Evaluation of Mechanical Properties with M30C

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Company Background

Stainless Foundry and Engineering Inc., located in Milwaukee Wisconsin, employs approximately 150 employees on site. With over 170 customers, Stainless Foundry is a multi-functional foundry as they pour investment castings and sand castings. The sand castings can be anywhere between 3lbs to 2,200lbs while the investment castings can be anywhere between a few grams to 150lbs. Over 250 alloys are poured with groups including: Stainless Steel-Hardenable & Non-Hardenable, Heat-Resistant Stainless Steel, Nickel Alloys, Cobalt Alloys, Carbon & Low Alloy Steels, Cast Irons, Tool Steels, and Specialty Alloys. The applications of the castings are used in Aerospace, Marine, Power Generation, Pulp & Paper, Pump & Valve, Food & Dairy, Nuclear, Pharmaceutical, Petrochemical, Structural, and more industries.

Purpose

M30C is a popular nickel-based alloy commonly used in military applications (particularly naval) because of its corrosion resistance to seawater and ease of weldability. M30C is an alloy that has been designed to be used as-cast. While Stainless Foundry & Engineering Inc. SFE pours this alloy on a regular basis, it occasionally has difficulty meeting the yield strength requirement. In July 2018, a high percentage of heats began failing yield strength. This prompted SFE to stop pouring the alloy to investigate the problem.

Metallurgical Attributes

Chemical Composition (%)									Mechanical Properties		
C, Max	**Mn, Max**	**Si**	**P, Max**	**S, Max**	**Cu**	**Fe, Max**	**Ni**	**Nb**	**Tensile (ksi)**	**Yield (ksi)**	**Elongation (%)**
0.30	1.50	1.0-2.0	0.03	0.02	26.0-33.0	2.50	balance	1.0-3.0	65	32.5	25

Table 1. Chemical requirements and mechanical properties from ASTM A494.

Specification requirements for the cast nickel/copper alloy M30C are found in ASTM A494. The specific composition and mechanical requirements are summarized above in Table 1. In this study, the requirement of 32.5 ksi yield strength is the primary dependent variable of interest. Based on previous experimentation at SFE, the two elements that have the greatest effect on yield strength are carbon and silicon. Unfortunately, if the elements carbon and silicon are adjusted, weldability and elongation are impacted directly. The addition of the niobium element enhances weldability. While heat treating can be used to age harden the alloy, it decreases the corrosion properties.

Experimental Design

In order to determine a proper experimental approach to solving the yield strength issue, our group discussed what independent variables were likely to have the greatest effect. These include test material, pour temperature, chemical composition, and shake-out time. We outlined an experiment that could test each variable.

To determine what chemical elements we, wanted to vary in our experiment, a data review was performed. Over 250 separate heats from the last four years were compiled in a spreadsheet, and plotted against yield strength. Two examples of this (carbon and silicon) are shown in Figures 1 & 2. Doing this helped us in determining if a trend was present for any of the elements. After analyzing this data, it was determined that there was a poor correlation for each trendline making it difficult to determine if any one element had an effect on yield strength.

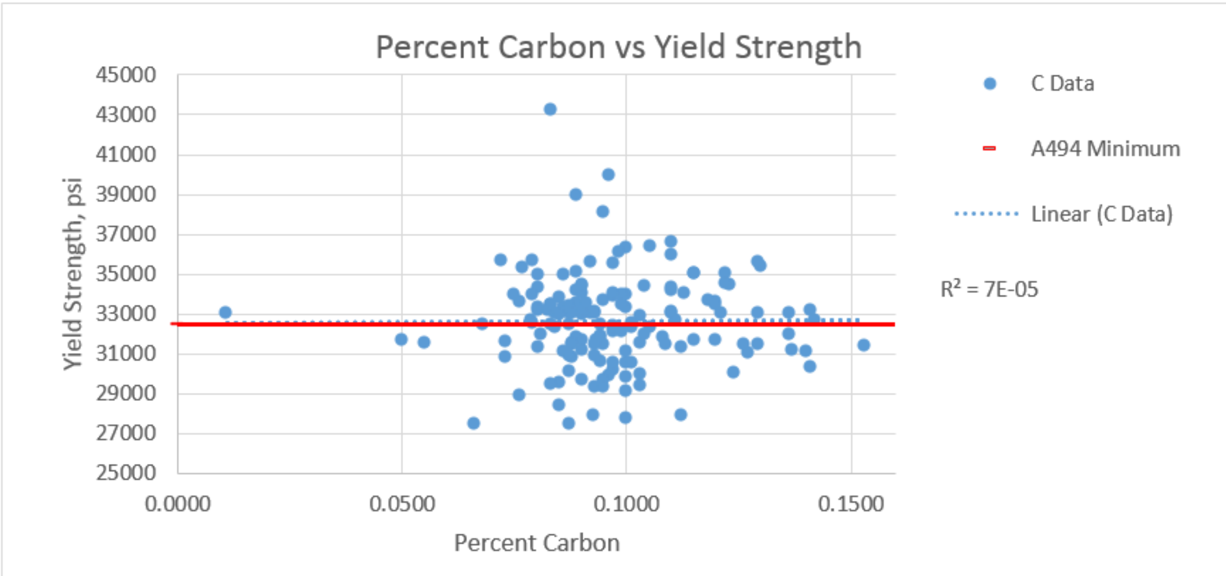


Figure 1 Percent carbon vs yield strength plot. Line is the ASTM A494 minimum required yield strength.

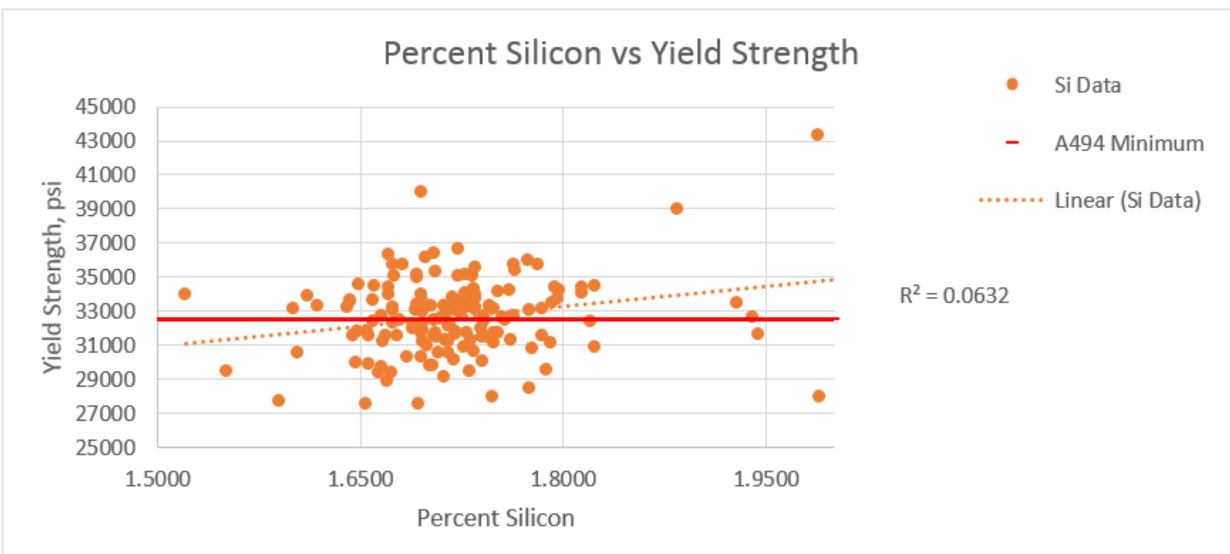


Figure 2. Percent silicon vs yield strength plot. Line is the ASTM A494 minimum required yield strength.

