Proceedings of the ASME 2022 14th International Pipeline Conference
IPC2022
September 26-30, 2022, Calgary, Alberta, Canada
IPC2022-87069

DUCTILITY-DRIVEN RANKING SYSTEM FOR API-GRADE STEELS IN HIGH PRESSURE GASEOUS HYDROGEN TRANSMISSION PIPELINE ENVIRONMENTS

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ABSTRACT

There is strong economic and environmental interest in hydrogen as an energy source to contribute to combatting climate change. Hydrogen diffusion into the steel with assistance through various mechanisms of corrosion and pressure will degrade the mechanical properties, primarily critical ductility properties of fracture toughness and fatigue, through embrittlement or hydrogen induced cracking. Fracture toughness as a measure of crack arrest performance through required Charpy (TCVN) performance represents a principal mechanical property requirement of the pipeline. Ductility performance, regardless of the environment, which consists of % RA, fracture toughness, fatigue, etc. is driven primarily by metallurgical components of the through-thickness microstructure such as average high angle grain boundary (HAGB) unit cell size and homogeneity of the HAGB's. A relationship can perhaps be developed of ductility attributes such as TCVN performance in air vs. fracture toughness in hydrogen. This correlation between TCVN ductility performance, in conjunction with through-thickness microstructural components, and fracture toughness performance in hydrogen will be used to create a ranking methodology and perhaps propose an additional "Option C" qualification to the ASME B31.12 Code for Hydrogen Piping and Pipelines. This paper will present the background analysis, evaluation, development of the logic, proposed B31.12 code language and how to implement the logic.

Keywords: Ductility, Fracture, Fatigue, Hydrogen, Microstructure, Pipeline steel

NOMENCLATURE

Dc20% - 20% of the area fraction of thru-thickness grains are greater than a specific critical grain size as determined by EBSD analysis.
DWTT - Drop Weight Tear Test
EBSD – Electron BackScatter Diffraction
EIGA - European Industrial Gas Association
FATT – 50% Ductile to Brittle Transition Temperature
HAGB - High Angle Grain Boundaries (≥ϑ15°)
IGC - Industrial Gas Companies
SMYS – Specified Minimum Yield Strength
TCVN - Transverse Charpy V-notch

1. INTRODUCTION

of Fracture toughness and fatigue crack growth rate are key pipeline steel ductility properties and these properties have been shown to degrade by 30% to 70% , for fracture toughness, and 10x, for fatigue crack growth rate, in the presence of high pressure gaseous hydrogen compared to that in air[1,2,3,4,5]. Ductility performance of pipeline steels is predominately driven by through-thickness metallurgical attributes of grain size and homogeneity, fine characteristic unit cell size of High Angle Grain Boundaries (HAGB), and microstructural banding tendencies[6,7]. There seems to be a relationship of these key ductility microstructural attributes to the ductility performance in high pressure gaseous hydrogen measured with fracture and fatigue tests. Understanding those relationships to the overall ductility performance can be used to develop an evaluation methodology for ranking steels in high pressure gaseous hydrogen applications. This can be further expanded to develop a methodology to characterize the overall ductility performance of a given steel as part of a qualification process to assure that there is sufficient ductility to accommodate the degradation seen in high pressure hydrogen applications. Since both fracture toughness and fatigue crack growth rate are mechanical properties of ductility, characterizing the fracture toughness performance is the simplest and least costly or time-consuming methodology that can be used.

Current available guidelines and codes for hydrogen pipeline service, EIGA Hydrogen Pipeline Systems IGC Doc 121/14 and ASME B31.12 – 2019 Hydrogen Piping and Pipelines, are driven by strength of the grades for qualification for hydrogen service[7,8]. IGC Doc 121/14 specifically covers grades up API X52 maximum for hydrogen pipeline applications. ASME B31.12-2019 has Option A qualification which limits maximum yield strength to 483 MPa (70 ksi) which in practicality covers up to API X60 with a minimal TCVN toughness requirement. Option A also has reduced limitations on operating pressure of 50% SMYS maximum. B31.12-2019 also has Option B qualification which limits maximum yield strength to 550 MPa (80 ksi) which in practicality covers up to API X65 with additional testing for determination of K_{IH} (via Article KD-10) with a limit of 55 MPa-m$^{0.5}$ minimum and fatigue crack growth rate testing. All of this is more of a strength-based methodology.

While increasing strength tends to decrease overall ductility performance, in the case of API Grade pipeline steels, metallurgical design strategies (alloy+processing) have created the opportunity to design higher strength steels with excellent overall ductility. Since hydrogen does not degrade strength properties in ferritic steels but degrades ductility properties, the methodology for qualification should be based on the overall ductility performance of the steel in high pressure gaseous hydrogen and not the strength [9,10].

A ductility-based option for ranking and potentially qualifying steels for hydrogen service could be introduced as a modification to the ASME B31.12 code for hydrogen piping and pipelines as an “Option C”. This would include TCVN testing along with detailed microstructural characterization and testing in high pressure gaseous hydrogen for fracture toughness (ASTM E1820-type) and perhaps fatigue crack growth rate. This could be further applied to the weld HAZ and weld metal. The cutoff values in this work for TCVN average energy and standard deviation energy are based on experience and may change as a result of discussions with code committees and industry. This work will describe the steps in this potential code modification and how each relates to the overall ductility of a steel. We will show this analysis using data on API pipeline steels from the literature tested at numerous laboratories in the U.S. and Canada.

2. MATERIALS AND METHODS

2.1 API X-grade Steel Ductility Performance

Ductility performance in all structural steels, including API grades, which includes properties and parameters such as fracture toughness, fatigue performance, % reduction of area (RA), elongation, and formability is driven by through-thickness microstructural attributes and can be described in Equation 1[6,11,12,16]:

$$50\%FATT(^\circ C) = -11Mn + 42Si + 700(Nfree)^{\frac{1}{2}} + 15(\%pearl + \%M/A)^{\frac{1}{3}} + 0.5\Delta\sigma_y - 14\left(D_{mean_{15^\circ}}\right)^{-\frac{1}{2}} + 39\left(\frac{Dc20\%}{D_{mean_{15^\circ}}}\right)^{\frac{1}{2}} + 23.9{D_{M/A}}^{1/2} \quad (1)$$

The contributing factors above and equation below are focused on fracture toughness, but those same metallurgical components are what also affect all the other ductility properties. The equation relates the fracture appearance transition temperature (50%FATT) to parameters such as the amount of alloying elements (Mn, Si and N), microstructural constituents (pearlite and martensite/austenite, M/A, constituents), yield strength, grain size and grain boundary parameters[7]. Two key parameters are the average unit cell size of features with HAGB ($D_{mean\_15^\circ}$, shortened to *D15°*) and the heterogeneity factor of the HAGB, *Dc20%/D15°*. In general the heterogeneity factor drives the transition temperature up while the *D15°* factor drives the transition temperature down.

Since 2005, many production API X-grade steels have been fracture and fatigue tested in high pressure gaseous hydrogen in a number of laboratories[3,5,6,14-16]. These represent steels produced and in-service since 1960's up to the 2000's and strengths from X52-X80 with various compositions and microstructural phases, Figure 1 [7, 15].

