White Paper

Performance Materials

Stress Corrosion Cracking / Sulfide Stress Cracking Testing in NACE MR0175 and ASTM G36 Environments of Copper-Beryllium Alloys

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1. EXECUTIVE SUMMARY

Det Norske Veritas (U.S.A.), Inc. (DNV GL) conducted testing of Alloy 25 and Alloy 3 copper beryllium alloys to ascertain their corrosion behavior in selected environments. The results of said testing and its corresponding report are referenced below. The objective was to baseline the performance of those alloys in regard to sour and chloride corrosion resistance. The testing encompassed sulfide stress cracking (SCC), stress corrosion cracking (SCC), and weight loss (WL) corrosion tests according to environments outlined in ANSI/NACE MR0175/ISO 15156-3 and ASTM G36-94. All stressed specimens were tested in the four-point bend (4PB) configuration at 100% (room temperature) minimum design yield strength (MDYS) provided by Materion according to aerospace standards in Metallic Materials Properties Development and Standardization [MMPDS].

The copper beryllium alloys tested showed minimal tendency for cracking in the tested environments with only one confirmed cracked specimen (Alloy 25 AT exposed at NACE Level V at 100% MDYS). The alloys experiences localized attack in the form of grain boundary etching and pitting at lower temperatures (≤ 194°F) or intergranular corrosion in high chloride/high temperature/low pH environments. Very high rates of general corrosion observed in NACE Levels V and VI may have prevented the materials from cracking at the higher temperatures.

2. INTRODUCTION

Det Norske Veritas (U.S.A.), Inc. (DNV GL) conducted testing of Alloy 25 and Alloy 3 copper beryllium alloys to ascertain their corrosion behavior in selected environments. The results of said testing and its corresponding report are referenced below. The objective was to baseline the performance of those alloys in regard to sour and chloride corrosion resistance. The testing encompassed sulfide stress cracking (SCC), stress corrosion cracking (SCC), and weight loss (WL) corrosion tests according to environments outlined in ANSI/NACE MR0175/ISO 15156-3 and ASTM G36-94. All stressed specimens were tested in the four-point bend (4PB) configuration at 100% (room temperature) minimum design yield strength (MDYS) provided by Materion according to aerospace standards in Metallic Materials Properties Development and Standardization [MMPDS].

3. EXPERIMENTAL APPROACH

3.1 APPROACH

Testing in NACE standard sour environments as well as in boiling magnesium chloride ($MgCl_2$) solution was performed to determine susceptibility to general (WL) and localized corrosion cracking (SSC or SCC) of six copper beryllium containing alloys

3.2 SCOPE

The project was categorized into three tasks:

- Task 1: SSC and SCC Tests on 4PB Specimens in NACE Sour Environments, with Additional WL Coupons
- Task 2: SCC Tests on 4PB Specimens in Boiling Magnesium Chloride
- Task 3: Analysis and Report (which has been referenced in the creation of this report)

The materials for testing were provided by Materion in the ready-to-test condition. The alloys, test types, and specimen sizes are listed in Table 1 below. In this table, the first column specifies the Materion alloy and temper, and the second column lists the nominal alloy composition. Columns three through eight list the NACE standard environment/test conditions for the work completed. The table also specifies the test standard and specimen geometry for each test.

SSC/SCC testing and weight loss measurements were performed on specimens cut from rod stock of six Cu-Be/Cu-Be-Ni alloys. The testing was planned for five NACE sour environment severity levels (II, IV, V, VI, VII) and also in boiling magnesium chloride. Table 2 provides additional details about the planned environmental conditions for testing. Based on the results in NACE Level VI, testing was not conducted at NACE Level VII – this test condition is listed for informational purposes only.

In Table 2, the first column lists the NACE standard environment/test condition, the second lists the pH, and the third column lists the calculated concentration of chloride ion in mg/L, added as NaCl. The fourth column lists the target solution volume to surface area ratio in mL/cm^2. The fifth column lists the test temperature in degrees Fahrenheit. Columns six through nine list the partial pressures in psia for CO_2, H_2S, H_2O, and N_2, respectively. The tenth and final column lists the total pressure target in psia (including the vapor pressure of water).

TABLE 1. Material and Condition Test Matrix

Material	Composition	ASTM G36	NACE MR0175				
			1" x 0.5" x 0.125" (ASTM G31 weight loss)				
		2" x 0.40" x 0.125" (ASTM G39 four-point bend beam)					
			Level II	Level IV	Level V	Level VI	Level VII
Brush Alloy 25 DSTO	Cu-2% Be		x	x	x	x	
Brush Alloy 25 DSTU	Cu-2% Be		x	x	x	x	
Brush Alloy 25 AT	Cu-2% Be		x	x	x	x	
Brush Alloy 25 HT	Cu-2% Be		x	x	x	x	
Brush Alloy 3 AT	Cu-0.5% Be-1.5% Ni	4PB only	x	x	x	x	
Brush Alloy 3 HT	Cu-0.5% Be-1.5% Ni	4PB only	x	x	x	x	

An "x" denotes a test with triplicate specimens tested (four-point bend and weight loss).

TABLE 2. Details of Test Conditions

NACE Level	pH	Calculated Cl	Minimum Solution Volume Ratio	Temperature	PP_{CO2}	PP_{H2S}	PP_{H2O}	PP_{N2}	Total Pressure Target
		mg/L	mL/cm^2	°F	psia	psia	psia	psia	psia
ASTM G36	Natural pH	338,200	-	311 ± 1.8	-	-	-	-	-
II	≈ 3 with 0.5 wt% acetic acid	33,700	10	77 ± 5	-	14.7	< 1	-	14.7
IV	Natural pH	101,000	10	194 ± 9	100	0.4	10	800	1000
V		101,000	20	302 ± 9	200	100	70	630	1000
VI		139,000	20	347 ± 9	500	500	131	-	1131
*VII**		*180,000*	*20*	*401 ± 9*	*500*	*500*	*260*	*-*	*1260*

*Condition planned but not tested.

FIGURE 1
ASTM G39 Four-Point Bent Beam Specimen

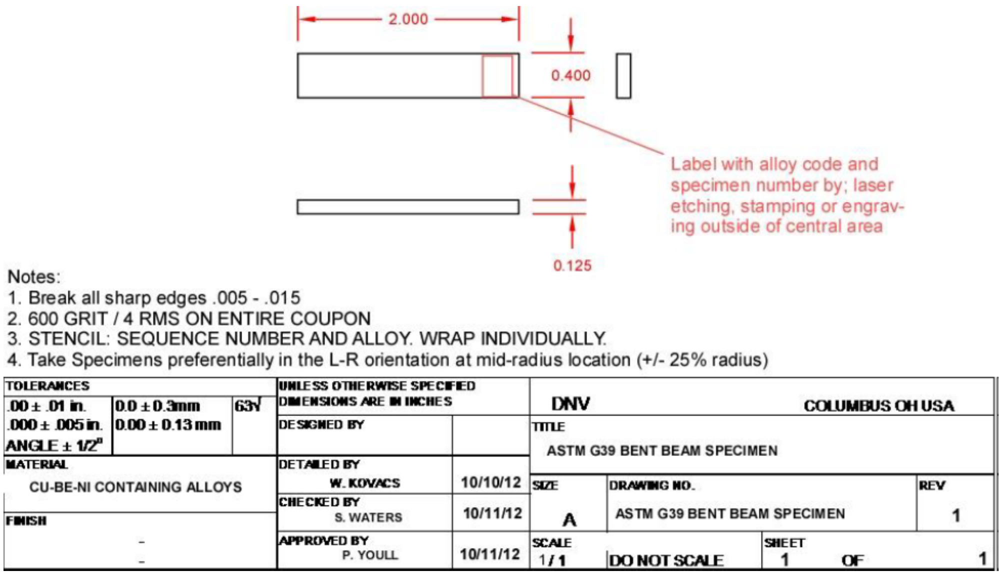
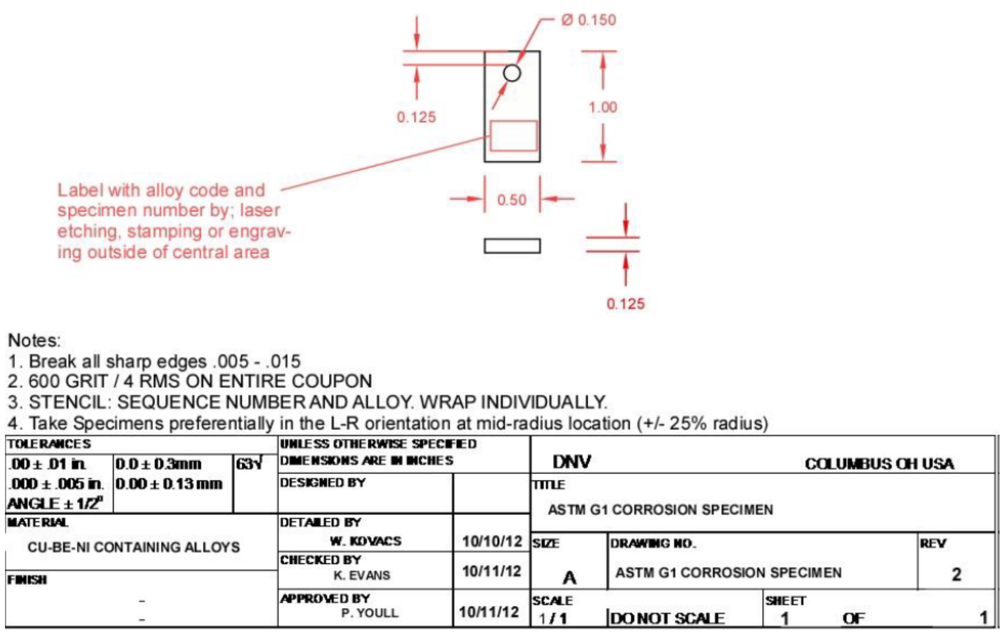


FIGURE 2
ASTM G31 Weight Loss Specimen



3.2.1 TASK 1: SSC AND SCC TESTS ON 4PB SPECIMENS IN NACE SOUR ENVIRONMENTS, WITH ADDITIONAL WL COUPONS

This task involved ASTM G39 constant load testing (4PB) at 100% MDYS for 30 days (720 hours) in the conditions specified in Table 2. Triplicate stressed 4PB specimens of 2" × 0.40" × 0.125" dimensions and triplicate unstressed WL specimens of 1" × 0.5" × 0.125" dimensions were tested for each condition/material combination, as shown in Table 1. The specimens had a 600 grit/4 RMS finish applied in the longitudinal direction. The specimens were removed in the L-R orientation so that: 1.) the applied stress on the 4PB specimens was parallel with the axial direction of the rod (the likely principal stress direction for machined components), and 2.) the end grain was of a limited surface area on the weight loss specimens. Materion provided the materials as finished samples (per DNV GL drawings, see Figures 1 and 2).

