On the Correlation of Charpy Impact Energy and Hydrogen Charging in 4340 Steel

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Background

- Hydrogen embrittlement is a corrosion mechanism in which hydrogen atoms diffuse interstitially through a metal.

- It is a common problem in high strength steels and titanium alloys.

Current Methods of Testing

- ASTM F326: Standard Test Method for Electronic Measurement for Hydrogen Embrittlement From Cadmium Electroplating Processes
- ASTM F1624-12: Standard Test Method for Measurement of Hydrogen Embrittlement Threshold in Steel By the Incremental Step Loading Technique

Suggested Simpler Solution

- Using Charpy Impact testing to detect hydrogen charging in metals

- This will be done in four phases.

Phase 1:

Can Charpy Impact testing quantitatively detect hydrogen charging [presence of hydrogen]?

Acknowledgements







Phase 1 Publication

- Effect of Tempering and Baking on the Charpy Impact Energy of Hydrogen-Charged 4340 Steel
  - Co-Authors: K. Mori, E.W. Lee, W.E. Frazier, K. Niji, G. Battel, A. Tran, E. Iriarte, O. Perez, H. Ruiz, T. Choi, P. Stoyanov, J. Ogren, J. Alrashaid, and O.S. Es-Said
  - JMEPEG (2015) 24:329-337

4340 Steel Composition

Element	wt%
C	0.37 - 0.43
Cr	0.7 - 0.9
Fe	96
Mn	0.6 - 0.8
Mo	0.2 - 0.3
Ni	1.65 - 2.0
P	Max 0.035
S	Max 0.04
Si	0.15 - 0.3

4340 Steel Applications

- 4340 steel alloy is commonly used in aircraft components such as landing gears and structural members.

- Other uses include piston pins, bearings, gears, dies and pressure vessels.

