Think Twice Before Flattening

David B. Futch, Francisco Linares, Tyler McDonald
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Abstract

Charpy v-Notch tests are a common laboratory test to infer the toughness of a material. These tests are quick, relatively inexpensive, and allow for the development of a ductile to brittle transition curve. Standard geometry is specified with a cross section of 10 mm x 10 mm. This cross section is typically not achievable when testing pipeline steels unless it's of thicker wall thickness and/or larger diameter so the curvature doesn't impact the specimen. Half-size (or smaller) specimens are more often than not required for vintage smaller diameter pipes.

Although not specially mentioned in industry codes and standards, fabrication of the specimens may require flatting to obtain a larger wall thickness during testing. However, flattening these specimens results in additional cold work, which may locally alter the material properties of the specimen. In some cases, it's necessary to flatten, however, in many cases a smaller subsize specimen is obtainable without flattening.

This study compares the results of flattened vs non-flattened specimens for varying vintage, seam type, and geometry (outer diameter and wall thickness). Results show both conservative and non-conservative shifts in the CVN transition curves when comparing flattened specimens to non-flattened specimens. Finally, these results are utilized to compare how the shift in CVN outputs affects a remaining life calculation where upper shelf CVN absorbed energy is an input.

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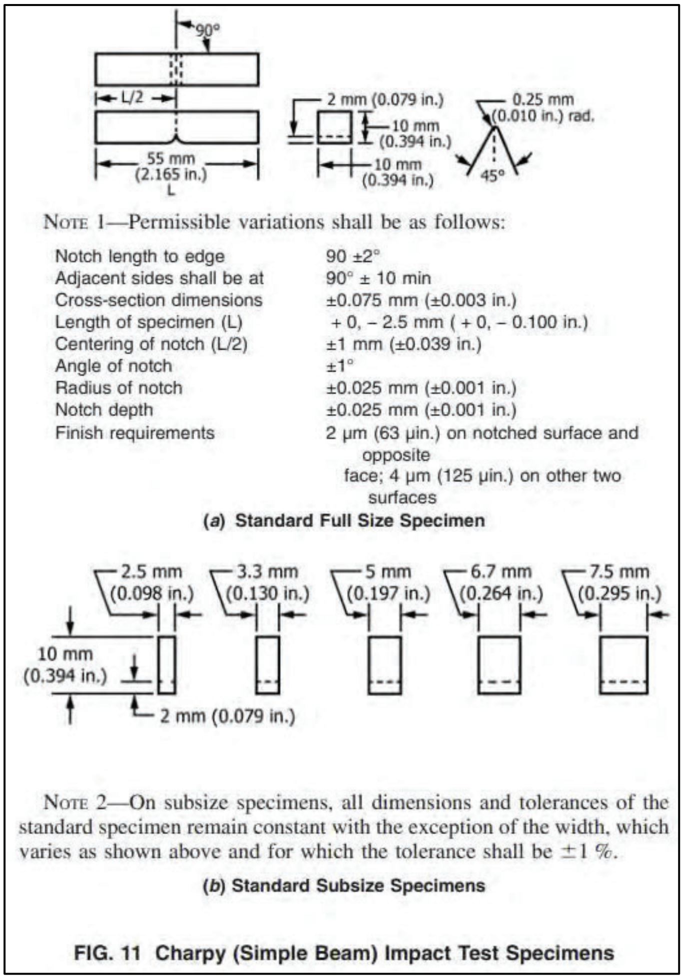
Introduction

This study examines the influence of Charpy v-Notch specimen preparation and its influence on the resulting properties, notably the absorbed energy. Charpy v-Notch tests are a common laboratory test to infer the toughness of a material. These tests are quick, relatively inexpensive, and allow for the development of a ductile to brittle transition curve.

Specimens are machined to standard sizes: full size specimens containing a cross section of 10 mm x 10 mm (0.394 in x 0.394 in) or subsize specimens when the pipe geometry does not allow for a specimen that is 10 mm (0.394 in) thick. ASTM A370 contains a schematic that shows the cross section of the resultant Charpy specimens, shown in Figure 1. A full-size cross section is typically not achievable when testing pipeline steels in the transverse direction unless it's of thicker wall thickness and/or larger diameter so the curvature doesn't impact the specimen. This results in a scenario where subsize, typically half-size (or smaller) specimens, are more often than not required for vintage smaller diameter pipes.



NOTE 1—Permissible variations shall be as follows:

Notch length to edge	90 ±2°
Adjacent sides shall be at	90° ± 10 min
Cross-section dimensions	±0.075 mm (±0.003 in.)
Length of specimen (L)	+ 0, – 2.5 mm (+ 0, – 0.100 in.)
Centering of notch (L/2)	±1 mm (±0.039 in.)
Angle of notch	±1°
Radius of notch	±0.025 mm (±0.001 in.)
Notch depth	±0.025 mm (±0.001 in.)
Finish requirements	2 µm (63 µin.) on notched surface and opposite face; 4 µm (125 µin.) on other two surfaces

(*a*) Standard Full Size Specimen

NOTE 2—On subsize specimens, all dimensions and tolerances of the standard specimen remain constant with the exception of the width, which varies as shown above and for which the tolerance shall be ±1 %.

(*b*) Standard Subsize Specimens

FIG. 11 Charpy (Simple Beam) Impact Test Specimens

Figure 1: Schematic showing varying specimen cross sections (ASTM A370).

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These cross sections imply a square (in the case of full-size specimens) or rectangular (in the case of subsize specimens) cross section that remains constant over the 55 mm (2.17 in) specimen length. In doing so, this limits the ability to machine the largest specimen possible due to curvature associated with pipe. Wall thickness required to machine a uniform, transverse specimen of various sizes are summarized in API 5CT organized by pipe diameter. API 5CT provides guidance for casing/tubing and is provided here as API 5L does not have a similar table. This guidance is shown in Figure 2. Achieving these specimen sizes are nearly impossible for smaller diameter pipe as typical vintage pipeline steels are significantly thinner than those listed in Figure 2.

