HERA Advisory Notice:

Welding to AS/NZS 1554.1 of Boron Containing Steel

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Abstract

This is a revised version of the HERA Advisory Notice that was first published in 2016. The revision was undertaken following comments from member companies.

Recent reports indicate that some imported steel may show elevated levels of boron. Traditionally, steel manufactured in Australia and New Zealand has been made without boron additions. The welding requirements of AS/NZS 1554 have been established without considering the effect of boron as an alloying element. This article discusses steps that should be undertaken by the fabricator to ensure the integrity of the steel fabrication work when welding structural steel with elevated boron levels.

Key Words

Structural steel, boron, welding, AS/NZS 1554

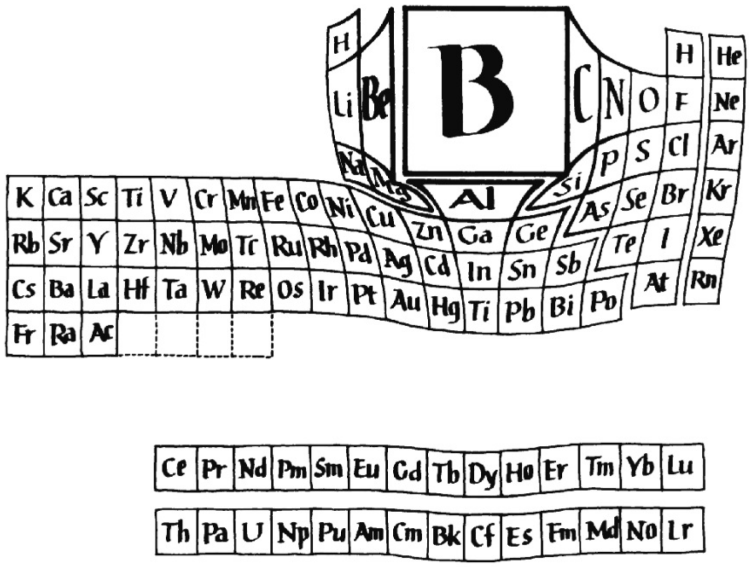
Introduction

Boron is a metalloid chemical element with the symbol B and atomic number 5. Boron does not occur in the elementary state, but is always combined with oxygen. It is available in the form of boron-containing oxides such as Borax, Boracite, etc.

Boron is added as an alloying element to many materials such as structural steel, quenched and tempered, high-speed-cutting steels and high-strength low-alloy (HSLA). Typical quantities which have to be added to the steel to achieve desired effects range between 0.0003 to 0.005% B.

While some steel standards leave boron alloying aspects to the discretion of the manufacturer or to agreement between the purchasers, standards such as AS/NZS 1594, AS 3597, EN 10025-6, etc., introduce a compositional limit for boron.

Only minor percentages of boron may be necessary to greatly increase the hardness and degrade ductility and toughness of the heat-affected zone of the welded steel [Duce 2016, Dillinger Huette 2014].



Bill's Periodic Table: Illustrated by Jean C. Evans

Boron is supplied to steelmakers as ferroboron or as one of several proprietary alloys. Choice of addition depends on steelmaking practice. Historically, boron has not been intentionally added to structural steel manufactured in New Zealand or Australia to AS or AS/NZS standards. However, some overseas steelmakers have added boron to structural steel to take advantage of export subsidies[1] or for other reasons, including improved impact energy.

Although the mechanical properties of boron-alloyed steels can be expected to comply with the steel standard (e.g. AS/NZS 1163), these standards do not address weldability issues related to boron.

Treatment of Boron in Structural Steel Manufacturing Standards

Prior to the publishing of the 2016 revisions, the suite of AS/NZS structural steel manufacturing standards did not address the issue of the intentional addition of boron. The latest revisions address this issue in the following manner:

AS/NZS 3679.1 and AS/NZS 3678

[1] Bloomberg, *China's Removal of Steel-Export Rebate to Reduce Shipments*, https://www.bloomberg.com/news/articles/2015-01-05/china-s-removal-of-steel-export-rebate-to-reduce-shipments, 5 January 2015 (Accessed 1 May 2017)

- Boron shall not be intentionally added to the steel without the agreement of the purchaser
- The chemical composition of boron must be reported on test and inspection reports
- No limit on the boron content is given.