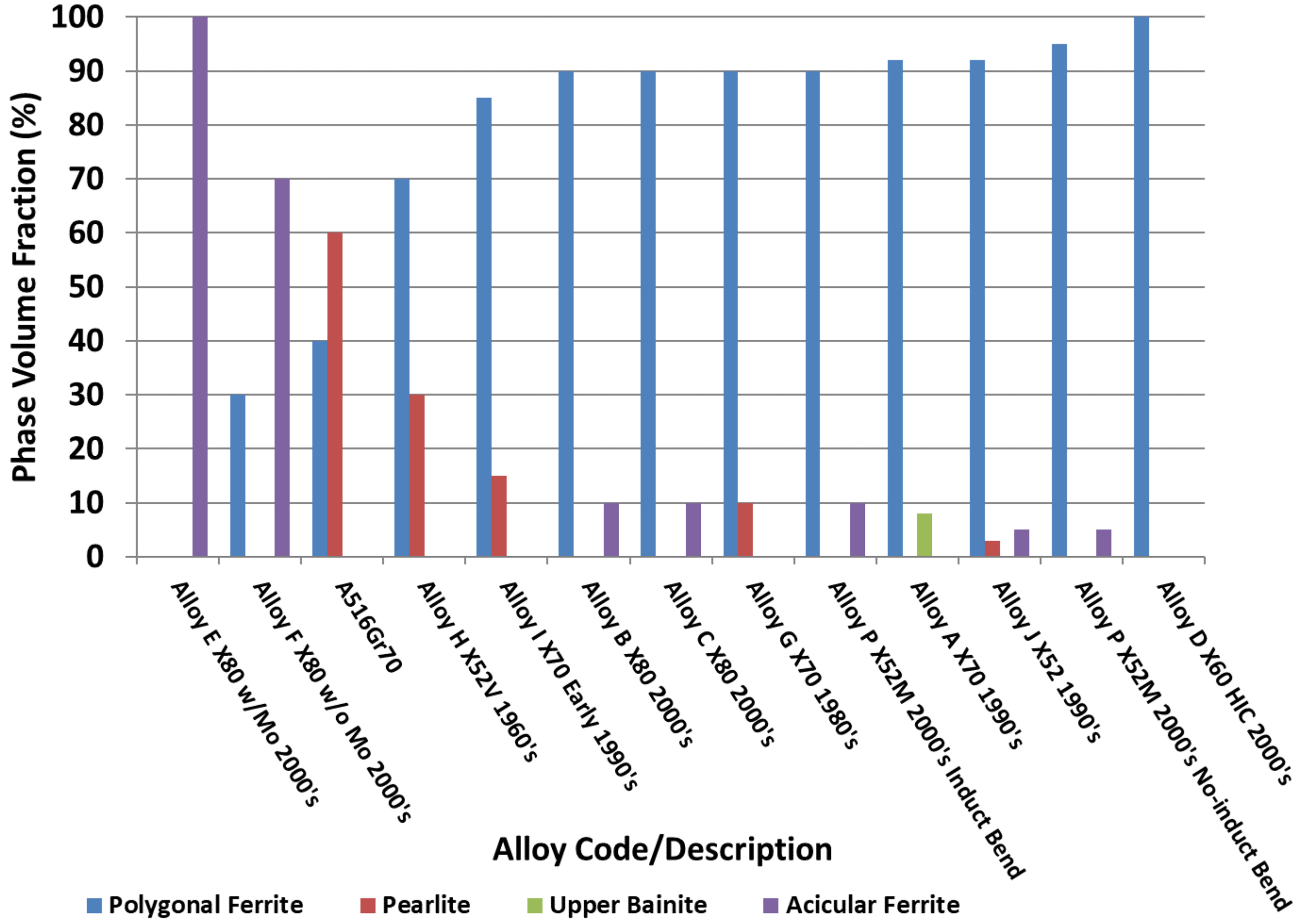


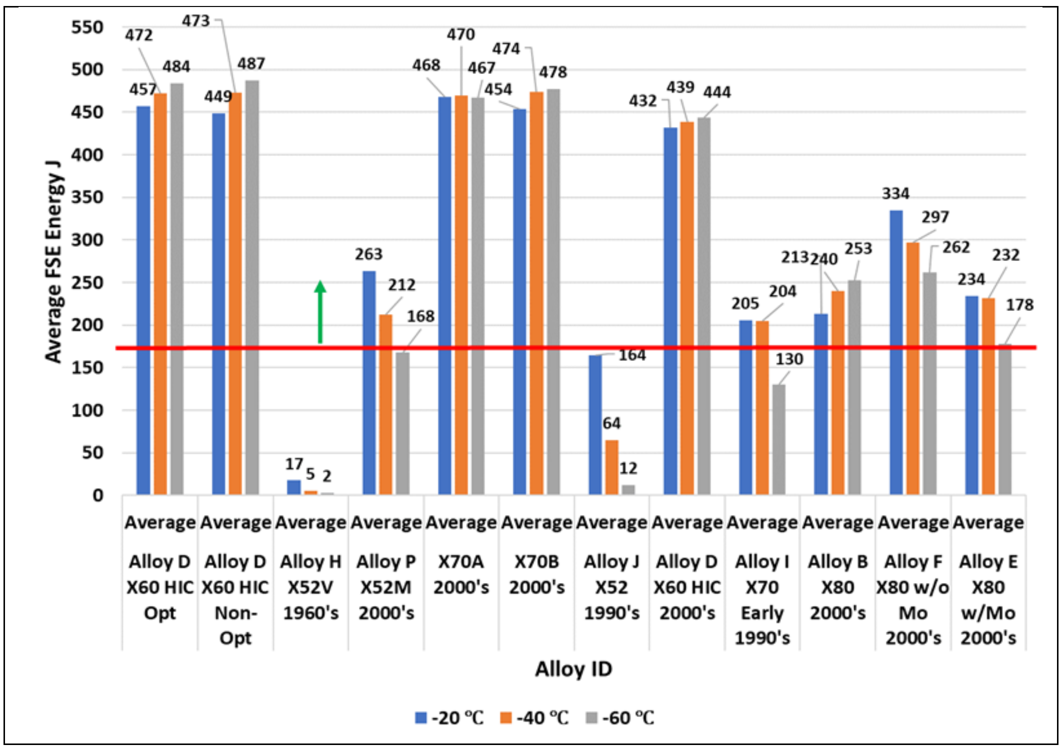
FIGURE 1. *Microstructures of various API X-grade steels tested in high pressure gaseous hydrogen.*

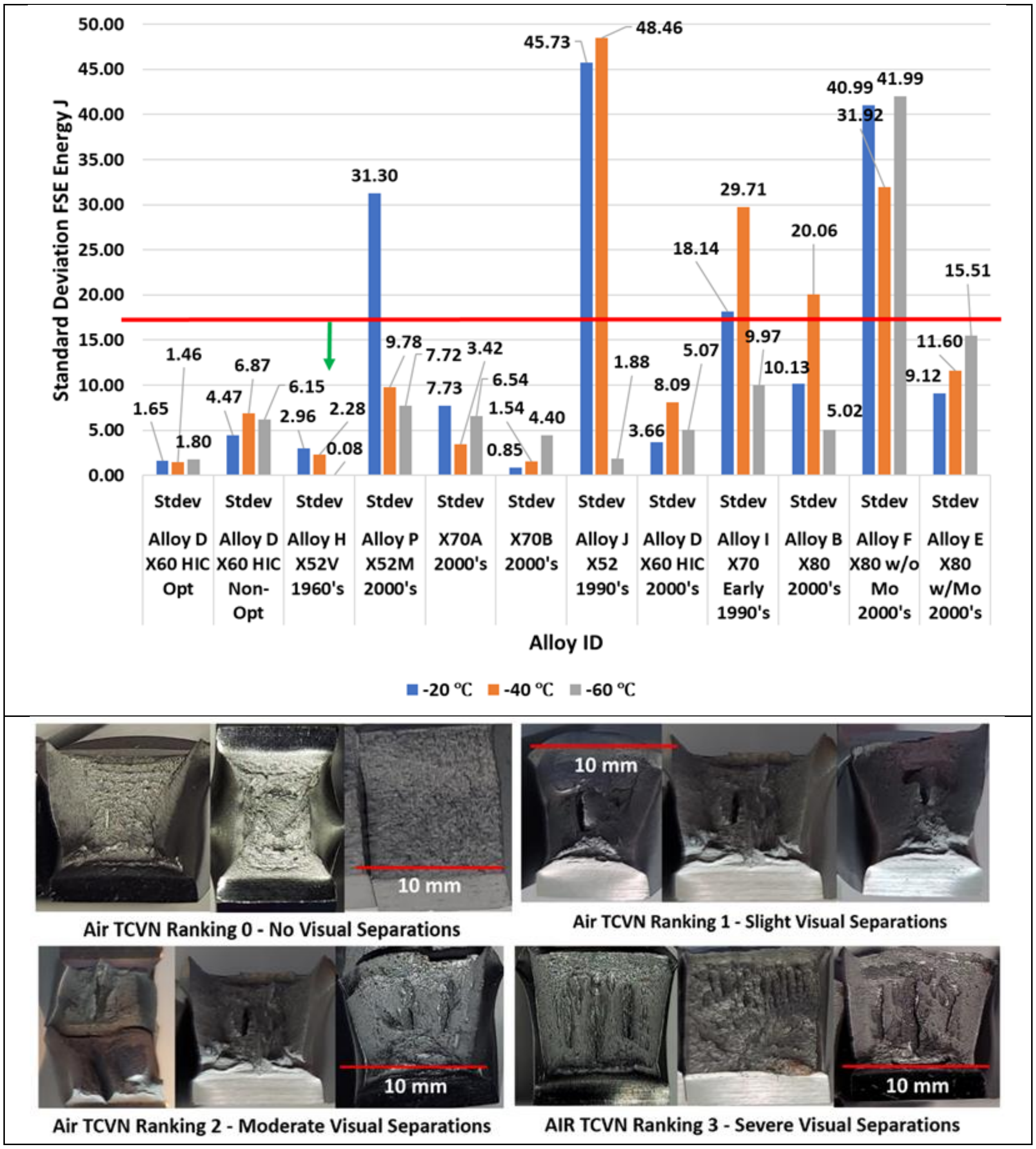
Samples from the various steels in Figure 1 were microstructurally characterized to analyze the through-thickness attributes for ductility performance as evaluated by the fracture toughness transition temperature equation, Eq. 1. One set of components in Eq. 1, $15(\%perl + \%M/A)^{\frac{1}{3}} + 23.9{D_{M/A}}^{1/2}$, relates to the homogeneity and heterogeneity of the average grain size, whereas another factor, $-14\left(D_{mean_{15^\circ}}\right)^{-\frac{1}{2}}$, relates to the average amount of high angle grain boundaries (measurable by electron backscatter diffraction, EBSD), whereas another factor, $+0.5\Delta\sigma_y$, relates to the dislocation density derived from kernel mapping (measurable by EBSD), and another factor, $+39\left(\frac{Dc20\%}{D_{mean_{15^\circ}}}\right)^{\frac{1}{2}}$, relates to the average size of the characteristic homogeneous part of the grain size distribution and the size of the characteristic heterogeneous part of the grain size distribution.