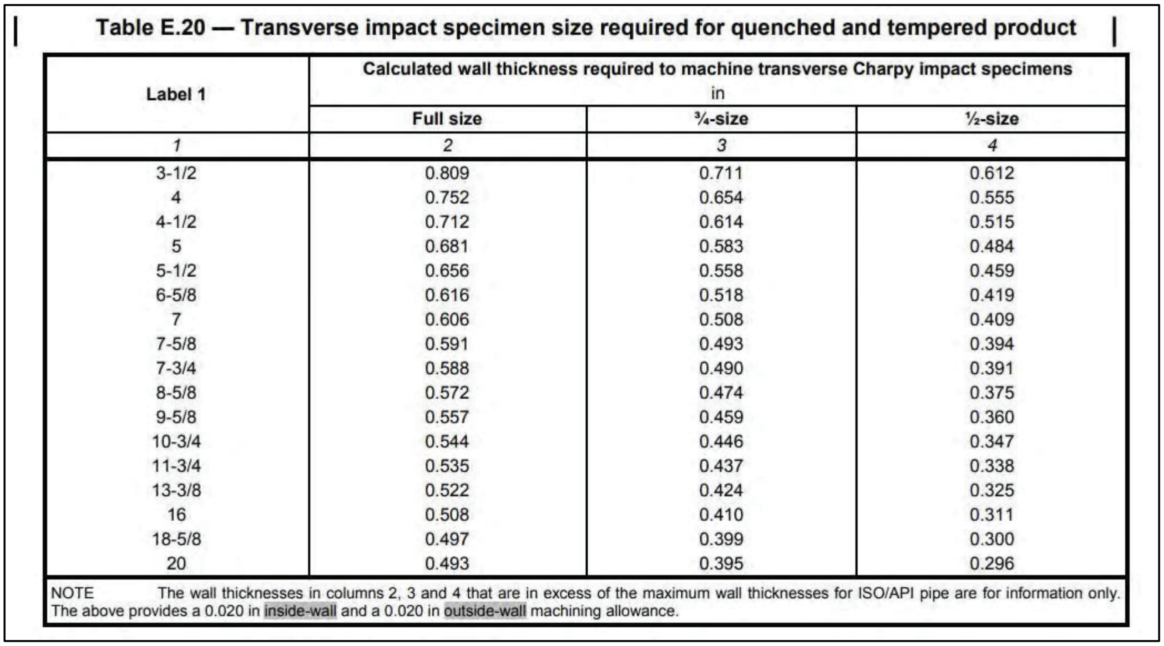


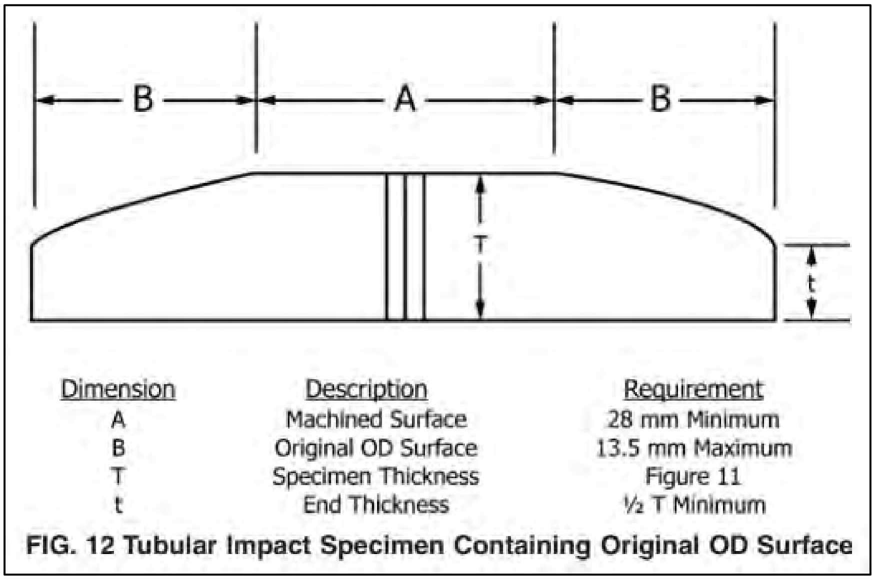
Table E.20 — Transverse impact specimen size required for quenched and tempered product

Label 1	Calculated wall thickness required to machine transverse Charpy impact specimens in		
	Full size	¾-size	½-size
1	*2*	*3*	*4*
3-1/2	0.809	0.711	0.612
4	0.752	0.654	0.555
4-1/2	0.712	0.614	0.515
5	0.681	0.583	0.484
5-1/2	0.656	0.558	0.459
6-5/8	0.616	0.518	0.419
7	0.606	0.508	0.409
7-5/8	0.591	0.493	0.394
7-3/4	0.588	0.490	0.391
8-5/8	0.572	0.474	0.375
9-5/8	0.557	0.459	0.360
10-3/4	0.544	0.446	0.347
11-3/4	0.535	0.437	0.338
13-3/8	0.522	0.424	0.325
16	0.508	0.410	0.311
18-5/8	0.497	0.399	0.300
20	0.493	0.395	0.296

NOTE The wall thicknesses in columns 2, 3 and 4 that are in excess of the maximum wall thicknesses for ISO/API pipe are for information only. The above provides a 0.020 in inside-wall and a 0.020 in outside-wall machining allowance.

Figure 2: Pipe wall thickness required to machine transverse Charpy specimens (API 5CT).

With this guidance being less than ideal for typical pipe geometry due to the curvature when machining a transverse specimen. Therefore, it's common practice to machine specimens leaving a portion of the curved external pipe surface at the edges of the specimen. This geometry is shown in Figure 3. Doing so, allows for a thicker specimen to be prepared. This is accounted for in the guidance material in API 5L, shown in Figure 4. While this increases the specimen sizes, it still results in a situation where achieving these specimen sizes are nearly impossible for smaller diameter pipes. It should be noted that the tables in API 5L only provide details down to half size specimens (5 mm x 10 mm) as this is the minimum size allowed by the standard. One third (3.3 mm x 10 mm) specimens are often used for thinner pipe material.



Dimension	Description	Requirement
A	Machined Surface	28 mm Minimum
B	Original OD Surface	13.5 mm Maximum
T	Specimen Thickness	Figure 11
t	End Thickness	½ T Minimum

FIG. 12 Tubular Impact Specimen Containing Original OD Surface

Figure 3: Schematic showing specimens prepared with a portion of the external surface (ASTM A370).