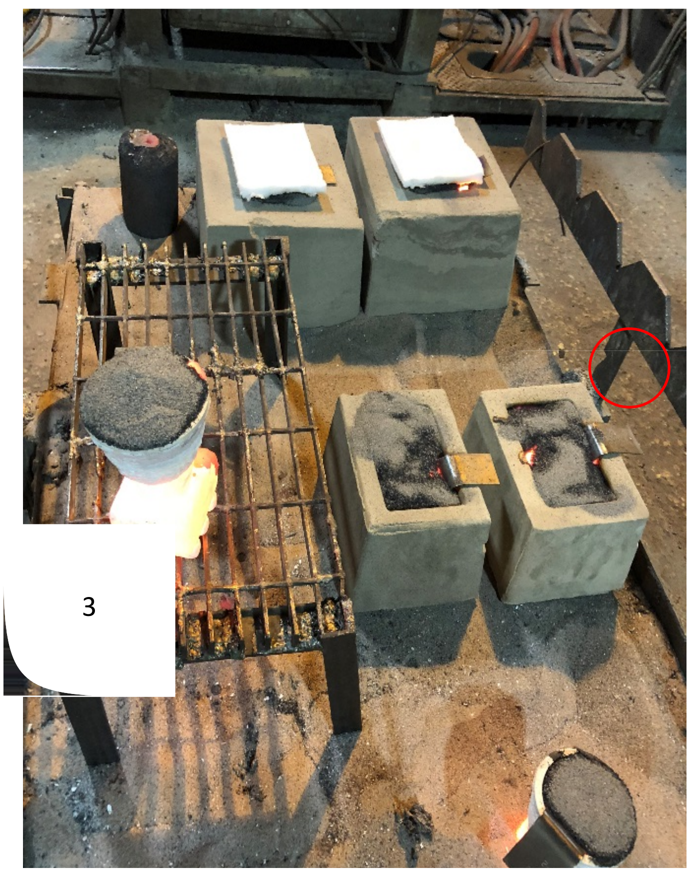
The difficulty of identifying one factor in the chemistries is shown in Figures 1 & 2. Each data point represents a unique heat. Both graph's correlation values were very low, meaning the correlation is very weak to the trend line. Unfortunately, this approach only allows us to review elements independently, and does not allow us to determine if the interactions between elements significantly affect yield strength. This data review did not provide much direction.

Our next approach was to review the grades historical aims and ranges. In past experiments, the effect of iron on yield strength was evaluated. Iron had an effect on the yield strength. We also did discover that the niobium and iron aims had been adjusted in the past, but is unknown why they were changed. We decided to vary niobium and iron aims in the experiment to determine if this past grade change had a negative effect on yield strength. Carbon and silicon were two other elements that help increase the yield strength, but they were already close to their maximum specification limit, so we are not able to use them.

Besides the chemical composition, there are several more possible factors for the low yield strengths. We wanted to vary solidification times and solid-state cooling rates to see what effect they have on yield strengths. To do this, we planned on varying poring temperatures and mold insulation. While we did not evaluate the effect that these modifications have on microstructure, it is known that changing them will affect grain size as well as the amount and size of secondary phases. Microstructure can be verified in future work.

Experimental Set-up

There were four different heats. The description of the test materials shown in the table next to Figure 3. One melter was needed for each heat, with some assistance from a second melter only when dealing with the investment molds. All the heats were virgin with the same melt practice, only varying niobium and iron levels. The temperatures of each pour were recorded immediately before the first test bar was poured.



1. Heavy walled keel block test coupon (0.500” final test bar diameter [3.5 inch wall thickness]) having a slower cool down time than #2. Block Covered with Kawool refractory grade insulating blanket, left in sand for 24 hrs.

2. Keel block test coupon (0.500” final test bar diameter [1.5 inch sand thickness]). Bar removed from mold after 10 minutes of pour

3. ICI (Investment Casting Institute) test coupon (0.250” final test bar diameter) with a quick cool down. Notice there is no insulation (excess sand) around any part of the mold compared to #4

4. ICI test coupon (0.250” final test bar diameter) with insulated cool down. Notice sand is covering the entire surface where test bars are located.

Note: The experimental set up was done by the melter for the assigned furnace. There was no interference from the observation team during the entire pour and cool down process. All test bars are in accordance with ASTM A370 and ASTM E8.

Figure 3. The experimental test bars after they were poured. All bars tagged per Table 2.

	Investment		Sand (thick wall)		Sand (thin wall)	
	Insulated	Air Cooled	Extended Shakeout (24 H)		Quick Shakeout (10 Min)	
Low Fe Low Nb	1	2	5	6	3	4
High Fe Low Nb	1	2	5	6	3	4
Low Fe High Nb	1	2	5	6	3	4
High Fe High Nb	1	2	5	6	3	4

Table 2. Matrix of test combinations. The columns are test bar types and cooling type, the rows are chemistry aims. The numbers show what they were tagged. Note there are duplicates of both sand test bar molds.

Note: Because of time requirements and third party impartiality, we sent out the test bars to an outside materials testing facility to get tested. There they tested for tensile strength, yield strength, percent elongation, and hardness.

Results and Confirmation Experiment

A total of ten passed and thirteen failed of all the test bars. Of that, three of the eight sand test bars passed while seven of the seven investment test bars passed.

	Investment		Sand (thick wall)		Sand (thin wall)	
	Insulated	Air Cooled	Extended Shakeout (24 H)		Quick Shakeout (10 Min)	
Low Fe Low Nb	1	2	5	6	3	4
High Fe Low Nb	1	2	5	6	3	4
Low Fe High Nb	1	2	5	6	3	4
High Fe High Nb	1	2	5	6	3	4

Table 3. Visual results from the first experiment. The red shows which test bars failed yield strength , the green shows which test bars passed yield strength, and the dark grey box is where some human error (stamping) occurred giving us no data for that portion of results.

All of the investment test bars had comfortably passing yield strengths. This data suggests that the cooler the metal, the better yield strength. Another factor resulting in faster cooling rate was that we had to move the investment molds about 200 feet after they were out of the preheat oven. This was because an oven was down for maintenance.

From this experiment, we concluded that a lower pouring temperature (lower than SFE's already low pouring temperature) and faster cooling rate was beneficial to yield strength.

The confirmation experiment was done on a production heat, where the pouring temperature was dropped below the previous experimental level and the faster cooling rate was utilized. Due to delivery requirements it was decided to run the niobium and iron levels at the higher level as it appeared slightly beneficial from the previous experiment. The mechanical properties passed specifications on these heats.

Conclusion

To achieve passing mechanical properties a few thing will be changed for the future M30C heats. First off, there will be an increase in the aims for both niobium and iron. Secondly, the pouring temperature will be lowered from the previous aim. Finally, the shakeout time will be reduced. With these changes to the process of creating M30C castings, the hold on the orders will be removed in order to fulfill customer orders.

Future Steps

When analyzing the chemical composition of each heat, the nitrogen is not taken in account for due to its low amount in M30C. As we continue to research more into this problem, we plan on calibrating our analyzer to test it and determine what effect it has on yield strength. With that we will be able to see if there is a trend in nitrogen as well in case of future problems. The microstructure of the test bars should also be something to review. When researching the alloy early on in the project a niobium nitride was described in the literature. We can also review what effect the pouring temperature, cooling rate, and iron and niobium levels have in the microstructure. It would be helpful to compare a failing microstructure to a passing microstructure to find artifacts that “stand out” or may be identified as detrimental.

Continued work (October 16, 2018)

M30C continued to fail mechanical tests, specifically yield strength. We had performed SEM on three samples. Two taken from heats failing mechanical properties and one heat that passed the minimum requirements of ASTM A494. EDS (Energy Dispersive Spectroscopy) was performed on phases observed during the SEM analysis. These can be found in Appendix III and IV. There were course phases of nickel, copper, and niobium found forming at the edge of the grains connecting to grain boundaries as well as fine niobium nitrides throughout. This leads us to question a few processing factors:

1. Pour temperature will affect the grain size and appears to affect the size and distribution of the phases.
2. The specific melting temperature of nickel-niobium charge material additions may be an issue.
3. A faster cooldown results in finer grains. There were no course phases found in the investment test bars, concluding that the test bar size and geometry is important.

These factors will be taken into account for further research.

