EFFECTS OF PROCESSING AND MICROSTRUCTURE ON THE MECHANICAL PROPERTIES OF BORON-CONTAINING AUSTENITIC STAINLESS STEELS

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ABSTRACT

Recent process innovations have led to the development of a new family of boron-containing austenitic stainless steels intended for nuclear applications. The new grade, designated NeutroSorb PLUS®[*], offers significantly improved impact strength and tensile ductility compared with conventionally manufactured steels of similar chemical composition. Such benefits provide greater design flexibility for the user and extend the utility of these alloys to structural members and other components for which conventional borated stainless steels have not been well suited because of toughness and ductility concerns as well as the lack of appropriate material standards. Furthermore, applicable chemical composition and mechanical property requirements for boron-containing stainless flat-rolled products now have been established through ASTM Standard A887-88.

INTRODUCTION

NeutroSorb™[**] steels represent a conventionally manufactured grade of Modified Type 304 with Boron alloy typically containing about (w/o) .04C, 1.5Mn, .5Si, 18.5Cr, 13.5Ni and up to 2.0B. Boron-containing stainless steels, such as NeutroSorb, have been utilized by the nuclear power industry for the storage, transportation and control of radioactive materials for about thirty years. The suitability of this type of alloy is attributed to a high thermal neutron absorption capability provided by boron, specifically because of the ^{10}B isotope, in addition to good corrosion resistance. Boron may be present in the steel as natural boron which contains about 18 w/o ^{10}B isotope (balance ^{11}B isotope), natural boron with an enrichment of the ^{10}B isotope or all ^{10}B. Applications have included spent-fuel storage racks, baskets for spent-fuel storage and transportation casks, reactor control rods, burnable poison and neutron shielding plates. However, these steels have not been widely employed as structural or load-bearing components because of toughness and ductility limitations associated with the boron addition, particularly when boron levels exceed about 1 w/o, as well as a lack of governing material specifications.

With increasing concern over nuclear waste disposal, there has been growing interest for a product which provides a more desirable combination of toughness, strength, corrosion resistance and neutron absorption for use as a structural material. In an effort to satisfy this need, an investigation was conducted to evaluate the effects of processing, boron content and microstructure on the mechanical properties of Modified Type 304 with Boron stainless steels. Results show that enhanced mechanical properties, exemplified by NeutroSorb PLUS steels, can be achieved by careful control of boride size, shape and distribution throughout the microstructure.

PROCEDURE

Two series of Modified Type 304 with Boron heats, one designated for conventional ingot casting and the other for processing via powder metallurgy (P/M) techniques, were prepared with nominal natural boron contents of 1/2, 3/4, 1, 1-1/4, 1-1/2, 1-3/4 and 2 w/o. An additional ingot-cast heat was melted to the same base analysis, but with residual boron content to serve as a reference Registered Trademark of Carpenter Technology Corporation Trademark of Carpenter Technology Corporation material. Conventional, or NeutroSorb, heats were vacuum-induction melted and cast as 45.5 kg (100 lb.), 114 mm (4.5")-square ingots. The P/M, or NeutroSorb PLUS, series was made from inert-gas atomized alloy powders subsequently consolidated to full density by hot isostatic pressing. Cylindrical P/M compacts weighed 36.5 kg (80 lbs.) and measured 140 mm (5-1/2")-diameter prior to hot working.

Ingots and compacts were forged to 102 mm x 38 mm (4" x 1-1/2") billets then hot-rolled to 114 mm x 16 mm (4-1/2" x 5/8") flat bars from furnace temperatures of 1163C (2125F). All bars were subsequently annealed at 1066C (1950F) followed by water quenching. Heat analyses corresponding to the NeutroSorb and NeutroSorb PLUS products at each boron level are provided in Table I.

The mechanical behavior of annealed products was compared via Rockwell hardness, smooth tensile properties at 22 and 350C (72 and 662F), Charpy V-notch impact strength at -29, 22 and 350C (-20, 72 and 662F) and bend-bar fracture toughness. Transverse tensile, impact and bend-bar samples were prepared with the intention of presenting a "worst-case" or least favorable specimen orientation relative to mechanical properties. Tests at -29 and 350C (-20 and 662F) were included to reflect the range of expected service temperatures. Microstructural characteristics were documented using light metallographic and image analysis techniques. X-ray diffraction and quantitative microprobe

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TABLE I
Modified Type 304 Stainless With Boron Heat Analyses.

