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Corrosion, Toughness, Weldability and Metallurgical Evaluation of Cast Duplex Stainless Steels

by Carl D. Lundin, Songqing Wen, William J. Ruprecht (The University of Tennessee), Raymond Monroe, Malcolm Blair (The Steel Founders' Society of America)

Abstract

Five types of cast duplex stainless steels (A890 1B [and a modification thereof], 4A, 5A, 6A) were characterized as to their corrosion, toughness and weldability performance and assessed microstructurally. These materials span the current range of alloys in commercial use. The solution treated cast materials were compared to their wrought "equivalents" in accord with ASTM A923. The cast duplex stainless steel materials were found to exhibit performance characteristics equivalent and, in some cases, superior to their wrought counterparts. The full range of testing strongly indicates that the cast materials can be evaluated in accordance with the A923 specification, which currently covers only limited wrought products.

The effect of welding on pitting performance was defined for both the cast and wrought materials. This evaluation revealed that a very strong potential for degradation of pitting resistance exists, upon autogenous welding, for both the wrought and cast materials. This potential should be addressed when selecting the type of duplex stainless steel for a particular service.

Key Words: cast duplex stainless steel, corrosion, toughness, weldability, microstructure

1. Introduction

Duplex stainless steels (DSS) are being specified for chloride containing environments due to their enhanced pitting and stress corrosion cracking resistance. They exhibit improved corrosion performance over the traditional austenitic stainless steels. Duplex stainless steels can also offer improved strength properties and are available in various wrought and cast forms.

In recent years, duplex stainless steels, in cast and wrought forms, have enjoyed rapidly increasing popularity. However, the availability of these alloys in the cast form has lagged behind the availability of the wrought form. Duplex stainless steel castings are often used in as pumps and valves in a variety of applications and are important components in all piping systems and, where unexpected service failures can result in significant operational problems and expense, performance is critical. Thus, of concern is variability and insufficient performance characteristics of DSS in all forms, which may be related to in-service operational conditions. Therefore, it is necessary to have available, suitable methods and procedures for enhancing the performance of DSS cast materials and to introduce methods for defining performance characteristics prior to service.

This paper presents part of the results of an “Improved Process Procedures for Upgrading & Repair of High Alloy Stainless Castings” program sponsored by the Department of Defense and the American Metal Casting Consortium, which involved two major areas of endeavor, interrelated and leading to a more fundamental understanding of the corrosion and fabrication behavior of DSS castings in comparison with wrought materials.

2. Materials

Five types of cast DSS, together with their wrought counterparts, were characterized; ASTM A890-4A, 5A, 6A, 1B, "CD7MCuN" and the wrought alloys, Alloy 2205, Alloy 2507, Zeron 100 and Ferralium 255. A total of sixteen cast heats and four wrought heats were evaluated. The castings were characterized in the as-cast, solution annealed (SA) static cast and SA centrifugal cast condition. The wrought materials were tested in the form of SA plate. Weld evaluations, including extensive assessment of autogenous welds and composite welds (SMAW), were performed on these materials.

3. Experimental Procedures and Results

3.1 ASTM A923 Methods A, B & C

ASTM A923, "Standard Test Method for Detecting Detrimental Intermetallic Phase in Wrought Duplex Austenitic/Ferritic Stainless Steels", is a specification that was developed for use with specific wrought duplex stainless steel (S31803). The purpose of these test methods is to allow detection of the presence of detrimental intermetallic phases in mill products to the extent that toughness or corrosion resistance is significantly affected. It contains three test methods (A, B & C). Method A is "Sodium Hydroxide Etch Test for Classification of Etch Structures of Duplex Stainless Steels," Method B is "Charpy Impact Test for Classification of Structures of Duplex Stainless Steels" and Method C is "Ferric Chloride Corrosion Test for Classification of Structures of Duplex Stainless Steels".

ASTM A923 was employed to test both the wrought and cast DSS in this program. It should be noted that only S31803 (Alloy 2205) is covered in the ASTM A923. However, base upon the evaluations conducted in the research reported here in, it was determined that ASTM A923 can be a suitable specification for both cast and wrought DSS of a variety of compositions, for defining performance characteristics prior to service.

3.1.1 ASTM A923 Method A

ASTM A923 Method A, was used to screen specimens intended for testing in Method B and Method C. The materials to be evaluated, were mounted, polished and etched utilizing sodium hydroxide. The etched surface was examined microscopically at 400X to 500X. Intermetallic phases were revealed and, depending on the etching time (5 to 60s), colored yellow or brownish. According to ASTM A923-A, signs of precipitation or waviness along the interphase (austenite-ferrite) boundaries are considered unacceptable. ASTM A923 Method A classifies the etched structures into four categories:

• Unaffected Structure - The ferrite has been etched without revelation of an intermetallic phase. The interphase boundaries are smooth.

• Possibly Affected Structure - The ferrite has been etched with isolated indications of a possible intermetallic phase. The interphase boundaries may show a fine scale waviness.

• Affected Structure - Indications of an intermetallic phase are readily revealed before or simultaneously with the staining of the ferrite during etching.

• Centerline Structure - An intermetallic phase is observed as a continuous or semi-continuous phase in the mid-thickness region of the product, with or without the affected structure out side of the mid-thickness region; indicative of segregation.

Samples, from ASTM A890-4A, 5A, 6A and 1B in the as-cast, and SA condition together with their wrought counterparts, were polished and NaOH etched according to ASTM A923 Method A. The typical microstructures of NaOH etched ASTM A890-4A, 5A, 6A and 1B are presented in Figures 1-1 to 1-4, respectively. All as-cast materials show an "Affected Structure", while all of the SA castings show "Unaffected Structures". Alloy 2205 and Alloy 2507 showed "Possibly Affected Structure". Zeron 100 and Ferralium 255 showed "Unaffected Structures".

3.1.2 ASTM A923 Method B

Test Method B determines in toughness characteristics which may result from processing irregularities. Variations in toughness may be attributable to an intermetallic phase or to other causes not necessarily detectable by Test Method A. This test method follows the procedure for conducting Charpy V-notch impact tests in accordance with ASTM A370 and E23 as a method of detecting the precipitation of detrimental intermetallic phases in DSS. Unless otherwise specified, the Charpy Impact test is performed at -40°F (-40°C). The acceptance criterion for wrought base metal is 40 ft-lbs. (54.2J) at -40°F (-40°C).

A total of ten heats were tested per ASTM A923 Method B and the results are presented in Table 1. The SA cast materials of ASTM A890-4A, 5A 1B and “CD7MCuN” reveal better impact toughness than their wrought counterparts at a test temperature of -40°F (-40°C). However, the wrought super duplex stainless steel, Zeron 100, shows the highest toughness at this temperature. Wrought Ferralium 255 is the only material that did not pass ASTM A923 Method B criteria.

3.1.3 ASTM A923 Method C

Test Method C, is a 24 hour pitting corrosion test in 6% ferric chloride, unless specified. The method detects a loss of corrosion resistance associated with a local depletion of chromium and/or molybdenum as a result of the precipitation of chromium-rich and possibly molybdenum-rich phases, but not limited to intermetallic phases. An affected structure should be associated with significant weight loss in the corrosion test. It defines the test temperature for base metal samples as 25°C, and for welds; 22°C. The corrosion rate is calculated in accordance with the weight loss and total surface area, using the formula below:

Corrosion rate (mdd*) = weight loss (mg) / [specimen area (dm^2) x time (days)]

* mdd: mg/ dm^2/day

The acceptance criterion is that the corrosion rate shall not exceed 10mdd.

It was found that all SA castings met the weight loss criteria. The SA + autogenously welded samples from ASTM A890-1B, 4A and "CD7MCuN" did not meet the criteria. The test results according to ASTM A923 Method C are summarized in Tables 2-1 through 2-5.

3.2 Critical Pitting Temperature (CPT) Testing

CPT evaluations were conducted in accordance with ASTM G48 Method C, entitled "Critical Pitting Temperature Test". CPT corrosion test samples of 1" X 1" X 1/8" in size with a 600-grit uniform surface finish were utilized. A water bath, with an accuracy of 0.1°C, was employed to control the test temperature and 5C° increments were used when defining the CPT. Each sample was weighed to the nearest 0.0001g and immersed in a 6% $FeCl_3$ solution when the water bath came to equilibrium at the temperature of interest. The test period is 24 hours. At the end of the test period, each sample was removed from solution and cleaned and weighed. Weight loss was calculated.