Experimental Procedure – 4PB:

Materion provided the statistically determined minimum design yield strength and elastic modulus (according to aerospace standards - Metallic Materials Properties Development and Standardization [MMPDS]) at room temperature for each material. DNV GL loaded the specimens to the strain equivalent to 100% MDYS at room temperature according to the formula listed in Equation 1, rearranged from Hooke's Law and the definition of the offset yield stress:

Target Strain, $\mu\varepsilon$ = (MDYS [Room Temp., psi] / Modulus [Room Temp., psi] + 0.002) * 1e+06 (1)

A longitudinal orientation strain gage was applied to the central, constant stress region of a reference specimen from each alloy and then it was deflected to the target strain. The deflection was measured on this reference specimen. The other specimens of the same material type were stressed to an equivalent deflection as the reference specimen. Small adjustments to the target deflection were made for difference in specimen initial thickness by adding or subtracting (as appropriate) the deflection difference indicated by ASTM G39 Equation 6 (4PB stress formula for sheet-gage specimens). A summary of the mechanical information provided for each alloy by Materion, the target strain and the target deflection values are provided in Table 3.

In Table 3, the first column lists the Materion alloy name / temper. The second column lists the room temperature yield strength for each alloy as provided by Materion in units of ksi. The third column lists the room temperature modulus for each alloy as provided by Materion in units of ksi. The fourth column lists the target strain calculated from the data listed in columns two and three using Equation 1 in units of microstrain. The fifth and final column lists the target deflection experimentally determined for each alloy in units of mils.

The C-276 loading fixtures were electrically isolated from the specimens using alumina ceramic isolating pins, and the test specimens were electrically isolated from each other as well as from the walls of the vessel during the exposure period.

At the end of the tests, the specimens were rinsed in distilled water and dried, then mechanically descaled with a brass brush before examination. The specimens were examined for evidence of cracking at 10-63x magnification. The specimens were further examined by Materion by sectioning, polishing and microscopic examination at the 1/3 and 2/3 positions across the central stressed region (longitudinal sectioning).

Experimental Procedure – WL:

Triplicate weight loss specimens were weighed before testing and following mechanical descaling by DNV GL/Materion post-immersion. During testing, the weight loss specimens were suspended in the immersed position with no contact between each other and the vessel walls.

Experimental Procedure – General:

The solutions used for these tests were thoroughly mixed prior to transfer into the de-aeration vessel. The solutions were de-aerated with laboratory purity nitrogen gas (99.999%) that had been sent through a commercial oxygen scrubber before introduction into the autoclave. An oxygen level less than 10 ppb in the solution was verified using the Rhodazine D method prior to solution introduction. The autoclave was evacuated and nitrogen purged several times before solution introduction. A solution volume to exposed coupon surface area ratio of approximately 10-20 mL/cm^2 or greater was maintained for the tests (see Table 2). The alloys were grouped together in a single test vessel for each exposure condition. After transferring the test solution into the autoclave, the test gas was added to the system.

For NACE Level II, the test gas was 100% H_2S with continuous slow purge during the test period. For NACE Level IV and V, the gas mixtures consisted of H_2S, CO_2, and N_2 with compositions specified by OLI Systems Inc., OLI Studio Analyzer 2.5.3 thermodynamic modelling software. For NACE Level VI, the gas composition was obtained through liquid loading of H_2S and CO_2 with amounts specified by OLI thermodynamic modelling. Once the test temperature was achieved, the 720-hour exposure period began.

TABLE 3. 4PB Loading Data

Material	Yield Strength (MDYS - room temperature)	Modulus (room temperature)	Target Strain at 100% Yield (calculated)	Target Deflection at 100% Yield (measured)
	ksi	ksi	$\mu\varepsilon$	mils
Brush Alloy 25 DSTO	110	19,000	7,789	33
Brush Alloy 25 DSTU	110	19,000	7,789	34.5
Brush Alloy 25 AT	130	19,000	8,842	42.5
Brush Alloy 25 HT	145	19,000	9,632	48
Brush Alloy 3 AT	80	20,000	6,000	28
Brush Alloy 3 HT	95	20,000	6,750	32

3.2.2 TASK 2: SSC TESTS ON 4PB SPECIMENS IN BOILING $MgCl_2$

This task involved ASTM G36 boiling magnesium chloride exposure of stressed 4PB specimens for 1000 hours at 155 ± 1°C. Triplicate stressed 4PB specimens of 2" × 0.40" × 0.125" dimensions were tested in the specified ASTM G36 conditions. The specimens had a 600 grit/4 RMS finish applied in the longitudinal direction. The specimens were removed in the L-R orientation so that the applied stress on the 4PB specimens was parallel with the axial direction of the rod (the likely principal stress direction for machined components). Materion provided the materials as finished samples (per DNV GL drawings, see Figure 1).

Experimental Procedure:

The four-point bend specimens were stressed as described above in section 3.2.1. The test procedure followed ASTM G36, and multiple specimens of copper beryllium were exposed together in a single test vessel. The test period was 1000 hours (at 155 ± 1°C). No intermediate specimen removal was performed.

At the end of the tests, the specimens were rinsed in distilled water and dried and then mechanically descaled with a brass brush before examination. The specimens were examined for evidence of cracking at 20x magnification per the standard. The specimens were further examined by Materion by sectioning, polishing, and microscopic examination. This examination was performed at specific locations (if indicated by 20x magnification by DNV GL), or at the 1/3 and 2/3 positions across the central stressed region for all others (longitudinal sectioning).

4. RESULTS AND DISCUSSION

Table 4 summarizes the results of the test program. The first column lists the Materion alloy name/temper in addition to the DNV GL sample number. The second column lists the cracking results (pass/fail) of boiling $MgCl_2$ exposure evaluated utilizing 20x optical examination post-test, with further detail provided by the microscopy performed by Materion at their facility. Columns three through six list the NACE standard environment/test condition results (including temperature in Fahrenheit and partial pressure of H_2S). Each of these columns is subdivided into one column of weight loss data reported in mils per year (mpy) and a second column listing cracking results (pass/fail) as a result of 10-63x optical examination.

The terminology used in this table includes "P" for passed (no cracks at 10-63x mag. for sour tests or no cracks at 20x for ASTM G36 boiling $MgCl_2$ tests), "F" for failed (with number of cracked specimens per set in parentheses), and "IGC" for intergranular attack.

Figures 3 and 4 graphically represent the data presented in Table 4 alongside information about the severity of the various environments in the work with regard to the partial pressure of H_2S, the concentration of chloride ion, the temperature, and the pH.

The first chart of Figure 3 represents the corrosion rate in mils per year (mpy) on the Y-axis vs. the alloy name/temper on the X axis. The results for NACE severity Level II are shown in blue, for NACE severity Level IV in green, the NACE severity level V in purple, and the NACE severity level VI in red.

The second chart of Figure 3 represents the cracking results obtained in this work. On the Y-axis the NACE severity level is listed (or ASTM G36 $MgCl_2$). On the X-axis, the alloy name/temper is listed. Three boxes are shown for each alloy type at a specific test condition. These three boxes represent the three tested specimens for that condition. Results shown in green are for specimens that passed the criteria (no cracks at 10-63x mag. for sour tests; no cracks at 20x mag. for ASTM G36); results shown in red are for those that failed the criteria (cracks evident at 10-63x mag. for sour tests; cracks evident at 20x mag. or during Materion post-test micrographic examination for ASTM G36); and results shown in yellow are those that displayed significant corrosion and specimen thinning (as evidenced by high corrosion rates in weight loss testing) which may have reduced the imparted stress on the specimen since they were loaded into fixed-displacement fixtures.

Figure 4 represents the information about the severity of the various environments in the work. The leftmost chart lists the partial pressure of H_2S in each condition (in psia). The adjacent chart lists the calculated concentration of chloride ion from each test environment (in mg/L Cl^-). The chart second to the right lists the temperature of the test condition in degrees Fahrenheit and the rightmost chart lists the pH of each test condition as calculated in OLI Thermodynamic software.

Stereomicroscope images supporting the results listed in Table 4 and Figures 3 and 4 are provided in Appendices A through E. The contents of the appendices are as follows:

- Appendix A – Alloy 3 Cu-Be ASTM G36 Boiling $MgCl_2$ Results
- Appendix B – Cu-Be Results in NACE Level II
- Appendix C – Cu-Be Results in NACE Level IV
- Appendix D – Alloy 25 Cu-Be Results in NACE Level V
- Appendix E – Alloy 3 Cu-Be Results in NACE Level V

No appendices are listed for the alloys exposed to NACE Level VI, as the specimens were completely corroded due to the exposure.

NACE II: Table 4 and Figure 3 indicate that the alloys passed according to the cracking criterion (no cracks at 10-63x mag.) for NACE Level II for the materials and tests conducted in this work. The corrosion rate for these alloys ranged from 9 – 16 mpy at NACE Level II. The corrosion rate was lower for Alloy 3 compared to Alloy 25 in the NACE Level II exposure. There was visible grain boundary etching for Alloy 25, but minimal grain boundary attack for Alloy 3.