Alloy	Element (w/o)								
	C	Mn	Si	P	S	Cr	Ni	B	Fe
NeutroSorb™	.018	1.68	.52	<.015	.002	18.39	12.76	<.01	Bal.
"	.017	1.60	.53	<.015	.002	18.07	12.83	.48	Bal.
"	.018	1.60	.53	<.015	.002	17.95	12.84	.74	Bal.
"	.040	1.64	.55	<.015	.004	18.38	13.61	1.03	Bal.
"	.034	1.70	.52	<.015	.002	18.46	13.46	1.28	Bal.
"	.034	1.70	.54	<.015	.002	18.53	13.46	1.54	Bal.
"	.035	1.70	.52	<.015	.002	18.48	13.32	1.73	Bal.
"	.034	1.71	.52	<.015	.002	18.58	13.28	1.98	Bal.
NeutroSorb PLUS®	.019	1.51	.55	<.015	.002	18.67	13.59	.45	Bal.
"	.020	1.69	.53	<.015	.002	18.54	13.58	.72	Bal.
"	.032	1.76	.55	<.015	.002	18.60	13.52	.97	Bal.
"	.040	1.78	.58	<.015	.002	18.43	13.63	1.20	Bal.
"	.040	1.80	.56	<.015	.002	18.54	13.73	1.48	Bal.
"	.044	1.80	.58	<.015	.002	18.51	13.70	1.75	Bal.
"	.065	1.80	.55	<.015	.002	18.59	13.57	2.03	Bal.

TABLE II
Room-Temperature Hardness and Transverse Tensile Properties of Modified Type 304 Stainless with Boron [(a,b)]

Alloy Type	Boron Content (w/o)	0.2% Yield Strength		Ultimate Tensile		% Elong. (in 4D)	% Reduction of Area	Hardness[(c)] (HRB)
		MPa	ksi	MPa	ksi			
NeutroSorb	<0.01	195	28.3	519	75.3	71.6	81.7	65.5
"	0.48	241	35.0	603	87.5	40.4	51.9	82.0
"	0.74	270	39.1	621	90.0	32.9	41.0	83.5
"	1.03	284	41.2	643	93.2	24.3	32.6	87.5
"	1.28	292	42.4	649	94.2	21.4	20.6	90.5
"	1.54	312	45.2	641	92.9	17.2	16.7	92.0
"	1.73	323	46.8	645	93.5	13.1	15.4	94.5
"	1.98	345	50.1	660	95.7	11.9	15.2	95.5
NeutroSorb PLUS	0.45	239	34.7	621	90.1	43.9	64.3	83.0
"	0.72	261	37.9	646	93.7	39.1	59.7	84.5
"	0.97	279	40.5	679	98.5	36.3	56.3	86.0
"	1.20	290	42.0	710	103.0	31.7	51.8	90.5
"	1.48	328	47.6	738	107.1	28.3	45.1	92.5
"	1.75	333	48.3	760	110.2	23.7	36.5	94.5
"	2.03	354	51.3	799	115.9	21.1	31.2	96.5

a. Hot-rolled/annealed 16mm (5/8") thick flat bars, b. average values of four 6.4mm (.252") dia. gage tensile specimens tested per alloy.

analyses also were conducted on some samples to identify boride structure and composition.

RESULTS

Mechanical Properties

Room-temperature hardness and transverse tensile properties of NeutroSorb and NeutroSorb PLUS stainless steels are listed in Table II. Tensile results are illustrated in Figs. 1 and 2. Both grades show increasing yield and ultimate tensile strengths and decreasing elongation and reduction of area with increasing boron content. NeutroSorb PLUS steels provide similar yield strength and slightly higher ultimate tensile strength compared with their NeutroSorb counterparts. More importantly, NeutroSorb PLUS products display significantly improved tensile ductility versus conventionally processed steels at comparable boron levels. Though hardness increased with boron content, no notable hardness differences were observed between the two grades.

At 350C (662F), both borated stainless grades experience some decrease in all tensile properties compared with room-temperature values as indicated in TableIII. However, results exhibit the same trends as those observed for room-temperature tests. Effects of temperature and boron content on the tensile properties of NeutroSorb PLUS stainless steels are demonstrated in Figs. 3 and 4.

Increasing boron content has a deleterious effect on the impact strength of these materials. However, substantially higher impact toughness is maintained with NeutroSorb PLUS steels compared with the conventional borated-stainless products at each level of boron. For example, at 2 w/o natural boron, NeutroSorb PLUS stainless exhibited a room-temperature impact energy of 22-23J (16-17 ft-lbs) compared with 5-7J (4-5 ft-lbs) for NeutroSorb stainless. Furthermore, because of a stable austenitic matrix existing in these steels, impact properties are affected minimally by temperatures within the range of 350 to -29C (662 to -20F). Effects of temperature on the impact energy of NeutroSorb PLUS alloys are illustrated in Fig. 6.

One should also recognize that further enhancement of the impact toughness and tensile ductility benefits of NeutroSorb PLUS steels can be achieved at an equivalent neutron absorption capability by substitution of some or all of the natural boron addition with 10B-enriched boron. Thus, the total boron content of a given composition can be reduced by as much as 80% by alloying with 10B isotope rather than natural boron.

