

Round Robin Test Program for Development of Hardness Conversions for Precipitation Hardened Nickel Alloys and Martensitic Stainless Steels

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Introduction

This API Technical Report documents the results of a round robin test program conducted jointly by API and ASTM. An API task group operating under API Subcommittee 21 provided coordination on behalf of API, and ASTM Committee E28.06.02 provided coordination on behalf of ASTM. Additionally, The API Committee for Standardization of Oilfield Equipment and Materials (CSOEM) provided financial support to the program to facilitate preparation of the test samples and procurement of certified hardness test calibration blocks.

The objective of the test program was to develop two independent sets of hardness conversions, one for precipitation hardened nickel alloys and the other for martensitic stainless steels, which could be used to ballot two new hardness conversion tables with corresponding hardness conversion equations for ASTM Standard E140.

The results of the round robin hardness test program indicated that existing hardness conversions in ASTM E140-12bE1 Table 1 for non-austenitic steels are not appropriate for martensitic stainless steels, such as those included in NACE MR0175/ISO 15156.

Round Robin Test Program for Development of Hardness Conversions for Precipitation Hardened Nickel Alloys and Martensitic Stainless Steels

1 Scope

This test program was designed to provide the data necessary to develop two independent sets of hardness conversions, one for precipitation hardened nickel alloys (PHNA) and the other for martensitic stainless steels (MSS), that could be used to ballot two new hardness conversion tables with corresponding hardness conversion equations for ASTM Standard E140.

The members of ASTM Committee E28.06.02 recommended the round robin hardness tests be performed at six different companies. The members of API Subcommittee 21 Task Group recommended the various alloys to test, and the desired hardness ranges for the test specimens.

2 Normative References

There are no referenced documents that are indispensable for the application of this document.

3 Raw Material for Test Specimens

3.1 Raw Material for Martensitic Stainless Steel Test Specimens

The test specimens for the MSS portion of this test program were made from three different alloys. They were only tested in the 1st round robin (RR1) test.

- UNS S41000
- UNS S42400
- UNS J91540

Annex [A.1](#) provides the information from the material certification for the martensitic stainless steels UNS S41000, UNS S42400, and UNS J91540. The test specimens from UNS S41000 were heat treated to four different target hardness values, while UNS S42400 and UNS J91540 were heat treated to five different target hardness values each.

3.2 Raw Material for Precipitation Hardened Nickel Alloy Test Specimens

The test specimens for the precipitation hardened nickel alloy portion of this test program were made from four different alloys. These alloys were supplied in the solution annealed and precipitation hardened condition, with each alloy having a different hardness level. They were tested in the 1st (RR1) and the 2nd (RR2) round robin tests. The alloys are as follows:

- UNS N09925 (ANSI/NACE MR0175)
- UNS N07718 Oil Patch Grade (API 6A718)
- UNS N07716 (ANSI/NACE MR0175)
- UNS N07718 Aerospace Grade (Similar to ASTM B637, AMS 5663)

The information from the material certification for the precipitation hardened nickel alloy test specimens is provided in Annex [A.2](#).

4 Test Facilities

Six companies volunteered and participated in the round robin hardness testing program. Included were one manufacturer of hardness test machines, two manufacturers of hardness test calibration blocks, and three metallurgical testing laboratories.

It should be noted that when the results of the round robin hardness testing are reported in Section 6, the test facilities are designated as A, B, C, D, E, and F. These designations are random with respect to the types of companies that performed the hardness measurements.

5 Procedure

5.1 Test Specimen Preparation—1st Round Robin Test

Except for one of the test specimens for the UNS J91540 material, the test specimens for the martensitic stainless steels and the precipitation hardened nickel alloys were ~6 in. in diameter and 1-in. thick. The exception was the lowest hardness UNS J91540 test specimen, which had to be supplied in two rectangular blocks due to a lack of availability of round bar. The relatively large test specimen size was used to permit the inclusion of the LEEB test method in this round robin hardness test program.

