BORATED STAINLESS STEELS (ASTM A887-88) A COMPARISON OF GRADE A - NEUTROSORB PLUS AND GRADE B - NEUTROSORB™

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ABSTRACT

Borated stainless steels have been used for neutron attenuation for over 30 years. Recent advances in the metallurgy and manufacture of them have led to the development of an advanced class of borated stainless steels.

This comparison of the advanced Grade A and the classical Grade B, ASTM A887-88, borated stainless steels is based on experience gained by Carpenter Technology Corporation in over thirty years of producing borated stainless steels. The superiority of the advanced GRADE A - NEUTROSORB PLUS stainless steel is clearly demonstrated through discussions on manufacturing and fabricating experiences, mechanical and physical properties, weldability, boride morphology, neutron attenuation and safety considerations.

Advantages offered by the Grade A materials include:

- Improved hot and cold workability - enable the manufacturer and fabricator to utilize fabricating techniques that are much closer to those of conventional austenitic stainless steels, than can be done with the Grade B materials.
- Improved impact resistance and ductility allows the designer to consider one material for both structural and neutron attenuation functions.
- Improved weld zone integrity.
- Improved neutron attenuation characteristics.

These advantages of the Grade A materials should not be ignored when addressing neutron shielding in handling, transportation and storage equipment for spent nuclear fuel. They better enable the designers and fabricators to optimize in fabricability, serviceability and safety.

INTRODUCTION

Borated stainless steels have been used to control neutron flux in reactors, transportation casks and spent fuel pool storage racks for over thirty years. These materials have been characterized as having ductility and impact resistance below what is generally considered acceptable for structural materials. Thus, they have historically been used for their neutron attenuation properties only.

A family of borated stainless steel that possesses both neutron attenuation properties as well as adequate ductility and impact resistance to be used as a structural material offers obvious advantage and is highly desirable.

Carpenter Technology Corp. has developed a family of borated stainless steels, with up to 2.25% B, which offer both neutron attenuation and improved mechanical properties. This family of alloys, NEUTROSORB PLUS, is covered by ASTM specification A887-88, Grade A. The conventional borated stainless steels, NEUTROSORB, are included in this specification as Grade B.

This comparison of the borated stainless steels, covered by ASTM specification A887-88, is based on experience gained in over thirty years of producing borated stainless steels. The superiority of the GRADE A is clearly demonstrated through the following discussions on; manufacturing experiences, mechanical and physical properties, weldability, boride morphology, neutron attenuation and safety considerations.

DEVELOPMENT AND MANUFACTURING

Carpenter Technology Corp. manufactured the equivalent of the Grade B material with boron less than 1.3% from the 1960's until the present. The inherently poor hot workability of boron containing stainless steels made it economically unfeasible to manufacture material less than 0.185" thick with boron contents above 1.3%. Thus, a development program that resulted in the improved Grade A - NEUTROSORB PLUS with significantly better hot and cold workability was undertaken.

The key to the improved hot workability of Grade A is to develop a microstructure consisting of an uniform dispersion of very fine borides. The boride morphology in Grade B is much coarser and less uniformly dispersed. The desired boride morphology is shown in Figs. 1 and 2 where it is compared to that of the Grade B materials for 1.0% and 2.0% boron, respectively. The fine uniform boride distribution also accounts for the improved room temperature