Transverse Charpy V-notch (TCVN) properties are a good starting point to define through-thickness ductility. The two main components of ductility (shown in Figure 1 equation) of D15˚ and the heterogeneity/homogeneity factor (Dc20%/D15°) can be correlated with the average TCVN values and the standard deviation in these values (between a minimum of 3 TCVN Charpy samples). HAGB D15˚ has shown a beneficial effect for ductility on fatigue crack growth in hydrogen[15]. We use cutoff values for TCVN average energy and standard deviation of that energy of 200 J and 20 J, respectively. These values are based on experience and could change based on opinions of code committees and new research.

The same steels were then tested via TCVN testing at -20 °C, -40 °C and -60 °C to establish the average energy, standard deviation energy, potential transition temperature, possible presence of fracture surface separations and in-air ductility performance within the range of test temperatures, Figure 2. The test temperatures were selected based on the lowest temperature likely to be seen in practice and the temperature where hydrogen diffusion activity is very low. The lines shown for average energy of 200 J and standard deviation of 20J are based on experience and may change based on comments from the ASME B31.12 code committee. Fracture surface separations were ranked on a scale from 0 to 3 based on increasing visual severity and is admittedly somewhat arbitrary. The ranking shown in Figure 2 represents the average for the three TCVN specimens at each temperature. Two key parameters that need to be factored into the ductility analysis which may relate to hydrogen performance are as follows:

1. All hydrogen testing is done at room temperature. It is well known that ductility will decrease with decreasing temperature.
2. The presence of fracture surface separations can be an indication of microstructural phase banding which is not desirable in the presence of hydrogen.





Standard Deviation FSE Energy J
50.00
45.00
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
1.65
1.46
1.80
4.47
6.87
6.15
2.96
2.28
0.08
31.30
9.78
7.72
3.42
7.73
6.54
1.54
0.85
4.40
45.73
48.46
1.88
3.66
8.09
5.07
18.14
29.71
9.97
10.13
20.06
5.02
40.99
41.99
31.92
9.12
11.60
15.51
Stdev Alloy D X60 HIC Opt
Stdev Alloy D X60 HIC Non-Opt
Stdev Alloy H X52V 1960's
Stdev Alloy P X52M 2000's
Stdev X70A 2000's
Stdev X70B 2000's
Stdev Alloy J X52 1990's
Stdev Alloy D X60 HIC 2000's
Stdev Alloy I X70 Early 1990's
Stdev Alloy B X80 2000's
Stdev Alloy F X80 w/o Mo 2000's
Stdev Alloy E X80 w/Mo 2000's
Alloy ID
-20 ℃
-40 ℃
-60 ℃
10 mm
Air TCVN Ranking 0 - No Visual Separations
10 mm
Air TCVN Ranking 1 - Slight Visual Separations
10 mm
Air TCVN Ranking 2 - Moderate Visual Separations
10 mm
AIR TCVN Ranking 3 - Severe Visual Separations

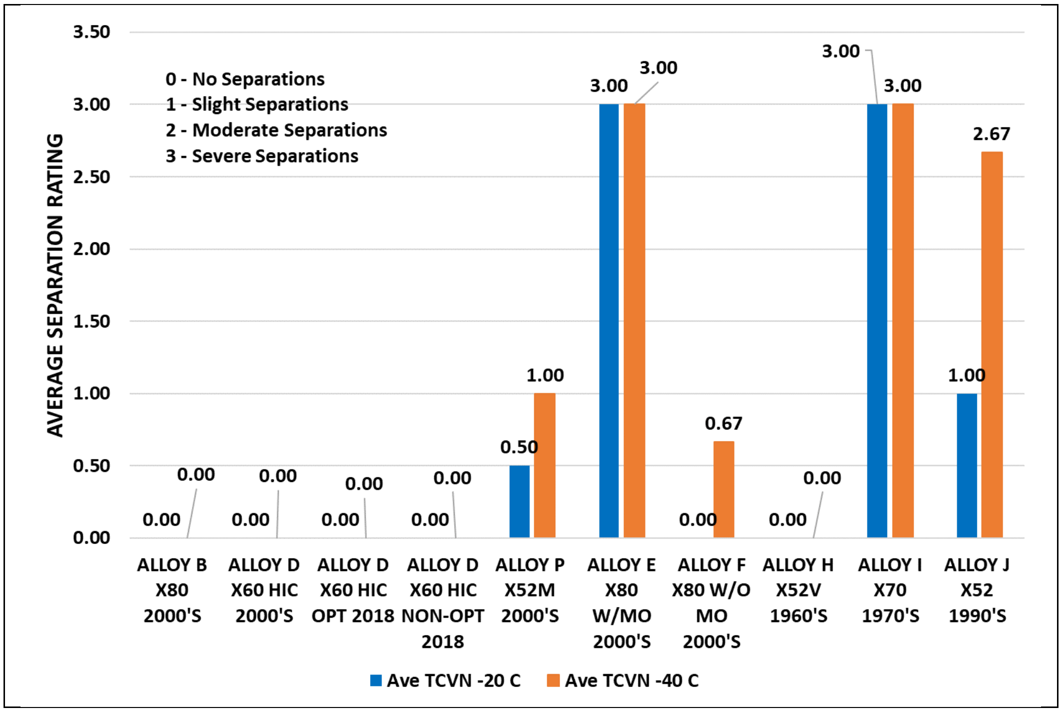


FIGURE 2. *TCVN average (top), standard deviation (next down), fracture surface separations (second from bottom) and separations ranking for various API pipeline steels at 3 test temperatures. A red line has been drawn at 200 J average and 20 J standard deviation which we selected based on our experience. The green arrows in the top two histograms show the direction of acceptable data.*

Using the data generated in the TCVN testing, a "picture" of the relative overall ductility performance between the various API X-grade steels can be used by comparing with results from fracture toughness and fatigue testing in high pressure gaseous hydrogen. Since both fracture toughness and fatigue crack growth rate are both properties of ductility that are controlled by through-thickness metallurgical attributes and TCVN fracture toughness is associated with crack arrest characteristics, the next step is fracture toughness in hydrogen, which can be considered a critical parameter for a qualification process for hydrogen service.

2.2 Hydrogen Ductility Performance

The steels shown in Figure 1 along with several others have been tested in high pressure gaseous hydrogen, typically up to 21 MPa (3000 psi), some to 35 MPa (5000 psi) and a couple to 103 MPa (15,000 psi) in both fracture toughness (ASTM E1820) and fatigue performance (ASTM E647). All E1820 tests were performed on compact tension (C(T)) specimens with geometries in accordance with ASTM E1820, with no pre-load, specimens typically in hydrogen gas for 2.5 hours before the onset of testing, and with pre-cracks of 0.45*W*. E1820 fracture toughness test results shown were performed at multiple labs (Sandia National Laboratories[18], PowerTech[1] in Canada, and NIST[7]). Figure 3 shows fracture toughness and fatigue performance of various API X-grade steels in air and hydrogen. For both fracture and fatigue, all steels follow the same general tendencies, but there are nuances that would demonstrate that some have microstructures or ductility performance that are better for hydrogen damage resistance. These steels show stable fracture toughness and fatigue performance in higher pressure gaseous hydrogen with an increase in hydrogen gas pressure. Some steels show stabilized fracture toughness results from tests in 5.5 MPA to 21 MPa hydrogen whereas some show fracture toughness decreases. For the Alloy D Opt and Non-opt steels the fracture toughness values are J_Q and not J_{IC} due to smaller specimen thickness such that conditions were not plane strain, resulting in likely toughness values in air higher than J_{IC}. It was observed for the three Alloy D steels that the one with the lowest TCVN standard deviation also had the best FCGR performance.

