

1. SCOPE

This Note provides guidance on the hardness testing of welds. The emphasis is on the hardness testing of carbon manganese and low alloy steels from a welding perspective but the principles discussed can be applied to other metals.

2. MEASUREMENT OF HARDNESS

The different types of hardness tests available for metals have been well documented elsewhere; in various Standards e.g. Reference 2 and websites References 3, 4 and 5. Useful tables to convert one hardness reading to another are available in Reference 4.

Hardness testing of welds and their Heat Affected Zones (HAZs) usually requires testing on a microscopic scale using a diamond indenter. The Vickers Hardness test is the predominant test method with Knoop testing being applied to HAZ testing in some instances. Hardness values referred to in this document will be reported in terms of the Vickers Number, "HV".

The Vickers hardness is obtained by dividing the load applied to indent the pyramidal diamond into the test piece by the area of indentation thus created. The larger the load used the larger will be the indentation created, so it is common for the Vickers to be reported as $ww\ HV_{xx}$ where "ww" is the hardness number and "xx" represents the load in kilograms used to create the indentation. (In principle, Vickers hardness is independent of load, but microstructural variations can cause local differences between say a 30 kg load and a 2 kg load. This is not the case with Brinell where the applied load must be reported with the Brinell Hardness Number).

3. PURPOSE OF THE HARDNESS TEST

Hardness testing of welds provides an indication of two parameters significant to the determination of a successful weld joint:

- a) Strength
- b) Microstructure of a known material.

These are discussed below.

4. STRENGTH DETERMINATION

The tensile strength of steel is proportional to its hardness. Indeed the tensile strength of steel in MPa, can be estimated simply by taking one third of its Vickers hardness multiplied by ten (divide by 3.1 for slightly more accuracy). Table 1 gives the hardness and strength of some common steels.

Table 1. Typical physical and chemical properties of common steels

Steel	Vickers Hardness HV	Yield Strength MPa	Reported Tensile Strength MPa	Calculated HV Tensile Strength $(HV / 3.1) \times 10$	Carbon Content wt%	Carbon Equivalent (IIW)
Grade 250	125 – 165	280 - 400	420 - 500	400 – 532	0.14 - 0.16	0.27 – 0.32
Grade 350	145 – 190	340 - 360	460 – 550	467 – 613	0.1 – 0.15	0.33 – 0.36
BisPlate 80	270	690 (min)	790 - 930	860	0.16 – 0.18	0.4 – 0.5
AISI 1010 Hot Rolled	98	180	325	316	0.08 – 0.13	0.13 – 0.23
ASTM A514 Gr. P	278	690	828	896	0.12 – 0.21	0.53 – 0.79
2.25% Cr. – 1% Mo	200	414 - 562	585 - 795	645	0.15 nom	0.75 – 0.99

For example a steel hardness of 300HV corresponds to a tensile strength of approximately 1,000 MPa. Thus the hardness test can become a quick screening test to determine if the steel in question has the expected tensile strength or is the right steel.

5. MICROSTRUCTURE

For a given steel composition the hardness measured is related to its microstructure. Table 2 provides some examples of how the hardness (and hence strength) of a steel can vary depending on the processing treatment applied the resultant microstructure achieved.

Table 2. Typical physical and chemical properties of structural steel

Steel	Vickers Hardness HV	Yield Strength MPa	Reported Tensile Strength MPa	Calculated Tensile Strength HV / 3.1 x 10	Carbon Content wt %	Carbon Equivalent (IIW)
AISI 1020 - Quenched & Tempered	170	275	475	548	0.18 – 0.23	0.23 – 0.33
- Hot Rolled	112	205	380	361	0.18 – 0.23	0.23 – 0.33
AISI 1040 -12mm Bar Q & T @ 540 °C	235	562	752	758	0.37 – 0.44	0.47 – 0.59
-100mm Bar Q&T @ 650 °C	178	378	586	574	0.37 – 0.44	0.47 – 0.59
AISI 4140H -Annealed	202	485	655	652	0.38 – 0.43	0.69 – 0.86
- Q & T @ 205 °C	552	1515	1795	1781	0.38 – 0.43	0.69 – 0.86

Amongst other things the microstructure can be changed and strength in steel increased by:

- increasing the alloy content;
- work hardening – for example cold rolling;
- combination of alloy content and work hardening – for example controlled rolling;
- Thermal treatment during processing – for example quench and tempering. There is a direct relationship between carbon content and hardness for plain carbon steels in the quenched condition.