We defined the evaluation criterion for pitting as: when a sample exhibits 2 or more pits when examined at a magnification of 20X is considered "pitted". The critical pitting temperature is defined as the lowest temperature at which such pitting occurs. The CPT test was conducted using 5C° increments, therefore the accuracy of the test is ±5C°.

All materials, ASTM A890-4A, 5A, 6A, 1B and "CD7MCuN", in the as-cast, SA static and SA centrifugal cast condition, as well as the wrought counterparts, were CPT tested. The castings of super duplex type ASTM A890-5A and 6A exhibit the highest solution annealed CPT, as compared to ASTM A890-4A, 1B and “CD7MCuN”, indicating improved pitting resistance. Autogenous welds made on SA castings degraded the CPT of all materials. The extent of decrease in CPT varied from alloy to alloy, and from heat to heat for the same alloy type. The CPT test results of all alloy types can be summarized as follows:

- The as-cast condition showed the worst pitting corrosion resistance. After solution annealing, the pitting resistance significantly improved. There is a slight variation in CPT between SA cast heats and casting procedures (SA static casting and SA centrifugal castings).
- Wrought materials have similar pitting corrosion resistance as compared to castings in the SA condition.
- Autogenous welding decreases the pitting corrosion resistance regardless of the cast material condition, and also similarly adversely affects the wrought materials.

The CPT test results are presented in Table 3-1 to 3-5.

Figures 2 through 4 show the microstructure of ASTM A890-4A Heats 1, in the as-cast and SA condition, together with wrought counterpart Alloy 2205, before and after the pitting test.

The microstructure of ASTM A890-4A Heat 1, in the as-cast condition, is shown in Figure 2a. In the as-cast condition, austenite islands in a ferrite matrix are evident, together with fine precipitates mainly along the ferrite/austenite boundaries. Figure 2b shows an OLM micrograph of the pitting behavior of the as-cast Heat 1. It is evident that pits initiate at the precipitates along the ferrite/austenite boundaries and preferentially grow into ferrite.

The microstructure of ASTM A890-4A Heat 1 in the SA condition is shown in Figure 3a. It is evident that the particles along the ferrite/austenite boundaries, observed in the as-cast condition, are dissolved upon solution annealing. Austenite islands with smooth boundaries (no precipitates) are obvious in the ferrite matrix. Inclusions in the matrix remain unchanged after solution annealing. Figure 3b shows an OLM micrograph of the pitting behavior of ASTM A890-4A SA Heat 1. In the SA condition, pits will initiate above the CPT at the ferrite/austenite boundaries and preferentially grow into austenite.

The microstructure of wrought counterpart Alloy 2205 is presented in Figure 4a. A rolling texture, from hot working, followed by a solution annealing and quenching, is evident in comparison with the cast material. The pitting behavior of wrought Alloy 2205, in terms of the initiation and growth, was determined to be identical to the corresponding ASTM A890-4A cast materials in the SA condition (Figure 4b).

The optical features of the pitting behavior of autogenous welds on ASTM A890-4A SA Heat 1 are shown in Figure 5. Pits were observed both in the fusion zone and at the fusion line, as shown in the figure. A finer austenite structure in the ferrite matrix is evident in the fusion zone, as compared to the cast base metal. This finer austenite microstructure shows the original solidification pattern in the autogenous weld fusion zone and reflects the rapid cooling upon welding. The autogenously (no filler metal was added) welded samples were tested in the as-welded condition. Thus, the fusion zone in these autogenous welds is truly an “Unmixed Zone”. It is to be expected that segregation of alloy elements in the fusion zone occurs during solidification. Greater extent of element segregation tends to occur in the fusion zone adjacent to the fusion boundary, as compared to the other fusion zone locations. The segregation of Cr and Mo in the solidification structure can have a significant influence on the corrosion behavior of autogenous welds. In addition, the loss of nitrogen from the fusion zone during welding should be considered in regard to a reduction of corrosion resistance of the autogenously welded fusion zone. The degradation of corrosion resistance, in term of pitting resistance, is reflected by the decrease in CPT. In this case, the CPT of SA ASTM A890-4A is 40°C and SA + autogenously welded; 30°C. However, a significantly greater degradation in CPT was obtained for some of the other alloys. Further research will be conducted on welded duplex castings to determine the causes for these differences.

3.3 Preliminary Study of Pitting Corrosion Performance of SMA Welded Castings

Since autogenous welding is not generally the most utilized welding practice for upgrading of castings or fabrication of DSS components, it is extremely important to have a better understanding of the corrosion performance of composite welds (weldments fabricated with matching or enhanced filler materials). It should be recognized that welding processes using a filler metal leaves a composite zone, an unmixed zone, a heat-affected zone (HAZ) and un-affected metal in the fabrication. The metallurgical characteristics of each zone can be significantly different from that of the unaffected base material in terms of microstructure, phase balance and alloy element distribution. Thus, the corrosion performance of welded components can be expected to be different from their respective original material condition. In addition, a paucity of data exists upon which specifiers /engineers can base service performance of welds. Thus, there is a need for a more comprehensive study of the behavior of welded DSS components. In order to “pave-the-way” and to capture a glimpse of future research work, trials involving pitting corrosion testing were initiated. Pitting tests were conducted on DSS casting SMA welds for the determination of the relative corrosion resistance between the composite zone, the unmixed zone, the heat-affected zone (HAZ) and the SA cast base metal. A total of five heats, one from each alloy system (ASTM A890-4A, 5A, 6A, 1B and “CD7MCuN”), were selected for this study. A widely applicable conclusion, based on the results, can be drawn as follows:

- SMA welding has a significant effect on the corrosion performance of DSS castings. Pits preferentially initiate in the composite zone, unmixed zone or the heat-affected zone, depending on material.

The preliminary results of these trial pitting corrosion tests on DSS castings clearly define the necessity for an additional detailed study on the corrosion performance of the DSS composite welds.

3.4 Charpy Impact Testing

Charpy impact tests in according with ASTM A923 Method B, were conducted in the temperature range of –80°C to +20°C on ASTM A890-4A, 5A, 6A, 1B, "CD7MCuN" and the wrought counterparts. Charpy toughness transition curves for all tested materials are shown in Figure 6.

It should be noted that, the two SA heats of ASTM A890-4A revealed significant differences in their toughness, as indicated in Figure 6. Figure 7 shows the microstructure of ASTM A890-4A Heat 2 in the SA condition. It is clear that Heat 2 reveals a microstructure identical to Heat 1 (Figure 3a) in the SA condition, in terms of austenite islands in a ferrite matrix. However, larger inclusions were observed in the Heat 2 matrix as compared to Heat 1. It is considered that these randomly distributed larger inclusions may have influenced the Charpy toughness.

4. Conclusions

A significant database for the corrosion performance of the duplex stainless steel castings has been established for cast DSS. Comparisons between DSS were made, and heat-to-heat and alloy system-to-system, conclusions derived from the obtained results. Conclusions can be drawn as follows:

- Both the pitting and intergranular corrosion resistance of cast duplex stainless steel are equal to or better than their wrought counterparts. Thus, cast and wrought products can be evaluated to the same performance standards.

- The corrosion test methods for wrought stainless materials are suitable for evaluation of duplex stainless steel castings.
- The data obtained in this study suggests that ASTM A923 can be expanded in coverage to include the cast duplex materials of ASTM A890. Thus, one specification will cover both wrought and cast materials making selection independent of product form.
- An appropriate screening test characterizing service performance of duplex stainless steel castings is ASTM A923 Method A (NaOH Etch Test), which is currently utilized for wrought S31803 (Alloy 2205) material. Cast duplex alloys can be added to this specification upon the inclusion of appropriate photomicrographs.
- Welding reduced the pitting and intergranular corrosion resistance for both the wrought and cast duplex alloys of similar composition. The effect of welding should be considered when selecting an alloy type for specific corrosion service. Thus, the same fabrication considerations apply to the entire cast/wrought system.
- Charpy impact test results show that castings can have equivalent toughness to their wrought counterparts in the temperature range of –80°C to +20°C. Thus, specification requirements are simplified for an entire system fabrication (both wrought and cast).