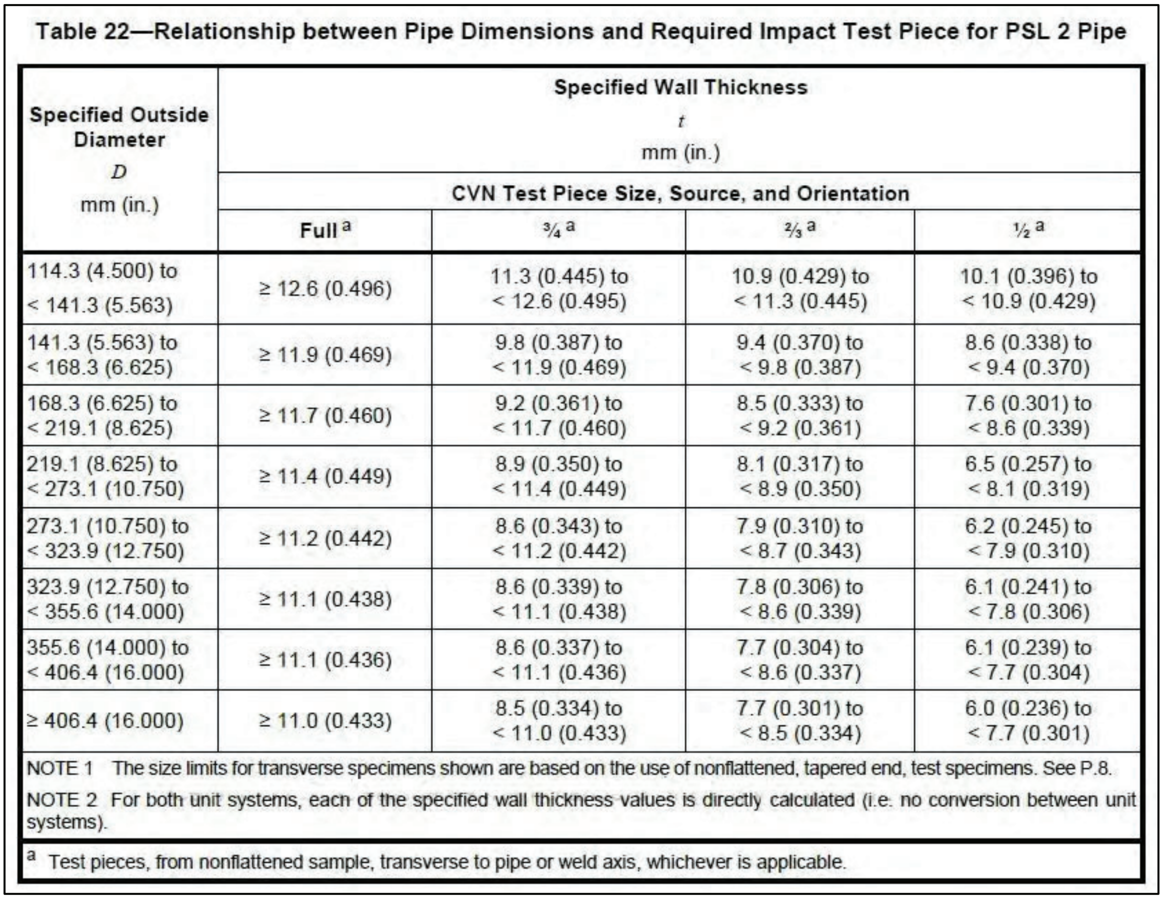


Table 22—Relationship between Pipe Dimensions and Required Impact Test Piece for PSL 2 Pipe

Specified Outside Diameter *D* mm (in.)	Specified Wall Thickness *t* mm (in.)			
	CVN Test Piece Size, Source, and Orientation			
	Full [a]	¾ [a]	⅔ [a]	½ [a]
114.3 (4.500) to < 141.3 (5.563)	≥ 12.6 (0.496)	11.3 (0.445) to < 12.6 (0.495)	10.9 (0.429) to < 11.3 (0.445)	10.1 (0.396) to < 10.9 (0.429)
141.3 (5.563) to < 168.3 (6.625)	≥ 11.9 (0.469)	9.8 (0.387) to < 11.9 (0.469)	9.4 (0.370) to < 9.8 (0.387)	8.6 (0.338) to < 9.4 (0.370)
168.3 (6.625) to < 219.1 (8.625)	≥ 11.7 (0.460)	9.2 (0.361) to < 11.7 (0.460)	8.5 (0.333) to < 9.2 (0.361)	7.6 (0.301) to < 8.6 (0.339)
219.1 (8.625) to < 273.1 (10.750)	≥ 11.4 (0.449)	8.9 (0.350) to < 11.4 (0.449)	8.1 (0.317) to < 8.9 (0.350)	6.5 (0.257) to < 8.1 (0.319)
273.1 (10.750) to < 323.9 (12.750)	≥ 11.2 (0.442)	8.6 (0.343) to < 11.2 (0.442)	7.9 (0.310) to < 8.7 (0.343)	6.2 (0.245) to < 7.9 (0.310)
323.9 (12.750) to < 355.6 (14.000)	≥ 11.1 (0.438)	8.6 (0.339) to < 11.1 (0.438)	7.8 (0.306) to < 8.6 (0.339)	6.1 (0.241) to < 7.8 (0.306)
355.6 (14.000) to < 406.4 (16.000)	≥ 11.1 (0.436)	8.6 (0.337) to < 11.1 (0.436)	7.7 (0.304) to < 8.6 (0.337)	6.1 (0.239) to < 7.7 (0.304)
≥ 406.4 (16.000)	≥ 11.0 (0.433)	8.5 (0.334) to < 11.0 (0.433)	7.7 (0.301) to < 8.5 (0.334)	6.0 (0.236) to < 7.7 (0.301)

NOTE 1 The size limits for transverse specimens shown are based on the use of nonflattened, tapered end, test specimens. See P.8.

NOTE 2 For both unit systems, eacn of the specified wall thickness values is directly calculated (i.e. no conversion between unit systems).

[a] Test pieces, from nonflattened sample, transverse to pipe or weld axis, whichever is applicable.

Figure 4: Pipe wall thickness required to machine transverse Charpy specimens (API 5L).

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Although not specially mentioned in industry codes and standards, fabrication of the specimens may require flatting to obtain a larger wall thickness during testing. This is increasingly required for small diameter, thinner wall thickness specimens. However, flattening these specimens results in additional cold work, which may locally alter the material properties of the specimen. This paper initially investigates the effects of flattening a sample blank equal to the length of the CVN specimens (55 mm). This process is likely the quickest method, and therefore, the most used method in fabricating flattened specimens. A schematic of this process is shown in Figure 5. A larger amount of plastic deformation would be required on smaller diameter pipes as compared to larger diameter pipes. The largest amount of plastic deformation would then be concentrated in the middle of the specimen, which would align with the notch location, which may include the seam weld bondline (if being tested). This strain can be estimated through the use of Equation 1.