AS/NZS 1163

- The chemical composition of boron must be reported on the test and inspection certificates
- No limit on boron content is given.

References to boron are also included in other standards, e.g. API Specification for Line Pipe 5L:

- Line pipes: No deliberate addition of Boron is permitted, and the residual B ≤ 0.001%
- Pipes for offshore service: B ≤ 0.0005%

Carbon equivalent formulas and preheat

The problem associated with the welding of boron-containing steel is that the weldability concept of AS/NZS 1554 Part 1 and Part 5 is based on carbon equivalent (CE or CE_{IIW}), which does not include the effects of boron:

$CE_{IIW} = C + Mn/6 + (Cr+Mo+V)/5 + (Ni+Cu)/15$

The applicable weldability model is based on controlling the factors responsible for hydrogen-assisted cracking in steels that include: diffusible hydrogen, tensile stresses and type of microstructure having a critical hardness. The latter one is a function of alloying (or residual) elements, including boron. Notwithstanding this, the CE_{IIW} formula is presented in AS 3597:2008 for maximum boron levels of 0.005% and 0.006% for cast and product analyses, respectively.

There are a variety of formulas available addressing effects of boron on the weldability of steels, e.g. Ito-Bessyo (P_{CM}) [Ito et al 1968] and CEN [Yurioka 1983].

The P_{CM} criterion was developed for steels with low carbon and low alloy content. It is used as a good indicator of hydrogen-assisted cracking in the HAZ, also for boron-containing steels. P_{CM} formula is given below:

$P_{CM} = C + Si/30 + (Mn+Cu+Cr)/20 + Ni/60 + Mo/15 + V/10 + 5B$

The limit on crack sensitivity index P_{CM} is included in the Japanese steel standards, such as JIS G 3106 *Rolled steels for welded structures* and JIS G 3136 *Rolled steel for building structure*. Steel products from both standards are referenced in NZS 3404.1:2009 and AS/NZS 5100.6: 2017 as acceptable steel grades.

Both standards include limits on essential chemical elements but allow other elements (such as boron) to be added as necessary. There is no absolute limit for boron. The limit is defined based on the P_{CM} formula, considering the influence of other elements. The limits for the crack sensitivity index P_{CM} and the carbon equivalent CE_{eq} of JIS G 3106:2008 and JIS G

3136: 2005 for JIS steels referenced in NZS 3404.1:2009 and AS/NZS 5100.6: 2017 are replicated in the Table 1.

Table 1 Limits for crack sensitivity index P_{CM} [JIS G 3106:2008; JIS G 3136: 2005]

Steel grade	Plate/product thickness, mm	
	50 mm	50 to 100 mm
SM400A, SN400A, SM400B, SM400C	0.28 max.	0.30 max.
SN400B	0.26 max.	0.26 max.
SM490YA, SM490YB, SN490B	0.24 max.	0.26 max.
SM520B, SM520C	0.26 max.	0.27 max.

The P_{CM} criteria is also included in other standards such as API 5L. For example, for PSL2 pipe steel with equal to or less than 0.12%C, the limit of 0.25 P_{CM} applies. The P_{CM} limit is lower for SMLS pipes ranging from 0.19 up to 0.23.

The carbon equivalent formula CEN, applies to both carbon-manganese (structural) steels (covered by CE_{IIW}) and low carbon low alloy steels (covered by P_{CM}).

$$CEN = C+A(C)*\{Si/24 + Mn/6 + Cu/15 + Ni/20 + (Cr+Mo+Nb+V)/5+ 5B\}$$

where:

$$A(C) = 0.75 + 0.25 \tanh\{20(C-0.12)\}$$

There is a good correlation between P_{CM} and CEN for structural steels, low-alloy steels (Ni-Cr-Mo type) and carbon steels for a carbon content up to 0.17 wt%; where the carbon content exceeds 0.17 wt% there is a better correlation between CEN and CE_{IIW} [Yurioka 1990]. In the higher carbon range, A(C) approaches 1 and CEN approaches CE_{IIW}. At low carbon levels, the CEN approaches Pcm. This behaviour of the CEN equation is due to the hyperbolic tangent function.