NACE IV: Table 4 and Figure 3 indicate that the alloys passed according to the cracking criterion (no cracks at 10-63x mag.) for NACE Level IV for the materials and tests conducted in this work. The corrosion rate for these alloys ranged from 1.7 – 2.0 mpy in NACE Level IV. The corrosion rate was similar for Alloy 3 compared to Alloy 25 in the NACE Level IV exposure. Widespread pitting was the main mode of observed attack for this test condition.

NACE V: Table 4 and Figure 3 indicate that the alloys passed according to the cracking criterion (no cracks at 10-63x mag.) for NACE Level V for the materials and tests conducted in this work, with the exception of Alloy 25 AT (the second-highest strength heat treatment level tested). However, the beams experienced significant thinning due to corrosion that would act to reduce the applied stress in the test since the fixtures were constant-deflection devices. The corrosion rates for the alloys were 224-365 mpy in NACE Level V. The corrosion rate was higher for Alloy 3 compared to Alloy 25. These alloys experienced significant thinning and had a wood grain appearance post-test (perhaps stress oriented pits) in the NACE Level V exposure.

NACE VI: The corrosion rate for the alloys in NACE Level VI was >500 mpy (completely consumed). As such, pass/fail with regard to cracking could not be assessed. For reference, NACE VI is more aggressive than NACE V in terms of partial pressure of H_2S, chloride level, temperature, and pH.

ASTM G36 Boiling $MgCl_2$: Only the Alloy 3 specimens were exposed to the ASTM G36 Boiling $MgCl_2$ test, and these passed according to the 20x cracking criteria. However, Alloy 3 AT had questionable features on micrographic cross section that appear to be IGC and could turn into cracking. Alloy 3 HT showed IGC also but with shallower pit bottoms and wider aspect ratios.

Since the bent beams in this work were loaded at room temperature to 100% of the room temperature MDYS, there was some question as to the effect of the applied stress at the test condition. An adequate exploration of this question would require both elevated temperature tensile testing and elevated temperature strain evaluation of specimens in the 4PB configuration.

Because of the high corrosion rates in NACE Levels V and VI, it is recommended to either use much larger solution volumes or omit these conditions from the cracking evaluation in an attempt to obtain meaningful cracking qualification data.

TABLE 4
NACE MR0175 and ASTM G36 Test Results

Alloy/Temper (DNV GL Sample #)	ASTM G36 (Boiling $MgCl_2$)	NACE Level II (TM0177) 77F, PH2S 14.7 psi		NACE Level IV (MR0175) 194F, PH2S 0.4 psi		NACE Level V (MR0175) 302F, PH2S 100 psi		NACE Level VI (MR0175) 347F, PH2S 500 psi	
	Crack? (at 100% of RT YS)	Wt Loss (mpy)	Crack?	Wt Loss (mpy)	Crack?	Wt Loss (mpy)	Crack?	Wt Loss (mpy)	Crack?
Alloy 25 DSTO (2177)	n/a	15.2	P	1.7	P	308.6	sig. thinning	502	n/a
Alloy 25 DSTU (2178)	n/a	11.2	P	1.7	P	223.9	sig. thinning	502	n/a
Alloy 25 AT (2175)	n/a	13.4	P	1.9	P	276.1	F(1/3) - sig. thinning	504	n/a
Alloy 25 HT (2176)	n/a	16.3	P	2	P	266.3	sig. thinning	505	n/a
Alloy 3 AT (2189)	P (IGC)	8.7	P	2	P	364.9	sig. thinning	532	n/a
Alloy 3 HT (2190)	P (IGC)	10	P	1.8	P	363.9	sig. thinning	541	n/a

Key test conditions (TM0177 and MR0175 only): a.) 4-point bent beam, b.) initial loading to 100% of room temp., 0.2% minimum design yield strength in MMPDS datasheets, c.) only temperature and p_{H2S} shown in header of table – chloride, CO_2, N_2 not shown, d.) nominally 1000 psi total pressure.

FIGURE 3

Graphical NACE MR0175 and ASTM G36 Boiling $MgCl_2$ Results

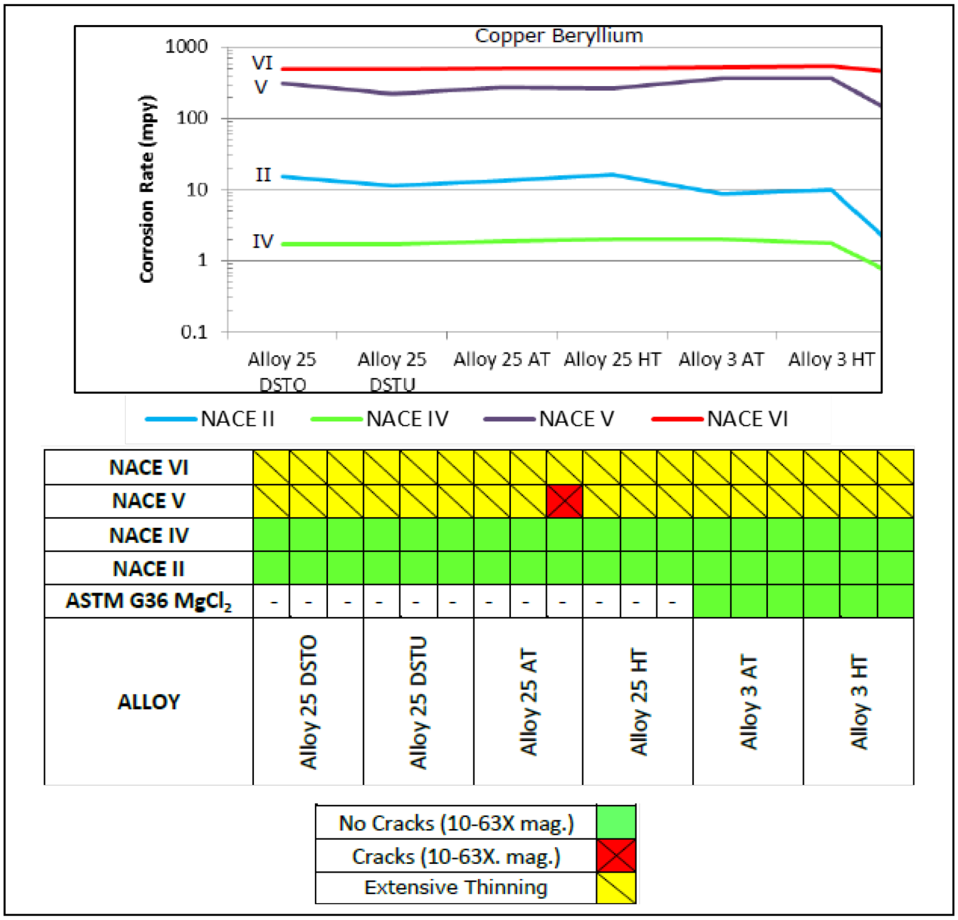
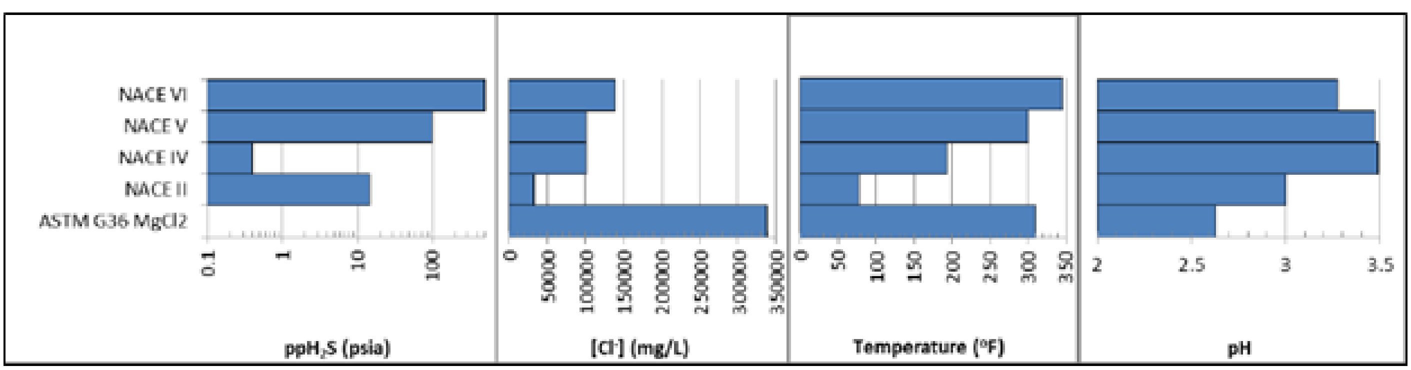


FIGURE 4

Graphical NACE MR0175 and ASTM G36 Boiling $MgCl_2$ Conditions



5. CONCLUSIONS

The alloys tested in this work showed minimal tendency for cracking in the tested environments (only one confirmed cracked specimen, Alloy 25 AT exposed to NACE Level V at 100% MDYS). These alloys experienced localized attack in the form of grain boundary etching and pitting at lower temperatures (≤ 194°F) or intergranular corrosion in high chloride/high temperature/low pH environments. However, very high rates of general corrosion observed in NACE Level V and VI may have prevented the materials from cracking at high temperatures.

6. FURTHER WORK

It is recommended to analyze the micrographs for all materials/conditions that passed the low magnification exam to determine if cracks initiating from intergranular attack are present subsurface.

Further testing of these materials at a reduced stress level could provide additional data as to the service limits of these materials.

7. REFERENCES

1. Det Norske Veritas (U.S.A.), Inc.: 2015 "Stress Corrosion Cracking/Sulfide Stress Cracking Testing in NACE MR0175 and ASTM G36 Environments of Copper, Beryllium, and Nickel Containing Alloys – Final Report" (Dublin, OH: DNV GL).