For the carbon steels under consideration in this note, the microstructure can vary from ferrite and pearlite, through to bainite and martensite. The propensity for any given microstructure to form is a function of the alloy content and cooling rate. The hardness range of AISI 4140 shown in Table 2 is a classic example of the effect of thermal processing on resultant hardness and thermal properties of a steel.

Welding can impose a variety of thermal cycles on steel at various locations that produce:

- undesirably hard microstructures susceptible to cracking and brittle fracture;
- excessively soft microstructures susceptible to plastic collapse under load.

Single pass welds tend to be harder than multi-pass welds of the same heat input due to the lack of tempering inherent in multi-pass welds.

The factors that can influence the resultant hardness include, pre-heat, weld heat input, cooling rate, total thickness at the weld, alloy content of the steel, alloy content of any fluxes plus the original microstructural condition of the steel plus postweld heat treatment and peening.

The hardness can therefore be a useful indicator to determine if the thermal cycle induced by welding has rendered the HAZ adjacent to the weld susceptible to cracking or plastic collapse.

6. CRACKING SUSCEPTIBILITY

High hardnesses increase susceptibility to cracking because of:

- the lower fracture resistance associated with hard microstructures;

- b) the susceptibility of hard microstructures to Hydrogen Assisted Cold Cracking (HACC);
- c) the high residual stress produced by the welding thermal cycle associated with hard microstructures.
- d) the lower ductility associated with hard microstructures.

The hardness of the weld HAZ provides such a good indication of crack susceptibility that the WTIA Technical Note 1 "Weldability of Steel" was developed largely on the hardness response of the steels being assessed. There are two rules of thumb used steel welding. Hardnesses in excess of 350 HV are generally regarded as being susceptible to HACC. Hardnesses in excess of 238 HV are generally regarded as being susceptible to sulphide stress cracking which is a form of stress corrosion cracking associated with the transport of sour gas or oil products.

Stress Corrosion Cracking (SCC) needs a corrosive environment (e.g. amine, ammonia, sulphide) and a susceptible microstructure under the influence of a tensile stress to occur. SCC is often associated with areas of high residual stress. The hardness of the heat affected zone gives an approximate indication of the level of residual stress that can be present and hence provides one indication of the propensity to SCC in service. From this principle, NACE International developed the MR 0175 specification for materials in sour service.

7. PLASTIC COLLAPSE

High welding heat inputs and high preheat/inter-pass temperatures result in slow cooling rates. Steels that have been quenched and tempered to achieve the desired mechanical properties can be susceptible to HAZ softening as a result of welding. This results in a localised loss of strength that can have a deleterious effect on structural performance. Again the hardness of the HAZ provides an indication of the level of softening (if any) that has occurred as a result of welding. It should be noted that aluminium alloys are inherently susceptible to HAZ softening as a result of over-aging or annealing of the alloy's microstructure during welding.

8. WELDING STRUCTURAL AND BOILER STEELS

Grade 250, Grade 350 structural steels, boiler 460 and 490 Grades and pipelines steels with yield strengths up to 500 MPa are all readily weldable. HAZ hardnesses in the range of 175 to 225 HV with weld hardness in the 205 to 240 HV range are typical when using MMAW, GMAW, FCAW welding processes. Welding heavy wall thickness components requires pre-heat. The pre-heat guidelines are given in WTIA Technical Note 1 "Weldability of Steels". Typical hardness of Australian steels is available through References 6, 7 and 8.

9. WELDING ALLOY STEELS

The weldability of alloy steels is primarily dependent on the alloy content of the steel measured using the carbon equivalent. Reference to Technical Note 1 is a pre-requisite to determine the welding precautions required. HAZ hardness in excess of 350 HV occur readily requiring high pre-heat temperatures, slow cooling and hydrogen controlled welding procedures.

10. WELDING QUENCHED AND TEMPERED STEELS

Extensive effort has been undertaken to produce readily weldable quenched and tempered steels. Nevertheless care is required to control cooling rate with limits to avoid excessive HAZ hardening on the one hand and excessive softening on the other. Weld cooling rates that are too high through the result of insufficient pre-heat or low welding heat inputs can result in HAZ hardening. Conversely excessive inter-pass temperatures coupled with high heat-input welding processes can lead to softening of the HAZ with associated loss of strength.

Anticipate HAZ hardness levels from 290 to 330 HV for quenched and tempered steels. Hardness values less than 270 HV indicate HAZ softening and those in excess of 350 HV a risk of hydrogen assisted cracking.

11. HARDNESS TESTING WELDS AND HEAT AFFECTED ZONES

As previously mentioned, Vickers Hardness is the predominant measurement technique for welds and HAZs. The diamond indentation can be made using a range of loads from 1 to 100 kg. The higher the load the larger the impression the diamond makes on the surface of the steel made and the more of an average the hardness reading becomes.

