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Specifying Hardness Testing of Materials and Weldments on Vessels and Piping in Wet Sour Services

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ABSTRACT

In oil and gas production as well as refining facilities, there are numerous services which are known to cause environmental cracking of steel components and/or weld zones if they have high hardnesses. The primary example is fluid services containing water and H₂S. For equipment and piping in these services, hardness limits are recommended in various industry standards including NACE documents MR0175, MR0103, SP0472 and 8X194. Hardness is not a fundamental material property but a response to measuring technique. Hence, there have been occasions where the reported hardnesses were inaccurate due to application of incorrect procedure, incorrect correlations of different hardness scales or confusion on testing requirements, resulting in schedule delays and unnecessary costs. This paper gives a brief summary of the services wherein metals are prone to cracking and because of which, checking hardness is critically important. It also discusses the variations in industry standards and their specified hardness limits. The paper delineates different types of hardness testing practices and the various testing instruments, for both laboratory and field testing, and gives references to conversion charts for reviewing readings from the different scales (which vary by materials). The considerations of testing in different locations, i.e. base metals, weld deposits and heat affected zones, are also addressed.

WHAT IS HARDNESS?

Numerous methods measuring hardness involve an indenter under a known load which is pressed onto the surface of steel to be tested and measurement is made of the size or depth of the indentation. The indenter is made of material with higher hardness. With these methods, it can be said that hardness is **the material's property to resist plastic deformation** when in contact with the indenter. Since plastic deformation always results, a hardness test cannot be repeated at the same point.

Since there are a variety of testers, hardness is not a fundamental material property but response to measuring technique⁽¹⁾. It is also composite property influenced by the modulus of elasticity and strength and the method of hardening. A material's hardness is usually affected by being formed or welded. During welding, the rapid heating and cooling of the metal edges causes the base metal hardness to change locally in the Heat Affected Zones (HAZ). When hardness in any part of the fabricated vessel or piping is predicted to increase significantly to the point where it is no longer acceptable for service and/or operation, postweld heat treatment is often specified to lower the hardness.

The three most commonly used hardness tests and their ASTM Standards are as follows:

- 1. Brinell Hardness, per ASTM E10⁽²⁾, Hardness designated by suffix HBW (and in the past, often designated as HBN)
- 2. Rockwell Hardness, per ASTM E18⁽³⁾, Hardness designed by suffix HRCW or HRBW
- 3. Vickers Hardness, ASTM E384⁽⁴⁾ and ASTM E92⁽⁵⁾, Hardness designed by suffix HV

The first two methods are used in laboratories and manufacturing shops, while Vickers testing is typically only done in the lab. Field construction sites and some manufacturing shops use more portable hardness testers such as:

- 4. Comparison Testers, per ASTM A833⁽⁶⁾,
- 5. Testers using Ultrasonic Contact Impedance Method per ASTM A1038⁽⁷⁾
- 6. Testers using the Rebound Principles, per ASTM A956⁽⁸⁾
- 7. Portable Brinell and Rockwell Testers, per ASTM E110⁽⁹⁾

Each method will be discussed in more detail in later sections of the paper.

MATERIALS BEING TESTED

In refinery and gas production facilities under sour services measuring hardness is of great importance for quality assurance. Also, the most widely used material in this service is carbon steel also classified at P. No. 1 Group 1 or 2 materials per the ASME Boiler and Pressure Vessel Code Section IX⁽¹⁰⁾. To keep this paper to a reasonable length, it will focus on the significance of hardness testing on only carbon steel (P-1 materials) vessels and piping in sour service.

Some of the CS materials which are used for fabrication of equipment and piping are:

Plate: SA516 Grade 55 through 70

Pipe: SA106 Grade B or SA333-Grade 1 or 6

Forgings: SA 105 or SA-350, Grade LF2 or SA 266-Grade 1 or 4

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Fittings SA-234 Grade WCB or SA 420 Grade WPL 6

WHAT IS SOUR SERVICE AND HOW DOES IT LEAD TO CRACKING?