Opportunities to Improve

In these sets of experiments there were some lessons learned. In a DOE, randomization of the process makes a difference. In this experiment, we did not randomize the pouring order. This was because of ease of manufacturing for the melter. After looking back upon it, randomizing the pour order should have been taken into consideration over the ease of manufacturing.

Acknowledgments

I would like to thank Jeanne Wagner for working with me every step of this project. Without her help I do not believe this project would be anywhere close to being done today. I would also like to thank Mike Porfilio for showing me the project, Ryan Klug for helping me out with research and performing experiments, as well as everyone at Stainless Foundry & Engineering who took part in the experiment.

Resources

ASTM Standard A494 “Standard Specification for Castings, Nickel and Nickel Alloy,” ASTM International, West Conshohocken, PA, 2008, DOI 10.1520/A494, www.astm.org

Appendix I

Sampling of Chemistries

Heats	Chemisty in weight %															
	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Co	Cu	Nb	Ti	Pb	Cb	Fe
C80097	0.120	1.706	0.994	0.001	0.001	0.343	0.006	61.950	0.004	0.007	31.435	1.216	0.028	0.003	1.216	1.632
C80077	0.103	1.647	1.029	0.001	0.001	0.261	0.006	63.200	0.003	0.007	31.520	1.300	0.024	0.003	1.300	2.031
F80098	0.090	1.667	0.990	0.001	0.001	0.064	0.006	62.750	0.001	0.005	31.460	1.348	0.025	0.004	1.348	2.022
C80066	0.110	1.761	0.993	0.001	0.001	0.233	0.006	63.150	0.001	0.009	31.590	1.237	0.029	0.004	1.237	1.635
C80065	0.110	1.694	1.017	0.005	0.001	0.267	0.005	60.900	0.001	0.007	32.150	1.161	0.025	0.004	1.161	1.696
C80058	0.100	1.715	0.989	0.012	0.001	0.222	0.006	63.150	0.003	0.012	31.540	1.267	0.270	0.003	1.267	1.912
C80057	0.110	1.723	0.014	0.012	0.001	0.280	0.006	62.650	0.003	0.007	32.010	1.171	0.024	0.003	1.171	1.885
F80083	0.100	1.703	1.012	0.012	0.001	0.300	0.007	63.100	0.001	0.009	31.455	1.247	0.050	0.004	1.247	1.993
F80064	0.100	1.671	0.983	0.012	0.010	0.260	0.006	62.500	0.004	0.007	31.630	1.253	0.028	0.004	1.253	2.102
F80041	0.105	1.705	1.077	0.005	0.001	0.274	0.007	62.100	0.003	0.017	31.570	1.221	0.030	0.004	1.221	2.078
F80013	0.097	1.611	1.019	0.005	0.001	0.683	0.006	62.100	0.001	0.007	31.530	1.288	0.025	0.004	1.288	2.196
F70612	0.100	1.696	1.001	0.006	0.000	0.217	0.006	63.750	0.002	0.005	31.440	1.171	0.027	0.005	1.170	1.907
F70599	0.120	1.643	0.955	0.011	0.001	0.215	0.006	62.500	0.001	0.035	31.730	1.259	0.021	0.003	1.259	1.864
H71311	0.090	1.753	0.993	0.001	0.001	0.161	0.005	62.300	0.001	0.005	31.415	1.280	0.047	0.003	1.280	1.593
H71220	0.084	1.721	1.009	0.001	0.001	0.130	0.005	62.350	0.001	0.005	31.050	1.269	0.047	0.003	1.269	1.728
F70541	0.080	1.694	1.043	0.013	0.001	0.248	0.006	60.700	0.004	0.007	31.205	1.309	0.042	0.004	1.309	2.608
F70502	0.089	1.660	1.058	0.125	0.000	0.264	0.006	62.700	0.005	0.005	31.715	1.232	0.022	0.004	1.232	2.054
H71009	0.083	1.697	0.989	0.012	0.001	0.238	0.006	62.100	0.004	0.006	31.140	1.476	0.050	0.004	1.476	2.496
H70882	0.087	1.619	1.016	0.012	0.005	0.196	0.006	62.050	0.001	0.007	31.120	1.503	0.052	0.004	1.503	2.473
P70782	0.080	1.815	1.054	0.012	0.001	0.214	0.006	61.150	0.004	0.015	31.350	1.198	0.052	0.003	1.198	2.352
A70555	0.096	1.657	1.030	0.012	0.001	0.279	0.006	61.650	0.001	0.009	31.480	1.312	0.013	0.003	1.312	2.334
C70196	0.103	1.732	1.024	0.006	0.001	0.152	0.006	62.450	0.003	0.007	31.615	1.250	0.025	0.004	1.250	1.587
C70195	0.073	1.778	1.006	0.006	0.001	0.184	0.006	62.250	0.004	0.006	31.390	1.326	0.044	0.004	1.326	1.909
C70192	0.097	1.742	1.037	0.007	0.001	0.289	0.006	62.900	0.003	0.007	31.300	1.270	0.024	0.004	1.271	1.784
F70326	0.089	1.797	1.037	0.011	0.000	0.271	0.006	63.650	0.005	0.006	30.490	1.267	0.027	0.003	1.267	1.932
F70278	0.080	1.713	1.086	0.011	0.001	0.221	0.006	63.650	0.002	0.005	30.685	1.275	0.044	0.003	1.275	1.880
F70272	0.103	1.697	0.972	0.011	0.000	0.231	0.006	63.000	0.003	0.018	30.795	1.426	0.027	0.003	1.426	1.754
F70250	0.093	1.665	1.109	0.012	0.000	0.146	0.006	63.850	0.002	0.005	30.405	1.321	0.038	0.004	1.321	1.747
H70425	0.086	1.746	1.059	0.012	0.000	0.132	0.006	62.950	0.001	0.006	31.350	1.413	0.038	0.003	1.413	1.748
F70220	0.103	1.669	1.005	0.011	0.001	0.284	0.006	62.050	0.003	0.008	30.840	1.251	0.029	0.003	1.251	1.925

Mean	0.093	1.710	0.990	0.011	0.001	0.263	0.006	62.875	0.003	0.012	31.103	1.271	0.047	0.003	1.271	1.970
Median	0.096	1.705	1.006	0.011	0.001	0.261	0.006	62.900	0.003	0.008	31.350	1.257	0.034	0.004	1.257	1.935
Mode	0.090	1.671	0.993	0.011	0.001	0.279	0.006	63.650	0.001	0.005	31.350	1.267	0.025	0.003	1.267	2.022

Table 1.1 Thirty randomized samples from a pool of 250 samples. Elements not displayed (V, W, Sn, As, Ca, Se, Ta, B, N, Li, Bi, Zn, Sb, and O) due to elements being below the limits of destination in that matrix.

Appendix II

Sampling of Tensile Strength, Yield Strength, Percent Elongation, and Hardness

Heats	Mechanical Properties			
	Tensile (psi)	Yield (psi)	Elongation (%)	Hardness (HB)
C80097	74459	31747	35.5	128
C80077	73341	29961	43.5	124
F80098	75767	29726	45.5	123
C80066	78728	34214	38.5	130
C80065	75633	33050	36.0	129
C80058	71854	30580	40.0	121
C80057	75329	36629	34.0	133
F80083	76622	33318	38.5	125
F80064	74573	36282	38.0	127
F80041	79457	36390	35.0	130
F80013	76404	33900	40.0	130
F70612	77845	33965	31.0	128
F70599	76831	33600	34.0	128
H71311	72340	31699	37.0	135
H71220	76871	33062	40.0	144
F70541	74134	33293	37.5	119
F70502	76991	33590	36.5	121
H71009	73420	33508	35.0	144
H70882	78054	33303	41.0	134
P70782	77202	34337	37.0	137
A70555	70436	29901	37.0	128
C70196	72697	29446	46.0	114
C70195	73145	30819	46.0	149
C70192	74704	32412	35.0	156
F70326	75340	34183	35.0	123
F70278	75409	33253	35.0	130
F70272	78114	32921	39.0	120
F70250	72034	29348	44.5	119
H70425	77080	33326	43.0	135
F70220	75101	31538	43.5	141
F70214	75498	32986	36.5	134
C70108	73378	31721	41.5	126
F70208	86185	38928	39.0	138
C70087	80376	33990	40.5	139
H70272	72783	30852	37.0	135
C70078	76941	35964	43.0	137
C70077	75928	35729	38.0	135
H70214	84389	39939	58.0	165
F70126	75668	32722	35.0	134
F70125	76921	33463	38.0	135