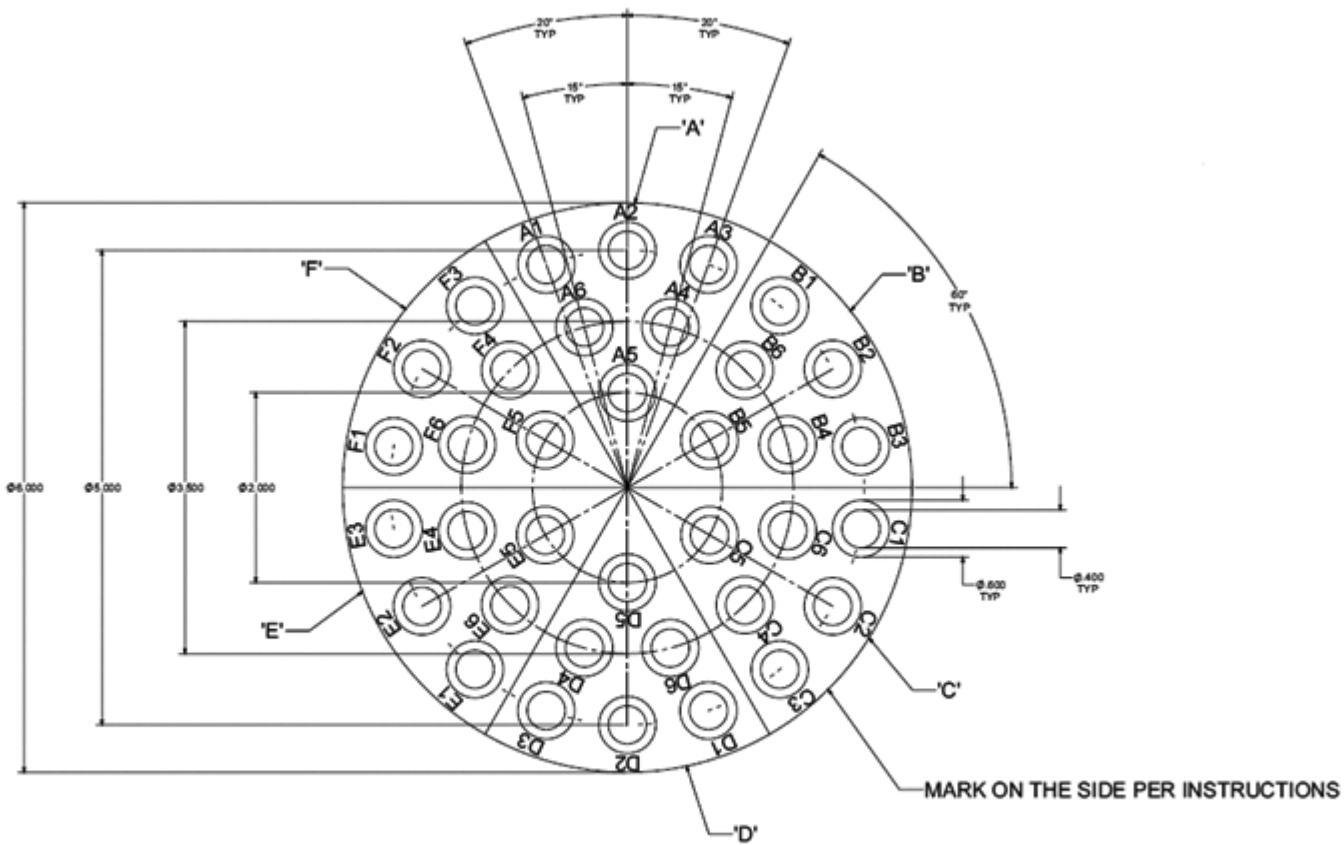
These large blocks of raw material were ground and lapped with the objective of achieving finish, flatness, and parallelism like a calibration block. The martensitic stainless steel test specimens were ground and lapped by one company, while the precipitation hardened nickel alloy test specimens were ground and lapped by another company.

The target requirements for the grinding and lapping were as follows:

- Deviation from flatness (test surface and bottom surface): ≤ 0.005 mm
- Deviation from surface parallelism (test surface and bottom surface): 0.0002 mm/mm
- Mean surface roughness (Ra) (test surface and bottom surface): < 0.003 mm (120 μ in.) center line average

After grinding and lapping, the test specimens were electro-etched by another company to provide a test pattern for the round robin hardness testing. The test pattern applied to the round test specimens is shown in [Figure 1](#) and the test pattern applied to the rectangular test specimens is shown in [Figure 2](#).

A detailed explanation of the location of the individual hardness test indentations is provided in [5.2](#).



TITLE:
ASTM E140 HARDNESS CONVERSION TEST BLOCK

REVISION: NC

NOTE:

1. ALL DIMENSIONS ARE IN INCHES
2. SCALE IS 1:1

Figure 1—Drawing for Etching of Test Pattern on Round Test Specimens



5.2 Hardness Test Procedure—1st Round Robin Test

The following procedure was provided to the six companies participating in the round robin test program.

Step 1—Hardness Machine Calibration

Prior to the start of testing on the test specimens, each hardness testing machine shall be checked for calibration by taking a single hardness measurement on the appropriate hardness calibration block supplied with the round robin test kit.

One set of hardness calibration blocks was shipped from test facility to test facility with the martensitic stainless steel hardness test specimens and in the first round of testing on the precipitation hardened nickel alloy specimens. Information from the hardness calibration block certification is provided in Annex [A.3](#).

The hardness measured, the hardness calibration block identifying information and the hardness range on the calibration block shall be recorded on the standardized data recording form that will be provided to the laboratory by the round-robin test program coordinator.

If the hardness measured on the hardness calibration block falls outside of the range on the calibration block, do not proceed any further with the test program. Contact the test program administrator.

Caution—Make a seating indentation on the Rockwell hardness calibration blocks immediately prior to performing a Rockwell calibration check to ensure proper seating of the Rockwell indenter.

Step 2—Hardness Testing Procedure and Sequence

Each test facility has been assigned a letter designation, from A to F. Each test facility shall only perform hardness tests in the locations assigned to them as indicated by the letter designation on the test blocks and in the Data Recording Forms.

Each test facility shall perform the hardness tests in the order shown below, with all the six tests of one method performed by the test facility before moving on to the next method.

The tests shall be performed in the locations indicated by the letter designation and number, and the tests shall be performed sequentially in the locations marked from 1 to 6.

The order of testing for the test methods shall be:

- a) Rockwell C (HRC) performed in strict accordance with ASTM E18.
- b) Rockwell 15N (HR15N) performed in strict accordance with ASTM E18.
- c) Vickers 10KG (HV10) performed in accordance with ASTM E384.
- d) LEEB 600 HLD (LEEB) performed in accordance with ASTM A956.
- e) Brinell (HBW 10/3000 or HBW) performed in strict accordance with ASTM E10.

Caution—It is extremely important that this test sequence be followed to avoid issues with one hardness indentation affecting another. When an individual test specimen is tested by a test facility, all the Rockwell C, Rockwell 15N, Vickers 10KG, and LEEB HLD tests shall be performed before any Brinell tests are performed by that facility.

The Rockwell C, Rockwell 15N, Vickers 10KG, and LEEB HLD indentations shall be placed in the space between the concentric circles, ~90-degrees apart as shown in [Figure 3](#).