Sour service in context of wet H_2S corrosion is the level of H_2S in refining or oil and gas production that would cause cracking of metallic materials. According to NACE Standard MR0103⁽¹¹⁾ susceptibility to sulfide stress cracking (SSC) for P-1 materials is significant under the following process conditions.

- 1. 50 ppmw total sulfide content in the aqueous phase or
- 2. \geq 1 ppmw total sulfide content in the aqueous phase and pH < 4, or
- 3. ≥ 1 ppmw total sulfide content and ≥20 ppmw free cyanide in the aqueous phase, and pH > 7.6, or
- 4. > 0.3 kPa absolute (0.05 psia) partial pressure H_2S in the gas phase associated with the aqueous phase of a process.

In petroleum refining, numerous units contain process environments containing wet H₂S which are known to have caused cracking as a result of hydrogen charging. These units include hydrotreating, hydrocracking, Amine Treating, Fluidized Catalytic Cracking (FCC), Cokers, Sour Water Strippers, Crude Distillation, etc.

Carbon and low alloy steels in services that promote cracking are likely to be affected by following damaging mechanisms, only the first of which is limited to high hardness materials or zones.

1. Sulfide Stress Cracking (SSC) occurs when atomic hydrogen from the corrosion mechanism at the metal surface diffuses into the metal and remains in the solid solution in the crystal structure. This reduces the ductility and deformability of steel, especially in materials or zones which are high hardness. In order to avoid SSC in wet H₂S environments, it is important to limit the hardness of weld deposits to below 22 HRC or 200 HBW, and hardness of HAZ to below 248 Hv10 by PWHT or other controls. The residual stresses from a non-heat treated weld, often approach the yield stress of the material which typically provides the stress required to cause SSC. Also cold working decreases the resistance to SSC due to increased hardness and/or residual tensile stress in the steel.



Figure 1: SSC in HAZ of Weld Reprinted from Reference⁽¹²⁾

2. Hydrogen blistering and HIC also can occur when atomic hydrogen diffuses into the steel, and for these mechanics, the atomic hydrogen recombines into molecular hydrogen at inclusions or laminations within the steel. The molecular hydrogen is then "trapped", and pressure can buildup causing blistering and/or cracking of the equipment wall. This mechanism can occur in both hard and soft areas of the metal. In SOHIC, failure appears as staggered cracks approximately perpendicular to the principal stress, either applied or residual.

The HIC, hydrogen blistering and SOHIC types of cracking are dependent on the cleanliness of the steel and can occur even if the hardness of the steel does not exceed 22 HRC.

NACE STANDARDS FOR WET SOUR SERVICES

The NACE standards MR0103/ ISO 17495⁽¹²⁾, MR0175/ ISO 15156⁽¹³⁾, SP0472⁽¹⁴⁾, and 8X194⁽¹⁵⁾ discuss the requirements of control and limits for materials and/or weld hardness for carbon and low alloy steels.

A. NACE MR0175 / ISO 15156⁽¹³⁾

This NACE standard is applicable to oil and gas production, and it allows CS materials, weldments and HAZ in wet sour service as long as the hardnesses are 22 HRC maximum for base metals and welds and **250 HV10 maximum for HAZ**.

B. NACE MR0103 /ISO 17495⁽¹²⁾

This NACE standard is applicable to the petroleum refining industry, and it allows CS base metal (ASME P-1, Group 1 or 2) in wet sour service as long as it meets one of the conditions, 1 through 6 below. These steels do not need to be hardness tested during manufacturing. **However the weld hardness shall be controlled as defined in NACE SP0472**⁽¹⁴⁾. Pipe bends in P-No. 1 material which are heated above the upper transformation temperature are allowed provided they meet the heat treated condition as described below prior to forming and the hardness on the bend area shall not exceed 225 HBW.