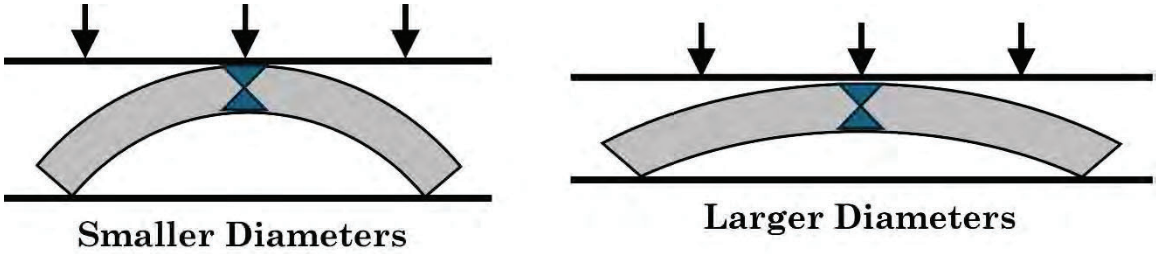

Figure 5: Schematic showing flatting of smaller vs larger diameter pipes.

$$Outer\ Surface\ Fiber\ Strain = \frac{Wall\ Thickness}{Diameter} \times 100 \quad (1)$$

While flattening allows for testing of a thicker specimen, it could result in local variations in material properties that may go unaccounted for during testing. Multiple loading and unloading cycles could result in a deterioration in mechanical properties due to the Bauschinger Effect. The Bauschinger Effect describes a phenomena whereby plastic deformation of a polycrystalline metal, caused by stress applied in one direction reduces the yield strength when stress is applied in the opposite direction, represented in a stress-strain curve shown in Figure 6[1]. As described in Dieter's Mechanical Metallurgy, material loaded in one direction (in this case tension), followed by loading in the opposite direction (in this case compression) results in a strain difference (represented by β). This represents the difference in strain between the tension and compression curves at a given stress.

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[1] G.E. Dieter, Mechanical Metallurgy, New York, 1961.

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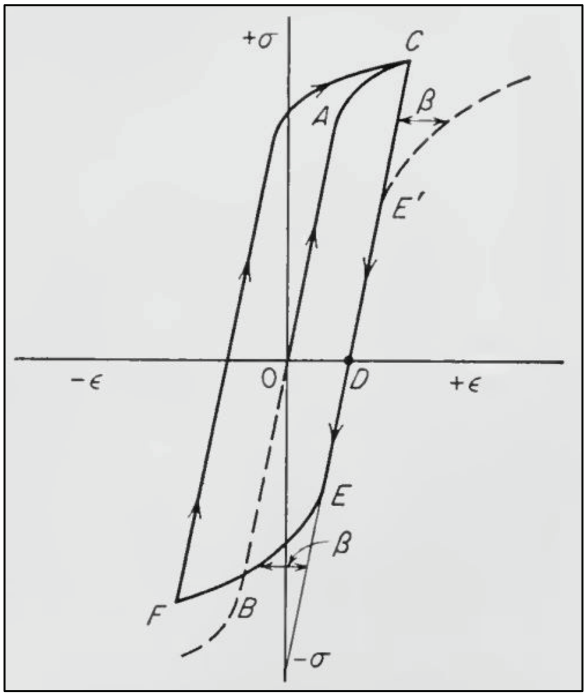

Figure 6: Bauschinger effect and hysteresis loop. [1]

The Bauschinger Effect reduces the yield strength, however, the additional cold work would effectively increase the tensile strength. All other properties held constant, it seems likely that the effective toughness would slightly increase – or over predicting the material toughness. This trend may hold true for modern steels, however, vintage pipeline steels, especially when testing a low frequency electric resistance welded (LF-ERW) seam weld bondline, stand a higher likelihood of opening up imperfections that would result in a lower toughness – or under predicting the material toughness.

This study compares the results of flattened vs non-flattened specimens for varying vintage, seam type, and geometry (outer diameter and wall thickness). This study continues on by suggesting a more appropriate manner of flattening to reduce the effects discussed above. This work is increasingly important as the advent of 49 CFR §192.712 may increase the removal and testing of pipe sections to document a material toughness. Improper preparation of the test specimens could then result in a less than adequate calculation result.

Initial Testing Program

The testing program initially examined the effects of flatting by cutting specimen blanks equal to the Charpy specimen length (55 mm), then flatting using a press in one (or few) strokes. This results in a quick flattening process enabling higher throughput. Once the blanks were flattened, transverse Charpy specimens were machined from the blanks per ASTM A370 with the notches placed in the area of interest (pipe body vs ERW bondline). Sufficient specimens and test temperatures were performed to generate a CVN transition curve.

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The initial phase examined two pipe types: LF-ERW and HF-ERW. The pipes selected for examination are described in Table 1. Charpy V-notch transition curves where generated using a hyperbolic tangent curve-fit (API 579, Annex 9F). The resulting CVN transition curves for the LF-ERW pipe are shown in Figure 7 and Figure 8. The resulting CVN transition curves for the HF-ERW pipe are shown in Figure 9 and Figure 10. The upper shelf (100% shear) values are also summarized in Table 1. Several trends can be observed from this:

- The additional cold work when flattening the specimens seemingly increased the absorbed energy within the pipe body, increasing between 13.6% and 18.3%.
- The HF-ERW pipe specimens when notched in the bondline also increased, however, the LF-ERW pipe specimens decreased. The increased likelihood of imperfections within the LF-ERW pipe is the likely origin of the reduced properties.
- The upper shelf toughness variation for the LF-ERW pipe notched in the ERW bondline is a conservative result (flattened results are lower than non-flattened (actual) results. This would result in increased examination as lower failure pressures would be predicted. PRCI MAT-8 predicted a 50 to 100 psi decrease in failure pressure or the diameter, wall thickness, and grade of pipe tested in this program.
- The other results are non-conservative as the flattened results are higher than the non-flattened results.