EDM [Electro-Discharged Machining] Unit

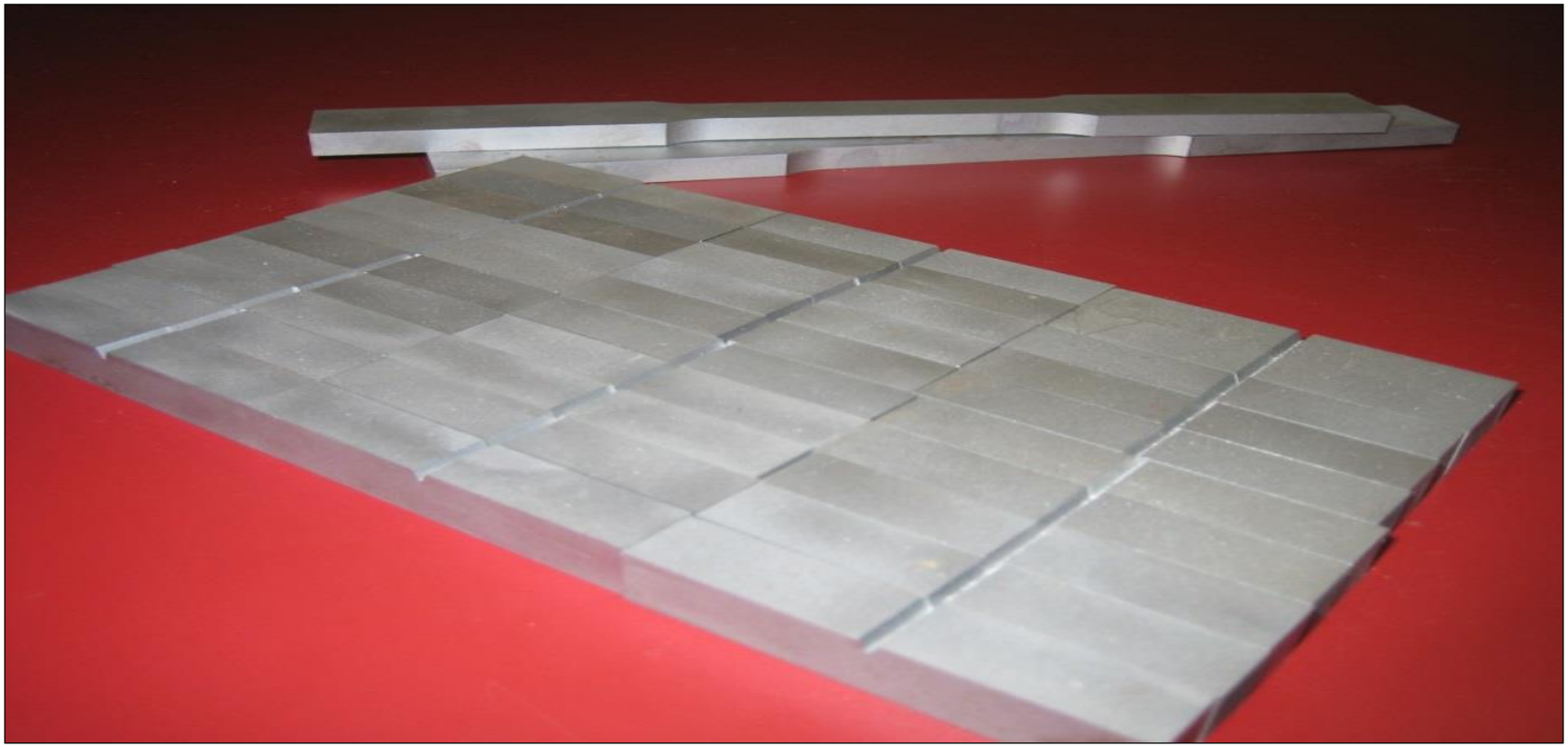


4340 Steel Plates Machined by EDM

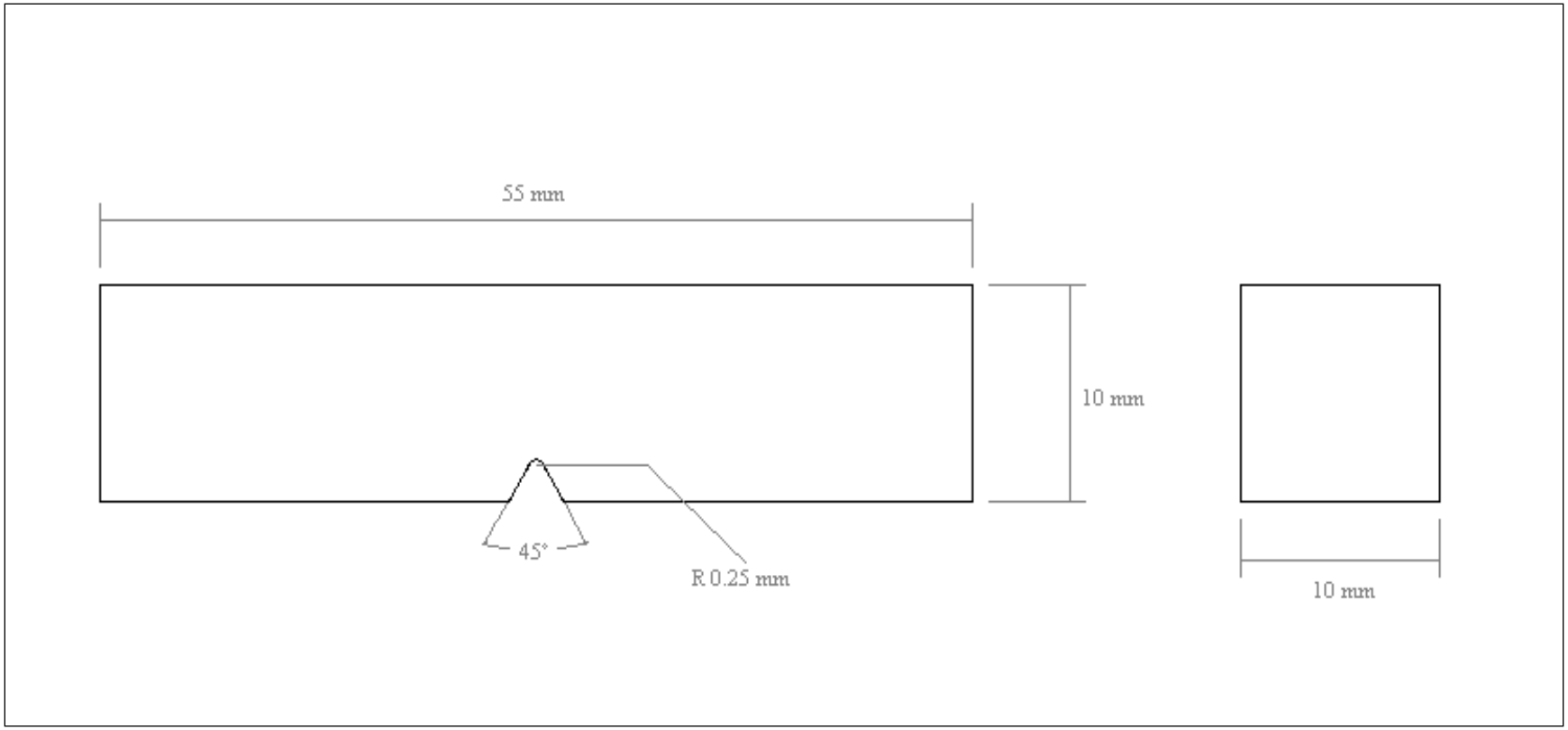
60x15x5 cm- Austentized, oil quenched and tempered at 232°C (450°F) for 2 hours