- 1. Hot Rolled
- 2. Annealed
- 3. Normalized
- 4. Normalized and Tempered
- 5. Normalized, Austenitized, Quenched, and Tempered
- 6. Austenitized, Quenched, and Tempered

C. NACE SP0472⁽¹⁴⁾

In order to prevent SSC, this standard recommends hardness of the completed weld deposit shall not exceed 200 HBW and hardness of HAZ shall not exceed 248 Hv10. The 200 HBW maximum

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hardness per this standard is lower than 22 HRC (237 HBW) listed in the NACE MR 0175/ ISO 15156 ⁽¹³⁾, and was chosen as it is the expected maximum hardness for properly made CS weldments. The standard lists weld deposit hardness testing exemptions when production weld is by certain welding process and filler metal combinations per NACE SP0472 ⁽¹⁴⁾, Table 2. According to this standard, the hardness readings shall be taken by a Brinell hardness tester in accordance with ASTM E10⁽²⁾ or with a comparison hardness tester in accordance with ASTM A833 ⁽⁶⁾. The testing shall be done after PWHT if PWHT is required. The weld deposits shall be hardness tested on the process side whenever possible however if access to the process side is not practical, such as piping or small diameter vessels, hardness testing shall be done on the opposite side.

The maximum allowable HAZ hardness shall not exceed 248 Hv10. The softening of HAZ hardness is generally achieved by PWHT and base metal chemistry controls for equipment. For piping, the HAZ hardness is controlled by either PWHT or one of two thermal methods (cooling time control or temper bead welding), along with base metal chemistry control and qualifying the weld procedure with a hardness survey.

D. NACE 8X194⁽¹⁵⁾

This standard, issued in 2006, is a dated overview of fabrication, postweld heat treatment, inspection and testing practices previously used by refiners, process licensors and engineering contractors for carbon steel equipment in wet H_2S refinery services.

HARDNESS TESTING METHODS

Hardness tests can be broadly classified based upon the magnitude of the indentation load used, as (a) Macrohardness, and (b) Microhardness.

When indentation load exceeds 1 Kg, the hardness measure is Macrohardness and when loads \leq 1 Kg (2 lbs) are used, the hardness measure is Microhardness or Microindentation hardness. Also, in Microhardness testing the area of indentation is studied instead of the depth of the indentation. Microhardness testing has made it possible to obtain hardness information where locations may be hard to access by more conventional testing methods which typically use higher loads and their external features does not allow them fit in small areas. Microhardness tests are used for "fine-scale" hardness testing where a metallographic specimen is prepared for microhardness testing.

STATIC HARDNESS TESTS

The load is applied statically or quasi-statically without shocks to the test piece and after removing the load the hardness value is defined as the ratio of the test load and surface or projected area of the permanent test indentation. Below are the three types of static hardness tests are commonly used to determine the effects of processing on the metals. All these tests are based on the size of an indentation by a known indenter applied with a known load.

1. Brinell Hardness Test (Macrohardness Test)

The Brinell hardness test is defined by ASTM E10, Standard Test Method for Brinell Hardness of Metallic Materials⁽²⁾. As shown in Figure 2 below, the test consists of impressing a hardened steel ball (Sphere) into the test surface using a specified load e,g. 3000 kg for a definite time, 10 to 15 seconds. The loads 1500 and 500 Kg may also be used but they are used less frequently. The surface of the permanent indentation after removal of the test force is determined. The Brinell hardness is defined as the quotient of the test force and indentation surface area of the permanent indentation. Since the hardness reading of the same work piece may vary with different loads, it is recommended that L/D^2 be maintained constant for a given material where L = Standard Load and D = Diameter of Ball.