5. Acknowledgements

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Table 1. ASTM A923 Method B Results

Code	Impact Energy At -40°F* (ft-lbs)	Method B P/F**
ASTM A890-4A Heat 1	55	P
ASTM A89-4A Heat 2	150	P
Alloy 2205	50	P
ASTM A 890-5A	80	P
Alloy 2507	44	P
ASTM A 890-6A	81	P
Zeron 100	172	P
ASTM A890-1B	82	P
CD7MCuN	62	P
CD7MCuN-CC	56	P
Ferralium. 255	23	F

* Charpy Impact test conducted according to ASTM A370 and E23 utilizing V-notched Charpy test samples

** Acceptance criterion of ASTM A923 method B of base metal is 40 ft-lbs (54J) at –40°F (-40°C)

Table 2-1 Duplex Stainless Steel ASTM A923 Method C Ferric Chloride Corrosion Test Results, ASTM A890-4A (6% $FeCl_3$, Base Metal@25°C & Weld Metal@22°C,24 hrs.)

Material	Code	Condition	Corrosion Rate (mdd**)	P/F***	CPT (°C)
ASTM A 890-4A	Heat 1	Solution annealed	0.73	P	40
ASTM A 890-4A	Heat 1	SA Autogenous welded	65.93	F	30
ASTM A 890-4A	Heat 2	Solution annealed	2.19	P	35
ASTM A 890-4A	Heat 2	SA Autogenous welded	65.93	F	≤0
ASTM A 890-4A	Heat 3	Solution annealed	0.00	P	50
ASTM A 890-4A	Heat 3	SA Autogenous welded	415.20	F	≤0
ASTM A 890-4A	Heat 4	Solution annealed	0.00	P	45
ASTM A 890-4A	Heat 4	Solution annealed	15.10	F	20
ASTM A 890-4A	Heat 4 CC*	Solution annealed	2.12	P	50
ASTM A 890-4A	Heat 4 CC*	SA Autogenous welded	33.34	F	15
Alloy 2205	Alloy 2205	Wrought	0.00	P	40
Alloy 2205	Alloy 2205	Wrought Autogenous welded	7.92	P	25

* CC - centrifugal cast
** mdd - $mg/dm^2/day$
*** The acceptance criterion is no corrosion rate shall excess 10mdd.

Table 2-2 Duplex Stainless Steel ASTM A923 Method C Ferric Chloride Corrosion Test Results, ASTM A890-5A (6% $FeCl_3$, Base Metal@25°C & Weld Metal@22°C,24 hrs.)

Material	Code	Condition	Corrosion Rate (mdd**)	P/F***	CPT (°C)
ASTM A 890-5A	Heat 1	Solution annealed	2.64	P	65
ASTM A 890-5A	Heat 1	SA Autogenous welded	3.05	P	45
ASTM A 890-5A	Heat 2	Solution annealed	0.00	P	50
ASTM A 890-5A	Heat 2	SA Autogenous welded	4.41	P	40
ASTM A 890-5A	Heat 3	Solution annealed	0.00	P	65
ASTM A 890-5A	Heat 3	SA Autogenous welded	0.00	P	45
ASTM A 890-5A	Heat 3 CC*	Solution annealed	0.00	P	50
ASTM A 890-5A	Heat 3 CC*	SA Autogenous welded	3.78	P	30
Alloy 2507	Alloy2507	Wrought	0.00	P	80
Alloy 2507	Alloy2507 (A-W)	Wrought Autogenous welded	0.00	P	45

* CC - centrifugal cast
* mdd - mg/dm^2/day
** The acceptance criterion is no corrosion rate shall excess 10mdd.

Table 2-3 Duplex Stainless Steel ASTM A923 Method C Ferric Chloride Corrosion Test Results, ASTM A890-6A (6% $FeCl_3$, Base Metal@25°C & Weld Metal@22°C,24 hrs.)

Material	Code	Condition	Corrosion Rate (mdd*)	P/F***	CPT (°C)
ASTM A 890-6A	Heat 1	Solution annealed	0.00	P	65
ASTM A 890-6A	Heat 1	SA Autogenous welded	4.47	P	55
ASTM A 890-6A	Heat 2	Solution annealed	0.00	P	70
ASTM A 890-6A	Heat 2	SA Autogenous welded	0.00	P	45
ASTM A 890-6A	Heat 3	Solution annealed	0.67	P	55
ASTM A 890-6A	Heat 3	SA Autogenous welded	2.70	P	40
Zeron 100	Zeron 100	Wrought	0.00	P	65
Zeron 100	Zeron 100	Wrought Autogenous welded	0.00	P	30

* mdd - $mg/dm^2/day$
*** The acceptance criterion is no corrosion rate shall excess 10mdd.

Table 2-4 Duplex Stainless Steel ASTM A923 Method C Ferric Chloride Corrosion Test Results, ASTM A890-1B (6% $FeCl_3$, Base Metal@25°C & Weld Metal@22°C,24 hrs.)

Material	Code	Condition	Corrosion Rate (mdd**)	P/F***	CPT (°C)
ASTM A 890-1B	Heat 1	Solution annealed	0.00	P	35
ASTM A 890-1B	Heat 1	SA Autogenous welded	16.79	F	25
ASTM A 890-1B	Heat 2	Solution annealed	0.00	P	40
ASTM A 890-1B	Heat 2	SA Autogenous welded	198.02	F	15
ASTM A 890-1B	Heat 3	Solution annealed	3.45	P	30
ASTM A 890-1B	Heat 3	SA Autogenous welded	133.92	F	15
ASTM A 890-1B	Heat 4	Solution annealed	2.87	P	35
ASTM A 890-1B	Heat 4	SA Autogenous welded	184.31	F	10
Ferralium 255	Ferr. 255	Wrought	1.96	P	45
Ferralium 255	Ferr. 255	Wrought Autogenous welded	66.39	F	25

** mdd - $mg/dm^2/day$

*** The acceptance criterion is no corrosion rate shall excess 10mdd.

Table 2-5 Duplex Stainless Steel ASTM A923 Method C Ferric Chloride Corrosion Test Results, CD7MCuN (6% $FeCl_3$, Base Metal@25°C & Weld Metal@22°C,24 hrs.)

Material	Code	Condition	Corrosion Rate (mdd**)	P/F***	CPT (°C)
CD7MCuN	Heat 1	Solution Annealed	0.00	P	45
CD7MCuN	Heat 1	SA Autogenous Welded	427.03	F	5
CD7MCuN	Heat 2	Solution Annealed	0.00	P	40
CD7MCuN	Heat 2	SA Autogenous Welded	142.64	F	15
CD7MCuN-CC	Heat 1 CC*	Solution Annealed	0.00	P	50
CD7MCuN-CC	Heat 1 CC*	SA Autogenous Welded	116.40	F	15

* CC - centrifugal cast
* mdd - mg/dm^2/day
** The acceptance criterion is no corrosion rate shall excess 10mdd.

Table 3-1 Duplex Stainless Steel CPT Test Results, ASTM A890-4A (ASTM G48, 6 % $FeCl_3$, 24 hrs.)

Material	Heat No.	Condition	CPT (°C)
ASTM A 890-4A	Heat 1	As-cast	25
ASTM A 890-4A	Heat 1	As-cast Autogenous welded	15
ASTM A 890-4A	Heat 1	Solution annealed	40
ASTM A 890-4A	Heat 1	SA Autogenous welded	30
ASTM A 890-4A	Heat 2	Solution annealed	35
ASTM A 890-4A	Heat 2	SA Autogenous welded	≤0
ASTM A 890-4A	Heat 3	Solution annealed	50
ASTM A 890-4A	Heat 3	SA Autogenous welded	≤0
ASTM A 890-4A	Heat 4	Solution annealed	45
ASTM A 890-4A	Heat 4	SA Autogenous welded	20
ASTM A 890-4A	Heat 4 CC*	Solution annealed	50
ASTM A 890-4A	Heat 4 CC*	SA Autogenous welded	15
Alloy 2205	Alloy 2205	Wrought	40
Alloy 2205	Alloy 2205	Wrought Autogenous welded	25

* CC - centrifugal cast

Table 3-2 Duplex Stainless Steel CPT Test Results, ASTM A890-5A (ASTM G48, 6 % $FeCl_3$, 24 hrs.)