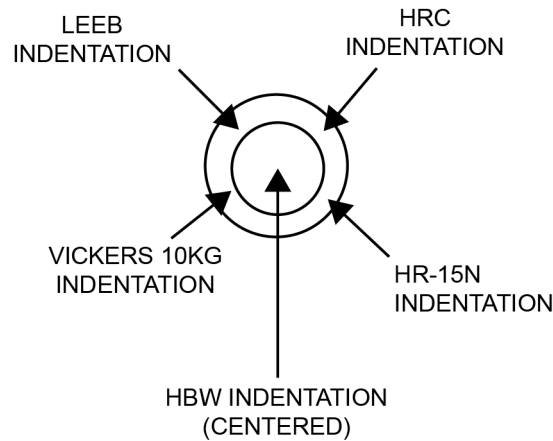


Figure 3—Location of Hardness Indentations on Test Samples

The assigned locations shall have ample space available to perform all the test indentations as planned. However, to ensure proper spacing and ensure that the Brinell indentations do not affect other hardness indentations, the Brinell indentations shall be centered in the large etched circles.

Caution—Since the hardness test specimens will have a polished finish, some automated Brinell measurement equipment may not be able to accurately measure the diameter of the Brinell indications. If this happens, simply use a standard 20X optical microscope for measuring the indentations.

Rockwell C Testing: Rockwell C testing shall be performed and reported in accordance with ASTM E18 using a benchtop tester.

Caution—Make a seating indentation on the Rockwell hardness calibration blocks immediately prior to performing Rockwell hardness indentations on the test samples to ensure proper seating of the Rockwell indenters.

Rockwell 15N Testing—Rockwell 15N testing shall be performed and reported in accordance with ASTM E18 using a benchtop tester.

Vickers 10KG Testing—Vickers 10KG testing shall be performed and reported in accordance with ASTM E384.

Caution—Measure each Vickers indentation prior to moving on to make the next Vickers indentation.

LEEB HLD Testing—LEEB testing shall be performed and reported in accordance with ASTM A956.

Brinell Testing: Brinell testing shall be performed and reported in accordance with ASTM E10 for the HBW 10/3000 test condition.

Bad Indentation or Erroneous Test Result—If a hardness indentation is believed to be bad or a hardness result is believed to be erroneous, perform another test near the original test. For a retest, a Brinell indentation may be made outside the circle. Record both values and make a note on the data recording sheet.

Indentation Placed in Wrong Area—If a hardness indentation or group of indentations is placed in the wrong area, for example, an area that has been assigned to another test facility, please contact the round-robin test program coordinator.

Step 3—Data Recording

The results of hardness testing on both the hardness calibration blocks and the test samples shall be recorded on the standardized Data Recording Forms provided.

5.3 Test Specimen Preparation—2nd Round Robin Test—Precipitation Hardened Nickel Alloys

As discussed in detail in [6.3](#), the test results from the initial round of testing of the precipitation hardened nickel alloys were deemed to be unusable. Thus, a new set of specimens was prepared.

To reduce the amount of time required for testing, a decision was made to prepare six new 4-specimen sets so that each test facility had its own set, and testing did not have to be performed with only one set of specimens moving sequentially from one test facility to the next as was done in the 1st Round Robin test.

The 24 new test specimens were rough machined by one company. The rough machined dimensions of each test specimen were 2.5 in. diameter × 1.0 in. thick. Twelve of the new test specimens were rough machined from four of the precipitation hardened nickel alloy discs that had been used in the initial round of testing by sectioning each of these four into three smaller pieces (note the side to be tested was from the untested face of the original specimen). The remaining 12 test specimens were similarly rough machined from each of four spare precipitation hardened nickel alloy discs.

The rough machined test specimens were shipped to another company for final machining, grinding, lapping, polishing, and marking. The specified diameter of the test specimens was 2.380 in. +0.00 in./−0.02 in., and the surface finish and parallelism of the flat surfaces was to be the same as used for Brinell hardness calibration blocks made by a manufacturer of hardness calibration blocks.

The company that did the final machining, grinding, lapping, and polishing engraved the side to be tested with two lines to divide the test area into four equally sized quadrants, and added a 10 mm diameter circle in each quadrant to indicate the location for the Brinell test indentation. See [Figure 4](#).

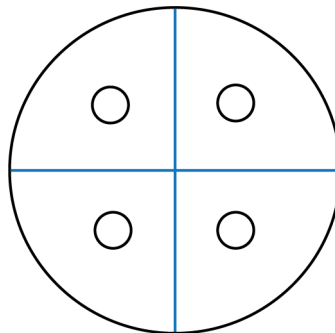


Figure 4—Drawing for Etching of Test Pattern for 2nd Round of Testing (Not-to-Scale)

5.4 Hardness Test Procedure—2nd Round Robin Test—Precipitation Hardened Nickel Alloys

The following procedure was provided to the six test facilities participating in the round robin test program.

Step 1—Hardness Machine Calibration

Prior to the start of testing on the test specimens, each hardness testing machine shall be checked for calibration by taking a single hardness measurement on an appropriate calibration block. Unlike the initial round robin test, calibration blocks are not being provided with the test specimens.

The hardness measured, the hardness calibration block identifying information and the hardness range on the calibration block shall be recorded on the standardized Data Recording Form that will be provided to the laboratory by the round-robin test program coordinator.

If the hardness measured on the hardness calibration block falls outside of the range on the calibration block, do not proceed any further with the test program. Contact the test program administrator.

Caution—Make a seating indentation(s) on the Rockwell hardness calibration blocks immediately prior to performing a Rockwell calibration check to ensure proper seating of the Rockwell indenter.

Step 2—Hardness Testing Procedure and Sequence

Each test facility shall perform the hardness tests in the order shown below, with all the tests of one method performed by the test facility before moving on to the next method.

The tests shall be performed in the locations indicated below, and the tests shall be performed sequentially in each of the quadrants on each of the four test specimens.