Figure 2: Brinell indentation process. (a) Indentation Process. (b) Measuring the indentation Reprinted from References⁽²³⁾

The verification of the apparatus, calibration of the test blocks and the examinations should be performed per requirements of Standard Test Method for Brinell Hardness of Metallic Materials, ASTM E10⁽²⁾. In case of performing hardness test on the equipment base material and welds, since traditional fixed hardness test instrument cannot be taken to the equipment, portable hardness testers are commonly used.

Compared to other methods, the Brinell ball makes the deepest and widest indentations, so the test averages the hardness across over wider amount of material. It is for this reason Brinell hardness test is mostly used on the weld caps and base materials and not appropriate for HAZ due to their small width compared to indentation size. For base metal hardness the precise location of hardness impressions is not important however it is advisable to ensure that the ball does not have any obstruction to cover the area to assure homogeneity. The hardness reading on the weld cap is taken on the center of the weld.

A smooth surface is the best practice in order to have precise measurements. The surface of the workpiece for Brinell hardness test should be filed and ground also filed with emery paper to allow clear review of the indentation edge and measurement of indentation. Two principle axes of the impression should be measured and averaged. The usual rule of thumb is that the distance of the center of the indentation from the edge of the specimen or edge of another indentation shall be 2.5 d (impression diameter). Below is the figure of an ideal indentation shape.



Figure 3: Ideal Ball Shaped Indentation

Indentation test will most likely be spurious if taken on highly curved surfaces. If the workpiece surface is curved, there is less lateral support for the material to resist the indentation force. Hence the readings may show low hardness values. The situation will reverse when testing is performed on a concave surface. Here additional material is available to resist deformation and hence it is likely the hardness readings will be higher compared to on a flat surface of the same hardness.

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The radius of curvature of test specimen should not be less than 1 in (25.4 mm). Usually the weld reinforcement is ground off to create a flat surface for readings on the weld cap; also any corners which obstruct the ball to indent perpendicularly on the prepared surface prepared are ground off. For a practical application standpoint the test piece thickness must be at least eight times (ten is preferred) the depth of the penetration.

The test surface should be perpendicular to the indenter axis. Since the ball indentations cause local workhardening at the impressions, the normal practice is to ensure there is adequate spacing between adjacent impressions.

2. Rockwell Hardness Test

The Rockwell hardness test is defined by ASTM E18, Standard Test Methods for Rockwell Hardness of Metallic Materials⁽³⁾. This test can be used on softer to highly hardened steels. Rockwell hardness test differs from the Brinell hardness method by the fact that the Rockwell hardness test determines hardness number by measuring the depth of the indentation.

A diamond cone or hardened steel ball mounted rigidly in a suitable holder is forced into test piece under a preliminary load (Fo) in Figure 7. When equilibrium is reached, an indicating device which follows the movement of the indenter responds to depth of penetration of indenter and sets this depth as the datum position. While the preliminary load is still applied, it is augmented by an additional load (F1) in Figure 7 with resulting increase in penetration of the indenter. Once the indentation with the additional load is complete it is removed but the preliminary load is maintained. This will result in partial recovery of the indentation causing reduction in the depth of the penetration, resulted from the application and removal of the additional load, which is used to calculate Rockwell hardness number. The entire process usually requires 5 to 10 seconds.

In a standard macrohardness Rockwell hardness test, the minor load (Fo) is 10 Kg and the major load (F1) could be 60, 100 or 150 kg.



a) Minor Load

b) Major Load

Figure 4: Rockwell Hardness Testing Reprinted from References ⁽¹⁶⁾

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Reprinted from ASTM E18⁽³⁾

There are different scales of Rockwell hardness measurements depending upon the materials strength properties. For carbon and low alloy steels where the hardness can vary from high HRB to low HRC, Rockwell hardness scales "B" and "C" are typically used as recommended by ASTM E18 ⁽³⁾, Table 1.

ASTM E18⁽³⁾ also covers another type of Rockwell test called the superficial Rockwell hardness test. The superficial Rockwell uses the minor load of 3 Kg and the major load may be 15, 30 or 45 Kg.