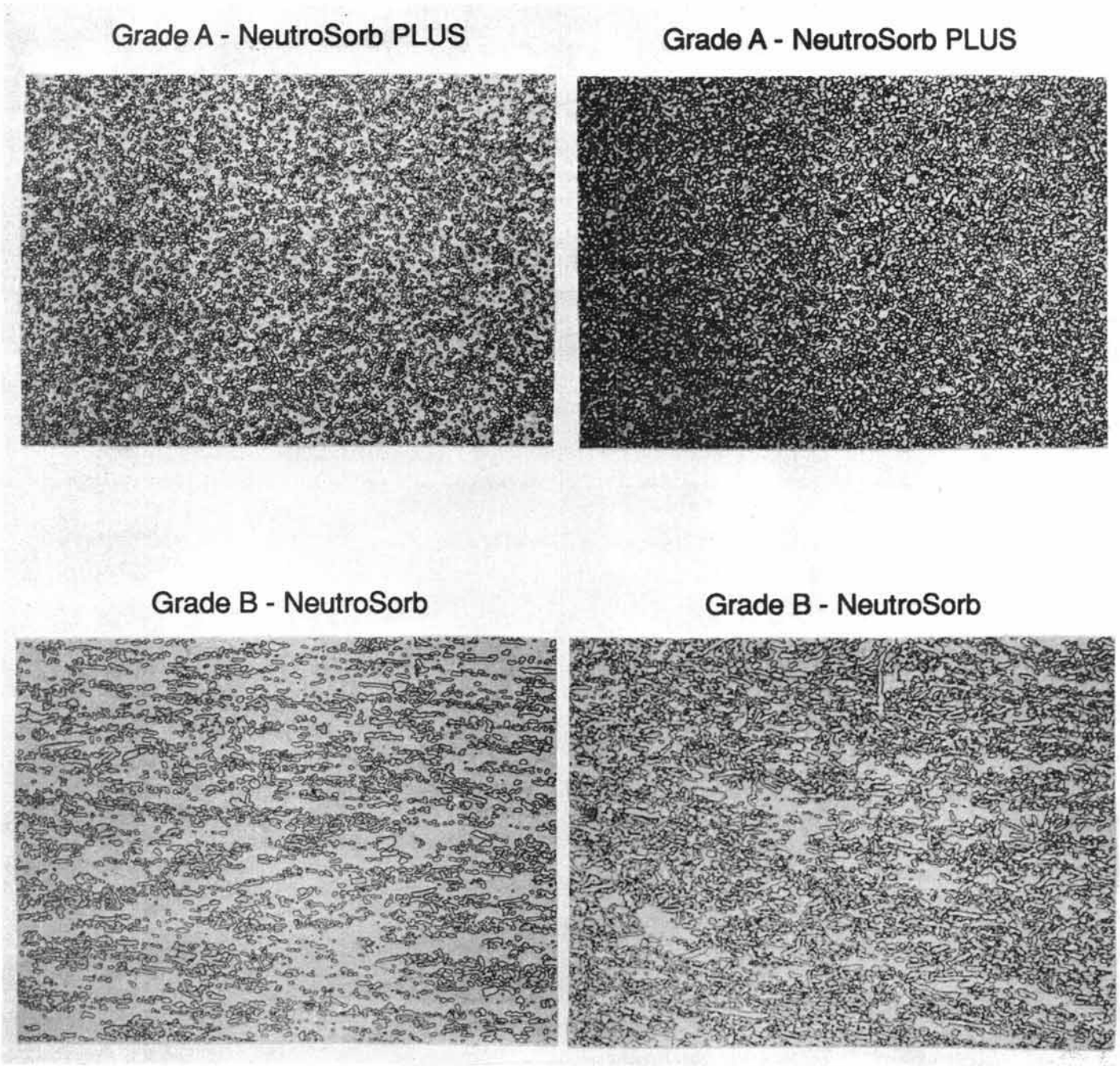

Fig. 1. Borated stainless steel ASTM A887-88, type 304B3 (1.0%B) 200x maginification, Kalling's Etchant.

Fig. 2. Borated stainless steel ASTM A887-88, type 304B7 (2.0%B) 200x magnification, Kallings Etchant.

ductility which allows the Grade A to be cold worked more severely than the Grade B at a given boron content.

Plate and plate coil, sheet, strip, bar and wire have been manufactured from the Grade A material. Material thickness as low as 0.05" are available. As are boron contents up to 2.2%, which may be present as natural boron, enriched B_{10} or a combination of both. Typically, Grade B materials are not available in thicknesses below 0.1" with boron contents above 1.0%. Boron contents up to 2.0% are available for thicker sections.