The factor of “5B” is used in both formulas to describe the effect of boron in increasing hardenability and therefore susceptibility to hydrogen-assisted cracking.

The CEN formula is included in the advanced algorithms developed by Yurioka to predict preheating temperature necessary to prevent hydrogen assisted cracking in the HAZ [Yurioka et al 1985, 1995] and Yurioka’s simplified Chart Method can be used to estimate the effects of all significant variables.

The so called CET method included in the Appendix C (Method B) of BS EN 1011-2 also allows estimation of minimum preheat temperature for boron containing steels. It is applicable to steels with boron content of 0.005% max. The method is applicable to arc welding of steels of groups 1 to 4 as specified in ISO 15608 (the same grouping system is used in AS/NZS 2980). This also includes quench and tempered steels.

The method of preheat prediction to AS/NZS 1554.1 was compared with that of the CET method for steel grade AS/NZS 3678 350 L15 for a butt weld. The results are shown in Figure 1. The estimated preheat temperature is more conservative using CET method.

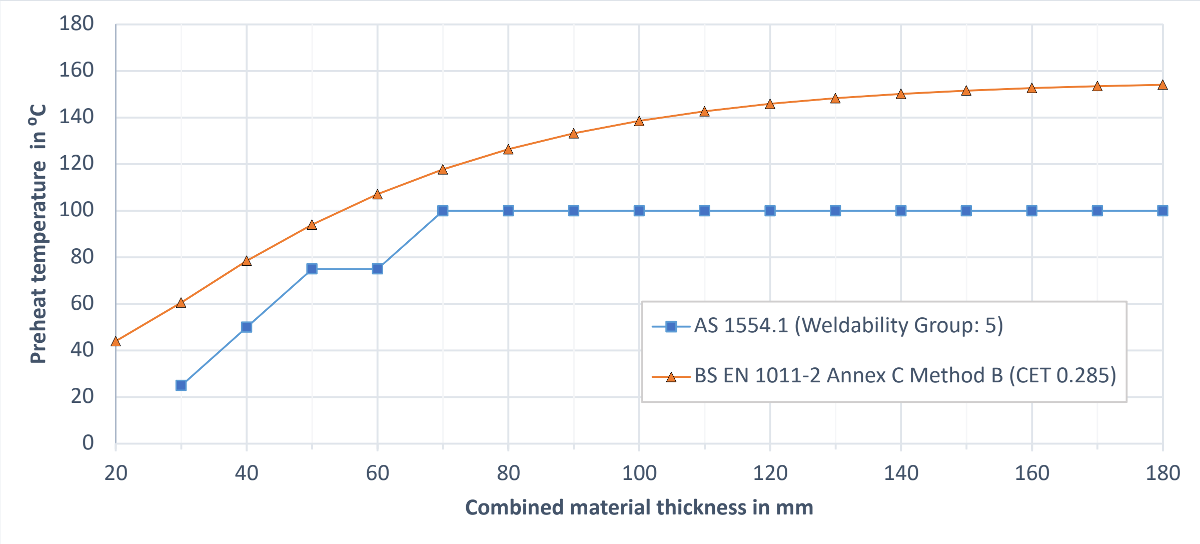


Figure 1: *Influence of material thickness on preheat temperature estimated in accordance with AS/NZS 1554 and EN 1011.1, CET method for a butt weld welded with FCAW; Arc energy input: Q=1 kJ/mm (AS/NZS 1554); Low hydrogen filler: 10ml/100g; Steel: AS/NZS 3678 350 L15.*

The difference in preheat temperature increases with the increase in plate thickness, ranging between approx. 30°C for a butt joint with a combined thickness of 90mm and 50°C for thicker plates. It should be noted that the preheat temperatures determined for butt welds using CET method can be reduced (by some 60°C) for fillet welds [BS EN 1011-2]. Considering this reduction, in the case of the fillet welds, both methods are expected to deliver comparable results.