Charpy Impact and Tensile Samples

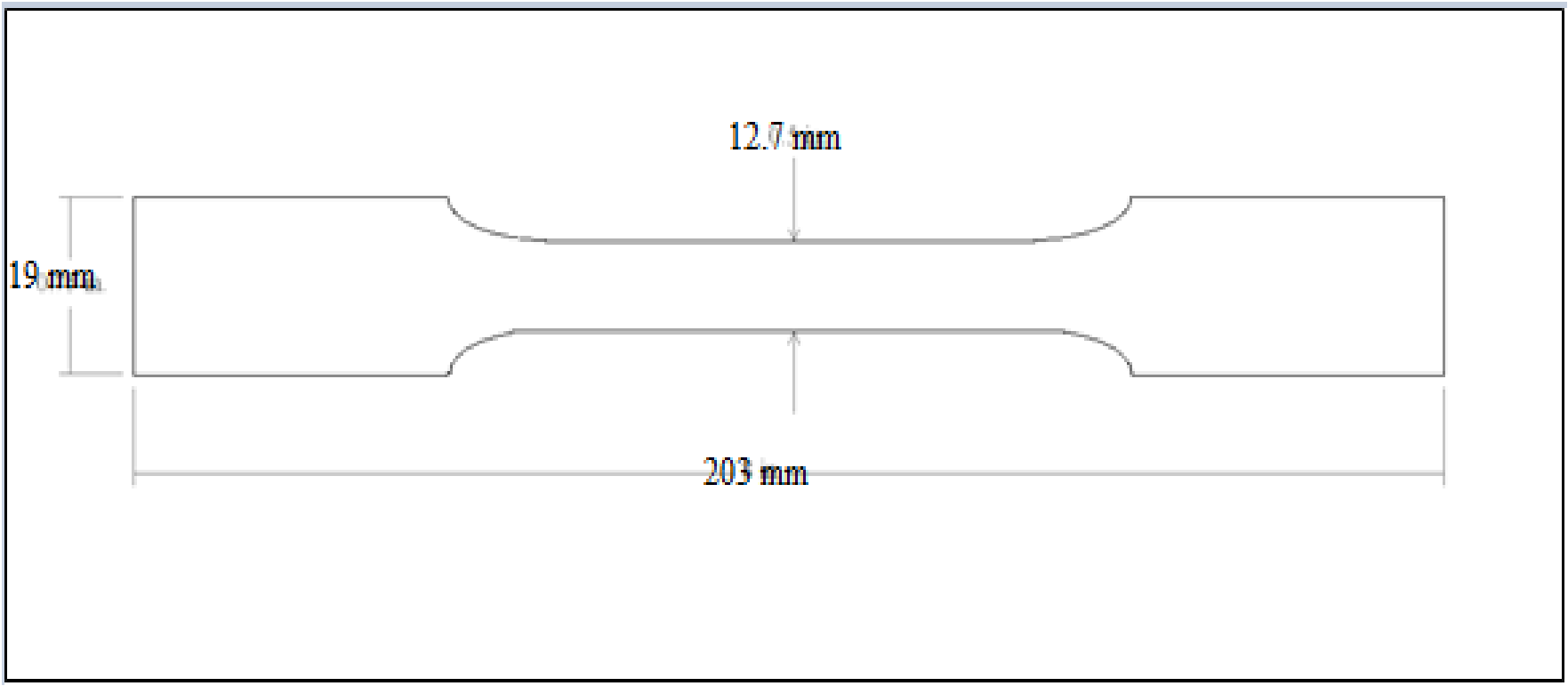


Charpy Impact Dimensions



ASTM E23-12c, Standard Test Methods for Notched Bar Impact Testing of Metallic Materials, ASTM International, West Conshohocken, PA, 2012, www.astm.org