2. ANSI/NACE MR0175/ISO 15156-3:2009 "Petroleum and natural gas industries —Materials for use in H2S-containing environments in oil and gas production — Part 3: Cracking-resistant CRAs (corrosion resistant alloys) and other alloys" (Houston, TX: NACE).

3. ASTM G36-94 (Reapproved 2000) "Standard Practice for Evaluating Stress-Corrosion-Cracking Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution" (West Conshohocken, PA: ASTM).

4. ASTM G31-72 (Reapproved 1999) "Standard Practice for Laboratory Immersion Corrosion Testing of Metals" (West Conshohocken, PA: ASTM).

5. ASTM G39-99 (Reapproved 2011) "Standard Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test Specimens" (West Conshohocken, PA: ASTM).

6. MMPDS "Metallic Materials Properties Development and Standardization Handbook" (Columbus, OH: Battelle).

7. European Federation of Corrosion Publication No. 17 (2nd Edition) "Corrosion Resistant Alloys for Oil and Gas Production: Guidance on General Requirements and Test Methods for H2S Service" (London, UK: Maney Publishing).

8. NACE TM0177-2005 "Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking and Stress Corrosion Cracking in H_2S Environments" (Houston, TX: NACE).

APPENDIX A

ALLOY 3 CU-BE ASTM G36 BOILING $MgCl_2$ RESULTS

FIGURE 1
Test M2 - Alloy 3 AT - DNV# 2189 4PB; Boiling $MgCl_2$

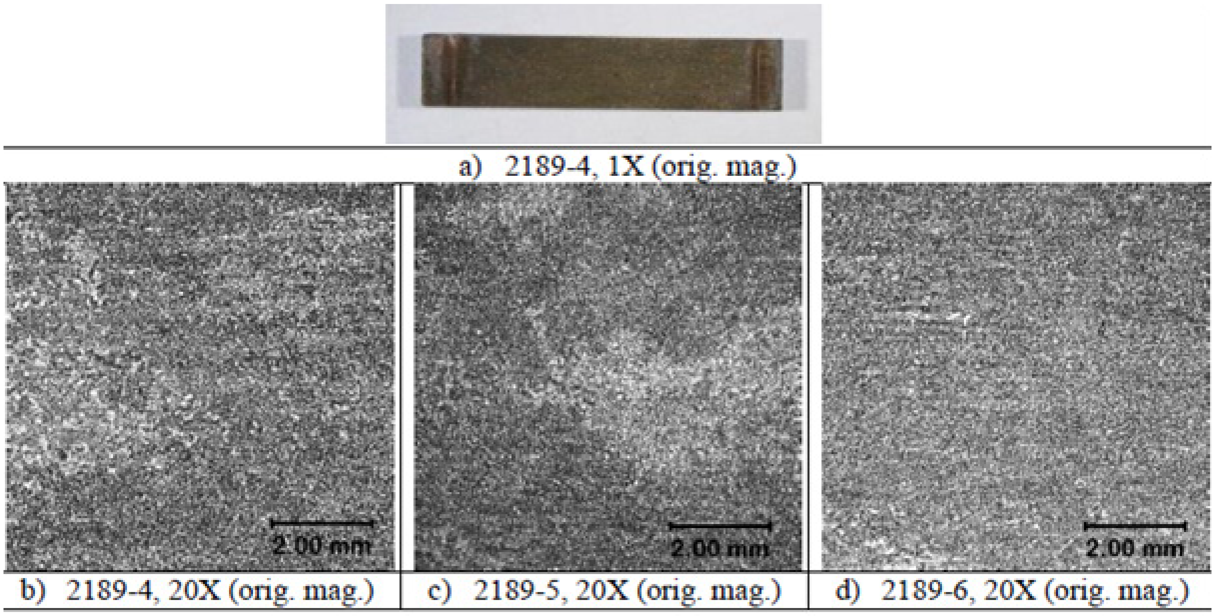
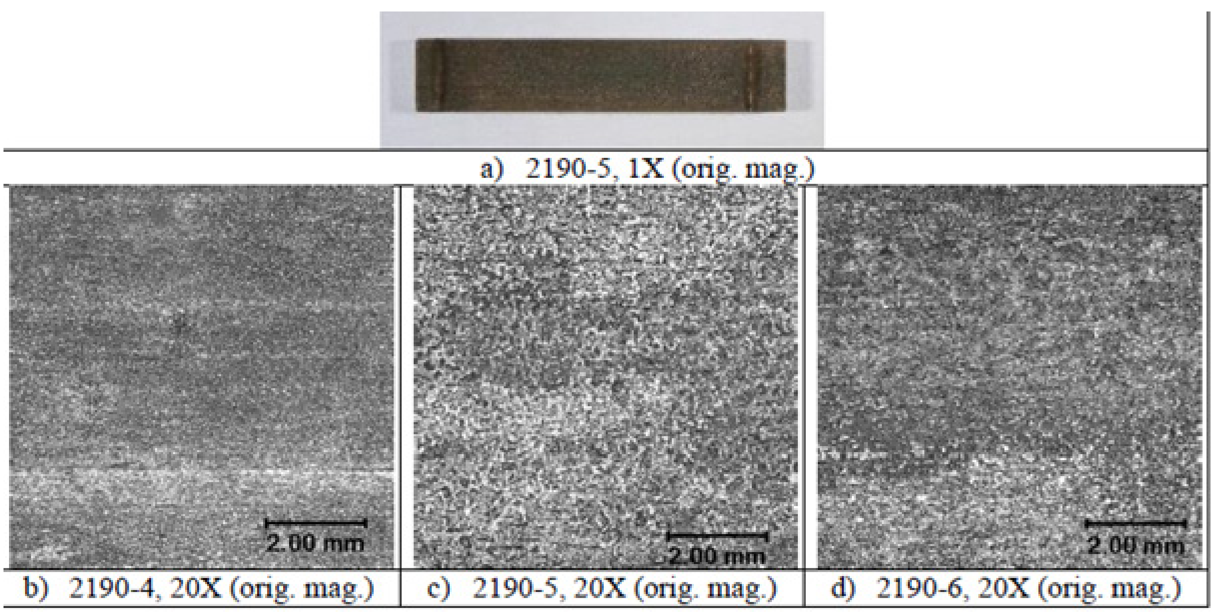