Results of fracture toughness tests conducted on 25.4 mm x 12.7 mm (1.00" x 0.50") bend bar specimens according to ASTM E399 (1) will not be discussed in detail. Because of the alloys' tendency to exhibit rapid crack-tip blunting within the austenitic matrix, plane strain conditions could not be met regardless of boron content or processing method. Consequently, valid critical stress intensity values (KIc) could not be obtained. Apparently, Modified Type 304 with Boron steels lack sufficient brittleness to be evaluated under the conditions of ASTM E399. Based upon the fracture behavior observed in these tests, the J integral approach, as described in ASTM E813 (2), should be considered for evaluation of fracture toughness in Modified Type 304 with Boron products. JIc may be used as an estimate of KIc and is more applicable to materials that tend to fracture by ductile tearing.

Microstructural Aspects

Mechanical property improvements afforded by NeutroSorb PLUS steels are attributed to microstructure. Representative micrographs of NeutroSorb and NeutroSorb PLUS products at three boron levels are compared in Fig. 7.

Borides present in the NeutroSorb PLUS products are much finer, less elongated and more uniformly distributed than in the conventionally manufactured NeutroSorb bars. These microstructural differences have been quantitatively assessed through image analysis as described in Table V.

Though many microstructural features can be discussed, the effects of boron content on boride length, cross-sectional area and boride areal density are considered to be the most distinguishing characteristics of NeutroSorb PLUS versus conventionally manufactured products. As shown in Fig. 8, average boride length and cross-sectional area increased with boron content. However, the degree of boride growth is significantly less for NeutroSorb PLUS than for NeutroSorb steels. With increasing boron content, borides formed in NeutroSorb PLUS steels tend to remain spherical while those present in NeutroSorb products exhibit substantial flattening and elongation especially at boron levels in excess of about 1-1/2 w/o.

Boride areal density (i.e. number of borides per unit area) results provided in Fig. 9 further demonstrate processing effects. For both grades, boride areal densities rose with boron content to a maximum level at about 1-1/2 w/o boron, then began to decline as boron content increased to 2 w/o. This inflection is indicative of boride agglomeration occurring at high boron levels which acts to reduce the number of discrete boride particles in a given area.

Boride areal density values for the NeutroSorb PLUS steels are well above those of corresponding NeutroSorb compositions. These curves also reveal a significantly greater resistance of the NeutroSorb PLUS alloys to boride agglomeration as indicated by the absence of a sharp decrease in boride areal density beyond 1-1/2 w/o boron.

Boride precipitates in these Modified Type 304 with Boron steels were identified via electrolytic extraction and x-ray diffraction analysis techniques as Cr2B -type. Other studies (3,4) have shown the Cr2B compound to have an orthorhombic crystal structure, though no effort was made in the current work to confirm this finding. Also, in-situ quantitative microprobe analysis was used to determine the chemical composition of borides in the present steels. Using this approach, analysis was limited to NeutroSorb samples having boride particle dimensions in excess of 3 m so that electron beam size restrictions could be satisfied. Borides were found to contain approximately (w/o) 46 Cr, 40 Fe, 3.5 Mn, 1.0 Ni and 9.5 B; in terms of atomic fractions, the boride formula can be expressed as (Cr.53Fe.42Mn.04Ni.01)2B. Though the Cr/Fe atomic ratio in the boride may vary

TABLE III
Transverse Tensile Properties of Modified Type 304 Stainless With Boron at 350C (662F)[a,b]

Alloy Type	Boron Content (w/o)	0.2% Yield Strength		Ultimate Tensile		% Elong. (in 4D)	% Reduction of Area
		MPa	ksi	MPa	ksi		
NeutroSorb	<0.01	152	22.0	390	56.5	40.4	76.4
"	0.48	207	30.0	466	67.6	27.8	49.2
"	0.74	239	34.6	491	71.2	21.6	40.1
"	1.03	251	36.4	543	78.7	19.4	26.3
"	1.28	263	38.1	540	78.3	16.1	24.0
"	1.54	266	38.6	558	80.9	14.2	22.7
"	1.73	281	40.8	555	80.5	12.1	18.6
"	1.98	321	46.5	574	83.2	11.2	15.8
NeutroSorb PLUS	0.45	221	32.1	469	68.0	29.3	59.9
"	0.72	242	35.1	485	70.4	27.4	55.4
"	0.97	261	37.9	536	77.8	25.7	51.3
"	1.20	285	41.3	576	83.6	24.1	43.9
"	1.48	316	45.9	609	88.3	21.5	42.2
"	1.75	344	49.9	627	90.9	17.8	31.3
"	2.03	319	46.3	697	101.1	15.2	21.8

a. Hot-rolled/annealed 16mm (5/8") thick flat bars, (b) Average values of four 6.4mm (.252") dia. gage tensile specimens tested per alloy.