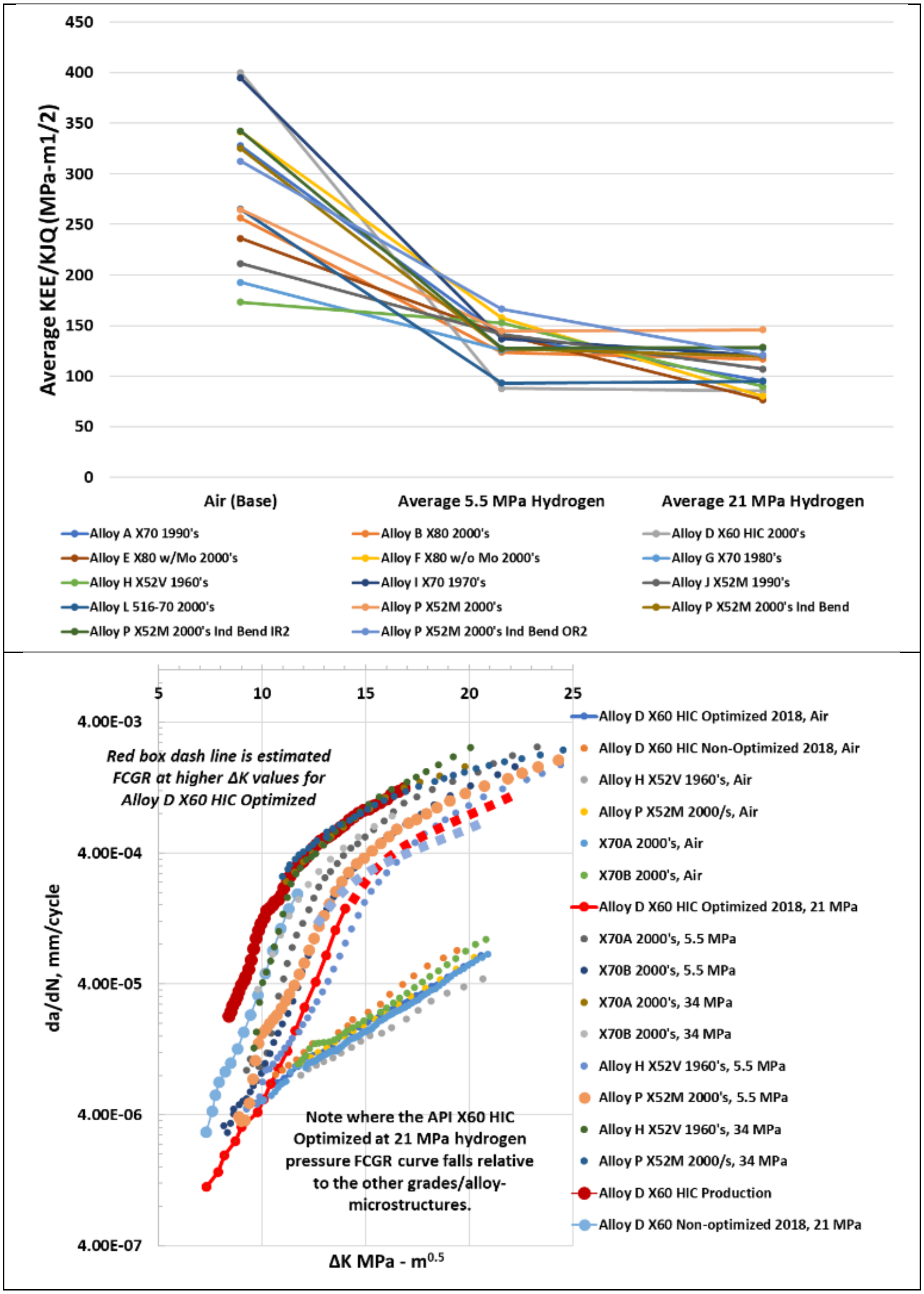


FIGURE 3. *Fracture toughness (top) and fatigue crack growth rate (bottom) in air and various hydrogen pressures of various pipeline steels. Note that the toughness values for Alloy D X60 HIC are estimates as this condition was not tested.*

In evaluating the fracture toughness testing in hydrogen, it can be seen in Figure 3 that upon exposure to hydrogen at 5.5MPa pressure the fracture toughness (ductility) decreases from that in air typically by 40% to 70% and then can continue to degrade as hydrogen pressure increases. Note that some steels, Figure 4, show that after the initial degradation, continued degradation is stabilized or ceases with increasing hydrogen pressure.

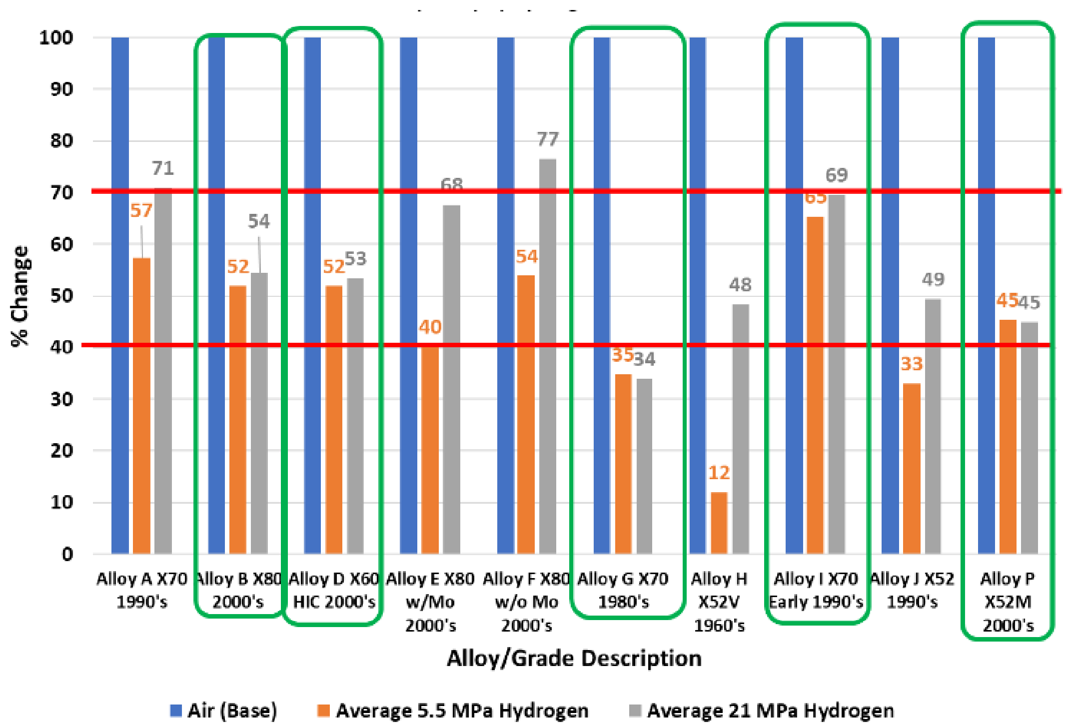


FIGURE 4. *Example of % change in fracture toughness when exposed to increasing hydrogen pressure. Note the green circled API X-grade steels had negligible changes in fracture toughness from 5.5 MPa to 21 MPa.*

The presence of separations in the fracture face of the CT specimens that were toughness tested (E1820) in both air and hydrogen can be seen similarly to what is seen in the TCVN fracture surface shown in Figure 2. Figure 5 shows examples of typical fracture surface separations and corresponding rankings, while Figure 6 shows rankings of different steels at 5.5 MPa and 21 MPa hydrogen pressure for CT specimens utilizing the same ranking system as used in the TCVN specimens. Figure 7 shows an example of an API X70 from the early 1990's tested in air, 5.5 MPa (800 psi) and 21 MPa (3000 psi) hydrogen along with the corresponding surface to center microstructure. Note the significant amount of microstructural phase banding and the corresponding fracture surface separations of increasing size and frequency as a function of increasing hydrogen pressure. Figure 8 shows an example of two API X80 steels from the 2000's with the only difference between the two being the presence of molybdenum in Alloy E and Alloy F without molybdenum. Both were tested at 5.5 MPa (800 psi), 21 MPa (3000 psi) and 103 MPa (15,000 PSI) hydrogen pressure. Note the significant difference in the fracture surface separations severity and frequency of the Alloy E with molybdenum vs. that of the Alloy F without molybdenum with increasing hydrogen pressure. There is an obvious presence of more center thickness microstructural banding present along with a higher average hardness in the center of the molybdenum-based Alloy E vs. that of the non-molybdenum-based Alloy F. It is assumed that the hydrogen in all three cases of the Alloy I X70 and the Alloy E and Alloy F X80 steels that the hydrogen is migrating to these areas of microstructural banding along with searching out additional areas of higher hardness microstructures, both of which are areas of higher stress intensity. The regions with microstructural banding tend to contain relatively hard phase constituents like MA constituents and pearlite, and often, non-metallic inclusion-like MnS. These regions may be more subject to stress-assisted hydrogen accumulation for a given loading condition, contributing to the hydrogen-related failure.