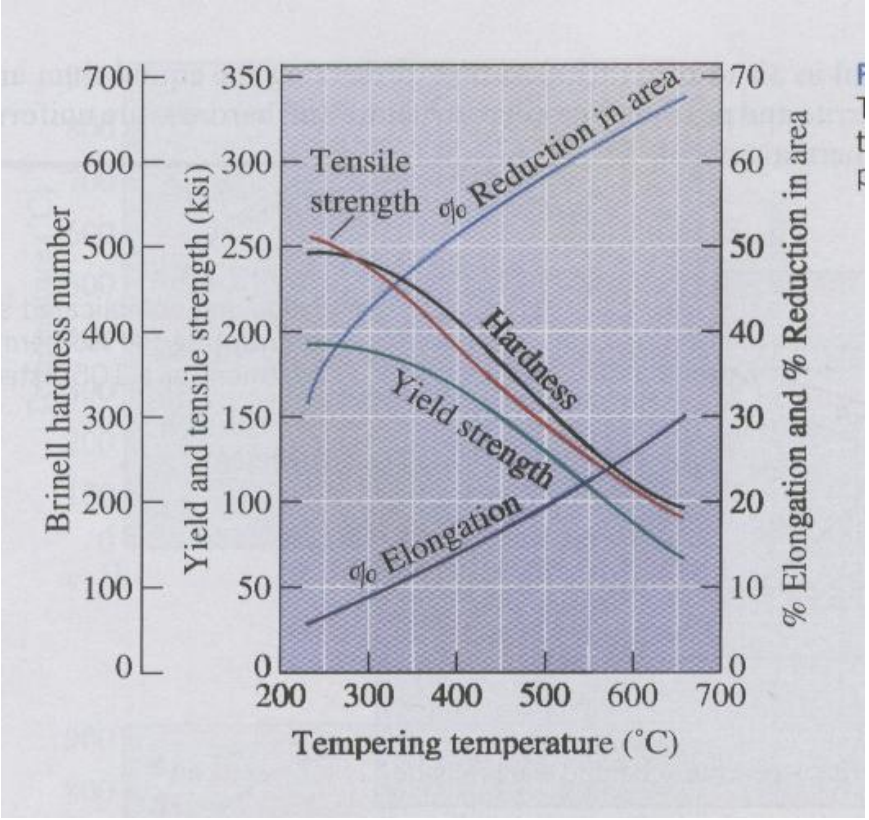
Tensile Bars Dimensions



ASTM E8 / E8M-09, Standard Test Methods for Tension Testing of Metallic Materials, ASTM International, West Conshohocken, PA, 2009, www.astm.org

Temper Optimization

- Trend expected after hardness and tensile testing of samples tempered at 10°C [50°F] intervals between 288°C [550°F] and 677°C [1250°F].



(Askeland, 2006)

Temper Treatment





Figure: Hardness, Ultimate tensile Strength, Yield strength, and % Elongation VS Tempering Temperature