The order of testing for the test methods shall be:

- a) Rockwell C (HRC) performed in strict accordance with ASTM E18 using a benchtop tester.
- b) Rockwell 15N (HR15N) performed in strict accordance with ASTM E18.
- c) Vickers 10KG (HV10) performed in accordance with ASTM E384.
- d) LEEB 600 HLD performed in accordance with ASTM A956.
- e) Brinell (HBW 10/3000) performed in strict accordance with ASTM E10.

Caution—It is extremely important that this test sequence be followed to avoid issues with one hardness indentation affecting another. When an individual test specimen is tested by a test facility, all the Rockwell C, Rockwell 15N, Vickers 10KG, and LEEB HLD tests shall be performed before any Brinell tests are performed by that facility.

The Rockwell C, Rockwell 15N, Vickers 10KG, and LEEB HLD indentations shall be placed in each of the quadrants as shown in [Figure 5](#).

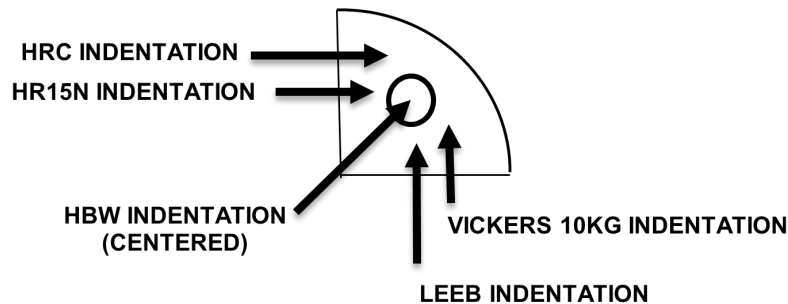


Figure 5—Location of Hardness Indentations on Test Samples

The selected locations should have ample space available to perform all the test indentations as planned without one test interfering with the another by being too close in proximity.

Caution—Since the hardness test specimens will have a polished finish, some automated Brinell measurement equipment may not be able to accurately measure the diameter of the Brinell indications. If this happens, simply use a standard 20X optical microscope for measuring the indentations.

Caution—Measure each Vickers indentation prior to moving on to make the next Vickers indentation.

For LEEB HLD testing, the test specimens will need to be coupled to a larger block of metal this time. LEEB testing is only accurate if the part being tested has enough mass, and these smaller hardness test specimens do not. A link to a video for guidance on proper coupling techniques for the LEEB test was provided.

Bad indentation or erroneous test result: If a hardness indentation is believed to be bad or a hardness result is believed to be erroneous, perform another test near the original test. For a retest, a Brinell indentation may be made outside the circle. Record both values and make a note on the data recording sheet.

Step 3—Data Reporting

The hardness test data shall be recorded in the Excel file provided by the round robin test coordinator.

6 Results

6.1 Hardness Calibration Results

The hardness calibration data from the 1st round robin test program for the six individual test facilities is shown in Annex [B.1](#), [Tables B.1](#) through [B.6](#), and summarized in [Table B.11a](#). The errors against the known certification values were tabulated and compared with the respective ASTM testing standards in [Table B.11b](#). The errors of facility A exceeded the ASTM standard values in all hardness test methods, except Rockwell C scale. Facility D had larger error in LEEB calibration than the ASTM standard value.

In the 2nd round robin test, facilities A and E failed to submit the hardness calibration test data. The hardness calibration data from the other four test facilities is shown in Annex [B.2](#), [Tables B.7](#) through [B.10](#), and summarized in [Table B.12a](#). Facility B had one deviation in HBW and facility F had two deviations in LEEB compared with the ASTM standard values as shown in [Table B.12b](#).

6.2 Hardness Test Results for Martensitic Stainless Steels

The hardness test data for the martensitic stainless steels is shown in tabular form in [Annex C](#), [Tables C.1](#) through [C.6](#) (UNS S41000), [Tables C.7](#) through [C.12](#) (UNS S42400), and [Tables C.13](#) through [C.18](#) (UNS J91540).

6.3 Hardness Test Results for Precipitation Hardened Nickel Alloys

The hardness test data for the precipitation hardened nickel alloys is shown in [Annex C](#), [Tables C.19](#) through [C.24](#) (1st round robin test), and [Tables C.25](#) through [C.30](#) (2nd round robin test). The correlation plots of the Rockwell C data with the results from other hardness scales for both round robin tests are shown in [Figure 6a](#) and [Figure 6b](#).

In the 1st round robin test, facility A showed noticeably poorer correlations between the hardness methods than the other test facilities. This behavior coincides with the deviations of facility A's calibration results discussed in [6.1](#). Samples NN3 and NN4 exhibited similar values using Rockwell C but different values using the other hardness methods. See [Figure 6a](#).

It was initially determined that there was so much scatter that the 1st round robin test results could not be used to develop a set of hardness conversions.

The surface finish of the precipitation hardened nickel alloy test specimens was visibly different from the surface finish of the martensitic stainless steel test specimens. The precipitation hardened nickel alloy test specimens had a dull matt finish, while the martensitic stainless steel test specimens had a mirror like finish, as is typical of hardness calibration test blocks.

The vendor that ground and lapped the martensitic stainless-steel samples was unable to grind and lap the precipitation hardened nickel alloy test specimens since they were non-magnetic, so the precipitation hardened nickel alloy test specimens were processed at another machine shop.

It was theorized that the grinding and lapping technique may have left some residual stress on or near the surface of the test specimens, affecting the ability to get reproducible test results.

Although the root cause of the scatter was not determined, it was decided to run a 2nd round robin test on precipitation hardened nickel alloy test specimens after being ground and lapped by a facility that had the ability to grind and lap to a mirror finish.

In the 2nd round robin test, more facilities showed poor correlations between the hardness test methods than in the 1st round robin test. See [Figure 6b](#). The 2nd round robin test showed a larger scatter than the 1st round robin test (excluding facility A) ([Figure 6c](#)).