The Rockwell test causes significant work hardening at the location of the test due to the indentation process. Hence spacing and the thickness of the test piece are important for a successful Rockwell hardness test. The thickness of the test piece shall be greater than 10 times the depth of the indentation and the center of one indentation to another must at least be at least 3 indentation diameters or diagonals.

3. Vickers Hardness Test

Vickers Macro Hardness Test is defined by ASTM E92, Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials⁽⁵⁾. This hardness test uses a highly polished pyramidal-shaped diamond indenter for hardness test. The indentation load is applied smoothly, without impact, and is held in place for 10 to 15 seconds.

A square based pyramid with a large angle of 136° between opposite faces was determined in such a way that over a large range the Vickers hardness (HV) values will approximately be equal to HB of the Brinell test. It was with this purpose such an indenter was adopted.



Figure 6: Vickers Hardness Testing per ASTM E92⁽⁵⁾

The material thickness should be thick enough so that the applied load does not produce a mark or bulge on the back side of the sample. ASTM E92⁽⁵⁾ recommends that the material thickness shall be at least 1.5 times the diagonal length.

Per ASTM E92⁽⁵⁾, the distance between the center of the indentation and the specimen edge and between the center of two indentations should be >2.5 d (diagonal of the impression). An ideal indentation shape would be symmetrical with edges of the indentation perfectly defined for measurement. The corners of indentation also should be seen clearly. However sometimes undesirable indentations like shown below may be obtained. These should be carefully evaluated. The Figure 7 shows an ideal indentation and three (3) types of undesirable indentations.

A standard Vickers macrohardness test uses loads from 1 to 120 kg however loads above 30 kg are hardly used; the most common load used is 10 Kg. Since wide range of test loads as small as 1 to 5 Kg may also be used for Vickers hardness test, it permits testing of much thinner workpiece compared to Brinell Testers. The outstanding advantage with Vickers indenter is that it produces the same hardness number with all test forces when testing a homogenous material except for test using very low forces or loads in microhardness testing. In performing the test, the sample surface should be perpendicular to the indenter axis within $\pm 1^{\circ}$. Otherwise the results can be erroneous as tilting of the indenter will likely produce nonsymmetrical impressions.

The Vickers microindentation hardness tests per ASTM E384⁽⁴⁾ uses smaller indenters and the indentations are studied using a microscope. Hence Vickers microindentation hardness tests are used to determine hardness of material over narrow zones like the weld HAZ. The HAZ hardness result by use of a standard Telebrineller indenter would be a "sweep" across the softer and harder of the weld and HAZ zones respectively. Considering peak temperatures during welding, width of the

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HAZ is estimated to be about 3 wide and the hardest HAZ region is likely to be in the region close to the fusion line but away from the fusion line as shown below Figure 8.







Figure 8: Most Susceptible Zone to Cracking

Reprinted from References⁽¹⁷⁾

Smaller indenters (with load loads such as HV5 or HV10) used in Vickers diamond-pyramid hardness test are ideal for assessment of hard or soft zones in the HAZ as shown below.



Figure 9: Vickers Hardness Test at the Heat Affected Zone (HAZ)

Reprinted from References⁽¹⁾

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As per NACE MR0103, the Vickers hardness acceptance criteria is 248 Hv10 and its direct conversion is 22 HRC. This also directly converts to 237 HBW in the Brinell hardness test. The test machine uses a diamond indenter of small geometry in which the test force may be adjusted in the range from 1 to 1000 g i.e. 9.8 N. The specimen must have a polished metallographic surface for viewing with a microscope. The distance between two Vickers microindentations shall be \geq 4d (length of Vickers diagonal) and the distance to the edge of the specimen shall be \geq 2 d (length of the Vickers diagonal).

The following photograph shows the various microindenters which may be used with Vickers microhardness test.