Material	Heat No.	Condition	CPT (°C)
ASTM A 890-5A	Heat 1	As-cast	≤0
ASTM A 890-5A	Heat 1	Solution annealed	65
ASTM A 890-5A	Heat 1	SA Autogenous welded	45
ASTM A 890-5A	Heat 2	Solution annealed	50
ASTM A 890-5A	Heat 2	SA Autogenous welded	40
ASTM A 890-5A	Heat 3	Solution annealed	65
ASTM A 890-5A	Heat 3	SA Autogenous welded	45
ASTM A 890-5A	Heat 3 CC*	Solution annealed	50
ASTM A 890-5A	Heat 3 CC*	SA Autogenous welded	30
Alloy 2507	Alloy2507	Wrought	80
Alloy 2507	Alloy2507	Wrought Autogenous welded	45

* CC - centrifugal cast

Table 3-3 Duplex Stainless Steel CPT Test Results, ASTM A890-6A (ASTM G48, 6 % $FeCl_3$, 24 hrs.)

Material	Heat No.	Condition	CPT (°C)
ASTM A 890-6A	Heat 1	Solution annealed	65
ASTM A 890-6A	Heat 1	SA Autogenous welded	55
ASTM A 890-6A	Heat 2	Solution annealed	70
ASTM A 890-6A	Heat 2	SA Autogenous welded	45
ASTM A 890-6A	Heat 3	Solution annealed	55
ASTM A 890-6A	Heat 3	SA Autogenous welded	40
Zeron 100	Zeron 100	Wrought	65
Zeron 100	Zeron 100	Wrought Autogenous welded	30

Table 3-4 Duplex Stainless Steel CPT Test Results, ASTM A890-1B
(ASTM G48, 6 % $FeCl_3$, 24 hrs.)

Material	Heat No.	Condition	CPT (°C)
ASTM A 890-1B	Heat 1	As-cast	15
ASTM A 890-1B	Heat 1	As-cast Autogenous welded	15
ASTM A 890-1B	Heat 1	Solution annealed	35
ASTM A 890-1B	Heat 1	SA Autogenous welded	25
ASTM A 890-1B	Heat 2	Solution annealed	40
ASTM A 890-1B	Heat 2	SA Autogenous welded	15
ASTM A 890-1B	Heat 3	Solution annealed	30
ASTM A 890-1B	Heat 3	SA Autogenous welded	15
ASTM A 890-1B	Heat 4	Solution annealed	35
ASTM A 890-1B	Heat 4	SA Autogenous welded	10
Ferralium 255	Ferr. 255	Wrought	45
Ferralium 255	Ferr. 255	Wrought Autogenous welded (Ar)	25
Ferralium 255	Ferr. 255	Wrought Autogenous welded (Ar + 5%N_2)	30

Table 3-5 Duplex Stainless Steel CPT Test Results, CD7MCuN (ASTM G48, 6 % $FeCl_3$, 24 hrs.)

Material	Heat No.	Condition	CPT (°C)
CD7MCuN	Heat 1	Solution Annealed	45
CD7MCuN	Heat 1	SA Autogenous Welded	5
CD7MCuN	Heat 2	Solution Annealed	40
CD7MCuN	Heat 2	SA Autogenous Welded	15
CD7MCuN-CC	Heat 1 CC*	Solution Annealed	50
CD7MCuN-CC	Heat 1 CC*	SA Autogenous Welded	15

* CC - centrifugal cast

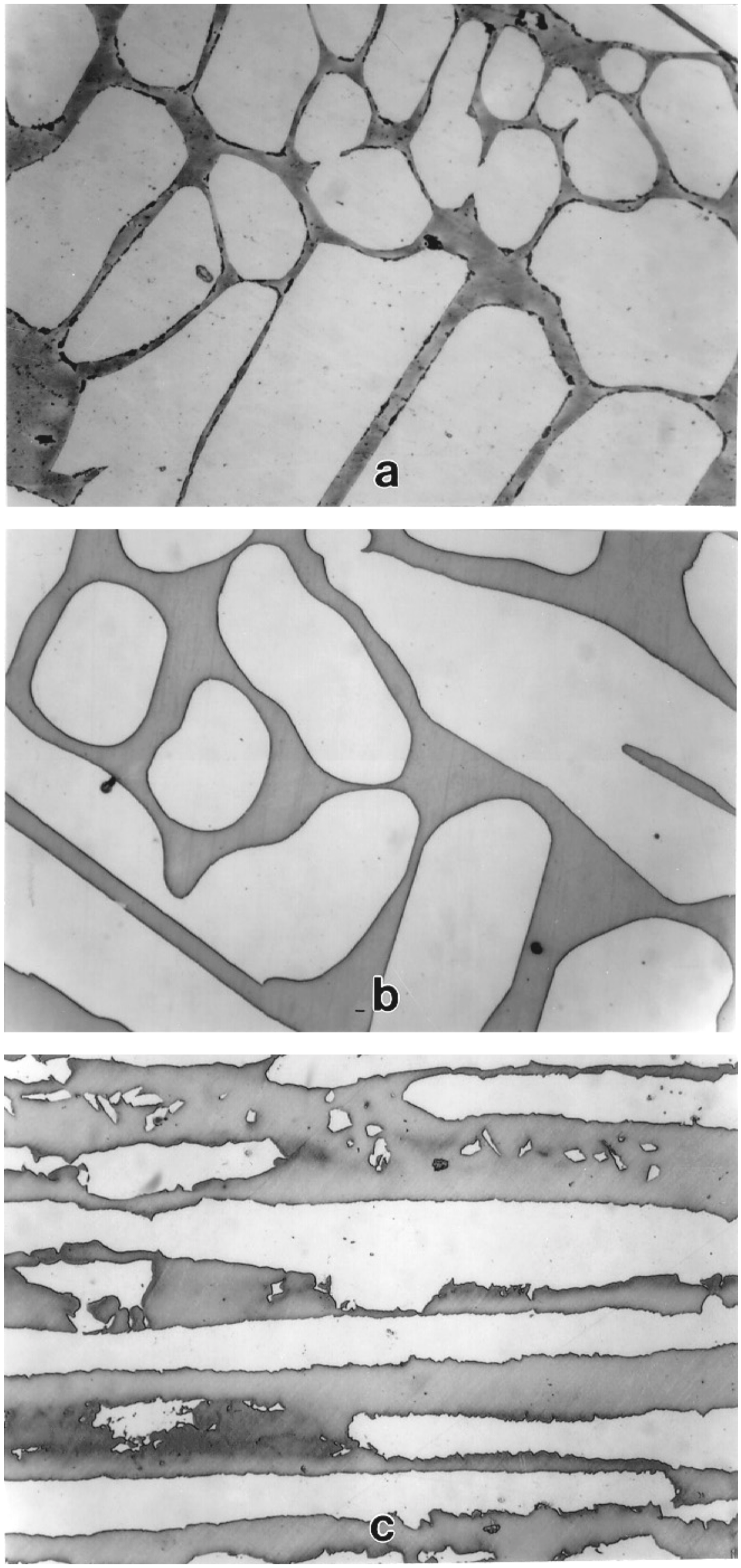


Figure 1-1. Sodium Hydroxide etched structure of ASTM A890-4A (a) As-cast, (b) SA Casting, (c) Wrought Alloy 2205, 400X