TABLE IV
Tranverse Charpy V-Notch Impact Energy of Modified Type 304 Stainless with Boron[a]

Alloy Type	Boron Content (w/o)	Test Temperature °C (°F)					
		22	(72)[b]	350	(662)[c]	-29	(-20)[c]
		J	ft-lbs	J	ft-lbs	J	ft-lbs
NeutroSorb	<0.01	>325	>240	260	192	290	214
"	0.48	62	46	66	49	56	41
"	0.74	31	23	37	27	35	26
"	1.03	22	16	22	16	22	16
"	1.28	15	11	19	14	16	12
"	1.54	11	8	14	10	11	8
"	1.73	8	6	12	9	8	6
"	1.98	7	5	8	6	7	5
NeutroSorb PLUS	0.45	95	70	98	72	87	64
"	0.72	73	54	76	56	71	52
"	0.97	60	44	61	45	58	43
"	1.20	49	36	52	38	47	35
"	1.48	39	29	41	30	41	30
"	1.75	30	22	34	25	33	24
"	2.03	22	16	24	18	23	17

a. Standard Charpy V-notch impact specimens (T-L orientation) were prepared from the center of hot-rolled/annealed 16mm (5/8") thick flat bars, b.Average value of four specimens, c. Average value of three specimens.

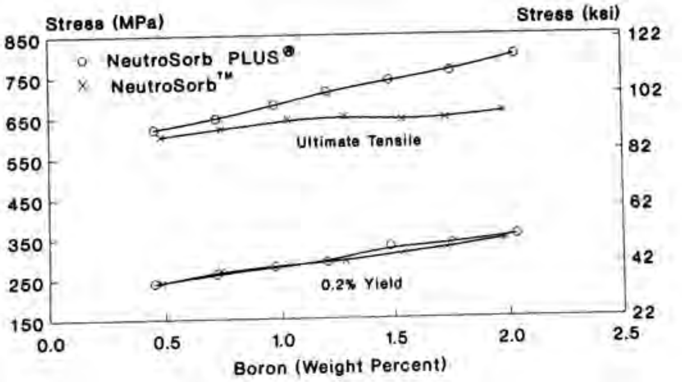


Fig. 1. Effect of Boron Content on Room-Temperature Transverse Yield and Tensile Strengths of Modified Type 304 Stainless.

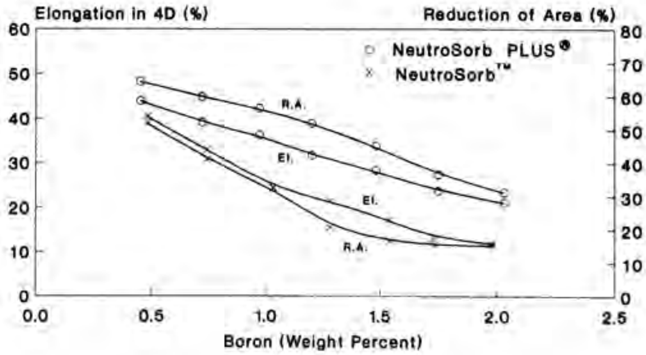


Fig. 2. Effect of Boron Content on Room-Temperature Transverse Tensile Ductility of Modified Type 304 Stainless.

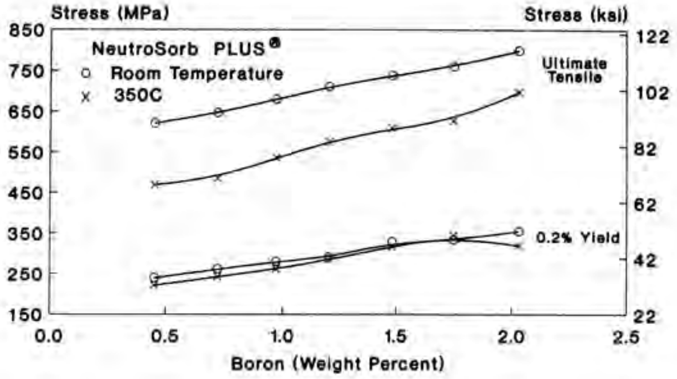


Fig. 3. Effects of Boron Content and Temperature on Transverse Yield nd Tensile Strengths of Neutro-Sorb PLUS Stainless.

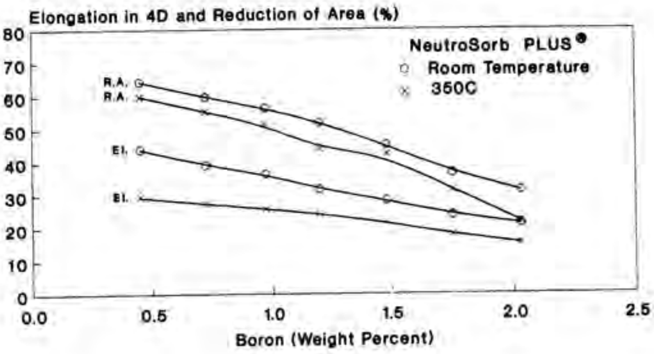


Fig. 4. Effects of Boron Content and Temperature on Transverse Tensile Ductility of Neutrosorb PLUS Stainless.