Figure 10: Examples of Vickers microindentations (use of 500, 300, 100, 50, and 10 gf loads and viewed with ~ 250 X magnification) Reprinted from References⁽¹⁸⁾

DYNAMIC HARDNESS TEST

Dynamic Hardness Test can be divided into two types.

- 1. Methods where deformation is measured: After the impact of the indenter, the size of indentation is determined optically or by means of a depth measurement, such as in Brinell or Rockwell Test.
- 2. Dynamic Rebound Hardness Test This hardness test method measures hardness of the specimen by elastic response of the material.

PORTABLE HARDNESS TESTERS

4. Comparison Hardness Testers (Telebrineller) per ASTM A833⁽⁶⁾

This method is used for hardness testing of large components which are difficult to fit under a Brinell hardness tester. As stated in ASTM A833⁽⁶⁾, this practice covers the indentation hardness testing of metallic materials using comparison hardness testers. The equipment includes an apparatus that contains the indentation ball as well as the comparative test bar.

The apparatus allows the impression on the comparative bar simultaneously with one produced on the workpiece. The comparison of the impression diameters together with the hardness of the comparative bar is used to determine hardness of the part. The indentations on the workpiece and comparative bar are measured using the microscope. The hardness of the part being tested is determined using an the equation in the ASTM A833, Annex A1 or the manufacturer of the

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apparatus can be consulted for the appropriate equation that should be used to calculate the hardness of the workpiece analytically.

The Brinell hardness of comparison test bar should be within ±15% of the anticipated Brinell hardness of the part. If the hardness of comparative bar varies from that of the material being tested, the readings are considered inaccurate.

5. Ultrasonic Microhardness Tester (Ultrasonic Contact Impedance Method) per ASTM A1038⁽¹⁷⁾

The UCI is a microhardness test performed using a portable hardness tester. The hardness is measured using indenter to which Vickers diamond attached to the contacting end per test method ASTM E384. The indenter rod is excited to its natural frequency (70 kHz) by piezoelectric converter. The resonant frequency of the indenter rod changes as the free end of the rod is brought into contact with the surface of a solid body. The shift in the frequency is compared with the frequency in air. Once the device is calibrated for the modulus of elasticity of the tested material, the area of contact between the diamond tip and the tested surface can be derived from the measured resonant frequency. Unlike standard Brinell or Rockwell hardness test, where the hardness is determined optically by the size of the indentation generated using certain load, in the UCI method the resonant frequency is changed by area of contact (impression) which is used to find the hardness number. The UCI probes use loads ranging from 100 g to 10 kg. UCI hardness testers are convenient for insitu hardness testing.



6. Leeb Hardness Tester per ASTM A956⁽⁸⁾ / ISO 16859⁽¹⁹⁾

The ASTM A956, Standard Test Method for Leeb Hardness Testing of Steel Products, defines the Leeb Hardness Test. An impact device is propelled into the sample using a spring for the initial energy (i.e. the device is initially pressed against a spring before it is released). The impact device travels a short distance until it hits the specimen. The device then rebounds away from the specimens based on its hardness and elasticity. The hardness is measured by the ratio of the impact and rebound velocities. The impact creates a plastic deformation of the surface due to which the impact device loses part of its velocity. The softer the material the greater would be the loss of velocity. The hardness Testers are calibrated with conversions to report hardness test in Brinell, Vickers, Rockwell hardness scales to allow them viable with industry requirements where hardness scales used are Brinell, Vickers or Rockwell. Leeb hardness testers are electronic hardness testers and the hardness can be read off from a digital display. The rebound testers operate on the bases of rebound velocity and hence cannot be used on thin materials because thinner materials may

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provide additional rebound based on the vibration of the test piece. A rougher surface also may impact the rebound velocity providing a softer reading.

The advantage with the portable Leeb Hardness Tester is that it can be easily used on the production welds that are quite narrow and inaccessible for any other type of portable hardness testing machines.