The uncertainties of the hardness conversion are affected by the precision of the test method (discussed in [6.4](#)). They also depend on the equivalency of materials and hardness test methods.

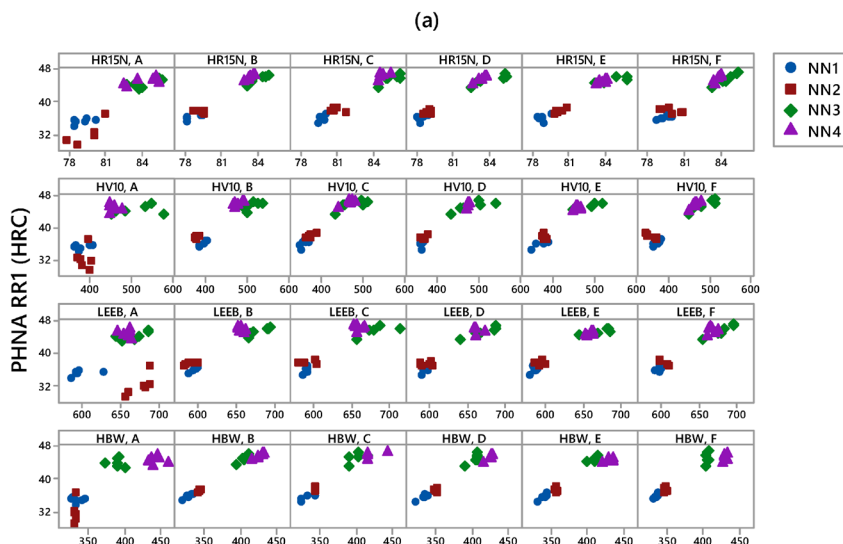


Figure 6a—Correlation Plots of Precipitation Hardened Nickel Alloys, 1st Round Robin Test

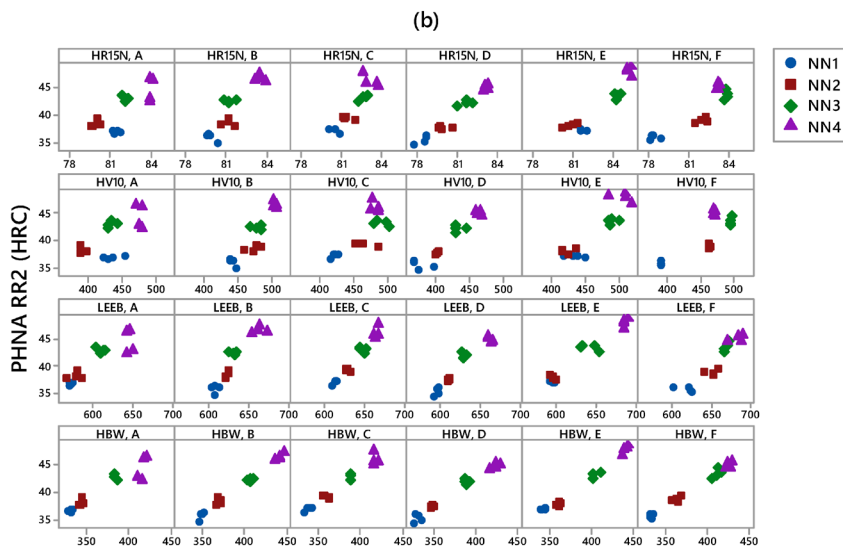


Figure 6b—Correlation Plots of Precipitation Hardened Nickel Alloys, 2nd Round Robin Test

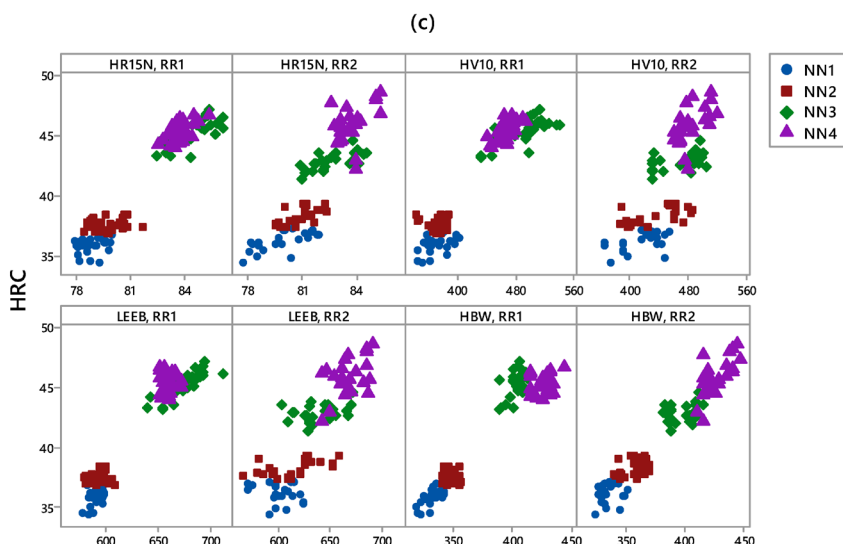


Figure 6c—Correlation Plots of Precipitation Hardened Nickel Alloys, 1st (Excluding Facility A) and 2nd Round Robin Tests

6.4 Precision Analysis

To understand the sources of variation discussed in [6.3](#), the round robin test results were analyzed for consistency and precision per ASTM E691-22 Sections 15 through 21. Results are summarized in [Annex D](#).

The imprecisions of the results of precipitation hardened nickel alloys are attributed to facility-to-facility variations and locational non-uniformity of the samples. The effect of surface finish discussed in [6.3](#) and the equivalency of material grades in their responses to the hardness test methods are also possible contributing factors.