TABLE V
Boride Morphology [(a,b)]

Alloy Type	Boron Content (w/o)	Volume Percent Boride	No. Borides per mm^2	Avg. Boride Length (μm)	Avg. Boride Area (μm^2)	Mean Spacing (μm)	Mean Free Path (μm)
NeutroSorb	0.48	3.06	16,645	1.96	1.84	30.94	30.00
"	0.74	4.90	16,540	2.65	2.96	23.01	21.88
"	1.03	7.08	18,617	3.10	3.80	17.52	16.28
"	1.28	9.89	25,384	3.06	3.90	13.02	11.73
"	1.54	12.15	27,691	3.27	4.39	11.53	10.13
"	1.73	17.44	23,570	4.95	7.40	9.01	7.44
"	1.98	28.96	16,481	7.63	17.57	8.07	5.73
NeutroSorb PLUS	0.45	2.98	28,493	1.05	1.05	33.51	32.51
"	0.72	7.09	39,794	1.43	1.78	17.65	16.39
"	0.97	9.94	44,730	1.62	2.22	13.78	12.41
"	1.20	12.51	48,209	1.78	2.60	11.65	10.19
"	1.48	15.98	51,564	1.99	3.10	9.77	8.21
"	1.75	20.42	50,799	2.33	4.02	8.45	6.72
"	2.03	23.60	50,034	2.60	4.72	7.70	5.88

a.Hot-rolled/annealed 16mm (5/8")thick flat bars, b) Values were determined through image analysis of transverse metallographic specimens across 100 fields.

somewhat depending upon the conditions of particle formation, results clearly indicate that a substantial amount of the chromium will be substituted by other metals.

Based upon the formation of an M2B phase containing about 46 w/o chromium and the quite low solubility of boron in Fe-Cr-Ni alloys, matrix chromium contents can be estimated for various boron additions. Such calculations, though not detailed here, can be helpful in understanding effects of boron content on corrosion resistance and matrix phase stability of Modified Type 304 with Boron steels.

Fabrication and Corrosion Resistance

NeutroSorb and NeutroSorb PLUS alloys can be welded employing a variety of techniques including, GTA, SMA and spot welding processes. Selection of E/ER308 or 308-L welding consumables should be considered; however, regardless of the process, heat inputs should be minimized to limit base metal dilution and extension of the weld heat-affected zone.

Annealed 16mm (5/8") thick flat bar stock from the 1.20 w/oB NeutroSorb PLUS heat (Table I) was processed to 3.4mm (.135") thick annealed strip to evaluate the effects of welding on mechanical properties. Tensile and Charpy V-notch impact data, respectively, for annealed and GTA-welded strip material are compared in Tables VI and VII.

Though strength was not adversely influenced by welding, tensile elongation was reduced slightly. Impact results of as-welded NeutroSorb PLUS steel decreased to values comparable to those observed for annealed NeutroSorb material at a similar boron level (Table IV). This impact behavior is attributed to the dissolution of initially fine borides in the NeutroSorb PLUS steel upon welding and the resultant formation of a dendritic/boride eutectic network in the weld. The heat-affected zone develops the boride eutectic phase in addition to undergoing agglomeration of boride precipitates. When practical, a 1065C (1950F) post-weld annealing treatment is suggested to restore much of this toughness and ductility loss as demonstrated by bend test results described in Table VIII. In weldments of thicker section size, e.g. 12.7 mm (1/2"), greater weld metal impact strength can be expected because of minimal boron dilution into a relatively large austenitic weld deposit. In this situation, heat-affected zone properties are the limiting factor.

Deleterious effects of increasing boron content on the corrosion resistance of Modified Type 304 with Boron steels can be shown through laboratory tests such as ASTM A262-C (boiling 65 w/o HNO3)(5). In this severe laboratory medium, general corrosion resistance of solution-annealed (non-sensitized) steel is influenced by matrix chromium-depletion occurring as a result of boride formation. However, typical service conditions, such as mild boric acid solutions of spent fuel storage pools, are much less aggressive and rarely present corrosion problems, even for steels containing up to 2 w/o boron. Precautions which may be taken to prevent corrosive attack include a) maintaining as-low-as-possible chloride levels in storage pool waters and b) employing a 20 v/o HNO3 *passivation* treatment on borated stainless parts when practical to remove potential pit initiation sites. Alloy composition modifications, such as increased chromium contents or molybdenum additions, are possible alternatives for improving corrosion

TABLE VI
Effects of Welding on Strip Tensile Properties of Neutrosorb PLUS (1.20 w/oB) Stainless [(a)]

Condition(b)	Test Temp. °C (°F)	0.2% Yield Strength MPa	0.2% Yield Strength ksi	Ultimate Tensile MPa	Ultimate Tensile ksi	% Elong. in 50.8mm(2.0")
Cold-rolled/annealed	22 (72)	321	46.6	725	105.1	36.1
As-GTA welded	22 (72)	330	47.8	723	104.8	28.4
Cold-rolled/annealed	350 (662)	240	34.8	596	86.4	25.8
As-GTA welded	350 (662)	290	42.1	591	85.7	21.5

a. Average values of duplicate specimens per condition. b. Cold-rolled/annealed 3.4mm (.135") thick strip GTA welded with AWS ER308-L filler wire.