Carpenter has commercially produced more than 150 orders of borated stainless, including; coils of heading wire, individual plates weighing in excess of 3000 lbs. and sheet/plate coils weighing in excess of 8000 lbs. Extensive

quantities of borated stainless bar and plate have also been manufactured on production equipment for test and development programs.

Examples of the product produced to date are

Material	Thickness	Boron Content
Grade A	0.276" plate	2.2%
Grade A	0.125" sheet	1.8%
Grade A	0.183" round wire	1.7%
Grade A	0.195" plate coil	1.4%
Grade A	0.083" sheet	1.4%
Grade B	0.220" plate	1.4%
Grade B	0.125" strip	1.1%
Grade B	1.250" bar	1.0%
Grade B	0.120" bar	0.9% B_{10}

A general guide to Carpenter's size and boron content capabilities are shown in Table I. This is only a general guide and sizes/boron contents not shown are considered on a case by case basis.

MECHANICAL AND PHYSICAL PROPERTIES

The mechanical properties of the Grade A material also benefit from the uniformly dispersed fine borides as does the workability of the material. Table II, III and IV show a comparison of typical mechanical properties of the Grade A and Grade B materials at room temperature and 350°C. Figures 3-8 present these data in graphical form.

For example:

The data for the 304B6 (1.50/1.74% B) materials illustrate the increased ductility (elongation and reduction) and impact resistance for the Grade A material.

Comparing the impact resistance 22 ft-lb (Grade A) vs 6 ft-lb (Grade B) shows that the Grade A material may be used as a sound engineering, structural, material in many applications where it would not be possible with the Grade B.

These improved mechanical properties not only enable a designer to use one material for both the structural and neutron attenuation requirements, but also allow the designer to add another dimension of safety to the application.

FABRICATION

The fabricability of the Grade A alloys is superior to the Grade B in a number of areas, including cold forming, machining and welding.

The cold formability of the Grade A material is significantly enhanced by the increased ductility. Bend radii of 1.5T to 2T are achievable in Grade A sheet with a 2.2% boron content while a radius of greater than 5T is required for the Grade B product containing 1.0% boron.

While specific machinability data comparing the two grades is not available, several machine shops have expressed the opinion that the Grade A material's machinability is superior to that of the Grade B material. This improvement is primarily seen in the cutter life. It is believed that the fine, uniform boride dispersion in the Grade A material is less abrasive than the large chunky borides in the Grade B.

In general, the borated stainless steels are readily weldable using conventional stainless steel welding consumables, such as, AWS E/ER 308-L for thin sections or AWS E/ER 309-L for sections over 0.250". There is a reduction in the impact resistance of the weld heat affected zone in both the Grade A and Grade B materials when welded with or without a filler metal. The use of a filler metal, as mentioned above, will significantly reduce this degradation of the weld metal itself. Typically, the impact resistance of the weld heat affected zone in the Grade A material will approach that of the Grade B base metal, while that of the weld heat affected in the Grade B material will be reduced to below that of the Grade B base metal. The result being a weld area in Grade A material with poorer impact resistance than the base metal, but superior impact properties to those of a weld area in Grade B material.

NEUTRON ATTENUATION

It is theorized that the uniformly dispersed fine borides in the Grade A material will be more effective, at a given boron content, in attenuating the neutrons than will the coarser, less uniformly dispersed borides in the Grade B material. This is caused by a greater amount of the boron being directly exposed to the neutron flow with the fine boride size. Boride shadowing is also significantly reduced with the finer borides. Research is continuing to support this theory with significant data.