Another method of estimating minimum preheat temperature applicable to boron-containing steels is given in AWS D.1.1, Appendix H. The method is referred to as a "hydrogen-controlled method". It is based on the P_{CM} composition parameter.

Both the AWS D.1.1, Appendix H hydrogen controlled method and CET method are more conservative than the CEN method for estimating preheat temperatures for carbon-manganese (structural) steels and a wide variety of other steels, also those containing boron [Yurioka 2003].

Standards-related aspects

The standards are consensus documents that reflect the prevailing opinion of the committee members.

The current argument is, however, that methodologies above have not been specifically evaluated for welding of Australian and Australian New Zealand structural steels welded to AS/NZS 1554.

Due to insufficient test data regarding an upper limit of boron that can be considered as safe for steel pipe, tube and plate products manufactured to Australian and New Zealand standards, Standards Australia Welding Committee WD-003 have recommended to limit it at 0.0008% in alignment with the steel classification standards ISO 4948-1 (Steels – Classification – Part 1: Classification of steels into unalloyed and alloy steels based on chemical composition) and EN 10020 (Definition and classification of grades of steel). It should be noted, however, that both ISO 4948-1 and EN 10020 do not consider weldability.

For procedural reasons, Standards Australia has removed boron-related provisions in AS/NZS 1554 Parts 1, 5 and 7 via a correction amendment published in September 2015. Specifically, this involves Clauses 2.1, 4.7.7.2 (for Parts 1 and 5 only) and 5.3.1 relating to the use of steel with boron content equal to or greater than 0.0008% by weight. 0.0008% is 8 parts per million (ppm). 8 grams per tonne!

The situation has changed again with the publication of the Technical Specification SA TS 102 *Structural steels—Limits on residual elements and Structural steel* and SA TS 103 *Structural steel welding – Limits on boron in parent materials*. Both documents have been published as Standards Australia documents in early 2016. They have not been adopted by Standards New Zealand and therefore have informative status only.

TS 102 sets maximum limits for residual elements to ensure products manufactured to these Standards are prequalified for welding to AS/NZS1554 Parts 1, 5 and 7. It does not allow for boron to be intentionally added to steel and limits the amount of residual boron to the level mentioned above.

PRODUCT DESCRIPTION

PRODUCT: 50x 50 x 1.60
SPECIFICATION: AS/NZS 1163:2009 C450L0
MATERIAL: ERW Steel Tube
STEELMAKING: Basic Oxygen, Fully Killed, Continuous Cast, Fine Grained
STEEL FEED: Coil from Hot Strip Mill

ITEMS COVERED BY THIS CERTIFICATE

GTIN	DESCRIPTION		Date Range
99317869210698	50X 50X1.6 DURAGALCLEAR 450+ 7.2M AS/NZS1163-C450L0		11/11/14 - 11/11/14 14315 - 14315

NOTES - Items:
(1) The Date Range indicates the mill manufactured date range. Line marking on further processed product may be after these dates.

CHEMICAL ANALYSIS

Test No	Heat No	Test Lab	Analysis Category	Percentage of Elements by Mass								
				C	P	Mn	Si	S	Ni	Cr	Mo	Cu
13033SPH/14	6399289	632	L	0.149	0.016	0.760	0.010	0.012	0.014	0.025	0.005	0.034
13033SPH/14	7425209	632	L	0.158	0.013	0.730	0.007	0.009	0.011	0.021	0.003	0.026
SPEC LIMITS			L/P	0.2	0.03	1.6	0.45	0.03	0.25	0.3	0.1	0.25

Test No	Heat No	Test Lab	Analysis Category	Percentage of Elements by Mass							
				Al-t	Ti	Nb	V	B	CE	CF2	CF3
13033SPH/14	6399289	632	L	0.031	<0.002	0.001	<0.003	<=0.0006	0.29	0.006	0.050
13033SPH/14	7425209	632	L	0.034	<0.002	0.001	<0.003	<=0.0006	0.29	0.006	0.040
SPEC LIMITS			L/P	0.02-0.1	0.04	0.15	0.1	0.0008	0.43	0.15	0.09