FIGURE 2
Test M2 - Alloy 3 HT - DNV# 2190 4PB; Boiling $MgCl_2$



APPENDIX B

CU-BE RESULTS IN NACE LEVEL II

FIGURE 1
Test S1 - Alloy 25 DSTO - DNV# 2177 4PB; NACE Level II

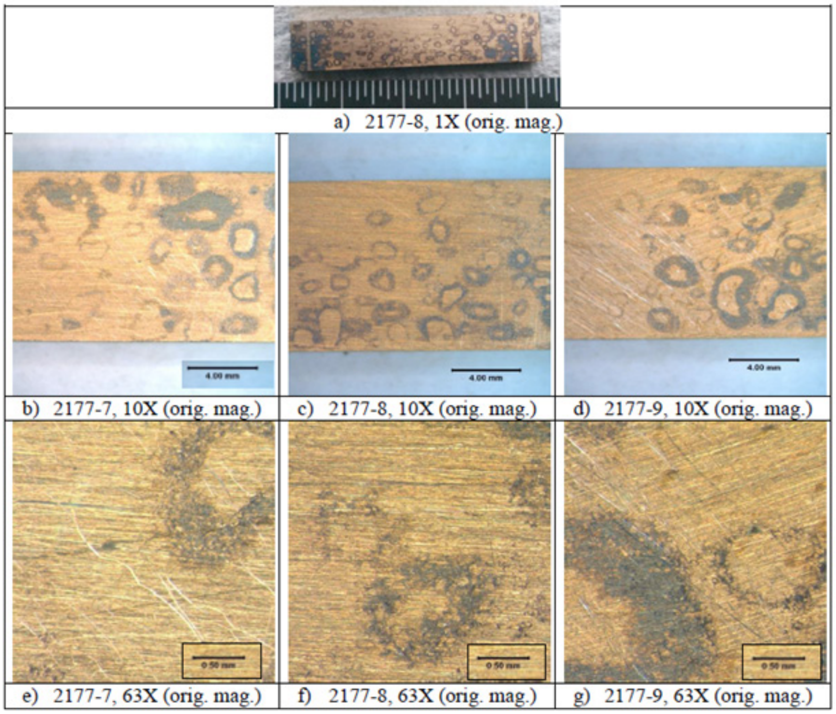


FIGURE 2
Test S1 - Alloy 25 DSTU - DNV# 2178 4PB; NACE Level II

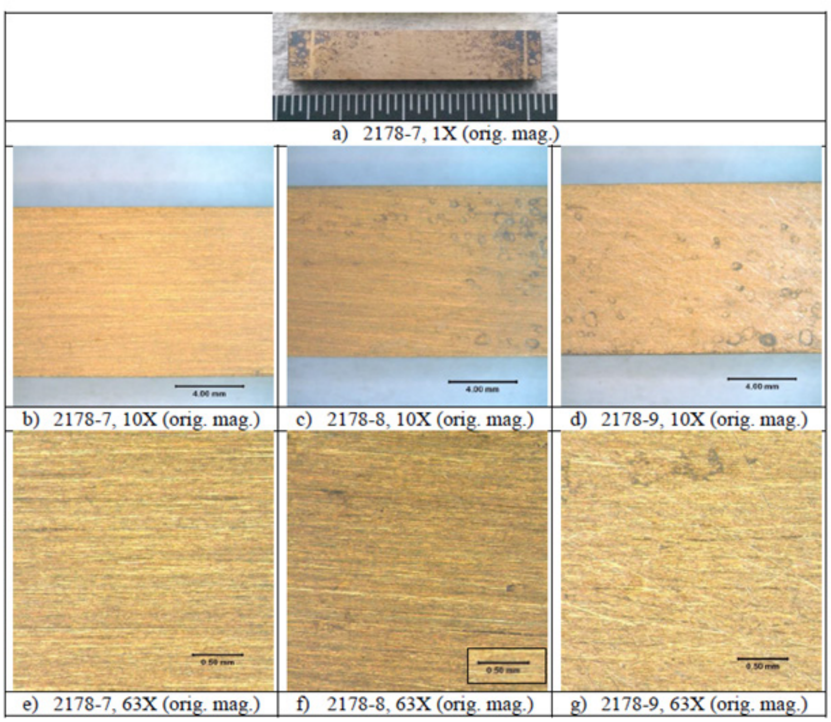
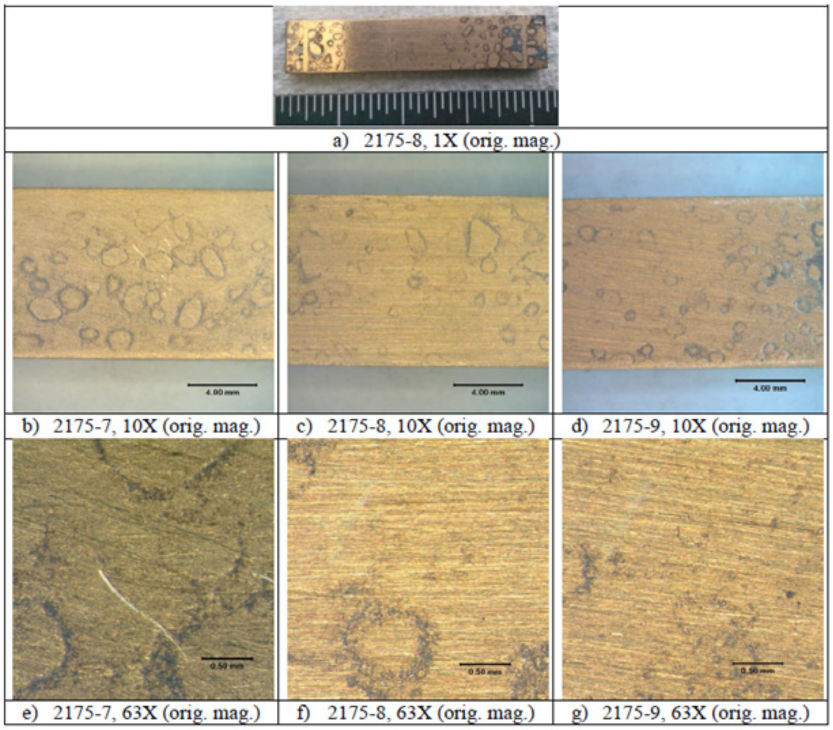
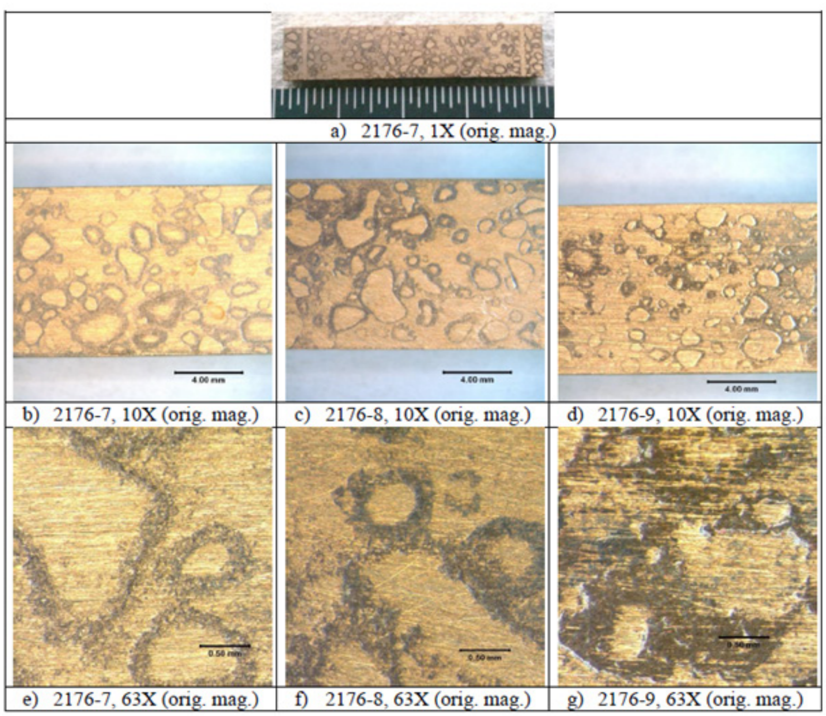


FIGURE 3
Test S1 - Alloy 25 AT - DNV# 2175 4PB; NACE Level II



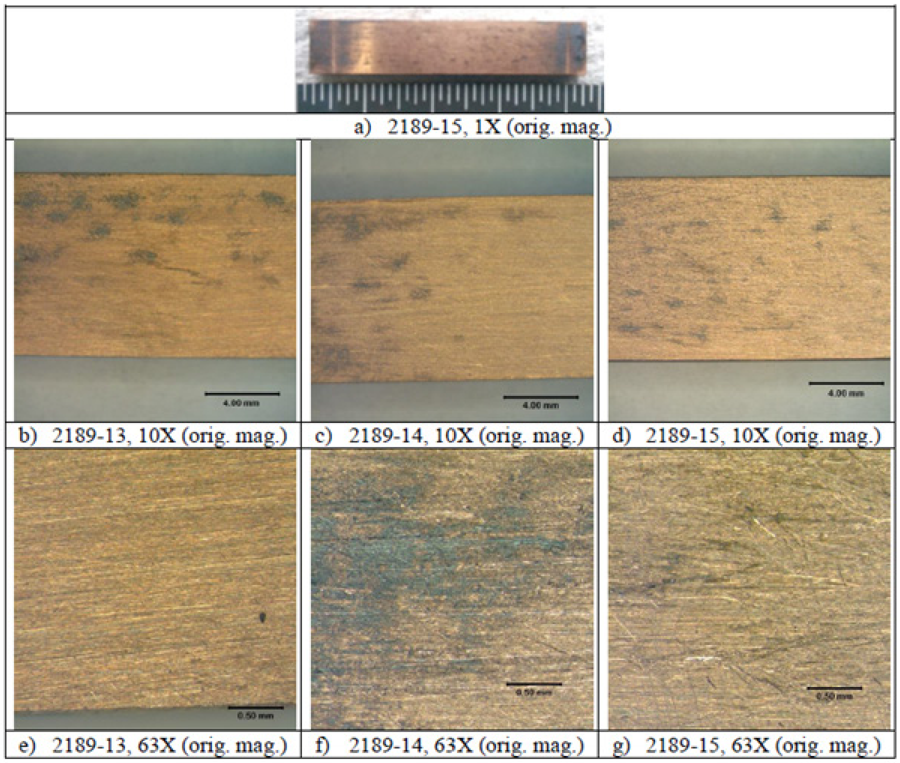
a) 2175-8, 1X (orig. mag.)
b) 2175-7, 10X (orig. mag.)
c) 2175-8, 10X (orig. mag.)
d) 2175-9, 10X (orig. mag.)
e) 2175-7, 63X (orig. mag.)
f) 2175-8, 63X (orig. mag.)
g) 2175-9, 63X (orig. mag.)

FIGURE 4
Test S1 - Alloy 25 AT - DNV# 2176 4PB; NACE Level II



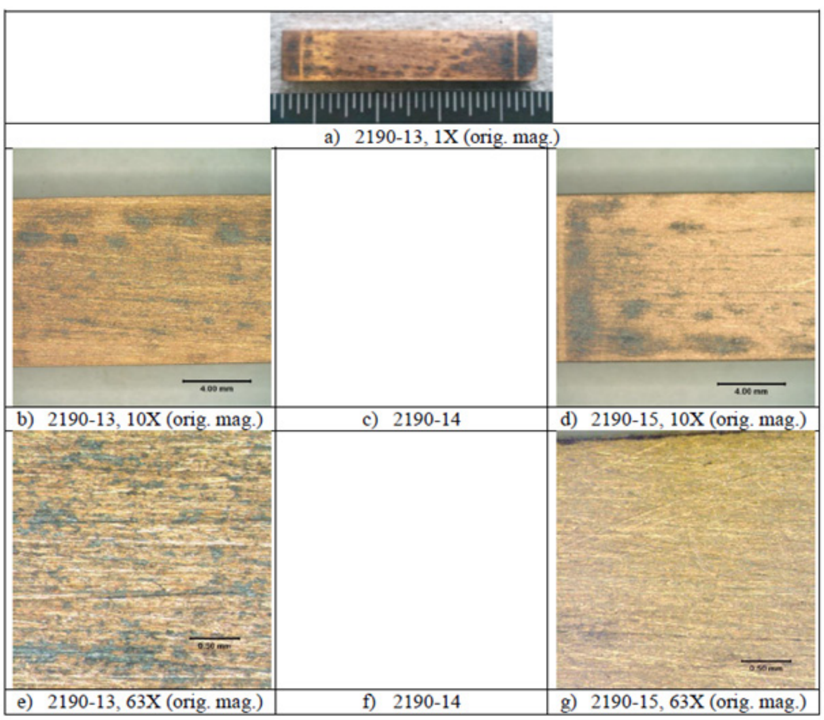
a) 2176-7, 1X (orig. mag.)
b) 2176-7, 10X (orig. mag.)
c) 2176-8, 10X (orig. mag.)
d) 2176-9, 10X (orig. mag.)
e) 2176-7, 63X (orig. mag.)
f) 2176-8, 63X (orig. mag.)
g) 2176-9, 63X (orig. mag.)

FIGURE 5
Test S1 - Alloy 3 AT - DNV# 2189 4PB; NACE Level II



a) 2189-15, 1X (orig. mag.)
b) 2189-13, 10X (orig. mag.)
c) 2189-14, 10X (orig. mag.)
d) 2189-15, 10X (orig. mag.)
e) 2189-13, 63X (orig. mag.)
f) 2189-14, 63X (orig. mag.)
g) 2189-15, 63X (orig. mag.)