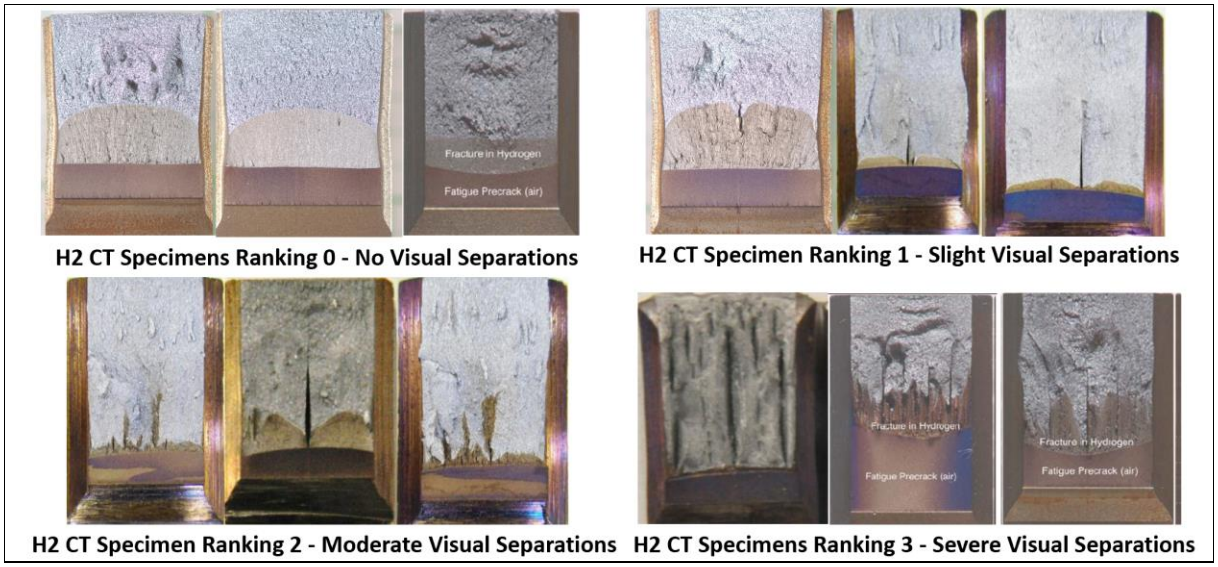


FIGURE 5. *Examples of CT specimen fracture surface separations from E1820 fracture toughness tests*

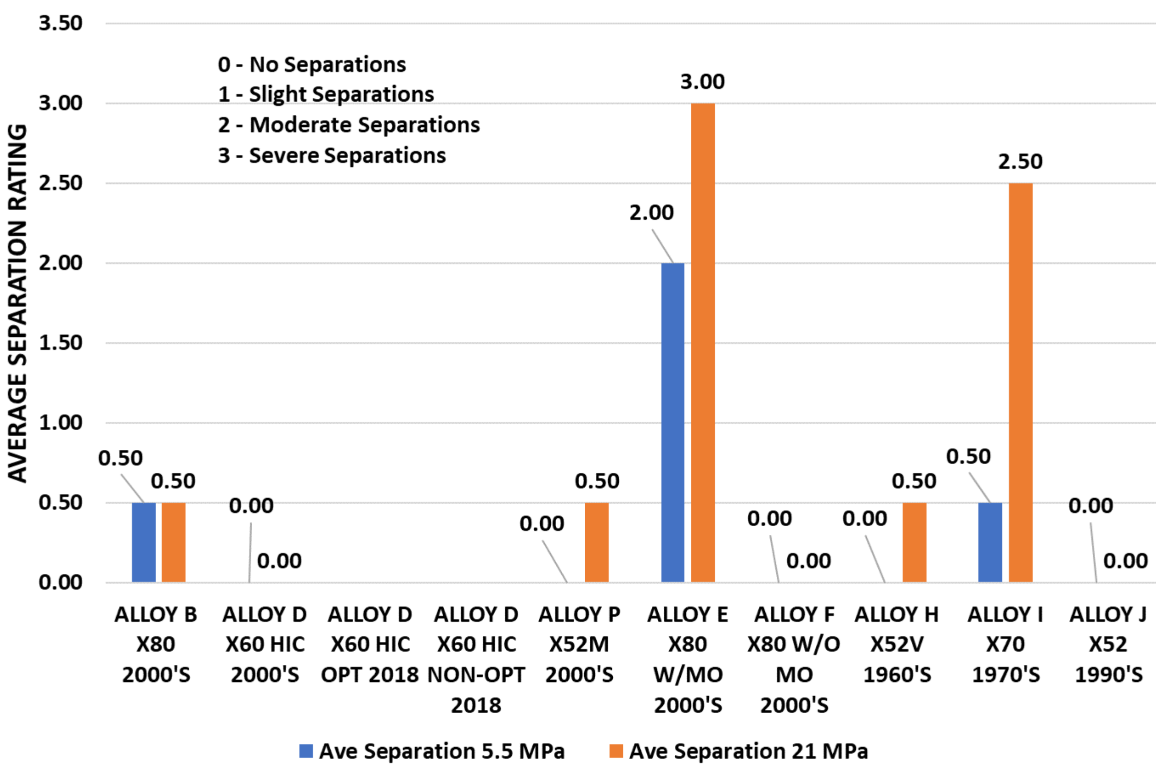


FIGURE 6. *Rankings of CT specimen fracture surface separations from E1820 fracture toughness tests in hydrogen*

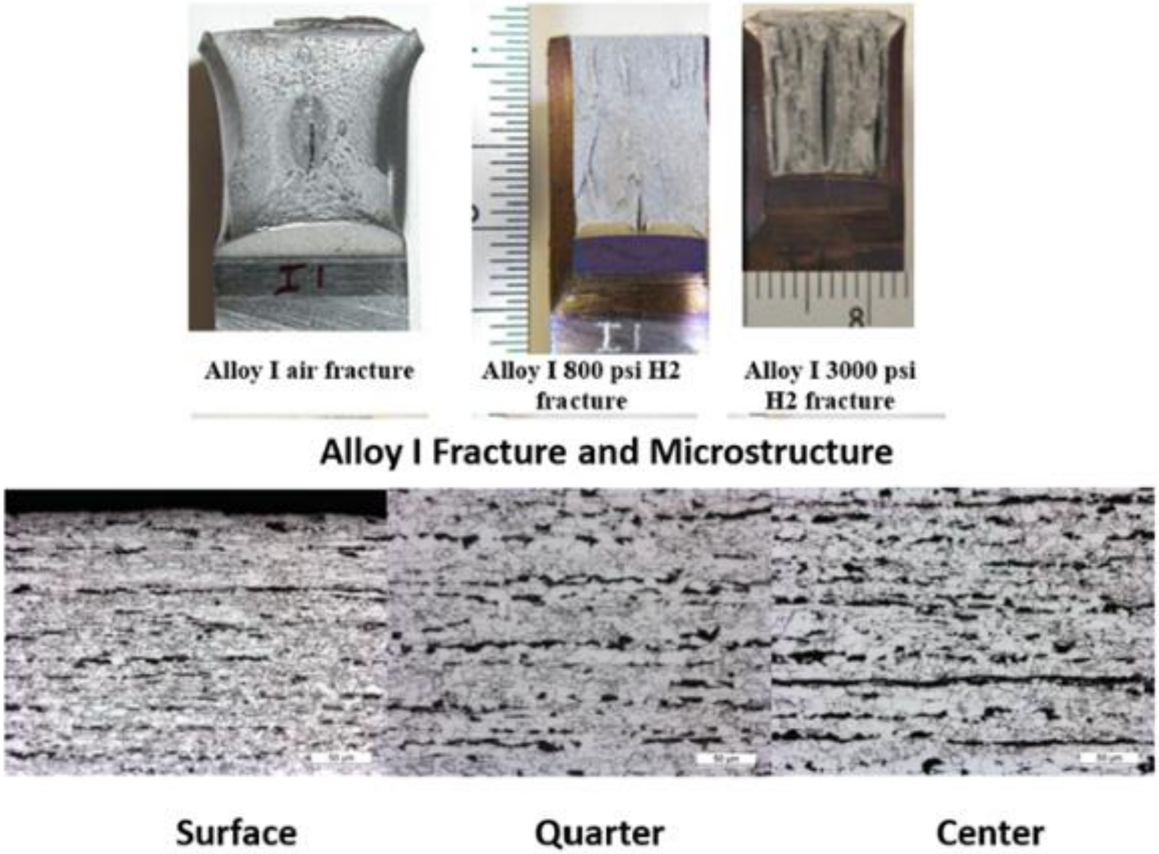


FIGURE 7. *Surface separations from E1820 fracture toughness tests in hydrogen of an X70 from the 1990s and microstructural banding from surface to center in this alloy*

FIGURE 8. *Surface separations from E1820 fracture toughness tests in hydrogen of two X80 steels from the 2000s where the top one contains molybdenum and the bottom one does not*

3. RESULTS AND DISCUSSION

3.1 Methodology for Ductility-Based Approach for Hydrogen Service Characterization/Qualification

We propose that qualification of API steels for high pressure hydrogen service should be based upon the overall ductility performance of the steel. Overall ductility performance is significantly influenced by the through-thickness average/homogeneity of the HAGB's which can be represented by the average and standard deviation performance of the TCVN results which can then be used as part of a testing methodology to characterize and qualify a steel for high pressure gaseous hydrogen service. In the comparison of TCVN performance at various temperatures with the fracture toughness in room temperature air, 5.5 MPa (800 psi) hydrogen and 21 MPa (3000 psi) hydrogen, some steels remain stable from 5.5 MPa to 21 MPa hydrogen, which was shown in Fig. 4. The steels that remained stable when tested for fracture toughness had consistently higher average TCVN energy at -40 °C (≥200 J), lower standard deviation of energy (≤20 J) and lower average fracture surface separations ranking (≤ 1.00). Those steels that continued to show degradation with increasing hydrogen pressure had various levels of inconsistent or low TCVN average energy, standard deviation energy and fracture surface separations in Charpy testing.