Based on the summary in [Annex D](#), it was decided to exclude the results of facility A from the 1st round robin tests of the precipitation hardened nickel alloys and the martensitic stainless steels in the regression analysis. Facility A was kept in the 2nd round robin test data of the precipitation hardened nickel alloys. In addition, a single outlier, the Vickers hardness at location F5 of specimen FF2 by facility F was excluded.

6.5 Hardness Conversion Results

6.5.1 General

The hardness conversion equations were derived using regression analysis. Y = Rockwell C (HRC) and X = one of the other four hardness test methods (HBW, HR15N, HV, or LEEB). After comparing several forms of equations including up to 3rd order polynomial, it was decided to keep only terms X and $1/X$ for the martensitic stainless steels and term X for the precipitation hardened nickel alloys, based on the statistical significance of the coefficients in the regression analysis. The regression was performed using statistical analysis software.

6.5.2 Martensitic Stainless Steels

[Annex E](#), [Figures E.1](#) through [E.4](#) present the regression curves including the 95 % confidence interval (C.I.) and prediction interval (P.I.) for the martensitic stainless steels. The regression results including the S and R -sq values are shown in [Table E.1](#). The regression results of LEEB-to-HRC show noticeably larger S value and lower R -sq value than the other three regressions. It is generally expected that the hardness conversions of martensitic stainless steels developed in this report are applicable to martensitic stainless steels of similar UNS composition and heat treatment.

The hardness input values (X) corresponding to the predicted nominal HRC values (Y) along with the 95 % prediction intervals (P.I.) are listed in [Table 1](#). The LEEB-to-HRC predictions have distinctively larger P.I. than the other predictions.

Table 1—MSS Hardness values (X) corresponding to predicted nominal HRC (Y)

Data set	X		Y ± P.I.	
RR1 All MSS	HBW	244, 283, 314	HRC	22, 28, 32 ±1.6
RR1 All MSS	HR15N	70.3, 74.1, 76.4	HRC	22, 28, 32 ±1.7
RR1 All MSS	HV10	250, 291, 324	HRC	22, 28, 32 ±1.7
RR1 All MSS	LEEB	517, 563, 588	HRC	22, 28, 32 ±2.6

The hardness conversions in [Table 2](#) were developed using Equations (1), (2), and (3) below from [Table E.1](#). The LEEB-to-HRC conversion is not included for the reasons stated above.

Equation (1) shows Brinell hardness (10-mm diameter tungsten carbide ball, 3000-kgf force) to Rockwell C hardness:

$$HRC = 38.7123 + 0.0502689 \cdot HBW - 6981.3 \cdot HBW^{-1} \quad (1)$$

Equation (2) shows HR15N hardness to Rockwell C hardness:

$$HRC = -355.46 + 3.42738 \cdot HR15N + 9594.54 \cdot HR15N^{-1} \quad (2)$$

Equation (3) shows Vickers hardness (500-gf force and greater) to Rockwell C hardness:

$$HRC = 34.9931 + 0.0533701 \cdot HV - 6571.11 \cdot HV^{-1} \quad (3)$$

Table 2—Approximate Hardness Conversion Numbers for Martensitic Stainless Steels

Rockwell C Hardness Number 150-kgf	Brinell Hardness Number 3000-kgf, 10-mm ball	Rockwell Superficial Hardness Number 15-kgf 15N Scale	Vickers Hardness Number 10-kgf
(HRC)	(HBW)	(HR15N)	(HV)
47	—	84.2	—
46	454	83.7	—
45	442	83.2	457
44	431	82.7	445
43	420	82.2	434
42	409	81.7	423
41	398	81.2	412
40	388	80.7	401
39	377	80.2	390
38	367	79.7	380
37	358	79.1	370
36	349	78.6	360
35	339	78.1	351
34	331	77.5	342
33	322	77.0	333
32	314	76.4	324
31	306	75.9	316
30	298	75.3	307
29	290	74.7	299
28	283	74.1	291
27	276	73.5	284
26	269	72.9	277
25	262	72.3	270
24	256	71.6	263
23	250	71.0	256
22	244	70.3	250
21	238	69.6	244
20	232	68.9	238
28	283	74.1	291

6.5.3 Precipitation Hardened Nickel Alloys

The precipitation hardened nickel alloys data exhibited large scatter per discussion in [6.3](#). The regression analysis was performed using the following data sets:

- PHNA RR1 excluding facility A.
- PHNA RR1 excluding facility A + PHNA RR2.

Figures E.5 through E.8 show the four regression curves using data set a). The regression results including the coefficients and R-sq values of both data sets a) and b) are tabulated in Table E.2. Data set a) yielded a better fit in all four regressions than those derived from data set b).

The hardness input values (X) corresponding to a predicted nominal 40 HRC (Y) along with the 95 % prediction intervals (P.I.) are listed in Table 3. The large P.I. values indicate poor predictability of the regression equations of the PHNA data. The uncertainties of the predictions would be even greater when imprecisions of the individual hardness test method are considered.

Table 3—PHNA Hardness values (X) corresponding to predicted nominal 40 HRC (Y)

Data set	X		Y ± P.I.	
RR1 excluding A	HBW	368	HRC	40 ±2.3
RR1 excluding A	HR15N	81	HRC	40 ±3.3
RR1 excluding A	HV10	422	HRC	40 ±4.5
RR1 excluding A	LEEB	621	HRC	40 ±3.5

Reliable hardness conversions cannot be developed for PHNA using the hardness results documented in this report. The regression results of PHNA in Annex E shall not be used for materials acceptance or rejection purposes.

7 Conclusions

Precision analysis according to ASTM E691-22 found that facility A is a major contributor among all facilities to the uncertainties of the 1st round robin test results of martensitic stainless steels and precipitation hardened nickel alloys. The 2nd round robin test of precipitation hardened nickel alloys showed poorer correlations between HRC and other hardness scales than the 1st round robin test partly due to locational non-uniformity of the samples. Therefore, reliable hardness conversions cannot be developed for precipitation hardened nickel alloys using the hardness results documented in this report.