FIGURE 6
Test S1 - Alloy 3 AT - DNV# 2190 4PB; NACE Level II

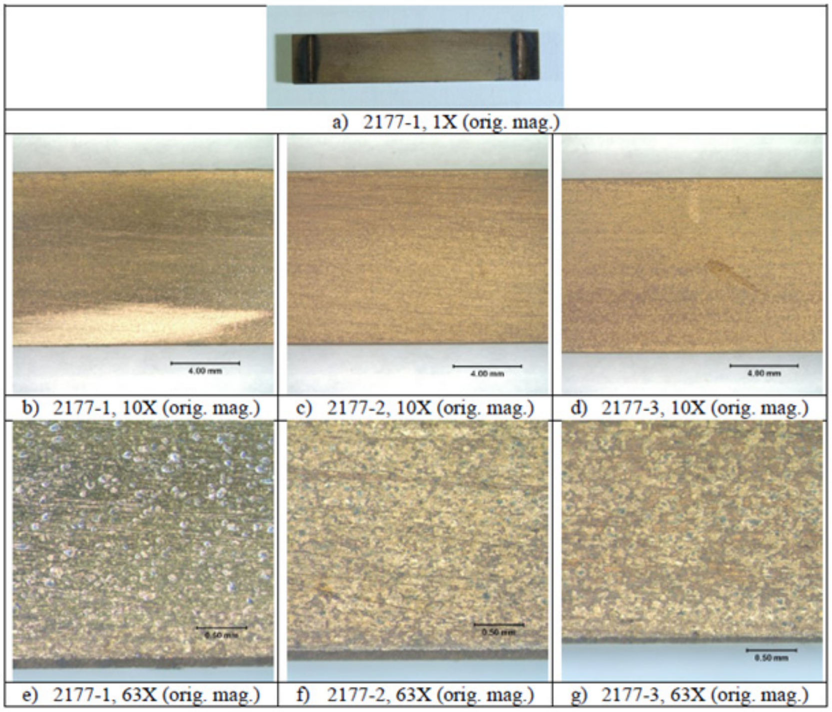


a) 2190-13, 1X (orig. mag.)
b) 2190-13, 10X (orig. mag.)
c) 2190-14
d) 2190-15, 10X (orig. mag.)
e) 2190-13, 63X (orig. mag.)
f) 2190-14
g) 2190-15, 63X (orig. mag.)

APPENDIX C

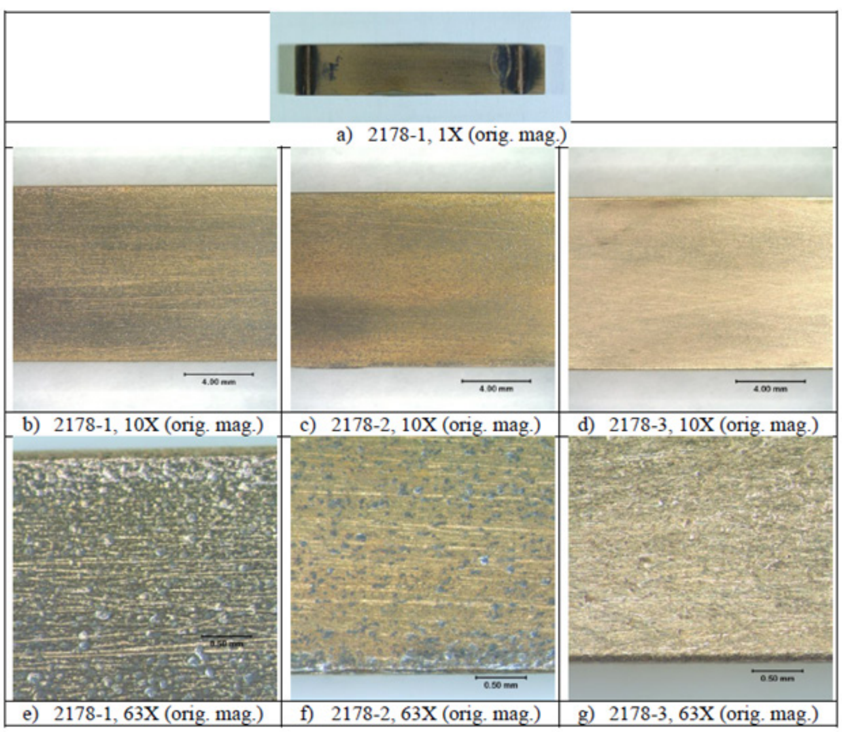
CU-BE RESULTS IN NACE LEVEL IV

FIGURE 1
Test S3 - Alloy 25 DSTO - DNV# 2177 4PB; NACE Level IV



a) 2177-1, 1X (orig. mag.)
b) 2177-1, 10X (orig. mag.) c) 2177-2, 10X (orig. mag.) d) 2177-3, 10X (orig. mag.)
e) 2177-1, 63X (orig. mag.) f) 2177-2, 63X (orig. mag.) g) 2177-3, 63X (orig. mag.)

FIGURE 2
Test S3 - Alloy 25 DSTU - DNV# 2178 4PB; NACE Level IV



a) 2178-1, 1X (orig. mag.)
b) 2178-1, 10X (orig. mag.) c) 2178-2, 10X (orig. mag.) d) 2178-3, 10X (orig. mag.)
e) 2178-1, 63X (orig. mag.) f) 2178-2, 63X (orig. mag.) g) 2178-3, 63X (orig. mag.)