7. Miscellaneous Portable Hardness Testers per ASTM E110⁽⁹⁾

Over and above the Comparison, UCI and Leeb Hardness Testers which constitute large domain of portable hardness testing devices used in the industry there are other "patented" portable hardness testers available in the market which operate per ASTM E110⁽⁹⁾. The loads, preloads, and method of using those devices are clearly described by the manufacturer. The hardness testing procedure is required to be complied with the manufacturer's directions.

These testers are configured to provide readings in the desired scale such as Rockwell, Superficial Rockwell as well as Vickers hardness. Some of these devices have capability to operate up to 360° positioning which includes upside down. The entire assembly fits into a convenient case so that it can be easily transported for in-situ hardness testing.

HARDNESS CONVERSIONS

Sometimes there is a need to convert hardness from one scale to another. This happens when labs are limited by availability of hardness testing tools and the types of testing they can perform, and the measurements are done using a different technique than the units of the specification limit. For this reason it may be necessary to take hardness reading in one scale and convert it to another scale.

It is advised that there are different hardness conversions, for different families of materials and different hardness conversions are required based upon elastic modulus and strain hardening capacities of the materials. In the case of sensitive weld zones, it is prudent to contain the indentation specifically within the region where hardness is of prime interest in the unit that is of importance for assessment. Hardness should be specified in the scale it is required to be measured. Conversion may be applied to materials using published tables that are recognized. The most reliable hardness conversion table are available in ASTM E140⁽²⁰⁾ or A370⁽²¹⁾ which are certainly a valuable resources. These standards have conversion charts for non-austenitic steels, austenitic steels and nickel alloys. Duplex SS have unique hardness conversion charts as described in API Technical Report 938-C⁽²⁸⁾.

CONCLUSION

There are different types of hardness tests and hardness testing devices available. Some of the hardness testing devices are patented. The following table summarizes the different hardness tests along with the reference to the ASTM standard, indenter characteristics and the typical force that is used.

HARDNESS TESTING METHODS

Test Method	ASTM Standard	Indenter	Typical Load
Brinell Hardness	ASTM E10	10 mm diameter hardened steel or tungsten carbide ball	500 to 3000 kgf
Rockwell Hardness	ASTM E18	128° Diamond Cone	10 kgf (minor force), 60 to 100 kgf (major force)
Rockwell Superficial	ASTM E18	128° Diamond Cone	3 kgf (minor force), 15 kgf (major force)
Vickers Hardness	ASTM E92	Square Pyramidal Shaped with face angles of 136°	1 gf to 120 kgf
Vickers Microhardness	ASTM E384	Square Pyramidal Shaped with face angles of 136°	< 1 kgf
Comparison Hardness (Telebrineller)	ASTM A833	10 mm diameter hardened steel ball	Impact Load of 1 to 2.25 kgf
Ultrasonic Hardness (UCI)	ASTM A1038	Vickers diamond tip	10 kgf for Microdur MIC-2010® (varies with different models)
Leeb Hardness (Equotip® Hardness Tester)	ASTM 956	3 mm Tungsten Carbide Ball	12 Nmm Impact Energy

Hardness testing is a useful tool to establish acceptability of materials, welds, and heat affected zones. The merits of device used to conduct hardness testing should be reviewed based on particular application so that it is able to provide meaningful hardness readings for quality assessment. Conversion of hardness readings from one scale to another scale should be avoided as much possible because doing so may lead us to an approximate reading. Whenever hardness testing critical for the application and conversions must be done, they should be using reliable hardness conversions tables.