Heats	Mechanical Properties			
	Tensile (psi)	Yield (psi)	Elongation (%)	Hardness (HB)
H70184	74918	33023	38.0	125
F70102	76497	33066	36.0	125
A70128	77843	30536	37.0	122
F70067	81053	34368	39.5	125
F70056	76562	31968	36.0	214
A70072	74186	34388	30.5	129
F70042	76185	33080	38.0	127
F70043	74996	33662	35.0	115
F70037	77633	33222	39.5	114
H70037	75807	32742	46.0	141
F70016	77463	31777	37.5	118
P70032	75986	31508	45.0	139
F70014	74140	32602	41.5	124
C70004	72878	29534	38.5	123
H61357	72463	31719	50.0	135
F60711	78234	33995	37.5	125
F60618	75130	33383	38.5	134
F60619	76225	34969	42.0	132
F60602	73564	35145	36.0	127
H61185	73964	30155	48.0	132
A60689	73634	29763	41.0	124
F60569	77445	34469	37.5	130
H61140	72680	33082	37.0	126
A60670	75433	31518	40.0	121
A60663	83312	34289	43.5	131
H61123	79497	32320	43.0	153
F60540	76523	33492	39.0	125
F60539	74265	31280	38.5	129
F60534	72103	28413	36.0	120
H61058	71523	31911	32.0	127
C60285	75261	33953	40.0	132
P60994	75585	31164	44.0	165
C60274	74000	30899	37.5	122
H61018	76838	31184	45.0	137
H61017	75926	31821	43.0	137
F60468	72828	30265	45.5	117
F60464	76671	29117	42.0	113
F60450	73881	31239	40.0	119
F60445	75394	29827	37.0	119
F80436	72667	27949	42.5	116
P60841	76413	32437	40.0	137

Heats	Mechanical Properties			
	Tensile (psi)	Yield (psi)	Elongation (%)	Hardness (HB)
Mean	75583	32670	40	131
Median	75542	32732	40	130
Mode	74186	32437	40	130

Table 1 *Eighty randomized samples from a pool of 250.*

Appendix III

SEM Micrographs

Stainless Foundry & Engineering Inc. S046

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Figure 1

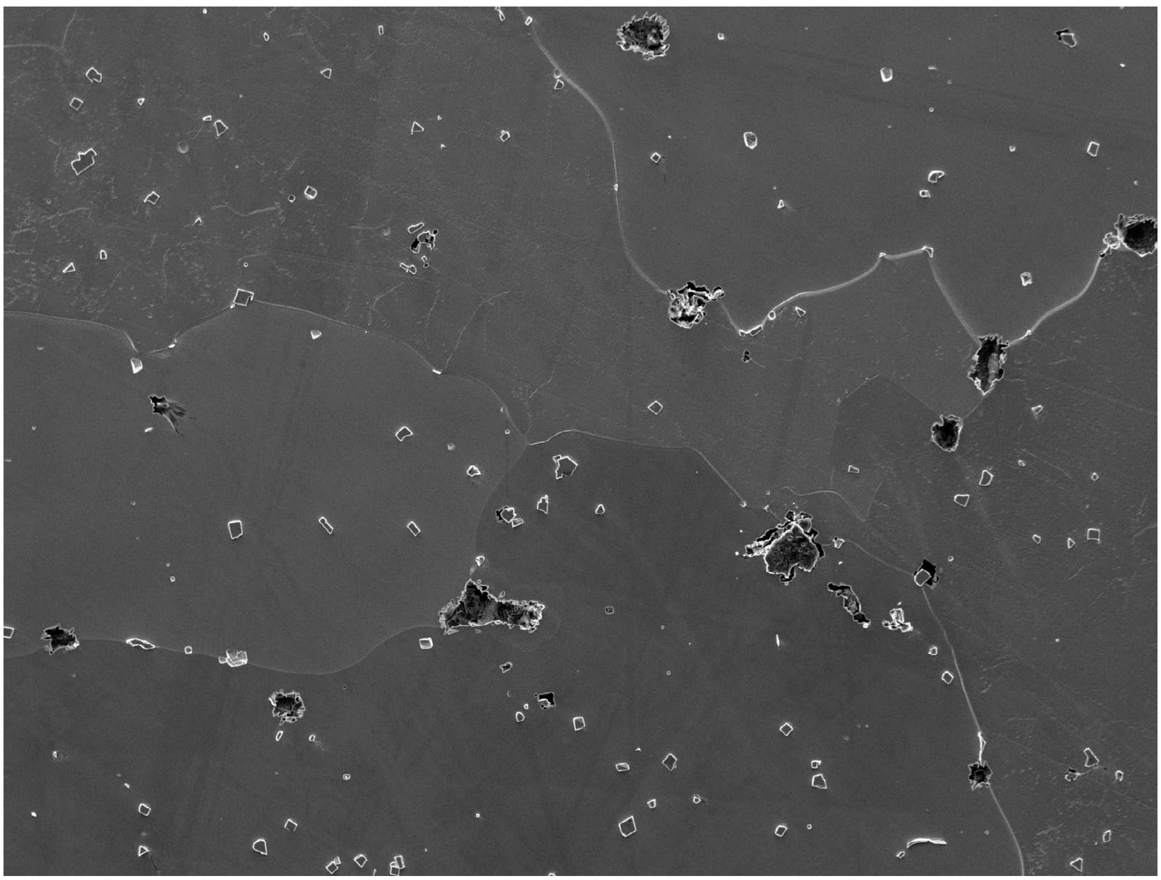

Figure 1 M30C SEM micrograph at 400X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 73897 psi, yield strength 32085 psi, and elongation of 43%. The mechanical properties do not meet the minimum required properties of ASTM A494, grade M30C, Table 3.