Table VII
Effects of Welding on Charpy V-Notch Impact Energy of Neutrosorb PLUS (1.20 w/oB) Stainless

	Impact Energy at Temperature(a)			
	22C(72F)(b)		350C(662F)(c)	
Condition	J	ft-lbs	J	ft-lbs
Cold-rolled/annealed	49	36	46	34
As-GTA welded	16	12	19	14

a. Cold-rolled/annealed 3.4 mm (.135") thick strip was GTA welded with AWS ER308-L filler wire. Full-size transverse specimens were prepared by laminating three strip layers, fastening them together with set screws and machining the laminated specimen to final dimensions. The notch was located through the weld centerline. b. Average value of four specimens. c. Average value of three specimens.

TABLE VIII
Effects of Welding on Transverse Bend Ductility of Neutrosorb PLUS (1.20 w/oB) Stainless (a,b)

Condition	Bend Radius (c)	Results (d)
Cold-rolled/annealed	3T or 9.5mm (3/8") 1-1/2T or 4.8mm (3/16")	148°, 148° - No cracks 165°, 166° - No cracks
As-GTA welded	3T or 9.5mm (3/8")	60° - Fusion-line break 62° - Weld break
GTA welded/annealed 1065C(1950F), 10 min., AC	3T or 9.5mm (3/8") 1-1/2T or 4.8mm (3/16")	155°,160° - No cracks 58°,72° - Fusion-line breaks

a. Cold-rolled/annealed 3.4mm (.135") thick strip was GTA welded with ER308-L filler wire. Transverse specimens were ground to 3.2mm (.125")thickness prior to bend testing. b. Duplicate specimens tested per condition. c. T = 3.2mm (1/8") = sample thickness. d. Specimens exhibiting no cracks were actually bent through 180°; angles shown are permanent bend angles.

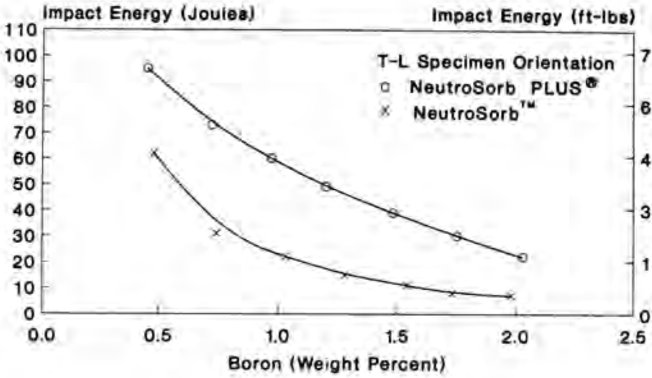


Fig. 5. Effect of Boron Content on Room-Temperature Transverse Charpy V-notch Impact Energy of Modified Type 304 Stainless.