In comparing the TCVN -20 °C energy to the ASTM E1820 fracture toughness testing in room temperature air, the overall ductility baseline performance is similar. The observed relationship of TCVN -20 °C energy to that of ASTM E1820 room temperature air testing could be used as a starting point to correlate the base air performance expected in E1820 fracture toughness testing, Figure 9. In general, there appears to be a correlation between -20 °C TCVN energy and fracture toughness by E1820 testing in air at room temperature which possibly points toward, in several grades, that there may be adequate ductility for high pressure gaseous hydrogen applications. The polynomial relationship shown in Fig. 9 provides an R^2 value of 0.99 with a cubic function.

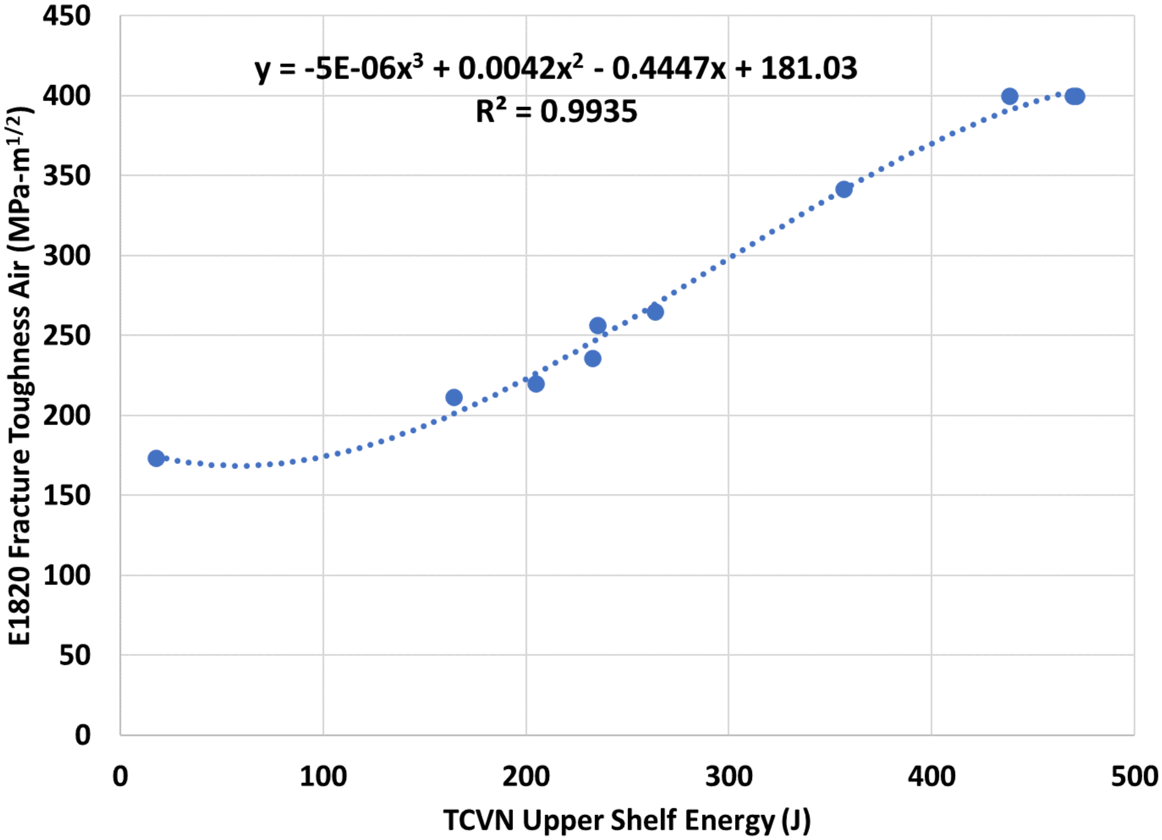


FIGURE 9. *Observed relationship of -20 °C TCVN energy with E1820 fracture toughness in room temperature air*.

We combine TCVN data and E1820 fracture toughness data on a single plot, Figure 10. Note that there is a division in the plot to emphasize the different units for TCVN energy (left side, J) and fracture toughness (right side, MPa-m$^{1/2}$). This provides a starting point for a ductility correlation methodology. All the steels tested have fracture toughness values in 21 MPa (3000 psi) hydrogen above the ASME B31.12-2019 Hydrogen Piping and Piping Pipelines Option B minimum requirement of 55 MPa-m$^{1/2}$, shown with a dashed line. However, to account for potential loss of ductility due to temperature, if a decrease is seen in TCVN average energy from -20 °C to -40 °C, this decrease could be applied to E1820 fracture toughness at 5.5 MPa (800 psi) and 21 MPa (3000 psi). There is no correlation between the mechanisms of ductility loss in this case, just a simple

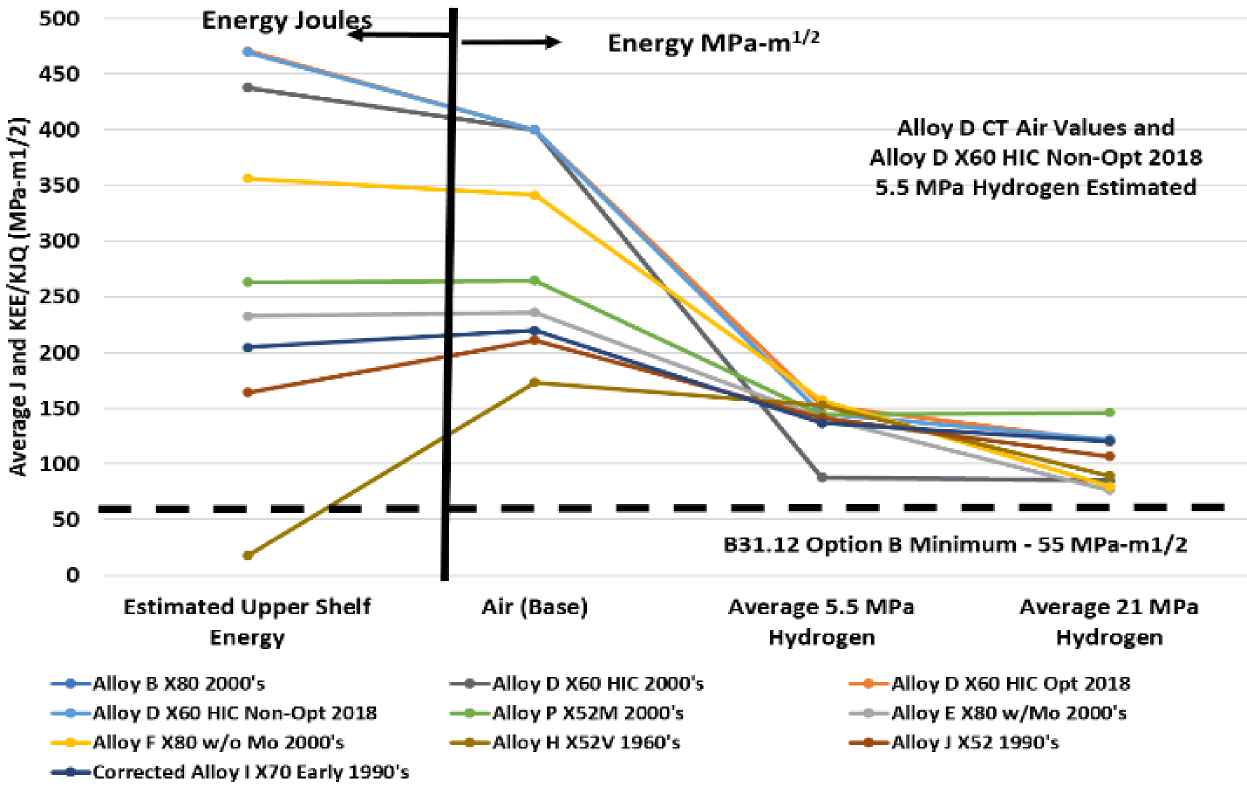


FIGURE 10. *Methodology for determining expected ductility performance using TCVN and E1820 fracture toughness testing.*

accounting of overall ductility. In the case of the ten API X-grades analyzed, four demonstrated large decreases occurring from -20 °C to -40 °C, Figure 11. The percentage decrease in ductility observed in the TCVN performance follows with what was observed in the through-thickness microstructural attributes (microstructural phases, average HAGB grain size, HAGB heterogeneity/homogeneity factor, fracture surface separations, etc.). The percentage decrease in TCVN average from -20 °C to -40 °C of the four API X-grades were as follows:

- Alloy F X80 w/o Mo 2000’s – 11 % decrease (334 J to 297 J TCVN average)
- Alloy P X52M 2000’s – 19 % decrease (263 J to 212 J TCVN average)
- Alloy J X52 1990’s – 61 % decrease (164 J to 100 J TCVN average)
- Alloy H X52V 1960’s – 71 % decrease (17 J to 5 J TCVN average)

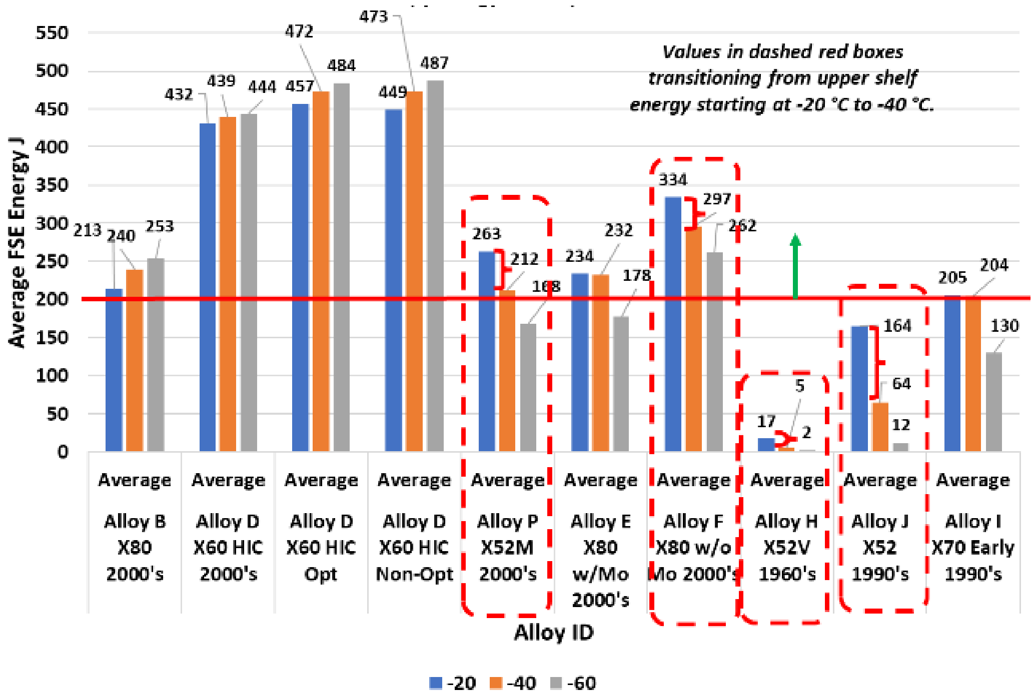


FIGURE 11. *Trends in TCVN energy at 3 temperatures. The steels in red dashed boxes show decreases in energy as a function of decreasing temperature.*

The other six API X-grades analyzed did not show any ductile to brittle transition appearing down to -40 °C. Based on that it is assumed that the ductility of the steel from TCVN testing down to -40 °C correlates roughly to that of the overall ductility of the steel shown from E8120 tests in high pressure gaseous hydrogen at room temperature (+20 °C). The E1820 results in hydrogen at 5.5 MPa and 21 Mpa hydrogen gas pressures then can be reduced by the percentages shown above for the four steels that demonstrated a start of ductile to brittle transition. This could allow for a reduction of fracture toughness values under hydrogen pressure to account for poor low-temperature toughness. Reducing the toughness values of the four steels by the percentage calculated, with no change to the remaining six steels, can be seen in Figure 12 with the inclusion of a dotted black line at the B31.12-2019 Option B minimum of 55 MPa-m$^{1/2}$ and solid green line with a suggested minimum conservative consideration. Of the ten API X-grades analyzed, only two have modified values that fall below the 55 MPa-m$^{1/2}$ minimum requirement.

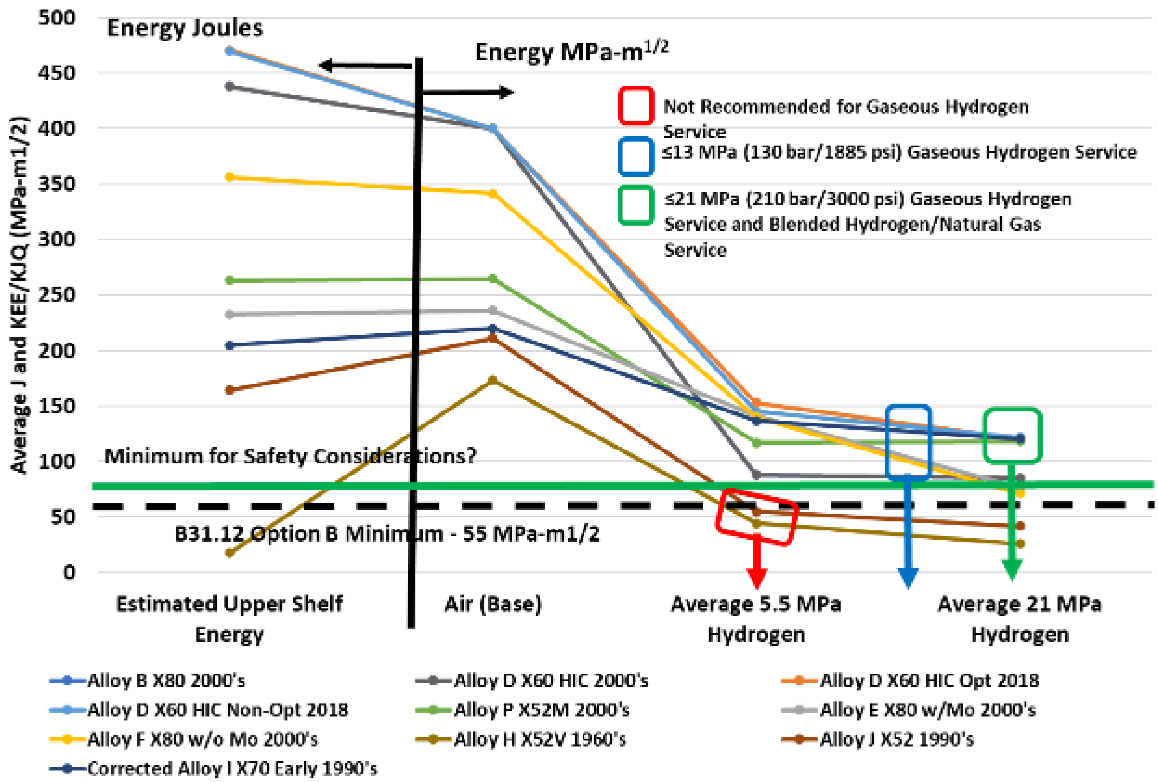


FIGURE 12. *TCVN at -40 °C and E1820 fracture toughness values in hydrogen, shown as reduced values if TCVN reduced from -20 °C to -40 °C.*

The work to this point is to help identify suitable pipeline steels for high pressure gaseous hydrogen service but has not yet accounted for potential effects from the presence of fracture surface separations (microstructural phase banding potential). To complete the analysis a composite rating system has been developed to complement the above methodology. TCVN average energy, standard deviation of energy and visual fracture face separations at -40 °C were used to create a composite rating of each steel. Ranking values that make up the composite rating along with example recommendations for each steel can be seen in Figure 13. The rankings could change based upon input from industry and the ASME B31.12 committee.