Table 1: Summary of Pipe Material during Initial Study

Pipe Type	**Outer Diameter (in)**	**Wall Thickness (in)**	**Grade**	**Notch Location**	**Upper Shelf (ft-lbs)**	**Flattened Upper Shelf (ft-lbs)**	**Δ**
LF-ERW	16	0.250	X52	Pipe Body	26.4	30	13.6%
				ERW Bondline	29	21	-27.6%
HF-ERW	12.75	0.250	X52	Pipe Body	24	28.4	18.3%
				ERW Bondline	14	18	28.6%

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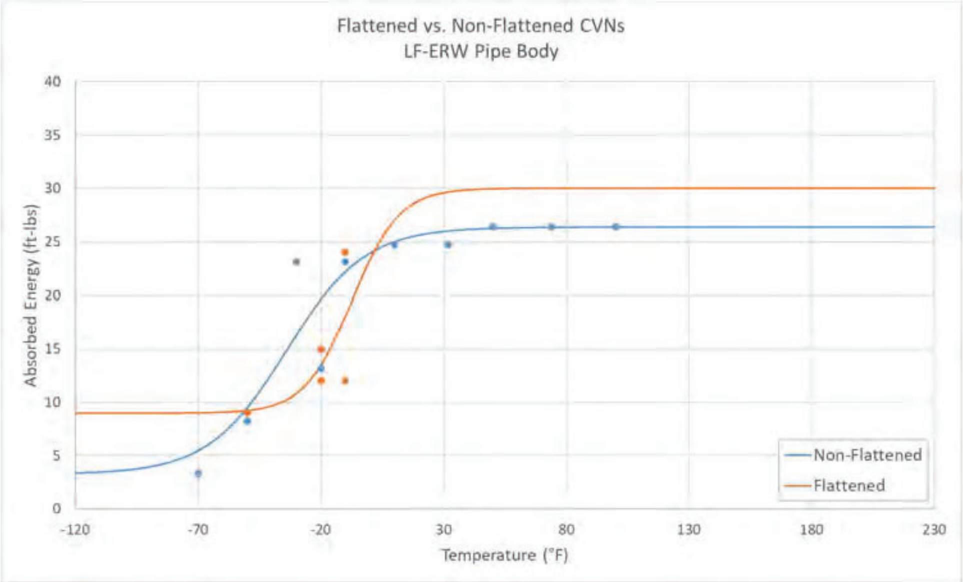

Figure 7: LF-ERW Pipe Body CVN transition curves.

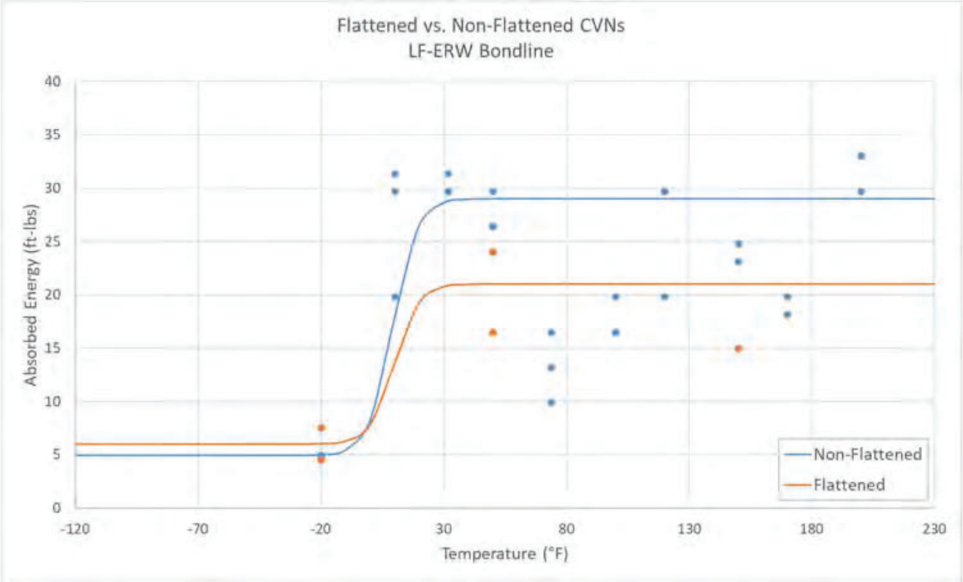

Figure 8: LF-ERW ERW Bondline CVN transition curves.

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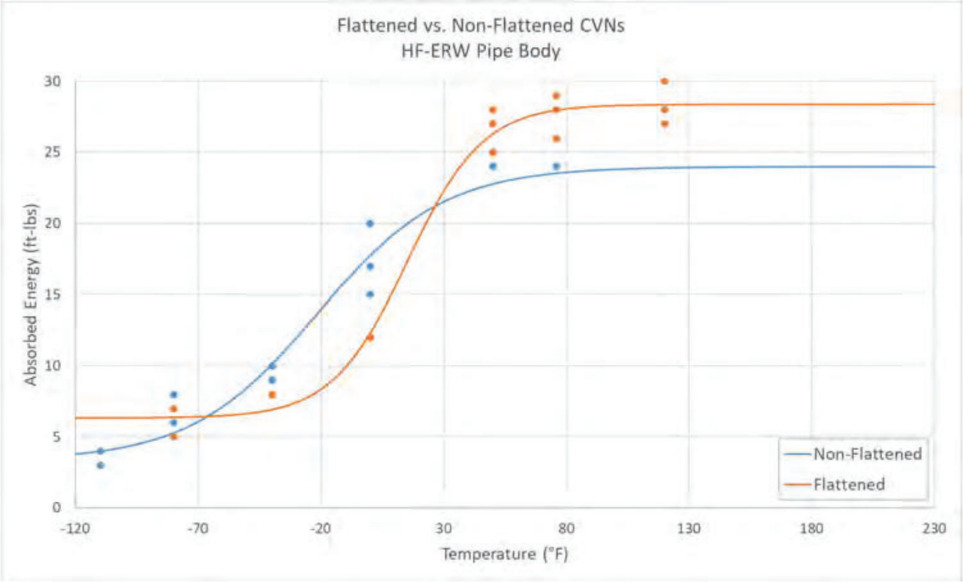

Figure 9: HF-ERW Pipe Body CVN transition curves.