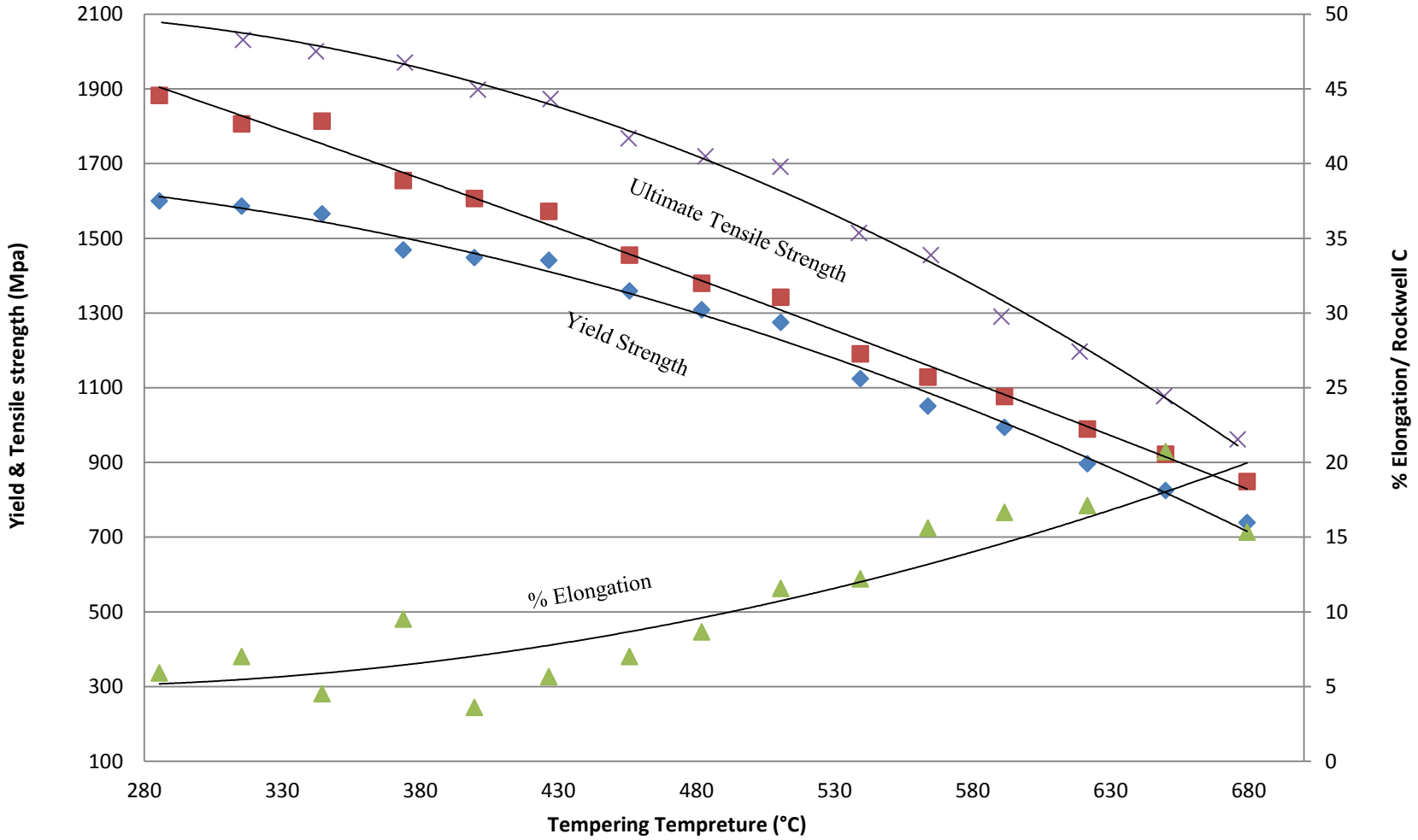


Figure: The Ultimate Tensile Strength VS Tempering Temperature

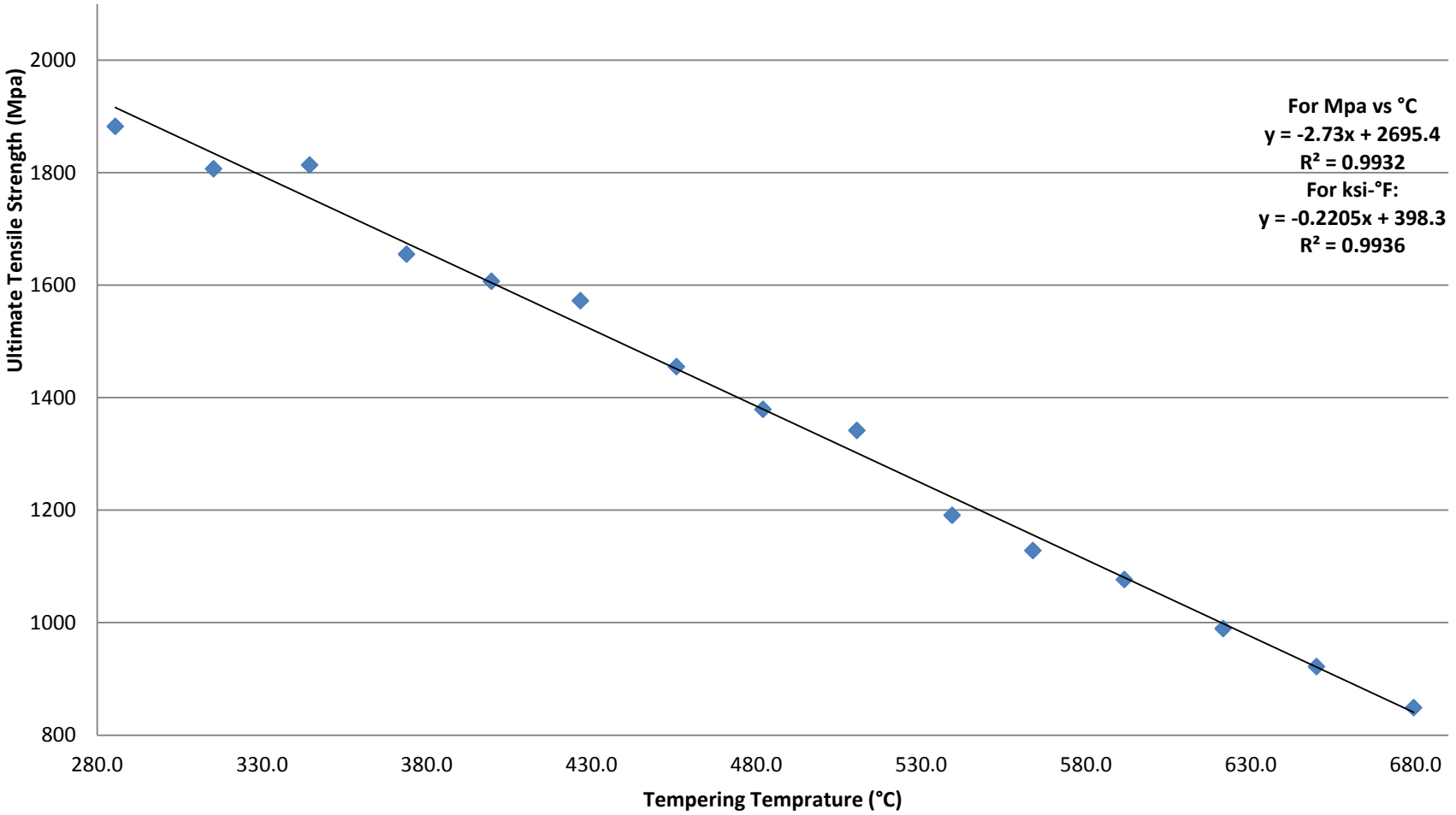