SPECIFICATION COVERAGE

The first specification devoted to borated stainless steels was issued approximately one year ago by the ASTM. This specification, ASTM A887-88, covers both Grade A and Grade B materials. Paragraph 10.1 covers an optional Charpy V-notch impact test. Table 3 lists the minimum acceptable values for this test. It should be noted that no

TABLE I

Borated Stainless Steel - ASTM A887-88 - Strip, Sheet and Plate Size Capabilities

TYPE	% BORON (NATURAL)	GRADE[1]	MINIMUM THICKNESS[2] (mm) WIDTH ≤ 245 mm	WIDTH ≤ 245 mm
304.B	0.2/0.29	A	1.3	1.3
		B	1.3	1.3
304.B1	0.3/0.49	A	1.3	1.3
		B	1.3	1.3
304.B2	0.5/0.74	A	1.3	1.3
		B	2.0	2.4
304.B3	0.75/0.99	A	1.3	1.3
		B	2.0	2.4
304.B4	1.0/1.24	A	1.5	1.5
		B	4.7	4.7
304.B5	1.25/1.49	A	1.8	1.8
		B	4.7	6.3
304.B6	1.5/1.74	A	3.2	3.2
		B	6.3	6.3
304.B7	1.75/2.25	A	3.2	3.2
		B	6.3	6.3

1. Carpenter NeutroSorb PLUS is Grade A.
   Carpenter NeutroSorb is Grade B.

2. Carpenter Technology Corp. is continually working to optimize our capabilities and products. The widths and thicknesses shown are subject to change as our capabilities are optimized.

values are shown for Grade B material with boron contents above 1.0% because the impact energy is considered lower than is commonly accepted for engineering materials.

Currently, work is underway to have the Grade A borated stainless steels included in the ASME Boiler and Presser Vessel Code. It is anticipated that this will be accomplished within the next 6 mos.

SUMMARY OF BENEFITS OF ASTM A887-88, GRADE A MATERIALS

The ASTM A887-88, Grade A materials offer a series of design, manufacturing and SAFETY related advantages over the Grade B materials that should not be ignored. These advantages include:

- Improved hot and cold workability - enable product to be manufactured and equipment to be fabricated that could not be produced reliably with the Grade B materials.
- Improved ductility - enables the fabricator to bend the materials on radii that are more nearly similar to non-borated stainless steels.
- Improved impact resistance - allows the designer to consider one material for both structural and neutron attenuation functions.
- Improved fabricability - allows the equipment manufacturer to reduce fabrication costs.
- Improved SAFETY margins of the finished assembly.

TABLE II

Borated Stainless Steel - ASTM A887-88 -

TYPICAL ANNEALED MECHANICAL PROPERTIES[1]
Room Temperature - Transverse

Type	Grade[2]	Boron Content (%)	.2% Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (% in 4D)	Reduction (%)	Rockwell Hardness (HRB)
304	-	<0.01	195	518	71.6	81.7	66
304B1	A	0.30/0.50	239	620	43.9	64.3	83
	B		241	602	40.4	51.9	82
304B2	A	0.50/0.75	261	645	39.1	59.7	85
	B		269	619	32.9	41.0	83
304B3	A	0.75/1.00	279	678	36.3	56.3	86
	B		283	641	24.3	32.6	88
304B4	A	1.00/1.25	289	709	31.7	51.8	91
	B		292	648	21.4	20.6	90
304B5	A	1.25/1.50	327	737	28.3	45.1	93
	B		311	639	17.2	16.7	92
304B6	A	1.50/1.75	332	758	23.7	36.5	95
	B		322	643	13.1	15.4	95
304B7	A	1.75/2.25	353	797	21.1	31.2	97
	B		345	658	11.9	15.2	96

(1) All values are the average of four tests.
(2) Carpenter NeutroSorb PLUS is Grade A. Carpenter Neutrosorb is Grade B.