The hardness conversion equations for martensitic stainless steels were developed using regression analysis and the data sets excluding facility A. LEEB-to-HRC conversion for martensitic stainless steels from the results of this report is not recommended due to the lower confidence in its regression analysis.

The results of the 1st round robin hardness test program indicate that some of the existing hardness conversions in ASTM E140 Table 1 for non-austenitic steels, particularly the HRC to HBW conversion, are not appropriate for martensitic stainless steels, such as those included in NACE MR0175/ISO 15156.

8 Recommendations

Based on the test results and conclusions, it is recommended that the hardness conversion table and equations developed for the martensitic stainless steels through this test program be used to ballot new hardness conversion table with corresponding hardness conversion equations for ASTM E140.

In the absence of the adoption of the hardness conversion table and corresponding equations of the martensitic stainless steels in ASTM E140, it is recommended the hardness conversion table and corresponding hardness equations be acceptable for conversions required for API equipment.

The regression results of precipitation hardened nickel alloys in Annex E should not be used for purposes of materials acceptance or rejection. No hardness conversion of precipitation hardened nickel alloys can be recommended from the results of this report for adoption into either API standards or ASTM E140.

Annex A (informative)

Material Certification Information

A.1 Martensitic Stainless Steels

Material Designation: AISI 410

Reference Specification(s): MPS 2300.R Rev. 9, 10/08; NACE MR0175 ISO 15156-3 2009+Cir1:2011

Size: 6.00 in. diameter

Chemical Composition:

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb
0.126	0.36	0.54	0.018	0.0015	13.15	0.04	0.43	0.05	0.029

V	Ti	Al	N	Fe
0.050	0.003	0.005	0.0590	85.10

Test Specimen SS-1

Heat Treatment:

Austenitize at 1000 °C for 4.5 hours and oil quench

Temper at 720 °C for 7 hours and air cool

Temper at 650 °C for 8 hours and air cool

Hardness: 237, 237, 236, 237 HBW

Test Specimen SS-2

Heat Treatment:

Austenitize at 1750 °F for 3 hours and oil quench

Temper at 1175 °F for 4 hours and air cool

Temper at 1150 °F for 4 hours and air cool

Hardness: Aim for 22–25 HRC

Test Specimen SS-3

Heat Treatment:

Austenitize at 1750 °F for 3 hours and oil quench

Temper at 1050 °F for 4 hours and air cool

Temper at 1025 °F for 4 hours and air cool

Hardness: Aim for 26 - 34 HRC

Test Specimen SS-4

Heat Treatment:

Austenitize at 1750 °F for 3 hours and oil quench

Temper at 675 °F for 4 hours and air cool

Temper at 650 °F for 4 hours and air cool

Hardness: Aim for 39 - 44 HRC

Material Designation: UNS S41500/UNS S42400

Reference Specification(s): ASTM A182 F6NM UNS S41500

Size: 180 mm diameter × 50 mm thick

Chemical Composition:

C	Mn	Si	Cr	Ni	Mo	P	S	N
0.013	0.69	0.43	13.06	4.00	0.54	0.019	0.0010	0.012

Test Specimen FF-1

Heat Treatment:

Solution Anneal at 1050 °C for 5 hours and air cool

Temper at 680 °C for 6 hours and air cool

Temper at 620 °C for 6 hours and air cool

Hardness: 240 HBW estimated

Test Specimen FF-2

Heat Treatment:

Solution Anneal at 1050 °C for 5 hours and air cool

Temper at 680 °C for 6 hours and air cool

Temper at 590 °C for 6 hours and air cool

Hardness: 260 HBW estimated

Test Specimen FF-3

Heat Treatment:

Solution Anneal at 1050 °C for 5 hours and air cool

Temper at 620 °C for 6 hours and air cool

Hardness: 280 HBW estimated

Test Specimen FF-4

Heat Treatment:

Solution Anneal at 1050 °C for 5 hours and air cool

Temper at 600 °C for 6 hours and air cool

Hardness: 300 HBW estimated

Test Specimen FF-5

Heat Treatment:

Solution Anneal at 1050 °C for 5 hours and air cool

Temper at 570 °C for 6 hours and air cool

Hardness: 320 HBW estimated

Material Designation: UNS J91540

Reference Specification(s): ASTM A487 Gr CA6NM Class B, MS03356 R2

Size: 100 mm × 100 mm × 150 mm

Chemical Composition:

C	Mn	Si	Cr	Ni	Mo	P	S	Cu	V	W
0.028	0.590	0.680	12.060	3.870	0.500	0.020	0.004	0.100	0.000	0.00

Test Specimen CC-1A and CC1B

Heat Treatment:

Normalize at 1050 °C for 5 hours and air cool

Temper at 680 °C for 6 hours and air cool

Temper at 620 °C for 8 hours and air cool

Hardness: 240 HBW estimated

Material Designation: UNS J91540

Reference Specification(s): ASTM A487 Gr CA6NM Class B, MS 02649 R2

Chemical Composition:

C	Mn	Si	Cr	Ni	Mo	P	S	Cu	V	W
0.027	0.80	0.40	11.66	4.26	0.470	0.017	0.002	0.083	0.028	0.022

Test Specimen CC-2

Heat Treatment:

Normalize at 1050 °C for 5 hours and air cool

Temper at 680 °C for 6 hours and air cool

Temper at 590 °C for 6 hours and air cool

Hardness: 260 HBW estimated

Test Specimen CC-3

Heat Treatment:

Normalize at 1050 °C for 5 hours and air cool

Temper at 620 °C for 6 hours and air cool

Hardness: 280 HBW estimated

Test Specimen CC-4

Heat Treatment:

Normalize at 1050 °C for 5 hours and air cool

Temper at 600 °C for 6 hours and air cool

Hardness: 300 HBW estimated

Test Specimen CC-5

Heat Treatment:

Normalize at 1050 °C for 5 hours and air cool

Temper at 570 °C for 6 hours and air cool

Hardness: 320 HBW estimated

A.2 Precipitation Hardened Nickel Alloys

Material Designation: UNS N09925 (Test Specimen NN1)

Reference Specification(s): ANSI/NACE MR0175/ISO 15156-3:2009, Cir.1:2011, Cir.2:2013, Cir.3:2014, Cir.4:2014

Size: 6.50 in. diameter

Chemical Composition:

C	Mn	Si	Cr	Ni	Mo	S	P	Cu	Al	Ti
0.011	0.50	0.04	21.2	43.9	2.91	0.0003	0.017	1.93	0.25	2.15

Nb	Ta	Fe	Ni + Co	Nb + Ta						
0.30	<0.005	26.6	44.0	0.30						

Heat Treatment:

Solution annealed

Aged

Hardness: 35 HRC

Material Designation: UNS N07718 OP (Test Specimen NN2)

Reference Specification(s): API 6A718 2nd Edition, December 2009, ANSI/NACE MR0175/ISO 15156-3: 2009, Cir.1:2011, Cir.2:2013, Cir.3:2014, Cir.4:2014

Size: 6.00 in. diameter

Chemical Composition:

C	Mn	Si	Cr	Ni	Mo	S	P	Cu	Co	Al
0.019	0.08	0.07	18.7	54.6	3.04	0.0002	0.007	0.04		

Sn	Ti	Nb	Ta	B	Pb	Mg	Fe	Nb+Ta	Se	Bi
<0.0050	0.88	5.02	<0.005	0.0041	<0.0005	<0.0010	17.03	5.02	<0.0003	<0.00003

Ca										
.0030										

Heat Treatment:

Solution annealed

Aged

Hardness: 37–38 HRC

Material Designation: UNS N07716 (Test Specimen NN3)

Reference Specification(s): ANSI/NACE MR0175/ISO 15156-3:2009, Cir.1:2011, Cir.2:2013, Cir.3:2014, Cir.4:2014

Size: 6.00 in. diameter

Chemical Composition:

C	Mn	Si	Cr	Ni	Mo	S	P	AL	Ti	Nb
0.01	0.04	0.07	21.2	61.5	8.06	0.0002	0.009	0.22	1.39	3.61

Fe										
3.84										

Heat Treatment:

Solution annealed

Aged

Hardness: 41–42 HRC

Material Designation: UNS N07718 AS (Test Specimen NN4)

Reference Specification(s): Similar to ASTM B637, AMS 5663

Size: 6.125 in. diameter

Chemical Composition:

Ni	Fe	Cr	Mo	Cu	Nb	Ti	Al	S	P	C
53.6	17.5	18.8	3.0	—	5.15	0.89	0.56	0.001	0.007	0.033

Heat Treatment:

Solution annealed

Aged

Hardness: 41.7 HRC

A.3 1st Round Robin Test Hardness Calibration Blocks

HRC Low Hardness Calibration Block

Hardness: 25.29 HRC

HRC High Hardness Calibration Block

Hardness: 46.02 HRC

HR15N Low Hardness Calibration Block

Hardness: 72.18 HR15N

HR15N High Hardness Calibration Block

Hardness: 85.44 HR15N

HV Low Hardness Calibration Block

Hardness: 236 HV

HV High Hardness Calibration Block

Hardness: 436 HV

Leeb Hardness Calibration Block

Hardness: Surface A—596.0 HLD, Surface B—597.0 HLD

HBW Low Hardness Calibration Block

Hardness: 225 HBW

HBW High Hardness Calibration Block

Hardness: 417 HBW

Annex B (informative)

Hardness Calibration Results

B.1 1st Round Robin Test

Table B.1—Hardness Calibration Results for Test Facility A

Calibration Block Results—Day 1 of Testing										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block	25.29	25.1			436	416	596	589	225	337
High Hardness Block	85.44		72.18	70.69						
Date of Test										

Table B.2—Hardness Calibration Results for Test Facility B

Calibration Block Results—Day 1 of Testing										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block					236	238				
High Hardness Block					436	442				
Date of Test					7/27/2018					
Calibration Block Results—Day 2 of Testing (if needed)										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block							597	596		
High Hardness Block							596	594		
Date of Test							7/31/2018			
Calibration Block Results—Day 3 of Testing (if needed)										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block	25.29	24.7	72.18	72.0						
High Hardness Block	46.02	45.8	85.44	84.6						
Date of Test	8/2/2018		8/2/2018							
Calibration Block Results—Day 4 of Testing (if needed)										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block									225	223
High Hardness Block									417	414
Date of Test									8/3/2018	
Calibration Block Results—Day 5 of Testing (if needed)										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block	25.29	24.8								
High Hardness Block	46.02	45.8								
Date of Test	8/22/2018									



Table B.3—Hardness Calibration Results for Test Facility C

Calibration Block Results—Day 1 of Testing										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block	25.29	24.85	72.18	71.58	236	238.3	596	596	225	229
High Hardness Block	46.02	45.77	85.44	85.55	436	436.8			417	415
Date of Test	1/25/2019		1/28/2019		1/29/2019		2/4/2019		2/5/2019	
Calibration Block Results—Day 2 of Testing (if needed)										
	HRC		HR15N		HV10		LEEB		HBW 10/3000	
	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading	Value on Block	Actual Reading
Low Hardness Block					236	238.8	596	595	225	229
High Hardness Block					436	437.6			417	415
Date of Test					1/30/2019		2/5/2019		2/6/2019	