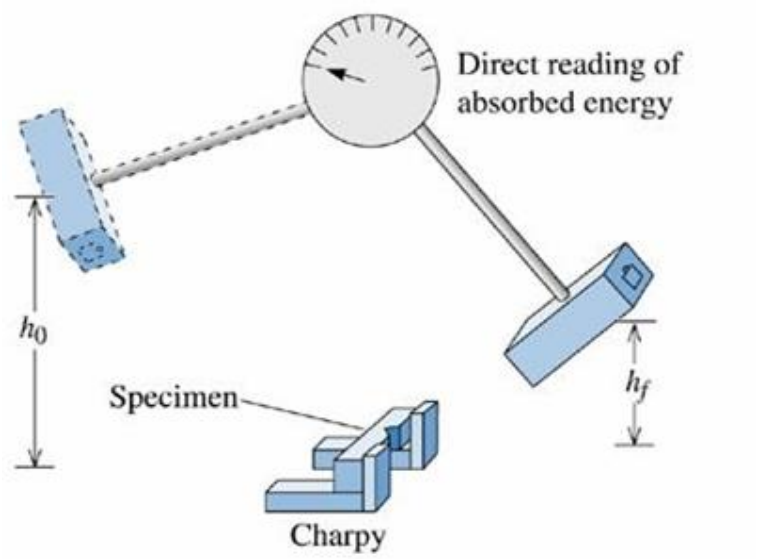
Table: Desired UTS and the obtained UTS after tempering at the specified temperature