TABLE III

Borated Stainless Steel - ASTM A887-88 -

TYPICAL ELEVATED TEMPERATURE MECHANICAL PROPERTIES[1]
632K - Transverse

Type	Grade[2]	Boron Content (%)	.2% Yield Strength (MPa)	Ultimate Strength (MPa)	Elongation (% in 4D)	Reduction (%)
304	-	<0.01	151	389	40.4	76.4
304B1	A	0.30/0.50	226	468	29.3	59.9
	B		208	465	27.8	49.2
304B2	A	0.50/0.75	241	484	27.4	55.4
	B		238	490	21.6	40.1
304B3	A	0.75/1.00	261	535	25.7	51.3
	B		250	542	19.4	26.3
304B4	A	1.00/1.25	284	575	24.1	43.9
	B		262	539	16.1	24.0
304B5	A	1.25/1.50	316	608	21.5	42.2
	B		266	557	14.2	22.7
304B6	A	1.50/1.75	343	625	17.8	31.3
	B		281	554	12.1	18.6
304B7	A	1.75/2.25	319	696	15.2	21.8
	B		320	572	11.2	15.8

(1) All values are the average of four tests.
(2) Carpenter NeutroSorb PLUS is Grade A. Carpenter NeutroSorb is Grade B.

TABLE IV

Borated Stainless Steel - ASTM A887-88 -

Room Temperature - Transverse

Type	Grade[1]	Boron Content (%)	Impact Energy Charpy V-notch[2] (joules)
304	-	<0.01	325
304B1	A	0.30/0.50	95
	B		62
304B2	A	0.50/0.75	73
	B		31
304B3	A	0.75/1.00	60
	B		22
304B4	A	1.00/1.25	49
	B		15
304B5	A	1.25/1.50	39
	B		11
304B6	A	1.50/1.75	30
	B		8
304B7	A	1.75/2.25	22
	B		7

(1) Carpenter NeutroSorb PLUS is Grade A.
Carpenter NeutroSorb is Grade B.

(2) Average of four specimen breaks.

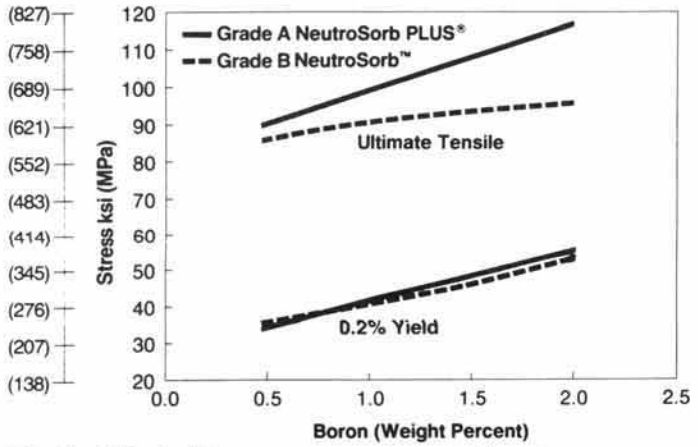

Fig. 3. Effect of boron on room-temperature transverse yield and tensile strength of borated stainless steel - ASTM A887-88.

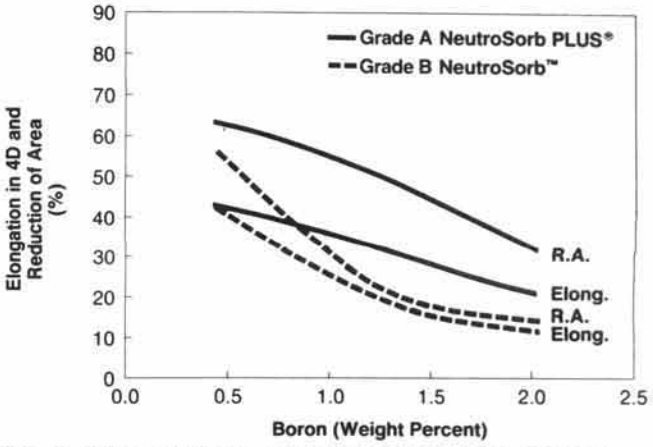

Fig. 4. Effect of boron content on room-temperature transverse tensile ductility of borated stainless steel - ASTM A887-88.