FIGURE 3
Test S3 - Alloy 25 AT - DNV# 2175 4PB; NACE Level IV

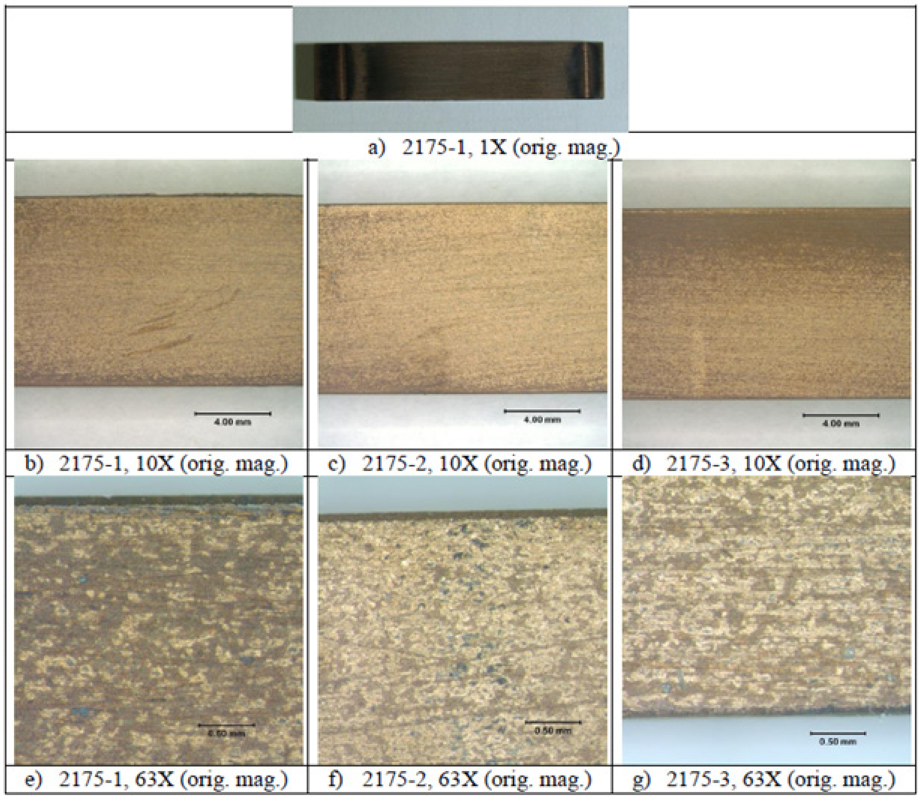


FIGURE 4
Test S3 - Alloy 25 HT - DNV# 2176 4PB; NACE Level IV

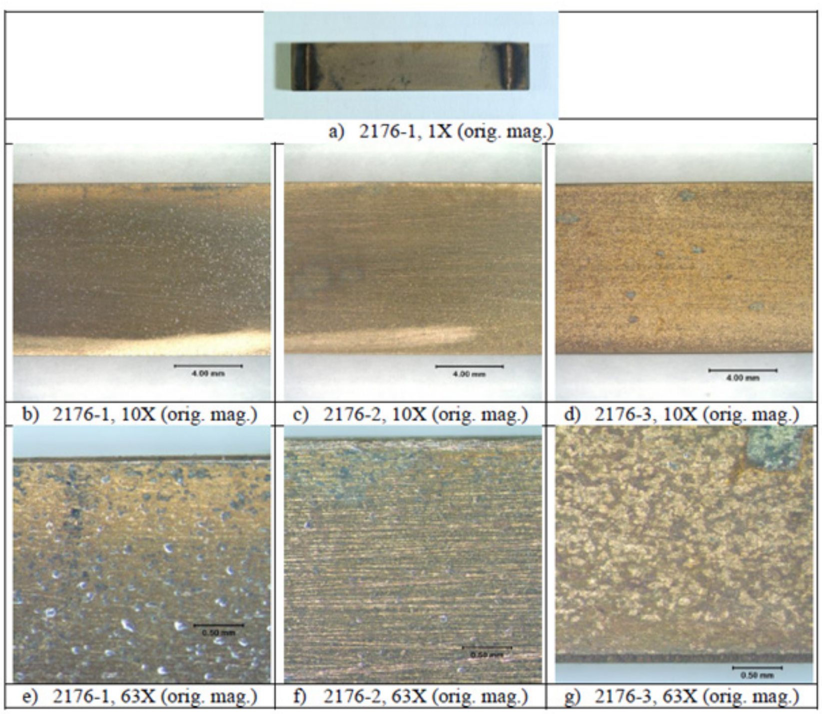
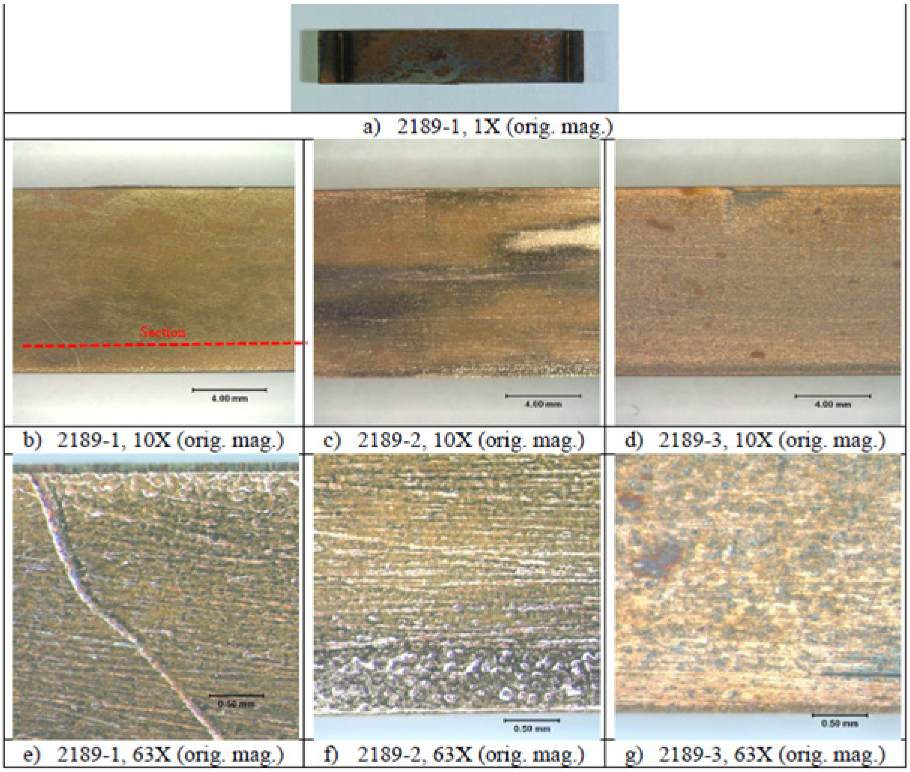
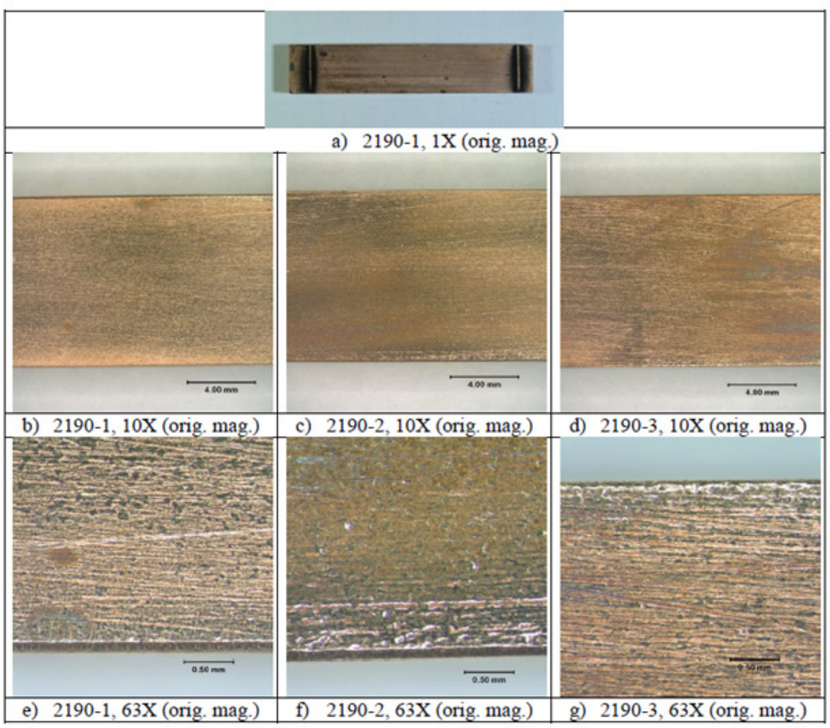


FIGURE 5
Test S3 - Alloy 3 AT - DNV# 2189 4PB; NACE Level IV



a) 2189-1, 1X (orig. mag.)
b) 2189-1, 10X (orig. mag.)
c) 2189-2, 10X (orig. mag.)
d) 2189-3, 10X (orig. mag.)
e) 2189-1, 63X (orig. mag.)
f) 2189-2, 63X (orig. mag.)
g) 2189-3, 63X (orig. mag.)

FIGURE 6
Test S3 - Alloy 3 HT - DNV# 2190 4PB; NACE Level IV

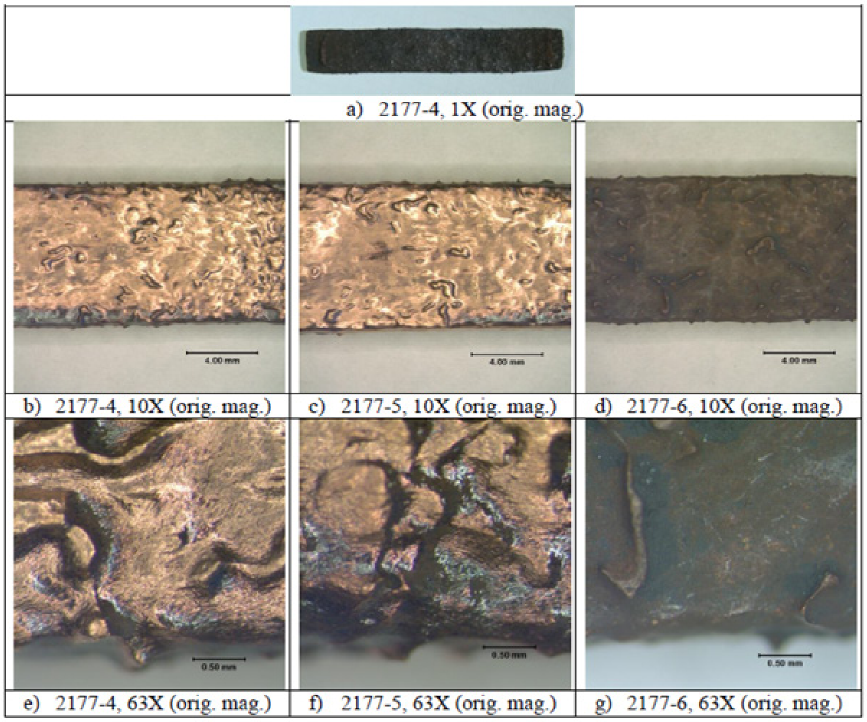


a) 2190-1, 1X (orig. mag.)
b) 2190-1, 10X (orig. mag.)
c) 2190-2, 10X (orig. mag.)
d) 2190-3, 10X (orig. mag.)
e) 2190-1, 63X (orig. mag.)
f) 2190-2, 63X (orig. mag.)
g) 2190-3, 63X (orig. mag.)

APPENDIX D

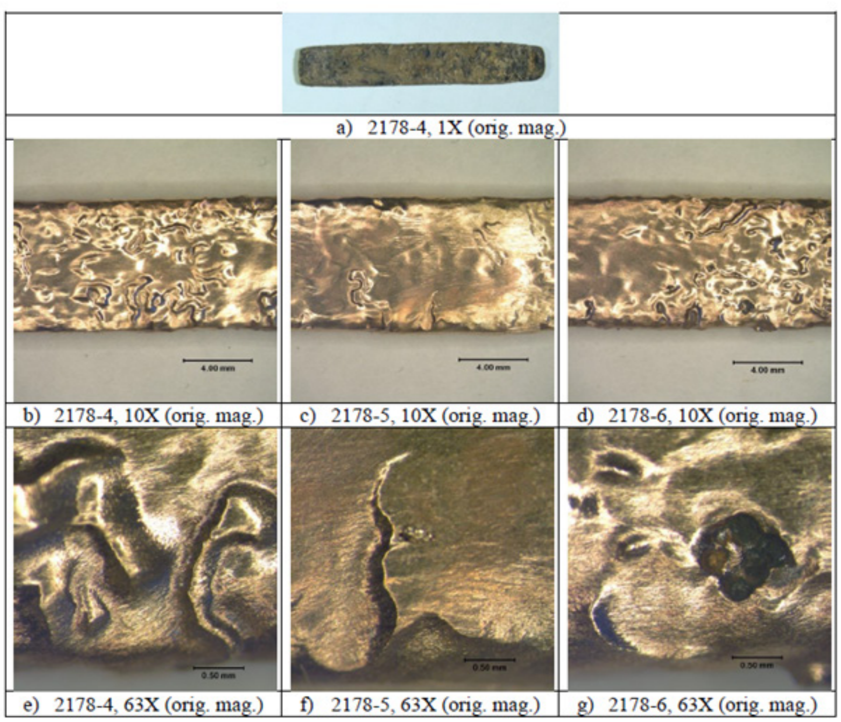
ALLOY 25 CU-BE RESULTS IN NACE LEVEL V

FIGURE 1
Test S5 - Alloy 25 DSTO - DNV# 2177 4PB; NACE Level V



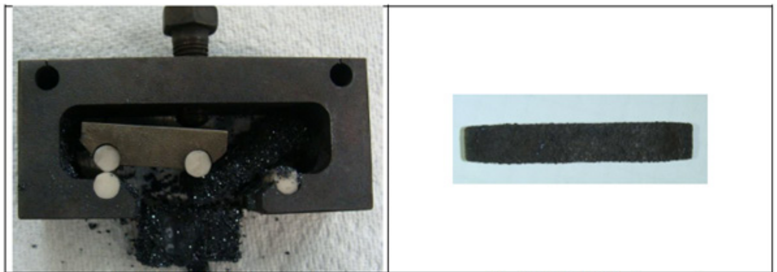
a) 2177-4, 1X (orig. mag.)
b) 2177-4, 10X (orig. mag.)
c) 2177-5, 10X (orig. mag.)
d) 2177-6, 10X (orig. mag.)
e) 2177-4, 63X (orig. mag.)
f) 2177-5, 63X (orig. mag.)
g) 2177-6, 63X (orig. mag.)