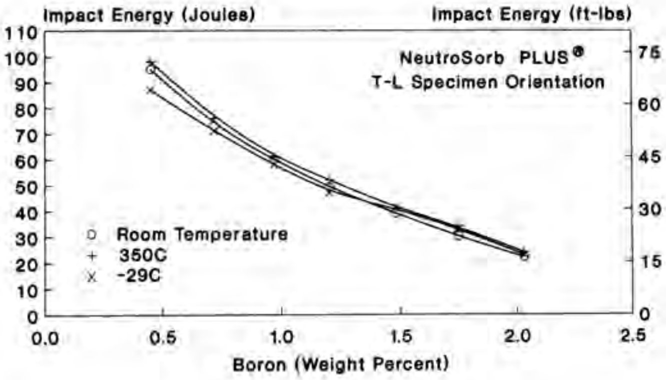
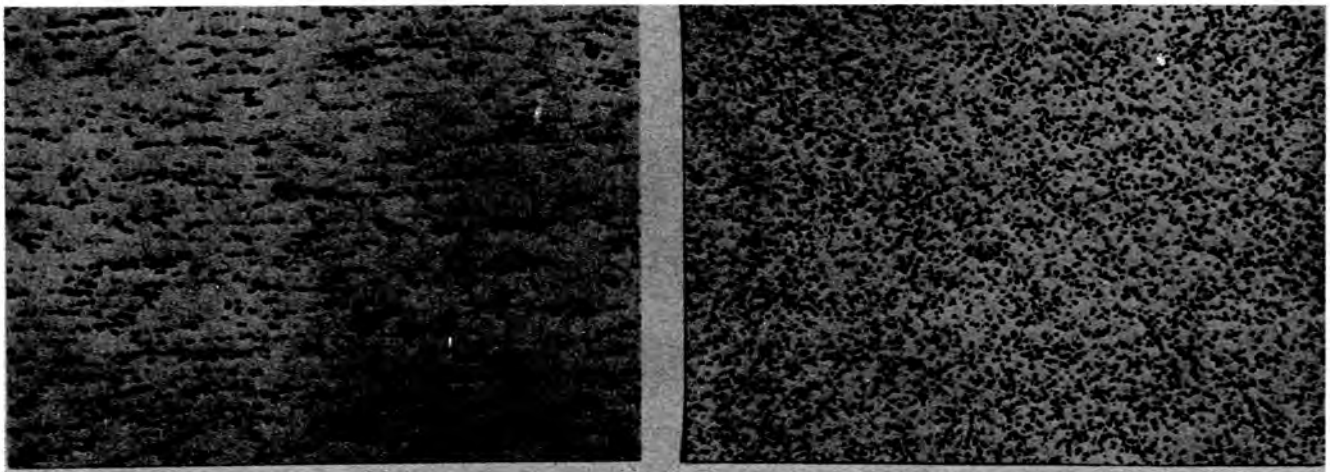
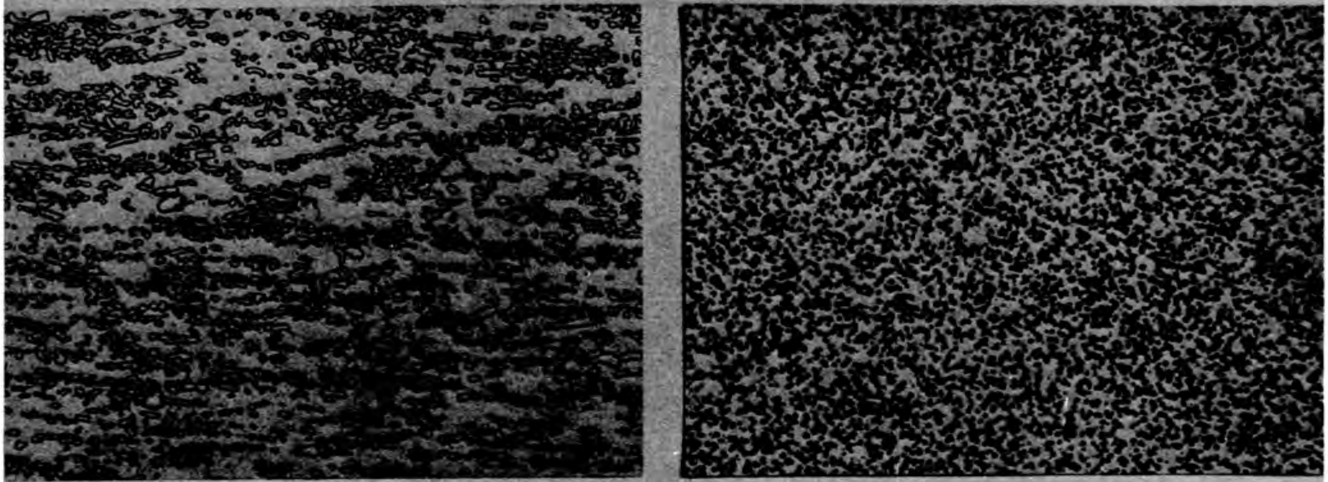


Fig. 6. Effects of Boron Content and Temperature on Transverse Charpy V-notch Impact Energy of NeutroSorb PLUS Stainless.



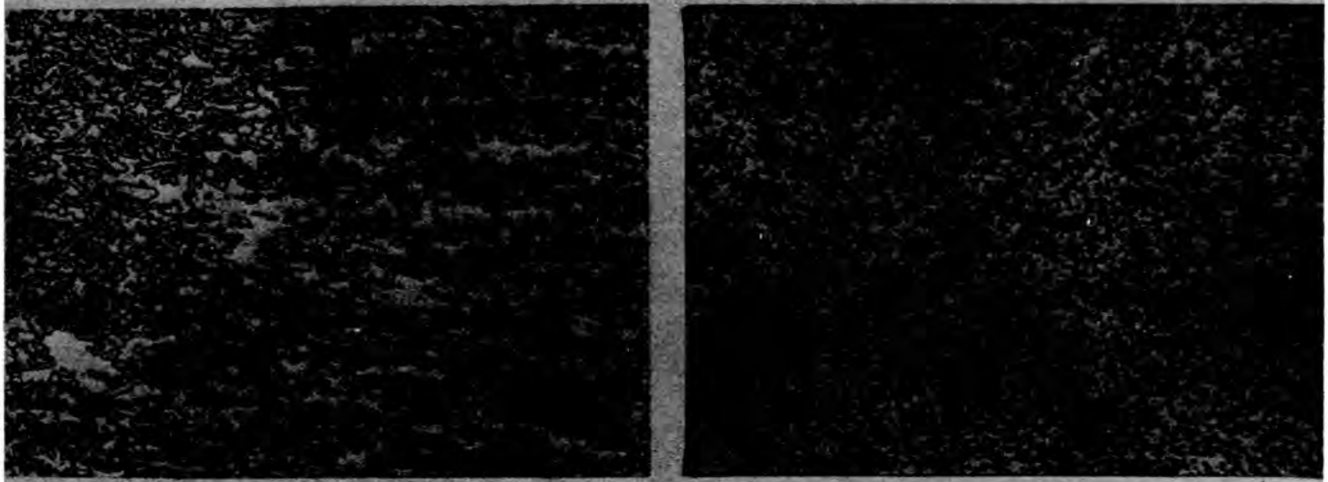
a) NeutroSorb (0.48 w/o B)