REFERENCES

- 1. Dr. Stefan Frank, Hardness 03/01 "Portable Hardness Testing Application Guide", Krautkramer
- 2. ASTM E10, "Standard Test Method for Brinell Hardness of Metallic Materials", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- 3. ASTM E18, "Standard Test Methods for Rockwell Hardness of Metallic Materials", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- ASTM E384, "Standard Test Methods for Microindentation Hardness of Materials", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States

NIGIS * CORCON 2017 * 17-20 September * Mumbai, India

- ASTM E92, "Standard Test Methods for Vickers Hardness and Knoop Hardness of Metallic Materials", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- 6. ASTM A833, "Standard Practice for Indentation Hardness of Metallic Materials by Comparison Hardness Testers, ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- 7. ASTM A1038, "Standard Test Method for Portable Hardness Testing by the Ultrasonic Contact Impedance Method", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- 8. ASTM A956, "Standard Test Method for Leeb Hardness Testing of Steel Products", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- 9. ASTM E110, "Standard Test Method for Rockwell and Brinell Hardness of Metallic Materials by Portable Hardness Testers", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- 10. ASME Section IX, "Welding, Brazing, and Fusing Qualifications", American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990
- NACE MR 0103/ ISO 17495 Petroleum, petrochemical and natural gas industries Metallic materials resistant to sulfide stress cracking in corrosive petroleum refining environments, NACE International, 15835 Park Ten Place, Houston 77084-5145
- NACE International Practice SP0276, "Detection, Repair, and Mitigation of Cracking in Refinery Equipment in Wet H₂S Environments", NACE International, 15835 Park Ten Place, Houston 77084-5145
- NACE MR 0175/ ISO 15156 Petroleum, petrochemical, and natural as industries Materials for use in H2S-containing environments in oil and gas production, NACE International, 15835 Park Ten Place, Houston 77084-5145
- 14. NACE International Practice SP0472, "Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments ", NACE International, 15835 Park Ten Place, Houston 77084-5145
- NACE International Publication 8X194, "Materials and Fabrication Practices for New Pressure Vessels Used in Wet H₂S Refinery Service", NACE FirstService Department, 1440 south Creek Drive, Houston, Texas 77084-7906
- 16. Jon L. Dossett, Howard Boyer, "Practical Heat Treating", ASM International, Materials Park, Ohio, 44073-0002
- 17. STP-58-058, "Temper Bead Qualification Hardness Test Acceptance Criteria" by David Abson, Adrienne Barnes and Sayee Raghunathan, ASME Standards Technology, LLC, Two Park Avenue, New York, NY 10016-5990
- 18. Arthur C. Reardon, "Metallurgy for the Non-Metallurgist", ASM International, Materials Park, Ohio, 44073-0002
- 19. BS/ EN/ ISO 16859, "Metallic Materials Leeb Hardness Test", CEN-CENELEC Management Center, Avenue Marnix 17, B-1000 Brussels

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- ASTM E140, "Stadard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vivker's Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and Leeb Hardness, ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- SA370, "Standard Test Methods and Definitions for Mechanical Testing of Steel Products", ASME Section II, Materials, American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990
- 22. ASTM Stock No. MNL46, "Metallographic and Materialographic Specimen Preparation, Light Microscopy, Image Analysis and Hardness Testing", ASTM International, 100 Barr Harbor Drive, PO box C700, West Conshohocken, PA 19428-2959, United States
- 23. ASM Handbook, Volume 8, "Mechanical Testing and Evaluation", P252-259, ASM International, Materials Park, Ohio, 44073-0002
- 24. George F. Vander Voort, "Metallography Principles and Practice", ASM International, Materials Park, Ohio, 44073-0002
- 25. J.R. Davis, "Metals Handbook Desk Edition", ASM International, Materials Park, Ohio, 44073-0002
- 26. M. Kompatscher "Equotip Rebound Hardness Testing After D Leeb", "Hardmeko 2004", 11-12 November, 2004, Washington, D.C., USA
- 27. Konrad Herrmann, "Hardness Testing Principles and Applications, ASM International, Materials Park, Ohio 40073-0002
- API Technical Report 938-C, "Use of Duplex Stainless Steels in the Oil Refining Industry", API, 1220 L Street, NW, Washington, DC 20005, February 2015