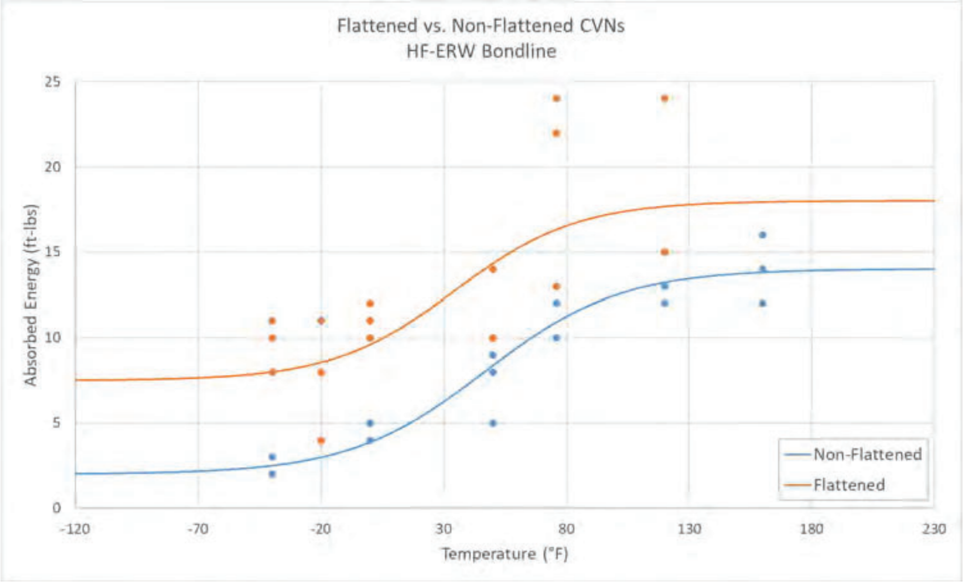

Figure 10: HF-ERW ERW Bondline CVN transition curves.

Optimized Testing Program

Knowing the trend presented above, it was then hypothesized that performing flattening in a more optimized manner would reduce the likelihood of increased cold work at the area of the notch or opening up seam imperfections in the case of a seam weld. This is much like performing flattening (gull winging) prescribed in ISO 15653 prior to performing single edge notch bending (SENB) fracture toughness. A schematic of this process is shown Figure 11.

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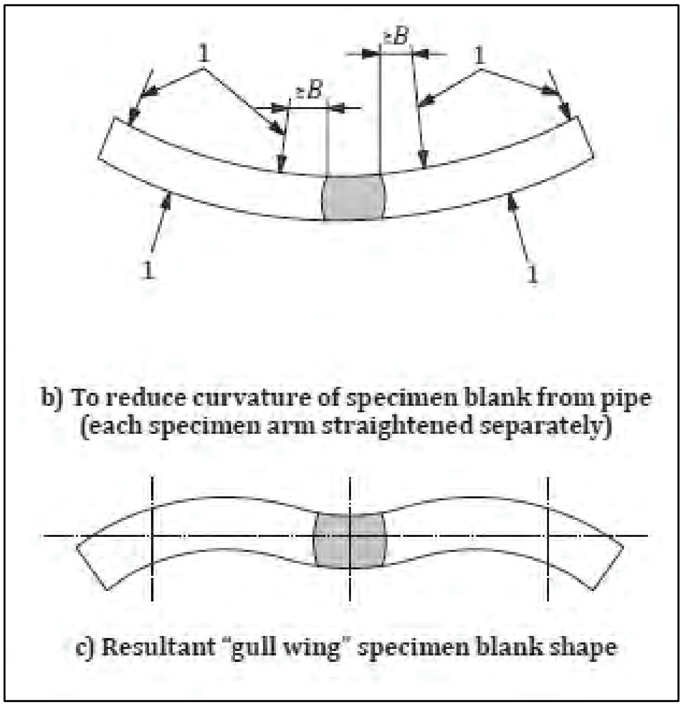

b) To reduce curvature of specimen blank from pipe (each specimen arm straightened separately)

c) Resultant "gull wing" specimen blank shape

Figure 11: Schematic showing ISO 15653 flattening process (ISO 15653).

This process would limit the effective thickness once milled or surface ground due to the "gull wing" shape, therefore, a similar process utilized for flattening transverse tensile specimens was selected for the optimized process. To do so, the ends remote of the notch location (pipe body and/or weld) are flattened in sequence approaching inwards toward the notch location. Doing so, limits the cold work at the notch. This results in a conceptual flattening process shown in Figure 12, progressing from location 1 to 3 prior to affecting the area of the seam (blue diamonds).

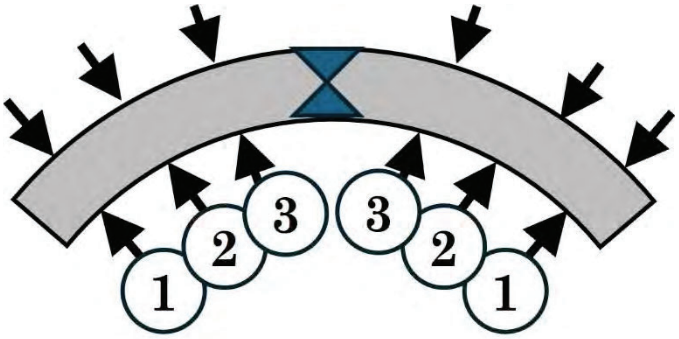

Figure 12: Schematic showing optimized flatting process, progressing from area 1 to area 3.

Once the blanks were flattened, transverse Charpy specimens were machined from the blanks per ASTM A370 with the notches placed in the area of interest (pipe body vs ERW bondline). Sufficient specimens and test temperatures were performed to generate a CVN transition curve.

This phase examined three pipe types: LF-ERW, EFW, and DSAW. The pipes selected for examination are described in Table 2. Charpy V-notch transition curves where generated using a

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hyperbolic tangent curve-fit (API 579, Annex 9F). The resulting CVN transition curves for the LF-ERW pipe are shown in Figure 13 and Figure 14. The resulting CVN transition curves for the EFW pipe are shown in Figure 15 and Figure 16. The resulting CVN transition curves for the DSAW pipe are shown in Figure 17 and Figure 18. The upper shelf (100% shear) values are also summarized in Table 2. Several trends can be observed from this:

- The additional cold work when flattening the specimens resulted in similar upper shelf absorbed energy between non-flattened and flattened specimens. Each of the transition curves appeared similar in appearance indicating a good fit between both the non-flattened and flattened specimens.

- This contained a much tighter scatter when comparing the initial study to the optimized study, indicating the benefit of flatting in the optimized manner.

- Burst pressure calculations were not performed as the variation observed is likely scatter within the data set.