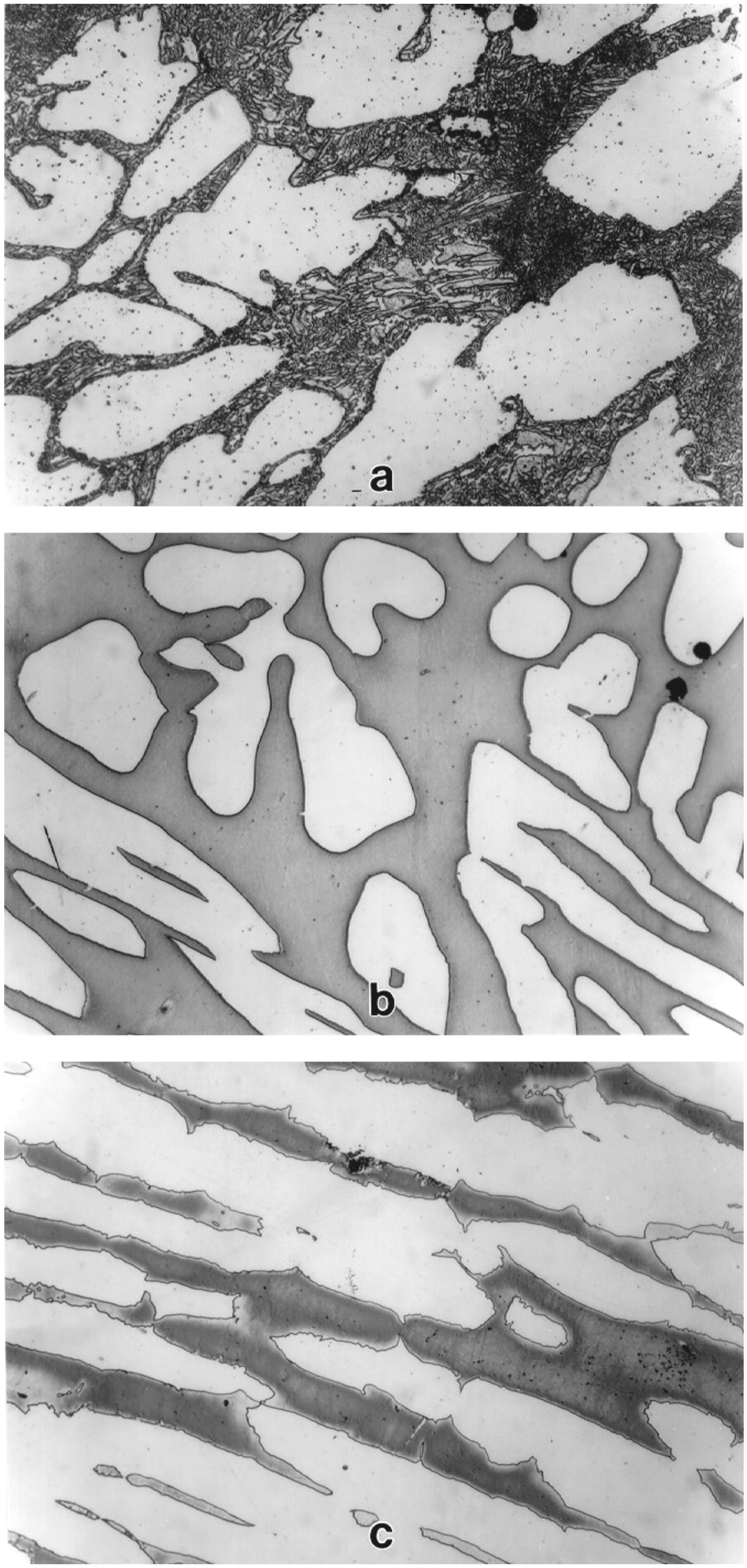


Figure 1-2. Sodium Hydroxide etched structure of ASTM A890-5A (a) As-cast, (b) SA Casting, (c) Wrought Alloy 2507, 400X

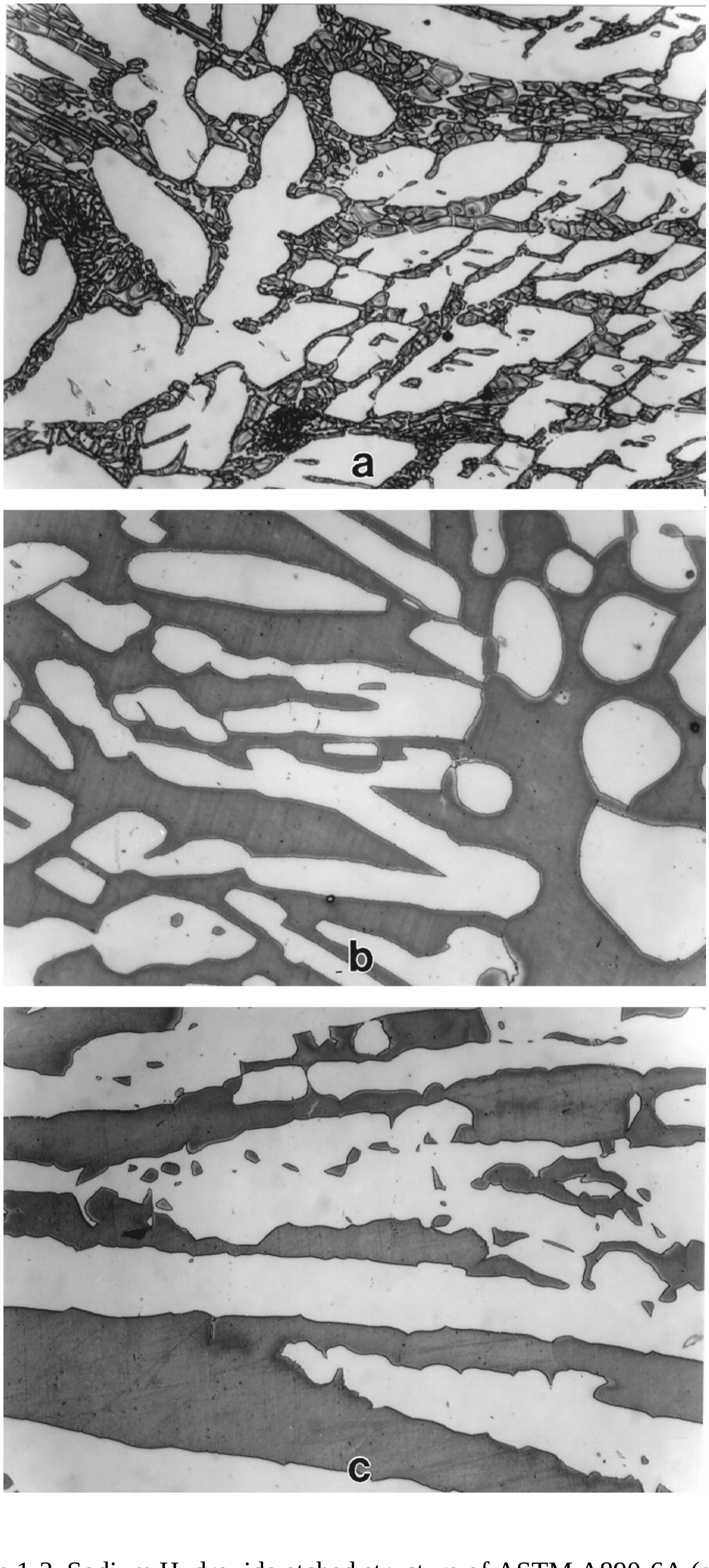


Figure 1-3. Sodium Hydroxide etched structure of ASTM A890-6A (a) As-cast, (b) SA Casting, (c) Zeron 100, 400X