Average TCVN Egy J @ -40 °C	Ranking Value	Average TCVN Stdev J @ -40 °C	Ranking Value	Average Visual TCVN Separations in Air	Ranking Value
≥0	-4	≥40	-3	0.00	1
≥25	-3	≥30	-2	0.50	0
≥50	-2	>20	-1	1.00	-1
≥100	-1	≤20	1	1.50	-2
≥150	0	≤10	2	2.00	-3
≥200	1	≤5	3	2.50	-4
≥250	2			3.00	-5
≥300	3				
≥350	4				
≥400	5				

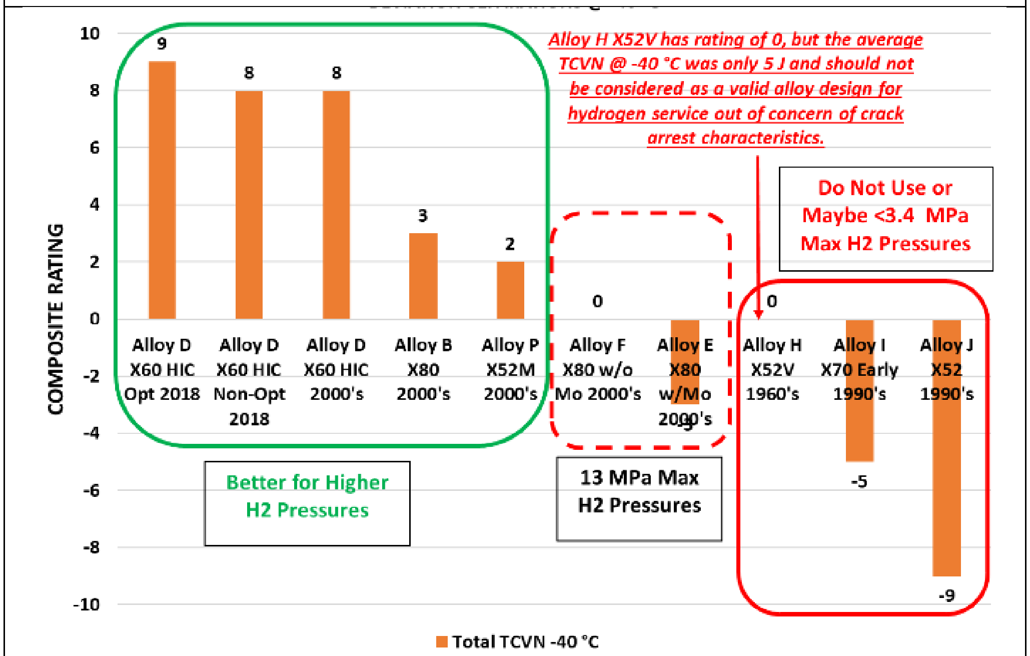


FIGURE 13. *Example of composite rating system utilizing TCVN average energy, standard deviation energy and fracture surface separations @ -40 °C*

An estimation of E1820 fracture toughness in air can be derived starting with the equation from Figure 9:

$y = 5E\text{-}6*x^3+0.0042*x^2-0.4447*x+181.03$,

where *y* is toughness and *x* is TCVN -20 °C energy.

Use of E1820 toughness correlation provides the basis for comparison between estimated and measured E1820 fracture toughness in hydrogen. This can be done by multiplying the expected E1820 air base value by 40 % and 70 % to give a range of *estimated* MPa-m$^{1/2}$ values in hydrogen testing and compared with those seen in Figure 4. The percentages given come from what is typically seen in the literature for the relative drop in fracture toughness from air to hydrogen tests.[2,10,14,19,20-22] Finally, TCVN performance values can be used to generate a composite rating, shown in Figure 13, for the desired API X-grade steel being evaluated for high pressure gaseous hydrogen service. Based on this information a decision can be made to move forward or not with E1820 fracture toughness testing in hydrogen.

Then ASTM E1820 fracture toughness testing in hydrogen utilizing a minimum of two CT specimens prepared with the notch in the TL direction to the rolling direction at a minimum of three conditions (air, 5.5 MPa and 21 MPa) hydrogen pressure should be performed to confirm the expected ductility performance relative to the 55 MPa-m$^{1/2}$ minimum requirement. An additional condition between 5.5 MPa and 21 MPa can be done at the desired operating pressure to fully confirm the desired steel's suitability for hydrogen service. After E1820 testing, the measured fracture toughness performance at 5.5 MPa (800 psi) and 21 MPa (3000 psi) should be modified if the TCVN performance shows a transition prior to -40 °C. The percentage decrease observed from the potential ductile to brittle transition from the -20 °C energy to -40 °C can be used to modify those measured values at 5.5 MPa (800 psi) and 21 MPa (3000 psi) of fracture toughness to be compared to the B31.12 minimum requirement of 55 MPa-m$^{1/2}$. This information will further assist in the decision process of what might be considered a reasonable hydrogen operating pressure.

Table 1 shows hypothetical examples of how a ductility- based methodology for qualification for hydrogen service might be utilized. All the as-measured fracture toughness values meet the B31.12 minimum requirement of 55 MPa-m$^{1/2}$ for all hydrogen pressures. However, in the hypothetical examples the X52-1 with the lower TCVN -20 °C energy and large percentage decrease in ductile to brittle transition temperature resulted in final hydrogen fracture toughness values falling below the B31.12 minimum requirement of 55 MPa-m$^{1/2}$. All the other values meet the minimum requirement with some better than others depending on the ductility performance for the grade.

TABLE 1. *Hypothetical examples of implementation of a ductility-based methodology for qualification for high pressure gaseous hydrogen applications (green text shows key parameters for making decisions on hydrogen service, whereas red values are below the ASME B31.12 toughness limit)*

Grade	**X52-1**	**X52-2**	**X70-1**	**X70-2**
TCVN -20 °C Energy J	**20**	**230**	**150**	**300**
TCVN Average Energy J @ -40 °C	**5**	**210**	**130**	**250**
TCVN Ductile to Brittle Transition % Change J (-20 °C Energy to -40 °C)	**75**	**9**	**13**	**17**
TCVN Standard Deviation J @ -40 °C	**3**	**10**	**30**	**15**
Visual Average TCVN Fracture Surface Separations Rating @ -40 °C	**0**	**0.5**	**2**	**0**
Composite TCVN Ductility Rating	**0**	**3**	**-6**	**4**
Predicted E1820 Air Room Temp MPa-m1/2 from TCVN -20 °C Energy @ -40 °C	**174**	**240**	**192**	**291**
Predicted E1820 5.5 MPa H2 Room Temp MPa-m1/2 from E1820 Air (40%)	**104**	**144**	**115**	**174**
Predicted E1820 5.5 MPa H2 Room Temp MPa-m1/2 from E1820 Air (60%)	**70**	**96**	**77**	**116**
Predicted E1820 21 MPa H2 Room Temp MPa-m1/2 from E1820 Air (40%)	**104**	**144**	**115**	**174**
Predicted E1820 21 MPa H2 Room Temp MPa-m1/2 from E1820 Air (70%)	**52**	**72**	**58**	**87**
Predicted E1820 40% 5.5 MPa offset by % TCVN ductile to brittle transition decrease	**26**	**132**	**100**	**145**
Predicted E1820 60% 5.5 MPa offset by % TCVN ductile to brittle transition decrease	**17**	**88**	**67**	**97**
Predicted E1820 40% 21 MPa offset by % TCVN ductile to brittle transition decrease	**26**	**132**	**100**	**145**

Predicted E1820 70% 21 MPa offset by % TCVN ductile to brittle transition decrease	**13**	**66**	**50**	**73**
Measured E1820 Air	**174**	**240**	**192**	**291**
Measured E1820 5.5 MPa	**100**	**165**	**130**	**155**
Measured E1820 21 MPa	**80**	**163**	**110**	**135**
Measured E1820 5.5 MPa offset by % TCVN ductile to brittle transition decrease	**25**	**151**	**113**	**129**
Measured E1820 21 MPa offset by % TCVN ductile to brittle transition decrease	**20**	**149**	**95**	**113**

4. CONCLUSION

The following conclusions can be made:

1. Using existing API X-grade steels tested in high pressure gaseous hydrogen, a relationship with TCVN fracture toughness and ASTM E1820 hydrogen fracture toughness was observed.
2. This relationship can be used to develop a ductility-based, separate from strength, methodology to assure significant ductility performance for high pressure gaseous hydrogen service.
3. The methodology can be used as a screening process and then followed up with ASTM E1820 fracture toughness testing at a minimum of 3 base conditions (air, 5.5 MPa H2 pressure and 21 MPa H2 pressure) to define the ductility degradation tendency of the steel.
4. The ductility-based methodology described can also be developed to address the weld metal and weld HAZ performance.
5. This ductility-based methodology can be implemented into the ASME B31.12 Hydrogen Piping and Pipelines code as either a modification to the existing Option B or an additional Option C approach.
6. Further development of a ranking system can be added to define varying operating regimes that correlate to the level of degradation of ductility in hydrogen.

ACKNOWLEDGEMENTS

The authors wish to thank CBMM for microstructural characterization work funding, Hyundai Steel Company RD for project specific laboratory samples, and the various steel, pipe and pipeline companies who have supplied API samples over the years for hydrogen testing.

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