FIGURE 2
Test S5 - Alloy 25 DSTU - DNV# 2178 4PB; NACE Level V

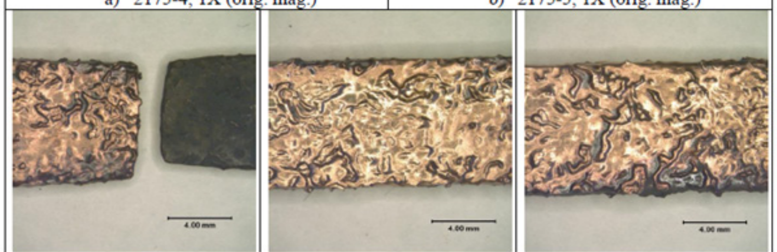


a) 2178-4, 1X (orig. mag.)
b) 2178-4, 10X (orig. mag.)
c) 2178-5, 10X (orig. mag.)
d) 2178-6, 10X (orig. mag.)
e) 2178-4, 63X (orig. mag.)
f) 2178-5, 63X (orig. mag.)
g) 2178-6, 63X (orig. mag.)

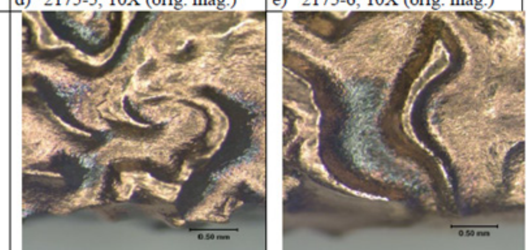
FIGURE 3
Test S5 - Alloy 25 AT - DNV# 2175 4PB; NACE Level V



a) 2175-4, 1X (orig. mag.) | b) 2175-5, 1X (orig. mag.)



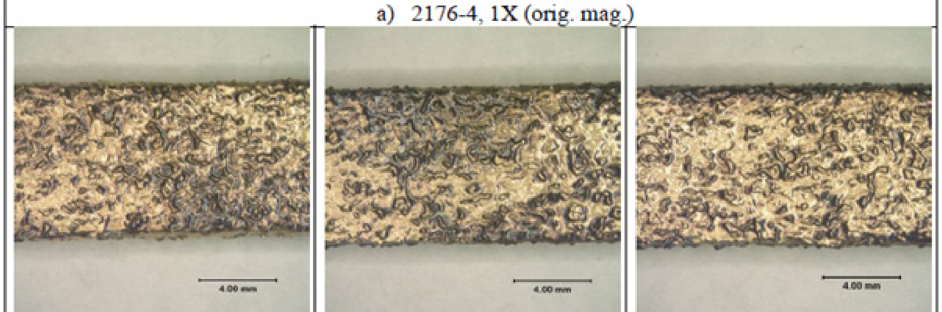
c) 2175-4, 10X (orig. mag.) | d) 2175-5, 10X (orig. mag.) | e) 2175-6, 10X (orig. mag.)



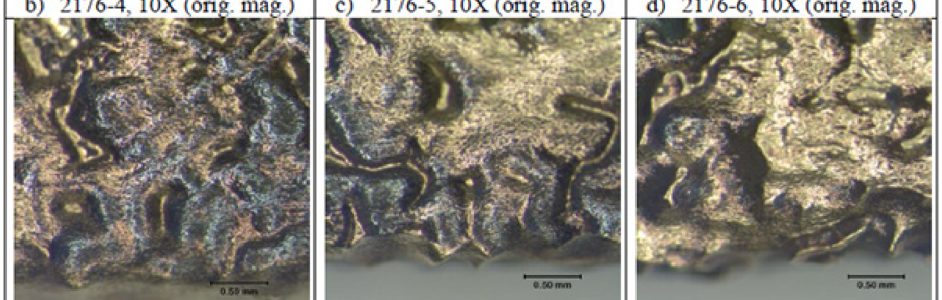
f) 2175-5, 63X (orig. mag.) | g) 2175-6, 63X (orig. mag.)

FIGURE 4
Test S5 - Alloy 25 HT - DNV# 2176 4PB; NACE Level V

a) 2176-4, 1X (orig. mag.)



b) 2176-4, 10X (orig. mag.) | c) 2176-5, 10X (orig. mag.) | d) 2176-6, 10X (orig. mag.)

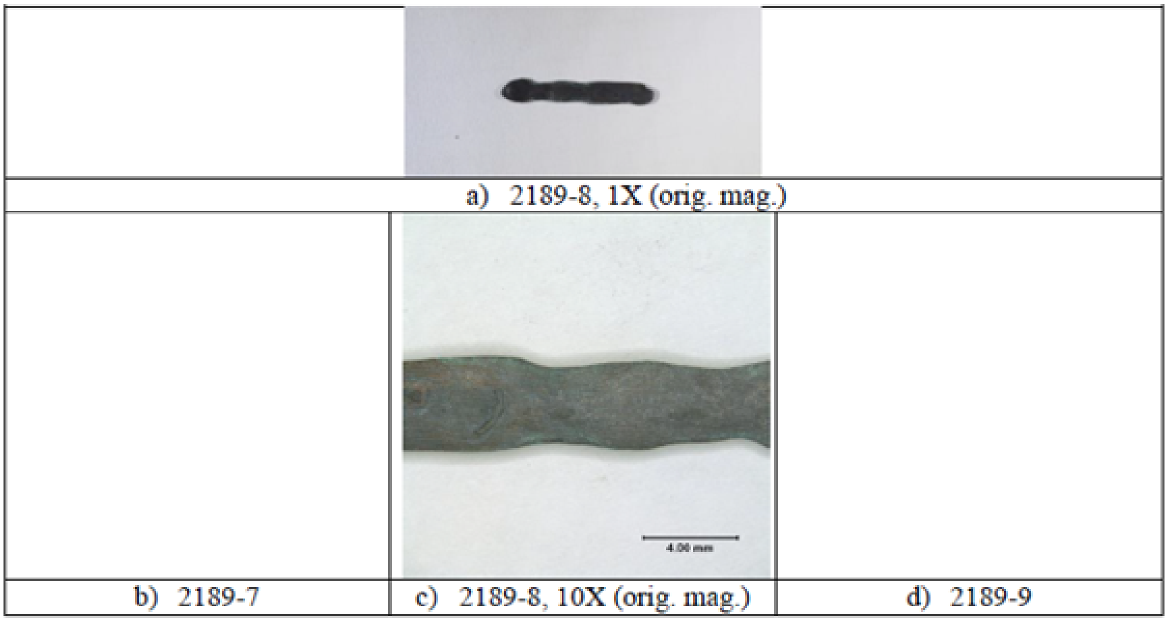


e) 2176-4, 63X (orig. mag.) | f) 2176-5, 63X (orig. mag.) | g) 2176-6, 63X (orig. mag.)

APPENDIX E

ALLOY 3 CU-BE RESULTS IN NACE LEVEL V

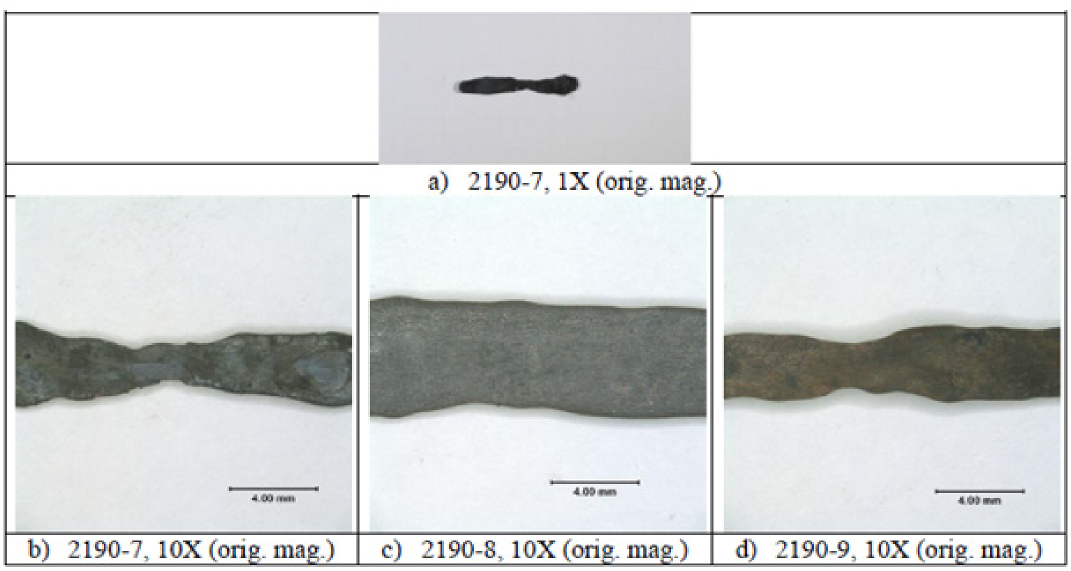
FIGURE 1
Test S7 - Alloy 3 AT - DNV# 2189 4PB; NACE Level V



a) 2189-8, 1X (orig. mag.)

b) 2189-7 | c) 2189-8, 10X (orig. mag.) | d) 2189-9

FIGURE 2
Test S7 - Alloy 3 HT - DNV# 2190 4PB; NACE Level V



a) 2190-7, 1X (orig. mag.)

b) 2190-7, 10X (orig. mag.) | c) 2190-8, 10X (orig. mag.) | d) 2190-9, 10X (orig. mag.)

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