For weld testing there is specific interest in the heat affected zone that is in the order of 1 or 2 mm thick. Thus it is necessary to use low loads, 1, 2 or 5 kg, in order to accurately assess the hardness in such cases. Australian Standard AS 2205.6.1 – 2003 provides a method for carrying out hardness testing and recommends use of a 5 kg load with traverses carried out 2 mm below the surface of the weldment.

The aim of weld and HAZ hardness testing is to identify:

- a) the hardness of the parent metal and make an approximate determination of the materials tensile strength to assure the correct material is being welded;
- b) the hardness of the weld to ensure the weld metal meets or exceeds the strength requirements of the parent metal;
- c) the hardness of the HAZ to ensure the welding heat input, preheat and interpass temperature have been controlled sufficiently to produce a HAZ with the appropriate strength and toughness;
- d) areas for fracture toughness testing when such testing is required.

12. MICRO-HARDNESS TESTING

Where specific information is required on the hardness of sub-structures within the HAZ zone (e.g. “coarse grain”, “fine grain”, “inter-critical” and “sub-critical” regions) it is necessary to carry out micro-hardness testing with loads in the 0.5 to 2 kg range.

For these applications purpose built micro-hardness testers are available using either the Vickers or Knoop test method. With these techniques, the area of interest is identified under a microscope and a hardness measurement made directly on the area of interest.

Such techniques are applied to critical welding applications such as temper bead welding where a primary basis of acceptance of the welding technique is the hardness test. Such testing is beyond the scope of standards such as AS 2205.6.1 and requires a technician or engineer with metallurgical experience to undertake such work.

13. REFERENCES

1. Exploring Temper Bead Welding, Walter J. Sperko Welding Journal July 2005, pp37 to 40
2. AS 2205.6.1 – 2003 Methods for destructive testing of welds in metal Method 6.1: Weld joint hardness test
3. TWI, Hardness Testing Part 1 and Hardness Testing Part 2, www.twi.org.uk (“Information & know-how : JoinIT technical information : Job Knowledge”)
4. Gordon England; www.gordonengland.co.uk/hardness/ (“Hardness Testing”)
5. Center for Advanced Life Cycle Engineering (CALCE) and the University of Maryland; www.calce.umd.edu/general/Facilities/Hardness_ad_.htm
6. BlueScope Steel; www.bluescopesteel.com.au
7. OneSteel; www.onesteel.com
8. Smorgon Steel Group Ltd: www.smorgonsteel.com.au

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	NATIONAL DIFFUSION NETWORKS PROJECT TECHNOLOGY QUESTIONNAIRE Pressure Equipment Industry Group “Hardness Testing of Welds”	Revision No: Rev 0
		Page 1 of 2 Date: 18 Nov 2005

As part of the WTIA National Diffusion Networks Project the Pressure Equipment Sector identified the need to understand and apply hardness testing in the development of welding procedures. The WTIA has prepared a Technical Guidance Note “Hardness Testing of Welds” to provide understanding of metal hardness and the best practice for measuring and assessing hardness levels in weld related applications. As a valued technology expert in this area we would like you to be part of the Technology Expert Group to review this note. Please complete this questionnaire so that we can gauge the success of meeting this need.

Objective 1: Identify the need for understanding and best practice for hardness measurement

Hardness testing is frequently required for welding procedure qualification but there is surprising little information available on the meaning and implications of the hardness readings. This guidance note is intended to provide the Pressure Equipment Industry understanding of hardness, and the best practice for measuring and specifying hardness. How well does the document achieve these aims?

poor average good very good

Comments: _____

Objective 2: Identify appropriate technology receptors in the Pressure Equipment Industry

This document was written for Welding Coordinators and Maintenance Engineers in the Pressure Equipment Industry. Are these people the appropriate individuals we should be targeting?

yes no

What other types of companies and/or personnel do you suggest we target? _____

Objective 3: Identify current best practice for measuring and specifying hardness

The document was written to reflect current best practice for the specification and measurement of hardness. Do you envisage opportunities for the use of this practice in the industry?

yes no

If yes, what and where, if no why not? _____

Objective 4: Is the information provided clear, concise and accurate?

yes no

If not, why? _____

Objective 5: Broad dissemination of technology to the Pressure Equipment Industry

Please indicate how best to disseminate this information to the appropriate Pressure Equipment Industry Recipients

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If poster, what size? A1 A2 A3 Laminated What selling price? \$

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Other format? _____