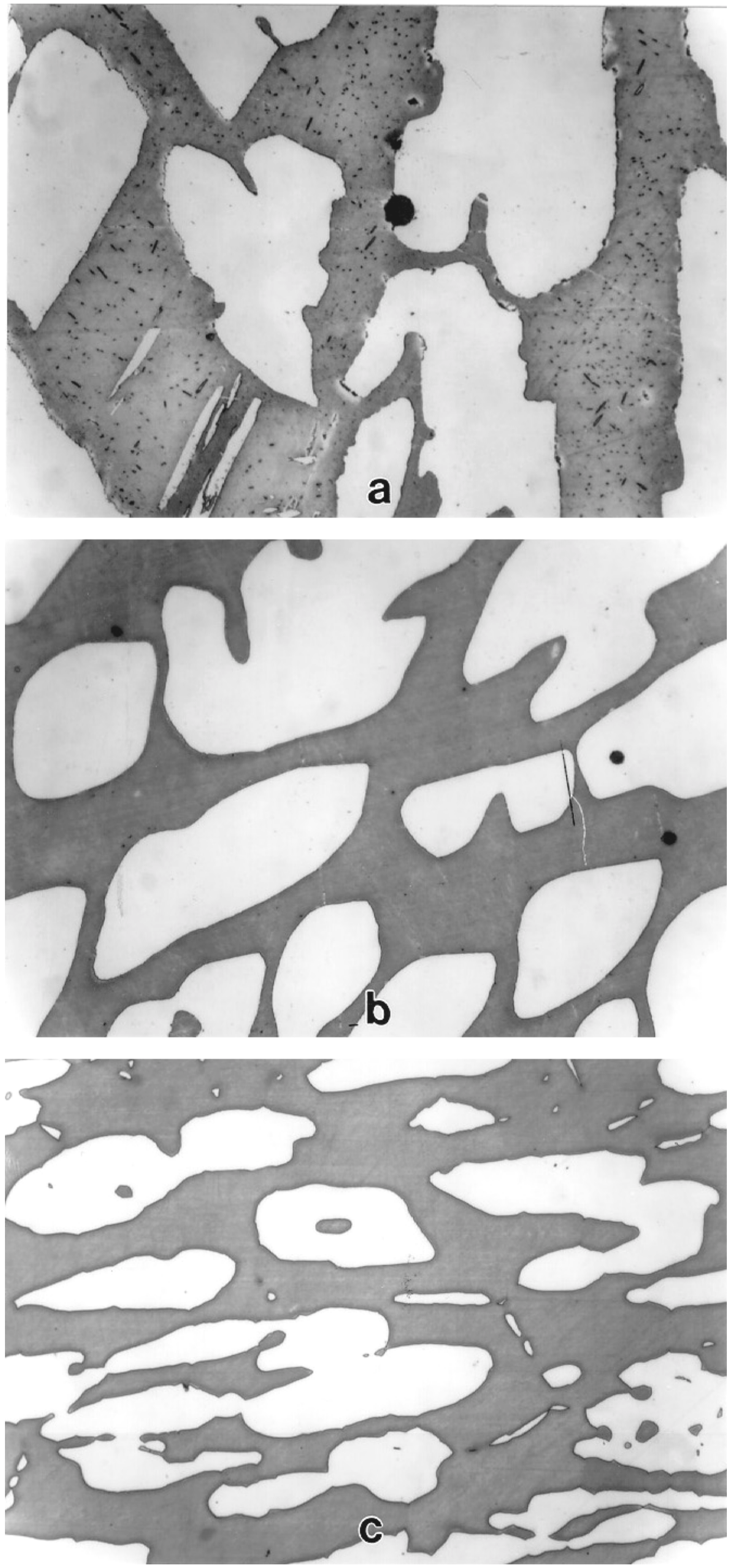
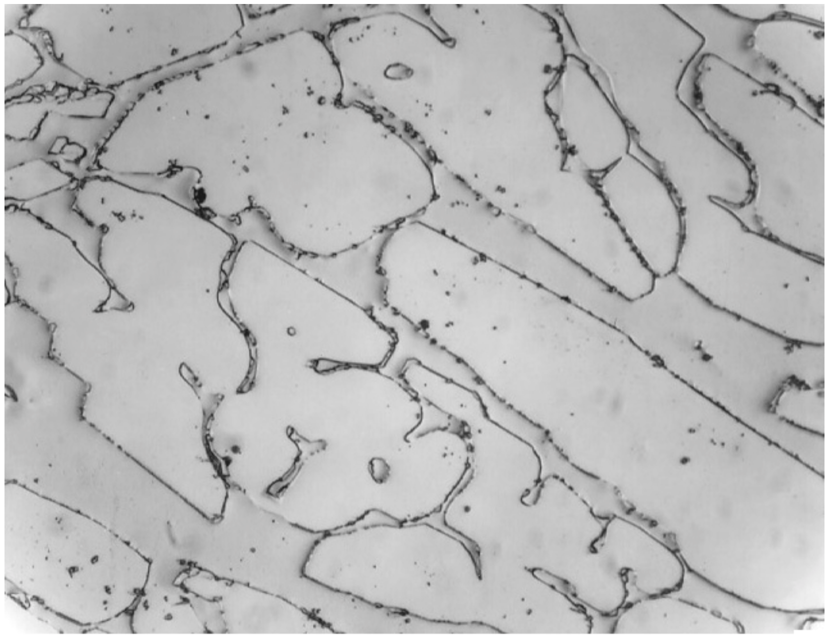
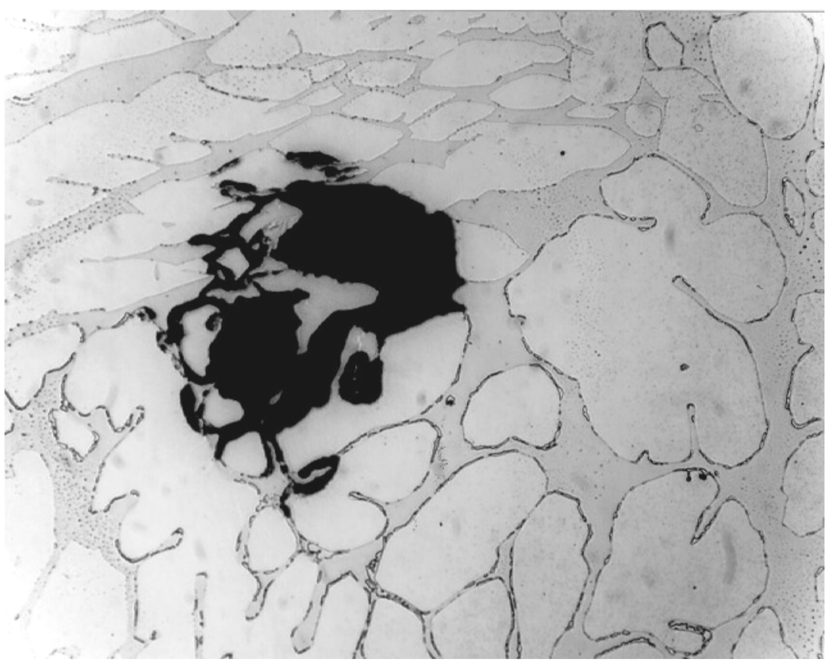


Figure 1-4. Sodium Hydroxide etched structure of ASTM A890-1B (a) As-cast, (b) SA Casting, (c) Ferralium 255, 400X

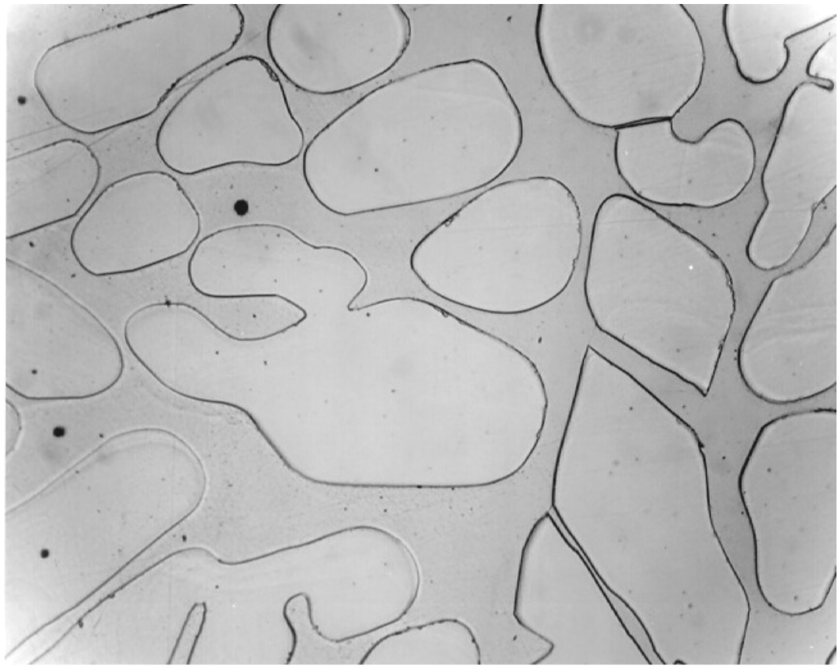


(a)