C80338

Figure 2

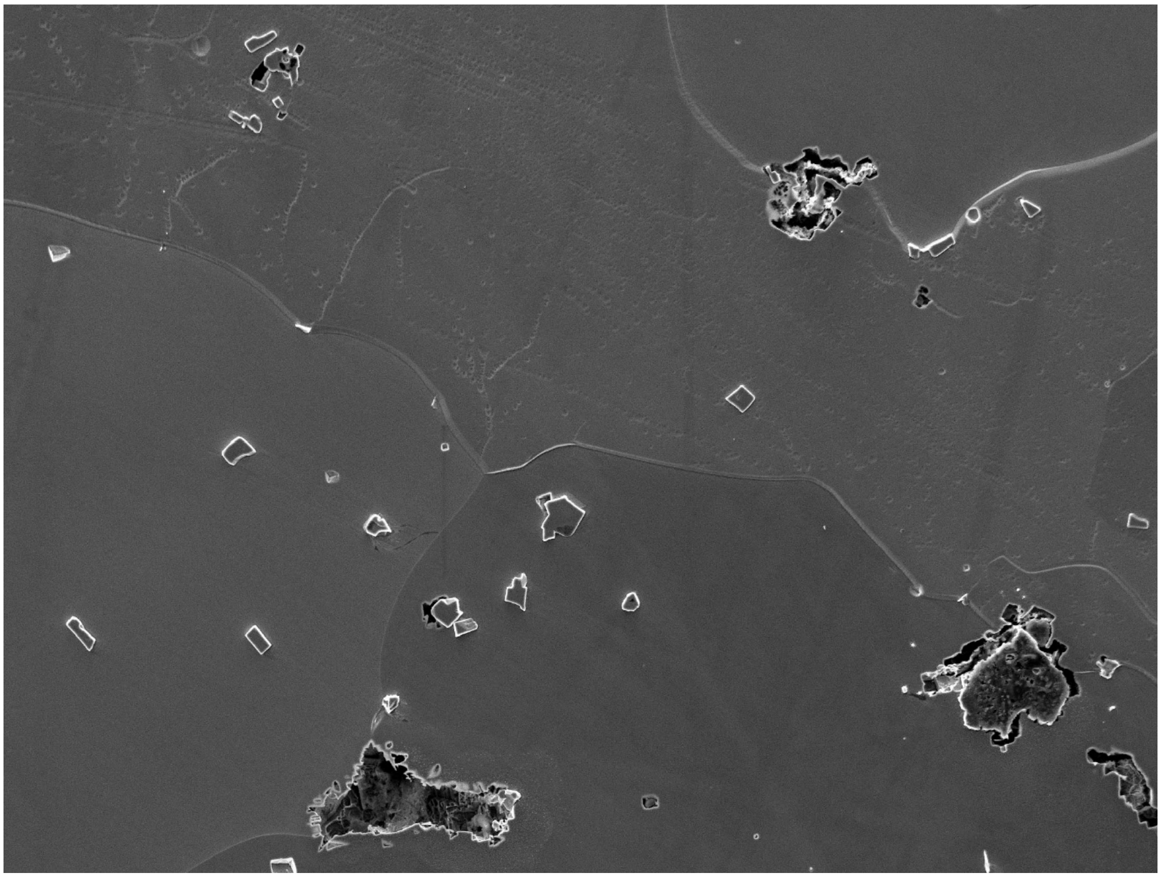

Figure 2 M30C SEM micrograph at 800X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 73897 psi, yield strength 32085 psi, and elongation of 43%. The mechanical properties do not meet the minimum required properties of ASTM A494, grade M30C, Table 3.

Stainless Foundry & Engineering Inc. S046

C80338

Figure 3

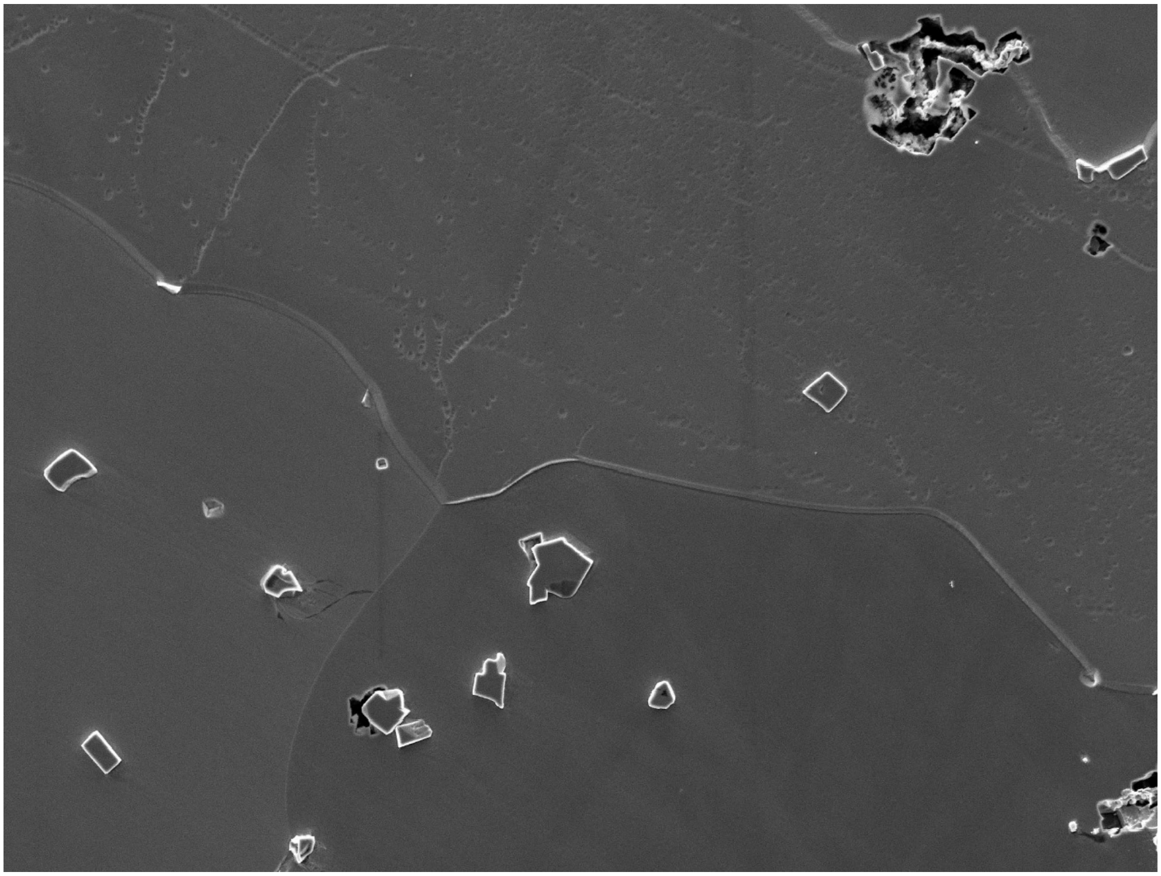

Figure 3 M30C SEM micrograph at 1200X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 73897 psi, yield strength 32085 psi, and elongation of 43%. The mechanical properties do not meet the minimum required properties of ASTM A494, grade M30C, Table 3.

P81047

Figure 4

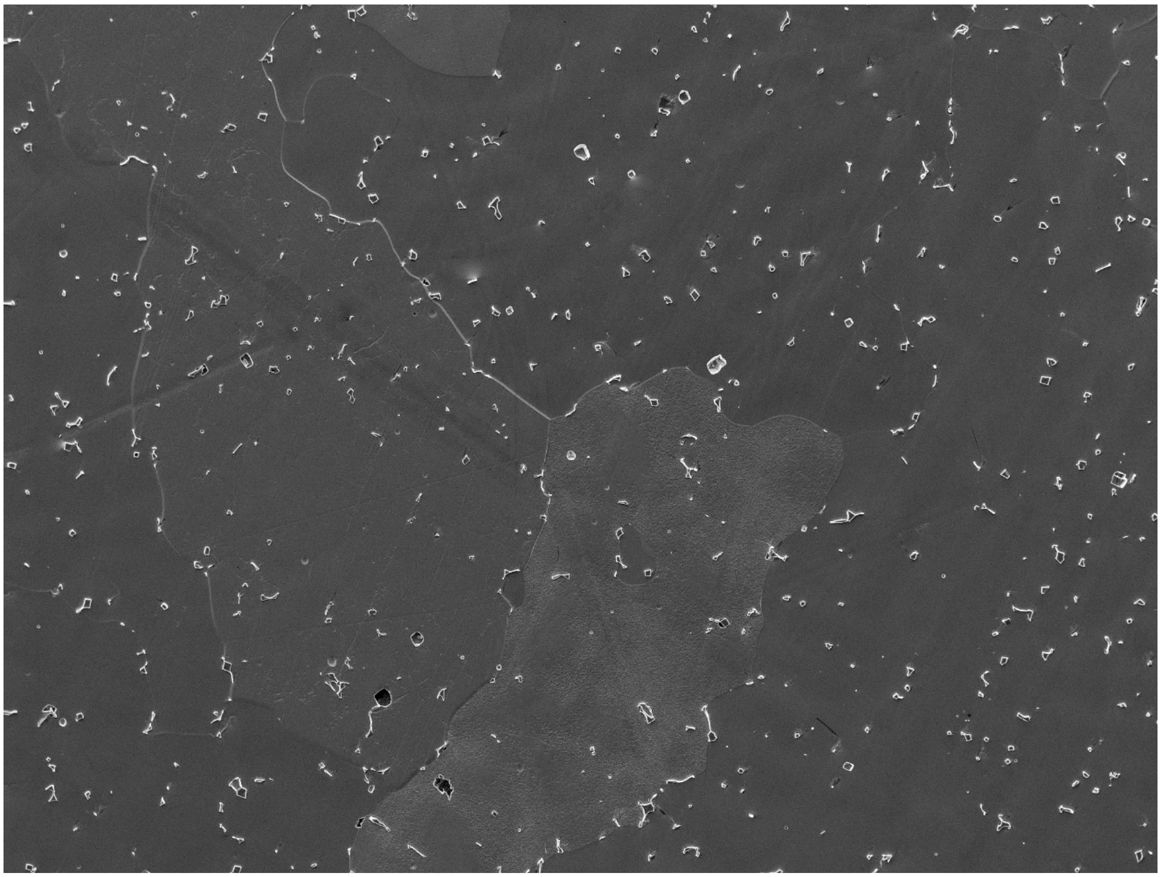

Figure 4 M30C SEM micrograph at 400X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 82986 psi, yield strength 36892 psi, and elongation of 45%. The mechanical properties meet the minimum required properties of ASTM A494, grade M30C, Table 3.