Temper (°F)	Temper (°C)	Desired UTS (ksi)	Desired UTS (Mpa)	UTS Obtained (ksi)	UTS Obtained (Mpa)	Percent Difference	YS (ksi)	YS (Mpa)	% Elong.
670	354	250	1724	247	1703	1%	221	1524	9
670	354	250	1724	246	1696	2%	220	1517	8
810	432	220	1517	211	1455	4%	198	1365	7
810	432	220	1517	211	1455	4%	**	**	7
875	468	205	1413	199	1372	3%	187	1289	11
875	468	205	1413	196	1351	4%	186	1282	9
945	507	190	1310	186	1282	2%	175	1207	11
945	507	190	1310	188	1296	1%	**	**	12
990	532	180	1241	179	1234	1%	167	1151	13
990	532	180	1241	179	1234	1%	167	1151	14
1040	560	170	1172	169	1165	1%	156	1076	14
1040	560	170	1172	165	1138	3%	153	1055	15
1080	582	160	1103	156	1076	3%	143	986	16
1080	582	160	1103	154	1062	4%	138	951	14
1150	621	145	1000	147	1014	1%	131	903	18
1150	621	145	1000	144	993	1%	130	896	18

Charpy Impact Samples

- Charpy impact samples were separated into uncharged and Hydrogen charged samples
- The charged samples were plated with 0.0076-0.012 mm (0.0003-0.0005 inches) thickness layer of cadmium.

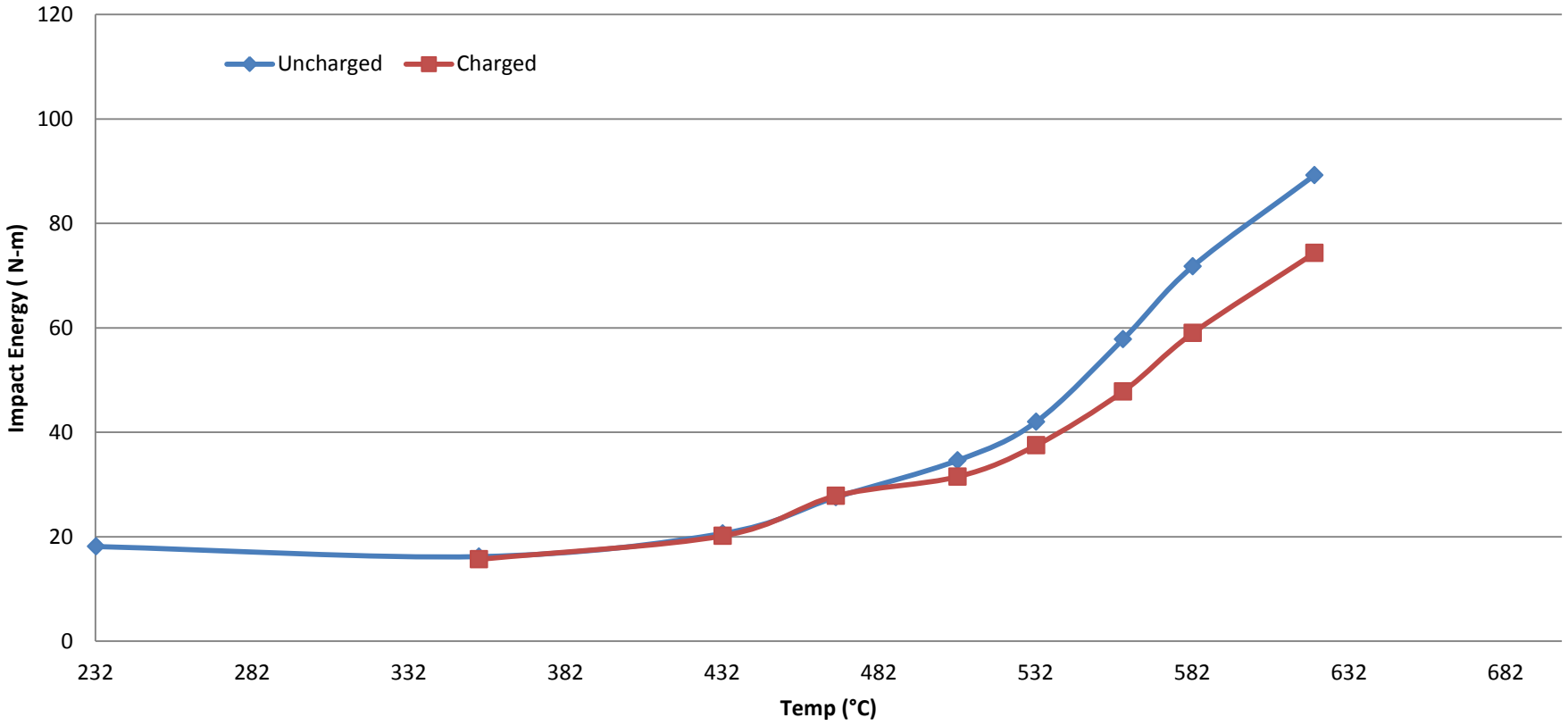
Charpy Impact Testing



(Askeland, 2005)