b) NeutroSorb PLUS (0.45 w/o B)



c) NeutroSorb (1.03 w/o B)

d) NeutroSorb PLUS (0.97 w/o B)



e) NeutroSorb (1.98 w/o B)

f) NeutroSorb PLUS (2.03 w/o B)

Fig. 7. Comparative Micrographs of Borated Stainless Products. Cross-Sections of Annealed 16mm (5/8") Thick Flat Bars. 200x Mag.-Kallings' Etchant

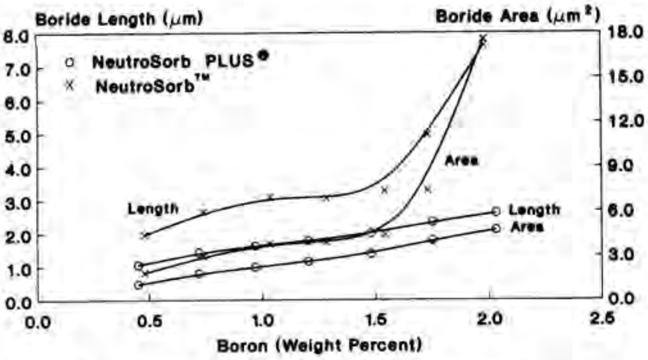


Fig. 8 Effect of Boron Content on Average Boride Length and Cross-Sectional Area.

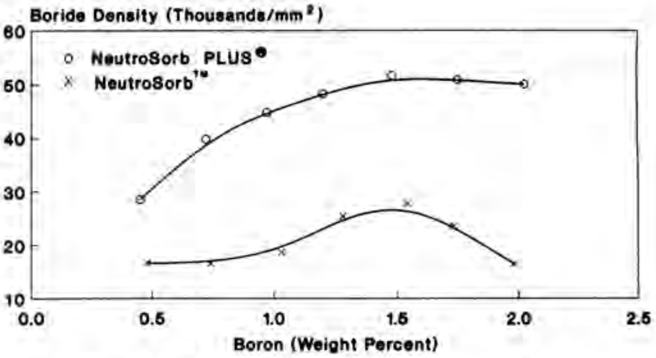


Fig. 9. Effect of Boron Content on Boride Areal Density.

performance but have not been addressed relative to current product specifications.

ASTM COVERAGE

Data generated in this work have been utilized to support a new ASTM standard, designated A887 (6) covering borated stainless steel plate, sheet and strip products for nuclear applications. The specification defines composition limits and mechanical property requirements for two grades of steel at eight boron levels ranging from 0.2 to 2.25 w/o. Grade A, exemplified by NeutroSorb PLUS stainless steel, represents products that provide superior ductility and impact strength. Grade B, exemplified by NeutroSorb stainless steel, represents products manufactured by conventional means and offers a lower level of mechanical properties for less stringent design requirements.

CONCLUSIONS

1. For both the NeutroSorb and NeutroSorb PLUS grades, hardness, yield strength and ultimate tensile strength increased with increasing boron content up to 2 w/o. Tensile ductility and impact strength decreased with increasing boron content.

2) Compared with NeutroSorb steels at similar boron levels, NeutroSorb PLUS products showed significantly greater impact strength and tensile ductility, slightly higher ultimate tensile strength and generally equivalent yield strength and hardness.

3) Compared with room-temperature results, test temperatures of 350 and -29C (662 and -20F) had little effect on the Charpy V-notch impact strength of NeutroSorb and NeutroSorb PLUS steels.

4) Mechanical property improvements provided by NeutroSorb PLUS steels are derived from a microstructure which exhibits finer, less elongated and more uniformly distributed borides than in a conventionally-manufactured product at the same boron level.

5) Data generated in this work have been utilized to establish a new ASTM standard, designated A887, covering borated stainless steel plate, sheet and strip products for nuclear applications.

6) Borides formed in Modified Type 304 with Boron steels were identified as Cr_2B-type containing approximately (w/o) 46Cr, 40Fe, 3.5Mn, 1.0Ni and 9.5B.

7) Modified Type 304 with Boron steels can be cold-formed and weld fabricated by conventional means, though, some additional care may be necessary for materials having boron contents approaching 2 w/o. When practical, a post-weld annealing treatment is suggested to provide optimum bend ductility and impact toughness.

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