM 316L SS, PM-HIP 316L SS, and Wrought 316L SS. Data Shown were Obtained from Solution-annealed Materials with Coarse Grain Structures. AM 316L SS in this Study Were Evaluated in Two Orientations.....	122
Figure 53	(Top) Surface Profiles and an Optical Image of a LOF Pore in HP 304L before (a) and after (b, c) Cyclic Polarization in 0.6M NaCl Showing Preferential Attack at the LOF Site. (Bottom) A Gas Pore in an HP Specimen without LOF Pores before (d) and after (e, f) Polarization Showing Attack in the Vicinity of the Pore	132
Figure 54	Relationship between Breakdown Potential of SLM 316L and Average Surface Roughness (S_a) in 3.5 wt% NaCl at 25 °C for a Variety of Surface Finish Treatments. Breakdown Potential for Ground Wrought 316L is also Shown.....	144

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 research 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 ₂ S-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 ₂ S 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 Pre-cracked 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 Re-passivation 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 Etefagh 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