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Figure 5

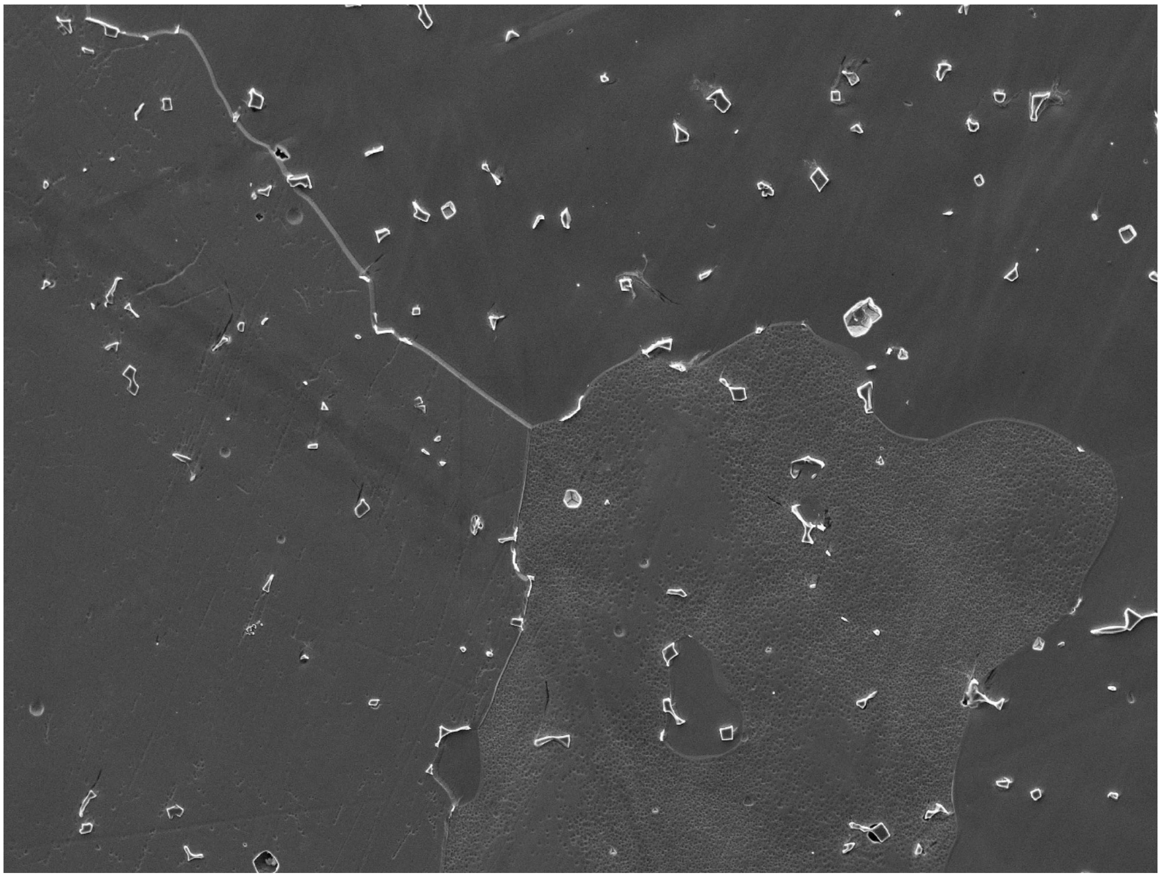


Figure 5 M30C SEM micrograph at 800X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 82986 psi, yield strength 36892 psi, and elongation of 45%. The mechanical properties meet the minimum required properties of ASTM A494, grade M30C, Table 3.

P81047

Figure 6

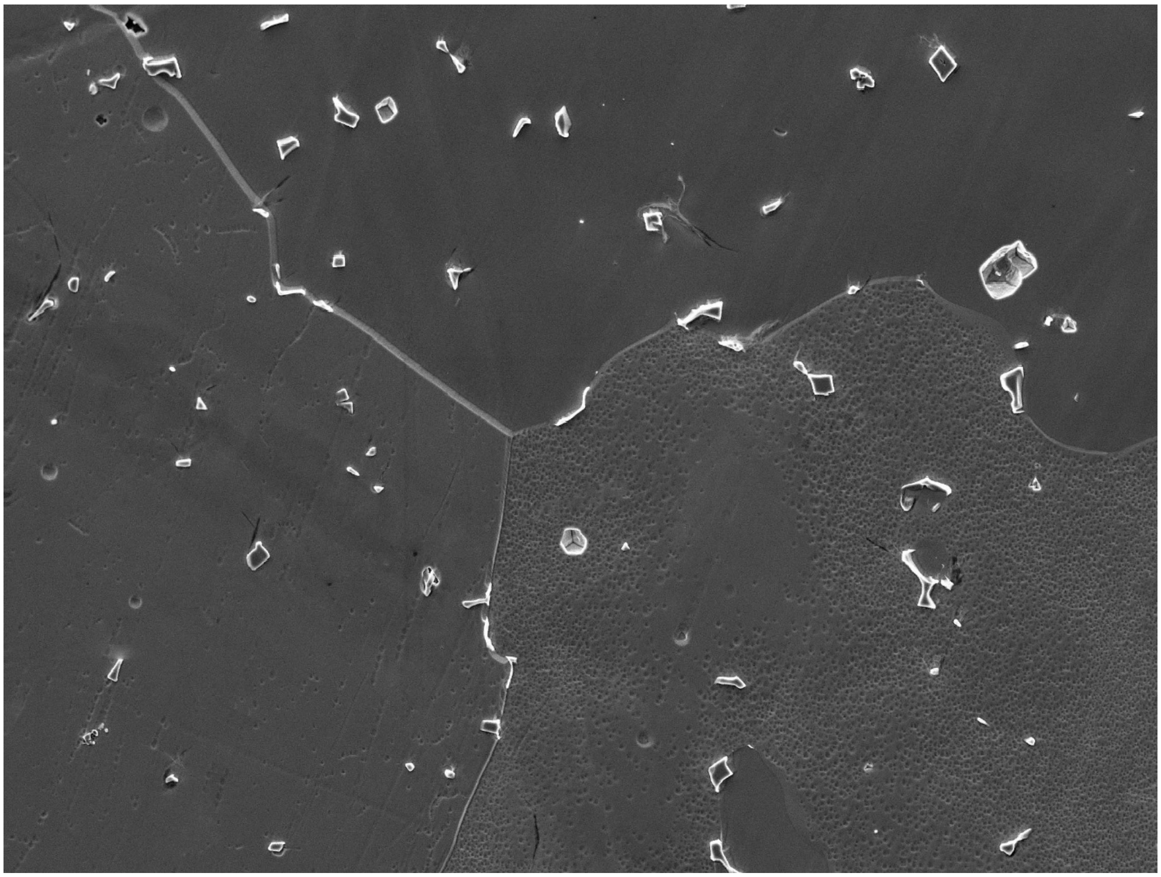


Figure 6 M30C SEM micrograph at 1200X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 82986 psi, yield strength 36892 psi, and elongation of 45%. The mechanical properties meet the minimum required properties of ASTM A494, grade M30C, Table 3.