Table 2: Summary of Pipe Material during Optimized Study

Pipe Type	Outer Diameter (in)	Wall Thickness (in)	Grade	Notch Location	Upper Shelf (ft-lbs)	Flattened Upper Shelf (ft-lbs)	Δ
LF-ERW	12.75	0.203	X52	Pipe Body	34.1	33.8	-0.9%
				ERW Bondline	31.8	30.7	-3.5%
EFW	26	0.281	X52	Pipe Body	35.3	33.7	-4.5%
				EFW Bondline	27	28	3.7%
DSAW	22	0.250	X52	Pipe Body	33.7	29.7	-11.9%
				DSAW Centerline	52	49	-5.8%

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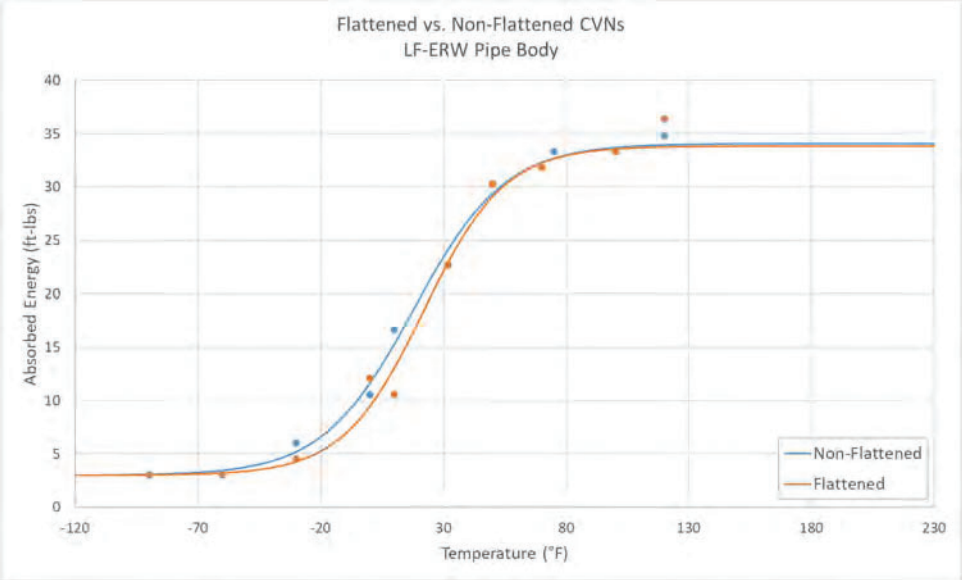

Figure 13: LF-ERW Pipe Body CVN transition curves.

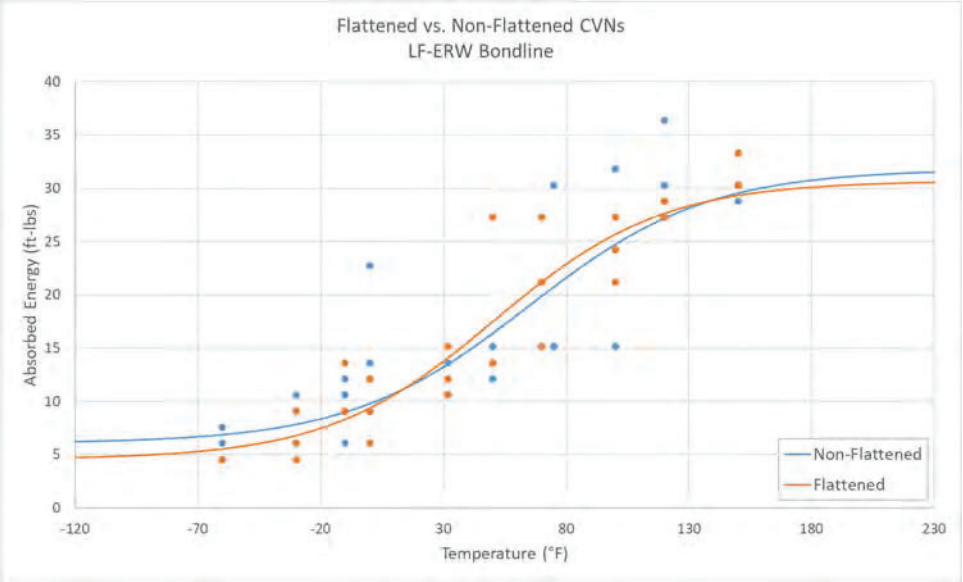

Figure 14: LF-ERW ERW Bondline CVN transition curves.

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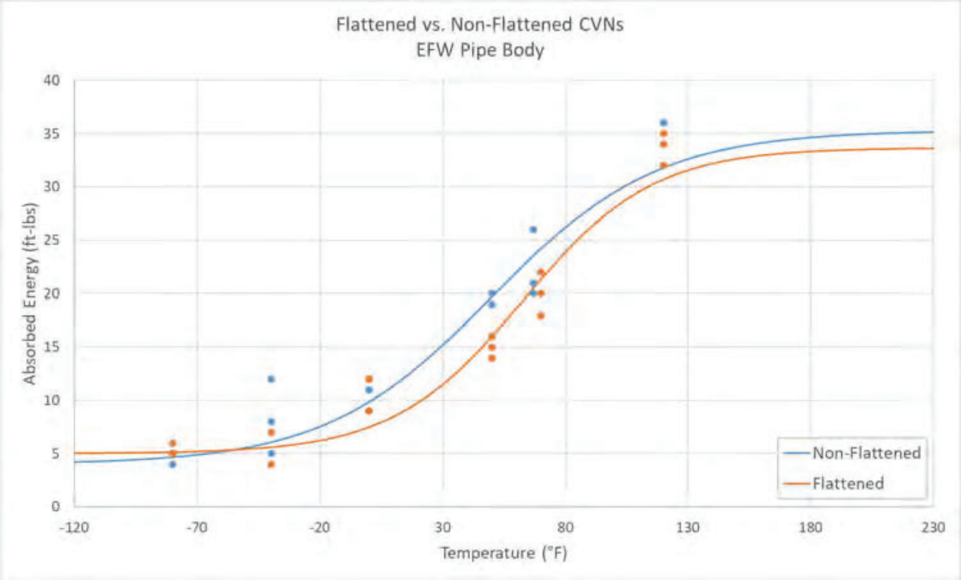

Figure 15: EFW Pipe Body CVN transition curves.