NOTES - Chemical Analysis:
(1) The Test No. represents the test report reference for this analysis

http://www.onesteelmetalcentre.com/

Welding of boron-containing steels

TS 103 defines requirements for welding procedure qualification tests for steel containing boron. Parent material containing total boron equal to or exceeding 0.0008% should be treated as non-prequalified. When qualifying these steels, weld heat-affected zone (HAZ)

Charpy testing shall be performed together with other tests in accordance with Section 4.7, AS/NZS 1554 part 1 or 5.

Qualification test will involve welding of a butt-weld test piece following a welding procedure including preheat requirements, that will be used on the job.

The Charpy test should be carried out on three test pieces taken out of the weld HAZ. The notch of the Charpy test specimen should be placed in the heat-affected zone (HAZ) adjacent to the fusion line of the weld. Position of the notch relative to the fusion line should be verified by light polishing and etching of the face of the specimen before testing. The test should be performed in accordance with the testing requirements of the applicable materials standard and AS 2205.3.1. The test temperature and minimum absorbed energy shall comply with those given in the applicable materials standard, e.g. AS/NZS 1163.

Additional qualification tests involve macro, tensile and bend as per Table 4.7.1, AS/NZS 1554 part 1 or part 5, following the route of not prequalified consumables and materials.

It is not needed to "re-qualify" all welding procedures. Only butt weld test(s) should be considered. Qualification tests should include a representative selection of a thicker plate(s) with the highest boron content. The intended tests should be discussed with the engineer.

The fabricator should verify that structural steels containing boron also comply with the limits for the crack sensitivity index P_{CM} given in Table 1. If the applicable limit of P_{CM} is exceeded, the suitability of the material for the intended application should be assessed and confirmed by a metallurgist.

The tests should follow a qualified welding procedure that will be used on the job. This also includes preheat requirements as established in accordance with AS/NZS 1554. The failure of the test should not be the sole reason for rejecting the plate, as preheat to AS/NZS 1554 does not consider the impact of boron. The preheat temperature will need to be increased for the subsequent re-testing.

The increase in the preheat temperature, in addition to the preheat calculated to AS/NZS 1554.1, should be a minimum of 30°C for a butt joint with a combined thickness of up to 90mm and 50°C for thicker joints. A preheat calculation to Appendix C (Method B) of BS EN 1011-2 can be used as an alternative method to estimate preheat.

Preheating the joint prior to welding and maintaining preheat temperature during welding is the best insurance against hydrogen-assisted cracking. However, note that the preheat recommendations above cannot guarantee that cracking will not occur. If in doubt, advice should be sought from the parent material manufacturer regarding welding and preheating requirements.

Compliance with limits for boron

Compliance to the limit on boron shall be demonstrated by either of the following:

(a) Reporting boron levels on test reports (mill certificates) compliant with the Australian Standard/New Zealand for that parent material; or

(b) Tests results of the boron levels performed by an accredited laboratory.

Although the use of the Technical Specifications above is optional, following engineering best practice, fabricators should require their steel supplier to declare the boron content of the material.

Some of the steel suppliers have already announced changes to their test certificates by adding Boron to the list. If the boron exceeds the limits described above, additional butt weld testing should be considered by the fabricator.

Measurement of boron in delivered steel

The determination of boron in steel is today typically achieved using two modern instrumental methods of analysis. The common technique is spark optical emission spectroscopy (OES) that allows for direct analysis of boron in a solid sample of steel.

Inductively coupled plasma optical emission spectrometry (ICP-OES) and plasma mass spectrometry (ICP-MS) are two other techniques that require a small sample of steel to be dissolved prior to determination of boron.

Scanning electron microscope based energy dispersive spectroscopy (SEM-EDS) and X-ray fluorescence (XRF) cannot determine low levels of boron in steel and hand held analysers are also not capable of this.