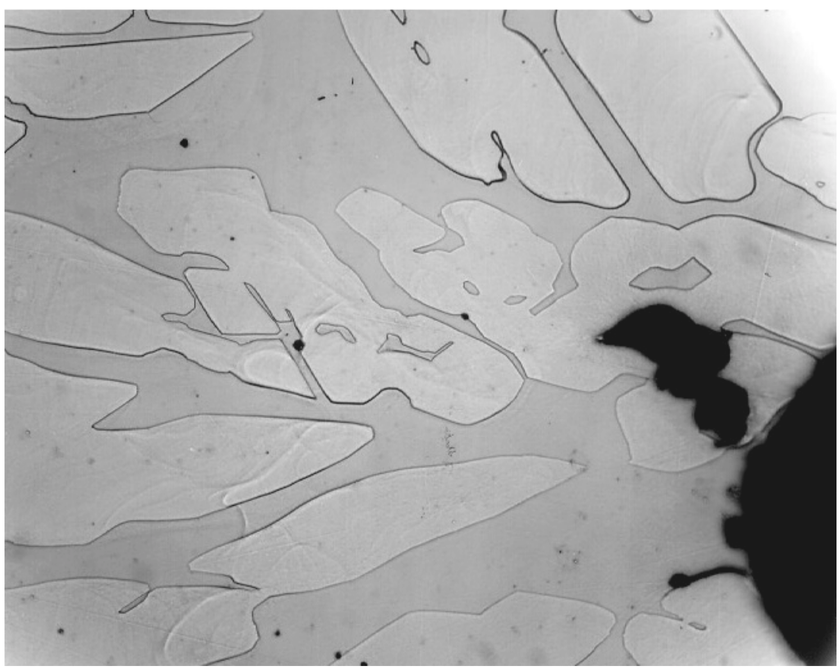


(b)

Figure 2. Microstructure of ASTM A890-4A Heat 1 in the As-cast condition, (a) Base Metal, 400X, (b) Pitting , 200X, Oxalic

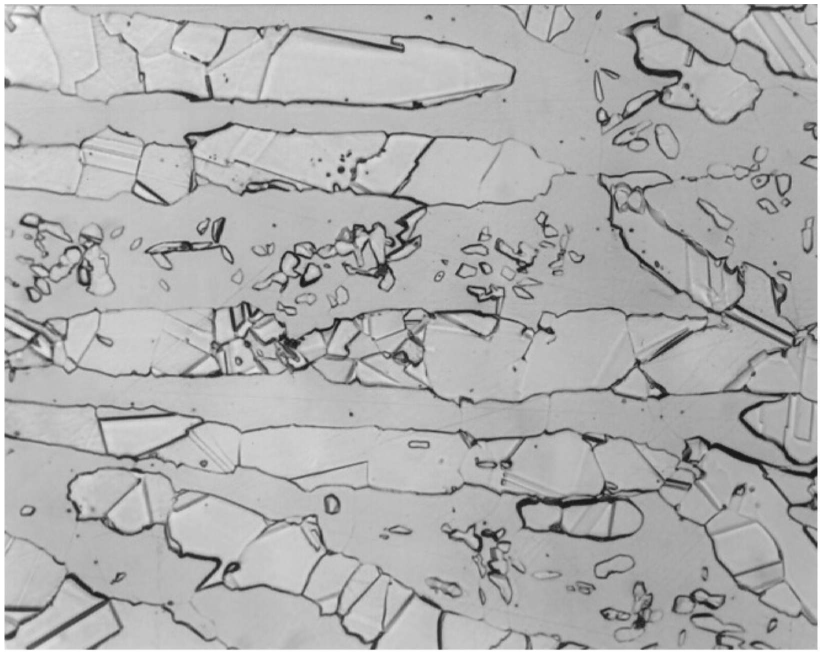


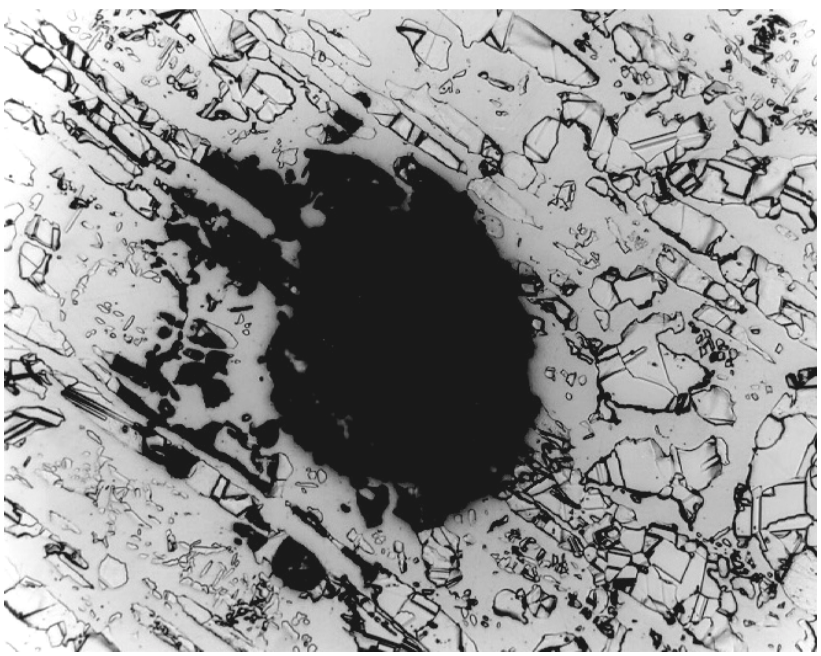
(a)



(b)

Figure 3. Microstructure of ASTM A890-4A Heat 1 in the SA condition, (a) Base Metal, 400X, (b) Pitting , 200X, Oxalic





(b)

Figure 4. Microstructure of wrought Alloy 2205, SA, (a) Base Metal, 400X, (b) Pitting , 200X, Oxalic