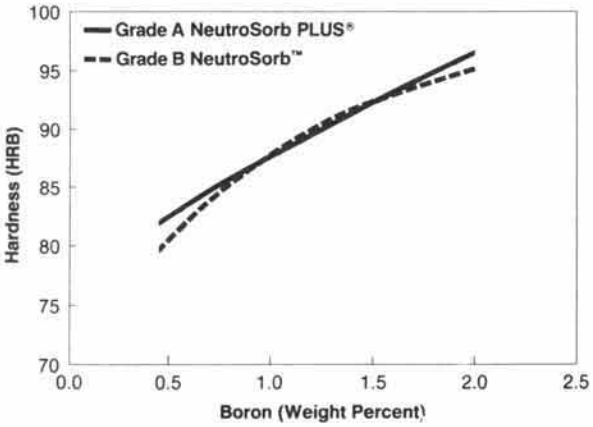

Fig. 5. Effect of boron content on annealed hardness of borated stainless steel - ASTM A887-88.

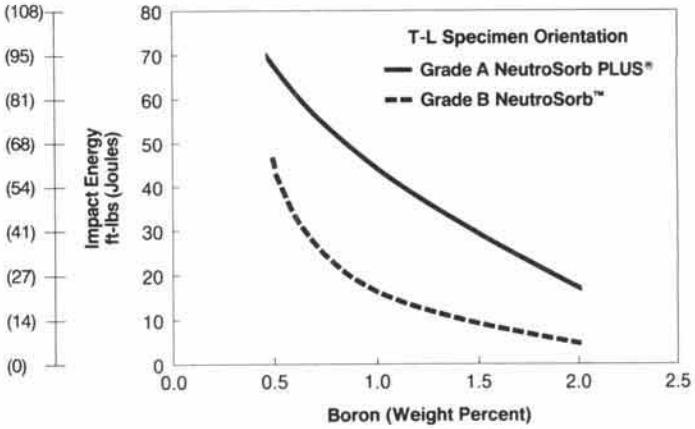

Fig. 6. Effect of boron on room-temperature transverse charpy v-notch impact energy of borated stainless steel - ASTM A887-88.

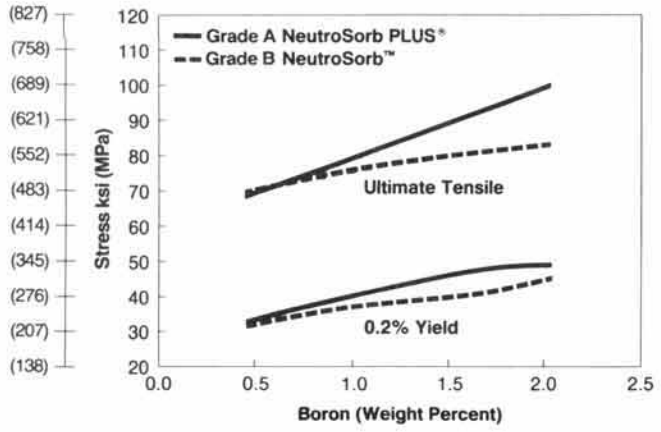

Fig. 7. Effect of boron on transverse yield and tensile strength of borated stainless steel - ASTM A887-88 - at 350°C.

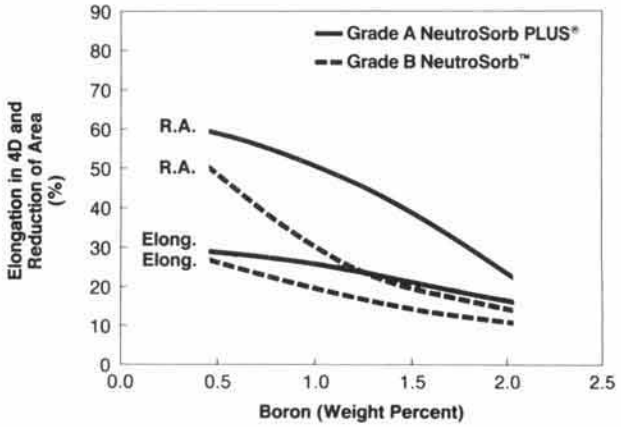

Fig. 8. Effect of boron content on transverse tensile ductility of borated stainless steel - ASTM 887-88 - at 350°C.