Spark-OES detection limit and precision (repeatability) are generally considered to be good. Precision is expected to be 0.0001% provided instrument operating conditions are as specified in ASTM E415:2015. However accuracy can be poor as accuracy is controlled by the quality of the calibration standards used and only truly certified reference materials (CRM's) must be used to calibrate and control the instrument.

For a laboratory reporting boron at 0.0008% the correct way to express this result is 0.0008 ± 0.0001% (at 95% CI - confidence interval) and this must be taken into consideration when comparing results from two or more laboratories.

From ASTM E415 for boron at 0.0006% - reproducibility R2 (at 95%CI) is 0.0005% and is the maximum difference expected between two or more laboratories all determining boron by spark-OES at this concentration. This degree of difference is typical when determining elements at such low levels.

For spark-OES, large differences in analyses between laboratories are typically the result of poor calibration and subsequent control of this calibration and not the instrumental technique.

In the case of a dispute, spectrophotometric determination of boron using the circumin – BS EN 10200 method (circumin is an organic reagent that forms a coloured complex with boron in a dissolved sample of steel that can be measured colourimetrically) – or determination by ICP-OES or ICP-MS – should be considered.

To understand the degree of difference typical for this analysis, consider the results reported for analysis certificates for CRM's [BCS 1988]: Eight analysts operating under rigorous conditions, all following method BS EN 10200 reported the following results:- 0.0016%, 0.0016%, 0.0011%, 0.0016%, 0.0014%, 0.0018%, 0.0015% and 0.0015%. The average result was 0.0015%.

The maximum limit prescribed in SA TS 102:2016 is 0.0008%, and thus, it is clear from above that results for boron exceeding 0.0008% should not be the sole arbitrator for non-conformance. For boron at 0.0008% the reproducibility is 0.0005%. For example, whilst one lab might report 0.0008%, another lab could report 0.0003% or 0.0013%.

Therefore, if a steelmaker is faced with a limit of 0.0008% total boron and knows that the test reproducibility is 0.0005%, they would need to set an internal target of 0.0003%. This would provide confidence (at approximately the 95% level) that another laboratory is unlikely to report a value exceeding 0.0008%. However, 0.0003% is an extremely low boron content and would likely require little to no use of scrap metal in the furnace charge.

The precision data quoted relates to carefully chosen and prepared samples. These samples are rigorously checked for homogeneity so that the sample does not influence the precision – only the analysis method. The real steel samples, e.g. steel plates, are not as homogeneous and decrease precision. The other issue with boron is that, like aluminium) exists in steel in both soluble (i.e. active) and insoluble forms, and this too decreases precision.

Recommendations for the fabricators

The addition of a relatively small amount of boron to steels may result in an increase in the hardenability, and this is a consideration for welding. The fabricator should require their steel supplier to declare the boron content. Additional butt weld testing to verify properties of the heat-affected zone is required to qualify welding procedures for steel containing total boron equal to or exceeding 0.0008% as recommended in the section "Welding of boron-containing steels".

This level of boron is close to the detection limit for commonly available analysis techniques. There can be (significant) deviations between results reported from two or more labs. In the case of a legal dispute, only primary methods of analysis are valid, and ICP-MS is the common technique to refer to, as this technique can be calibrated directly with standards that relate directly back to the weight of boron.

Recommendations for SA TS 103

It is likely that boron will continue to be found in some steels as a residual element due to additions of scrap in the steel-making process. The current limit for boron is set close to the limit of reproducibility by the commonly available analysis techniques; therefore, this may become a subject for dispute.

It is recommended to develop an alternative approach to the current limit for boron based on P_{CM} criteria such as those given in JIS G 3106:2008. In this way, the limit for boron will be set as a function of other elements included in P_{CM} individually based on actual steel composition.

References should also be included to the methods Method B, Appendix C of BS EN 1011-2 and AWS D.1.1, Appendix H hydrogen-controlled as alternative methods to determine preheat temperature for steels that comply with the P_{CM} composition parameter. Corresponding correction factors can be added to the preheat calculated to AS/NZS 1554 or preheat tables developed.

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AWS D1.1 Structural welding code – steels

API 5L Specification for line piping

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