C80412

Figure 7

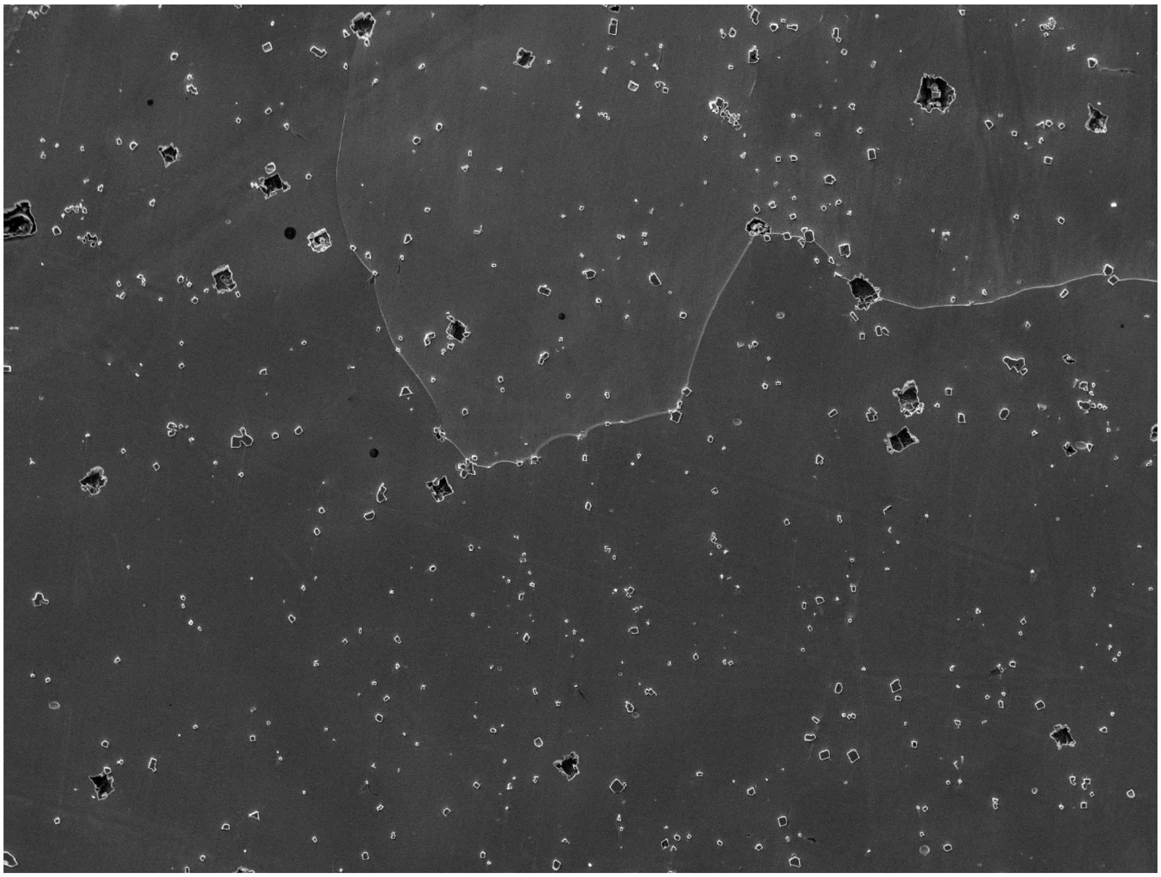


Figure 7 M30C SEM micrograph at 400X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 77020 psi, yield strength 30951 psi, and elongation of 45%. The mechanical properties do not meet the minimum required properties of ASTM A494, grade M30C, Table 3.

C80412

Figure 8

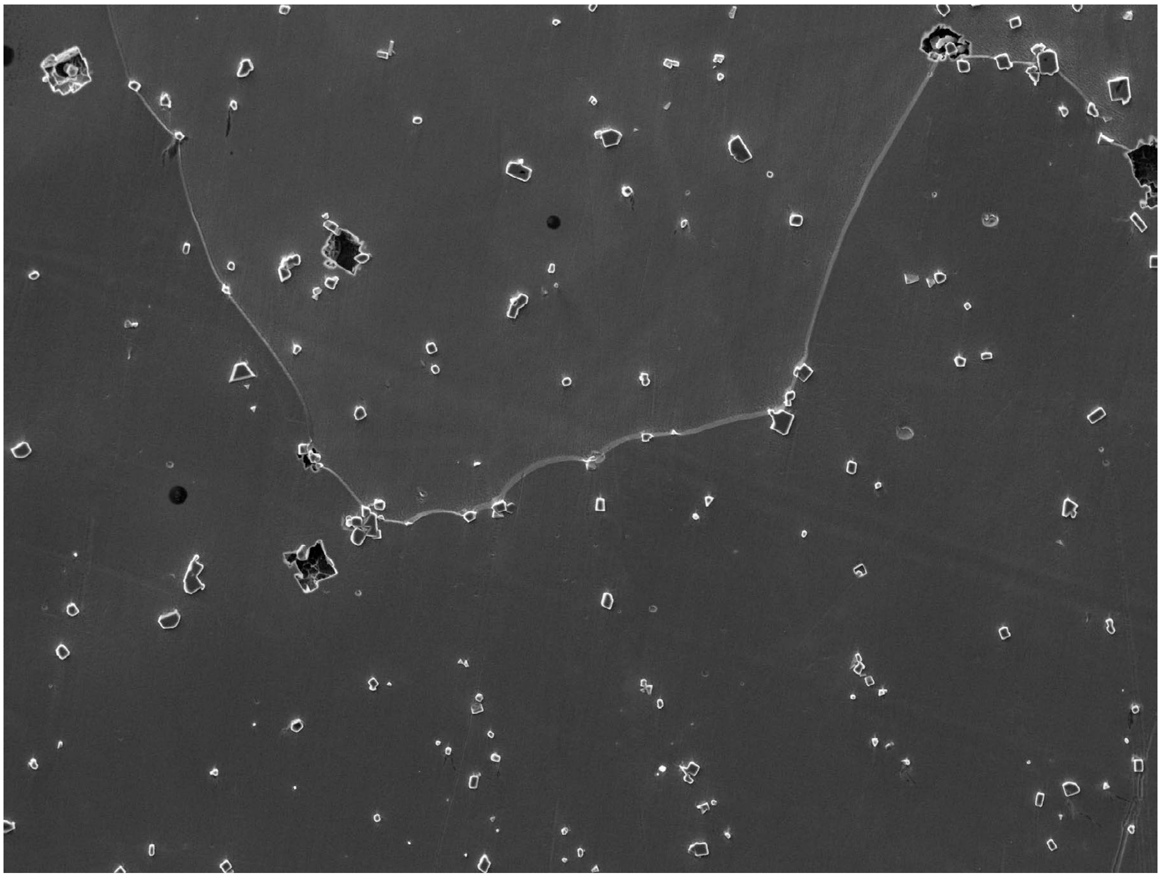


Figure 8 M30C SEM micrograph at 800X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 77020 psi, yield strength 30951 psi, and elongation of 45%. The mechanical properties do not meet the minimum required properties of ASTM A494, grade M30C, Table 3.