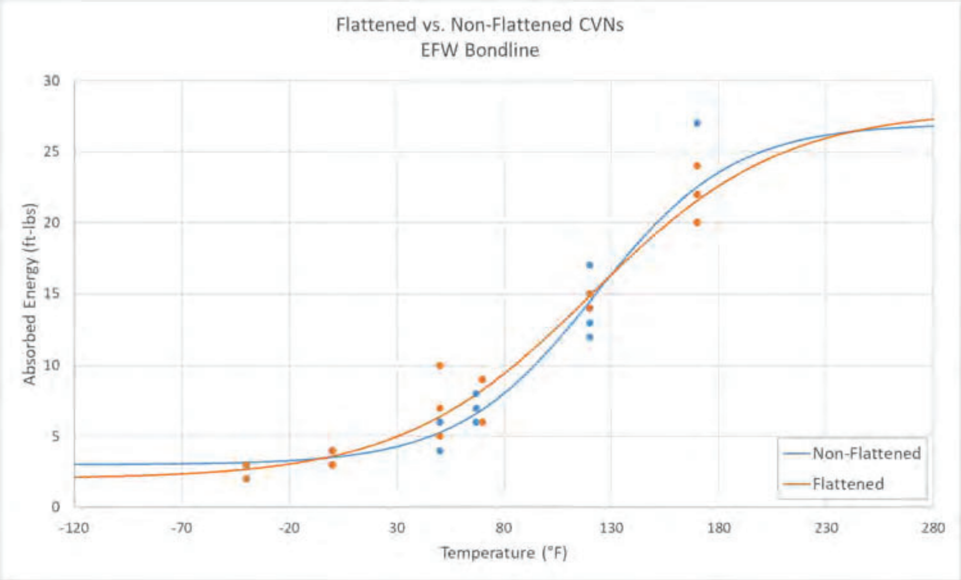

Figure 16: EFW Bondline CVN transition curves.

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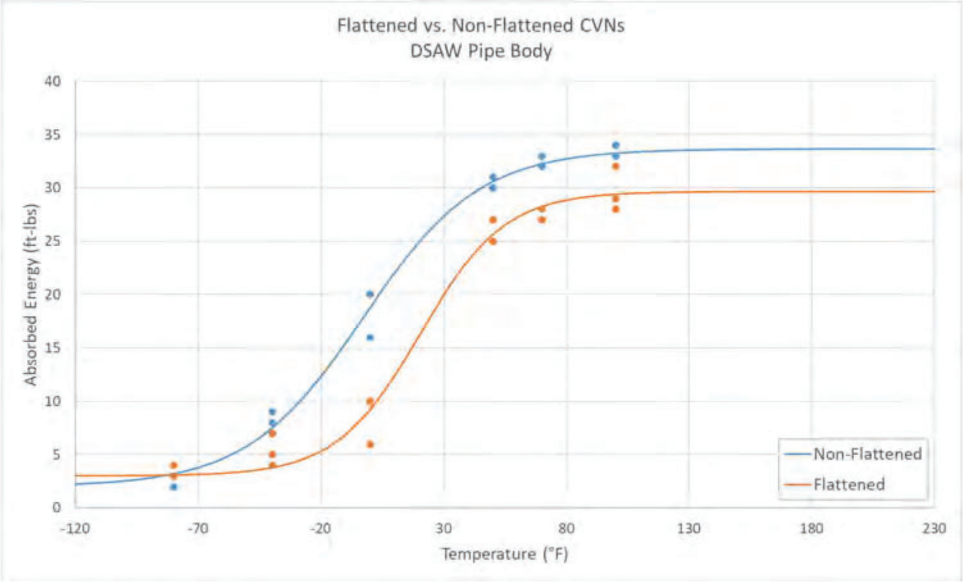

Figure 17: DSAW Pipe Body CVN transition curves.

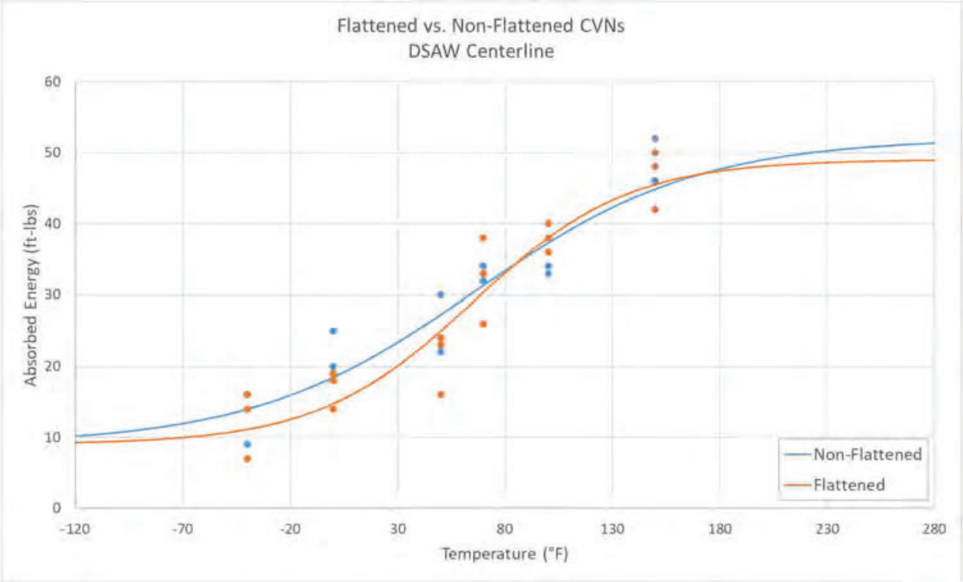

Figure 18: DSAW Centerline CVN transition curves.

Conclusions

The following was concluded based on this testing program:

- A non-flattened specimen is preferred over flattened to remove the possibility of scatter associated with the flattening process. However, this is not always possible with smaller diameter, thinner wall thickness pipe material.

- This study highlights the importance of considering specimen preparation procedures when performing Charpy testing. Flattening can shift the CVN transition curve in both conservative and non-conservative directions – in one case by 30% resulting in a less than adequate remaining strength calculation using those results.

- The proposed optimized flattening technique aims to reduce these uncertainties and provide more accurate toughness data and it is not dependent on yield strength or weld type.
- A similar response would be expected in the event the non-optimized flatting process is used for fracture toughness coupons, such as compact tension specimens.

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