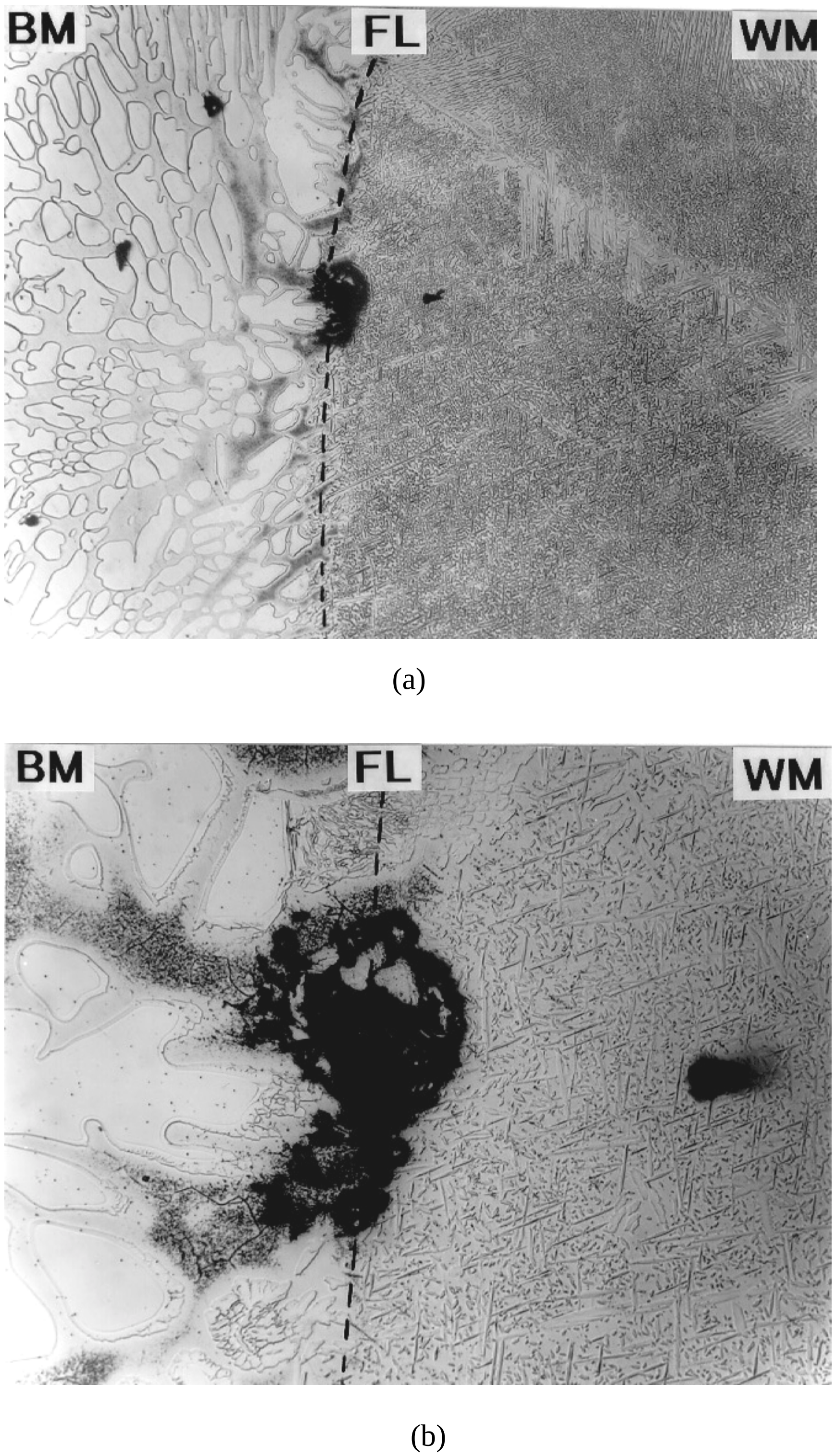
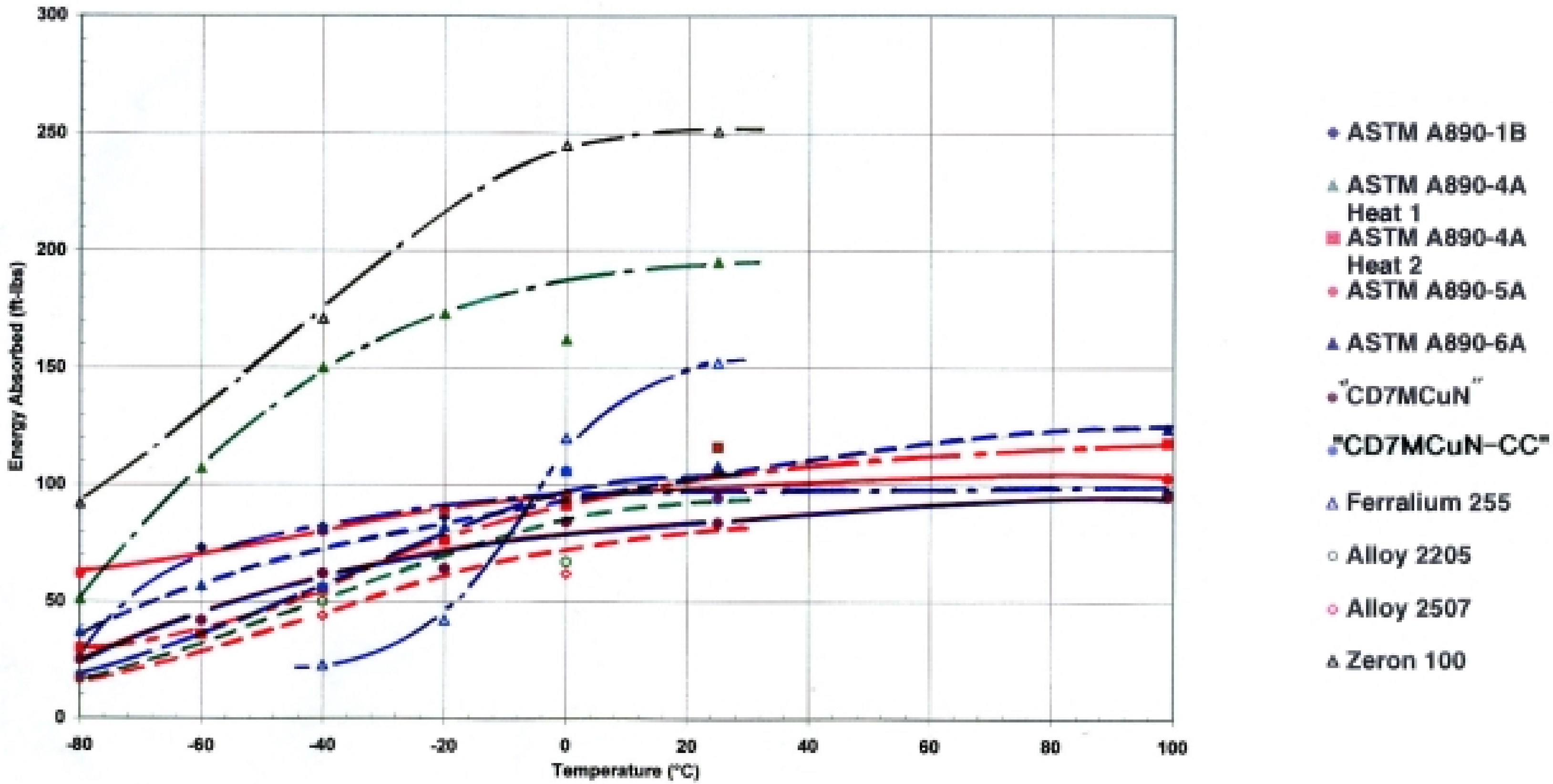


Figure 5. Pitting of autogenous weld on SA ASTM A890-4A Heat 1, (a) 50X (b) 200X, Oxalic



300
250
200
150
100
50
0
Energy Absorbed (ft-lbs)
-80
-60
-40
-20
0
20
40
60
80
100
Temperature (°C)
ASTM A890-1B
ASTM A890-4A Heat 1
ASTM A890-4A Heat 2
ASTM A890-5A
ASTM A890-6A
"CD7MCuN"
"CD7MCuN-CC"
Ferralium 255
Alloy 2205
Alloy 2507
Zeron 100

Figure 6. Toughness of solution annealed duplex stainless steel castings and companion wrought alloys

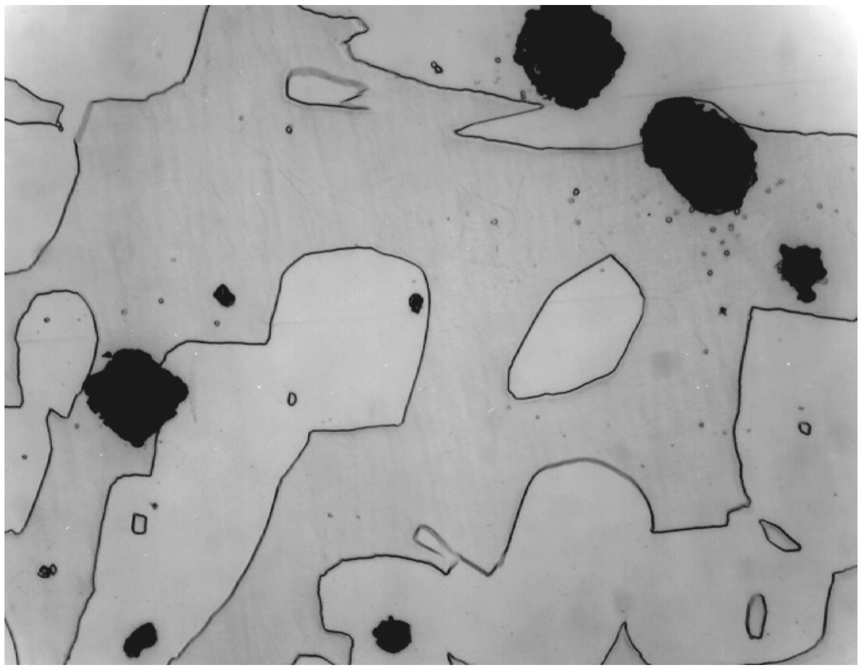


Figure 7. Microstructure of ASTM A890-4A Heat 2 SA, 400X, Oxalic