C80412

Figure 9

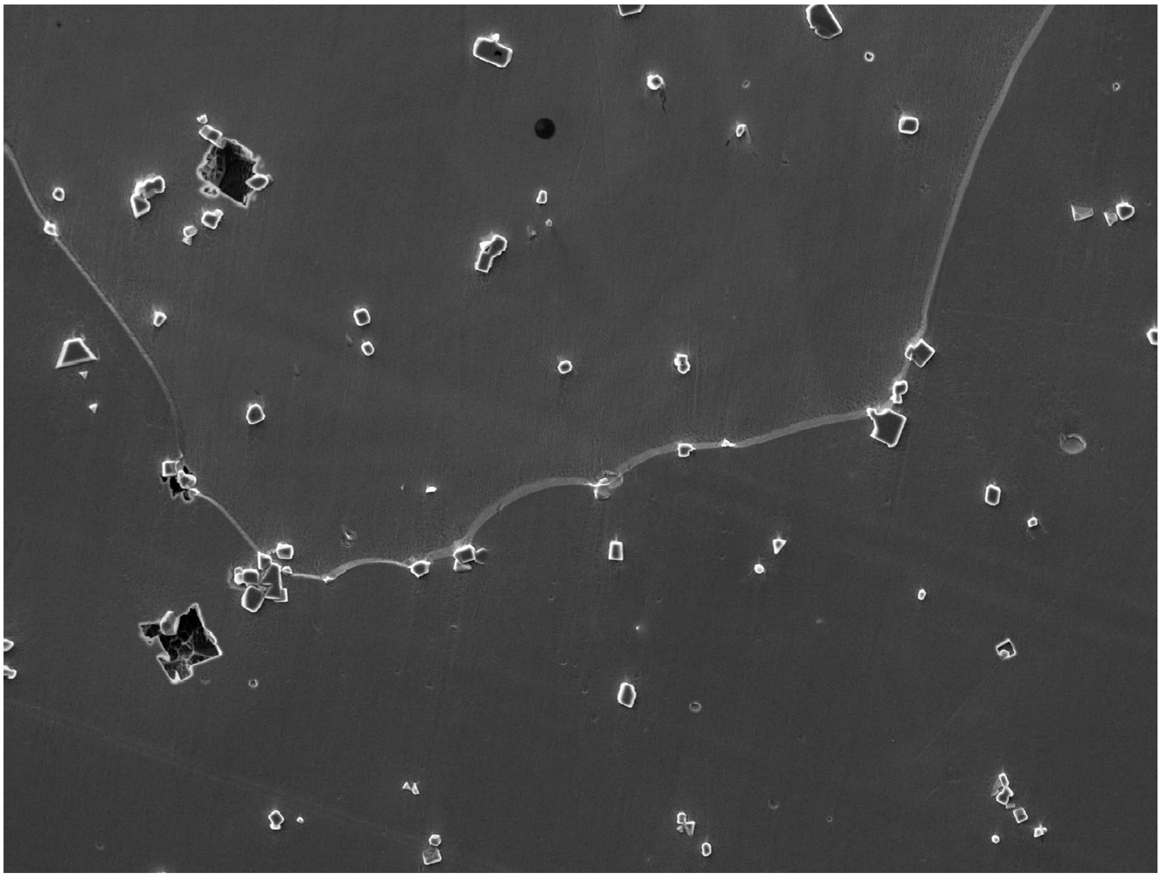


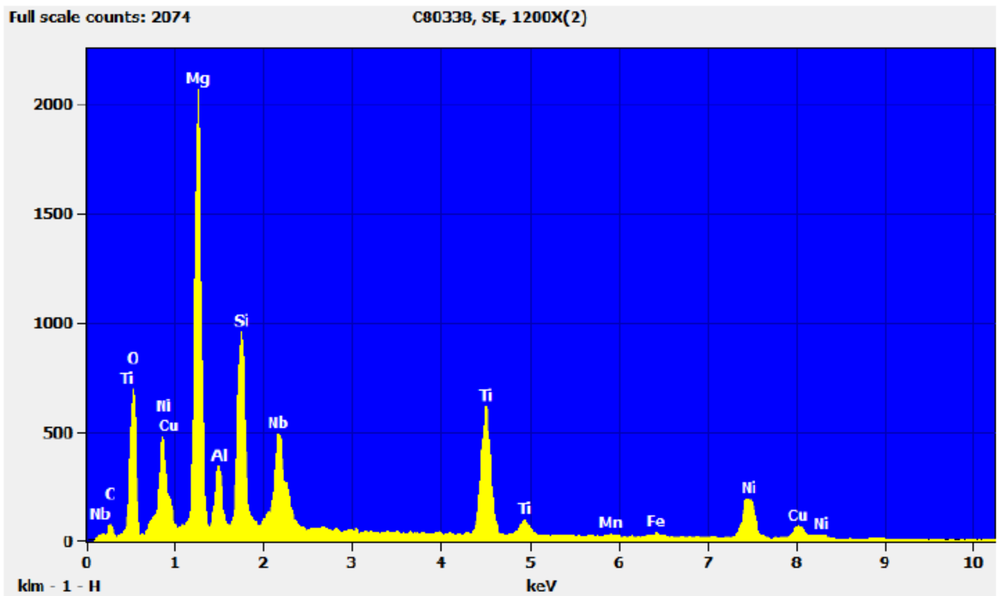
Figure 9 M30C SEM micrograph at 1200X magnification using marble's regent as an etchant.

Mechanical properties are as followed: tensile strength 77020 psi, yield strength 30951 psi, and elongation of 45%. The mechanical properties do not meet the minimum required properties of ASTM A494, grade M30C, Table 3.

Appendix IV

Energy Dispersive Spectroscopy (EDS)

Figure 1

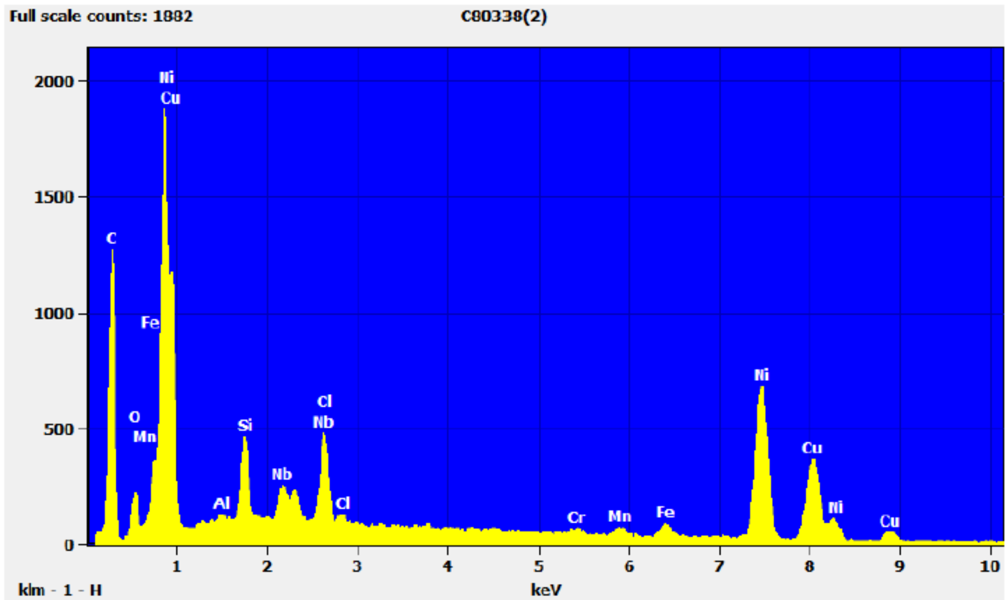


Quantitative Results for: C80338 – Isolated Occurrence

Element / Line	Weight %	Atom %
C K	7.0	13.5
O K	33.1	47.7
Mg K	20.1	19.1
Al K	2.8	2.4
Si K	7.8	6.4
Ti K	8.8	4.2
Mn K	0.4	0.2
Fe K	0.6	0.3
Ni K	8.2	3.2
Cu K	2.9	1.1
Nb L	8.1	2.0
Total	100.0	100.0

Figure 1 EDS of sample number C80338 directly on base metal from SEM.

Figure 2



Quantitative Results for: C80338 – Typical

Element / Line	Weight %	Atom %
C K	34.0	68.6
O K	3.3	5.1
Al K	0.1	0.1
Si K	1.6	1.3
Cl K	2.3	1.6
Cr K	0.4	0.2
Mn K	0.8	0.3
Fe K	1.1	0.5
Ni K	31.4	13.0
Cu K	23.4	8.9
Nb L	1.6	0.4
Total	100.0	100.0

Figure 2 EDS of sample number C80338 directly on niobium clump from SEM.