Figure: Average Impact Energy Vs Tempering Temperature for uncharged and charged specimens [in °C]



Average Impact Energy Vs Tempering Temperature for 8 Hour delay time + 25 minutes between coating and testing

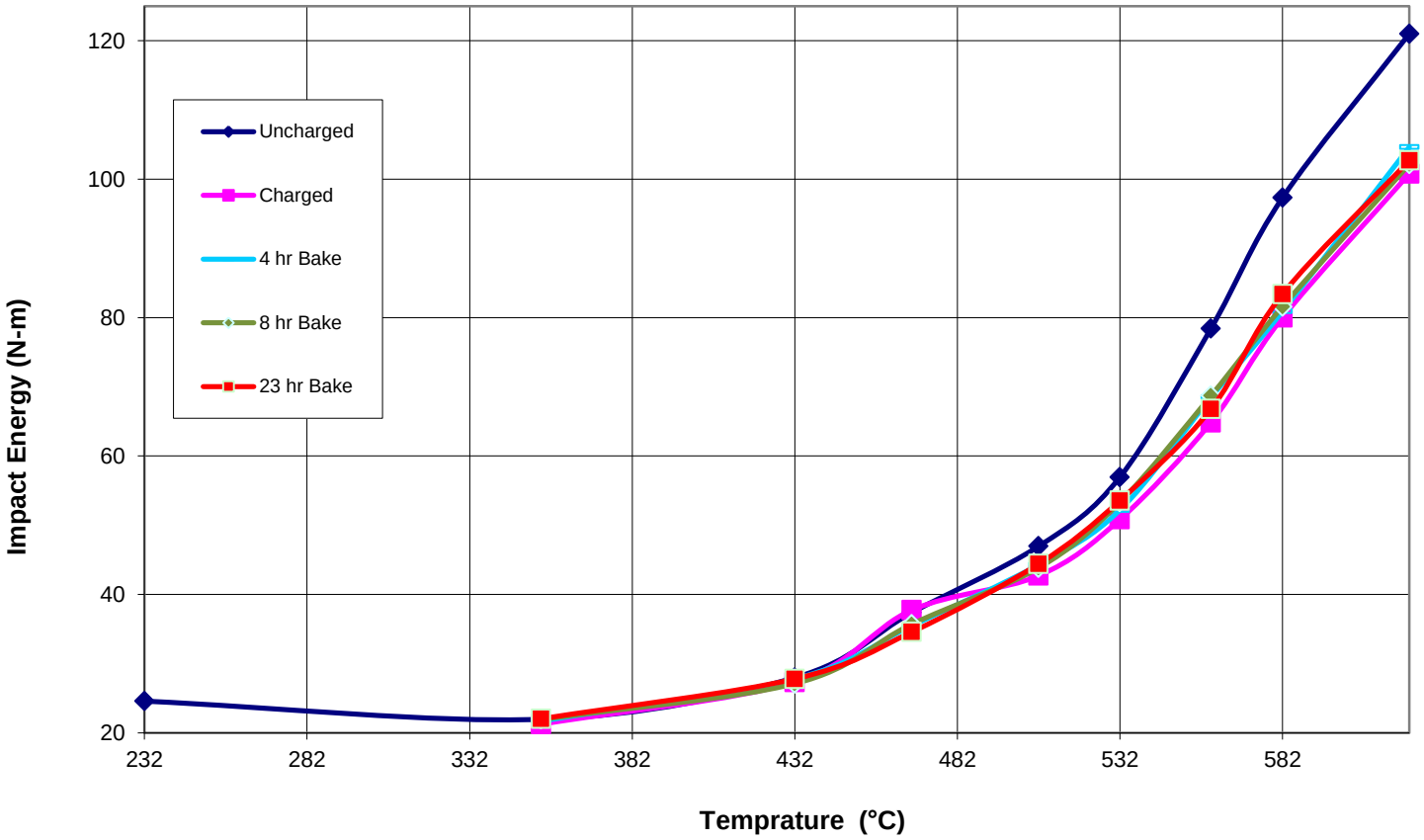


Figure: Sample Tempered at 354°C (670°F), No Hydrogen

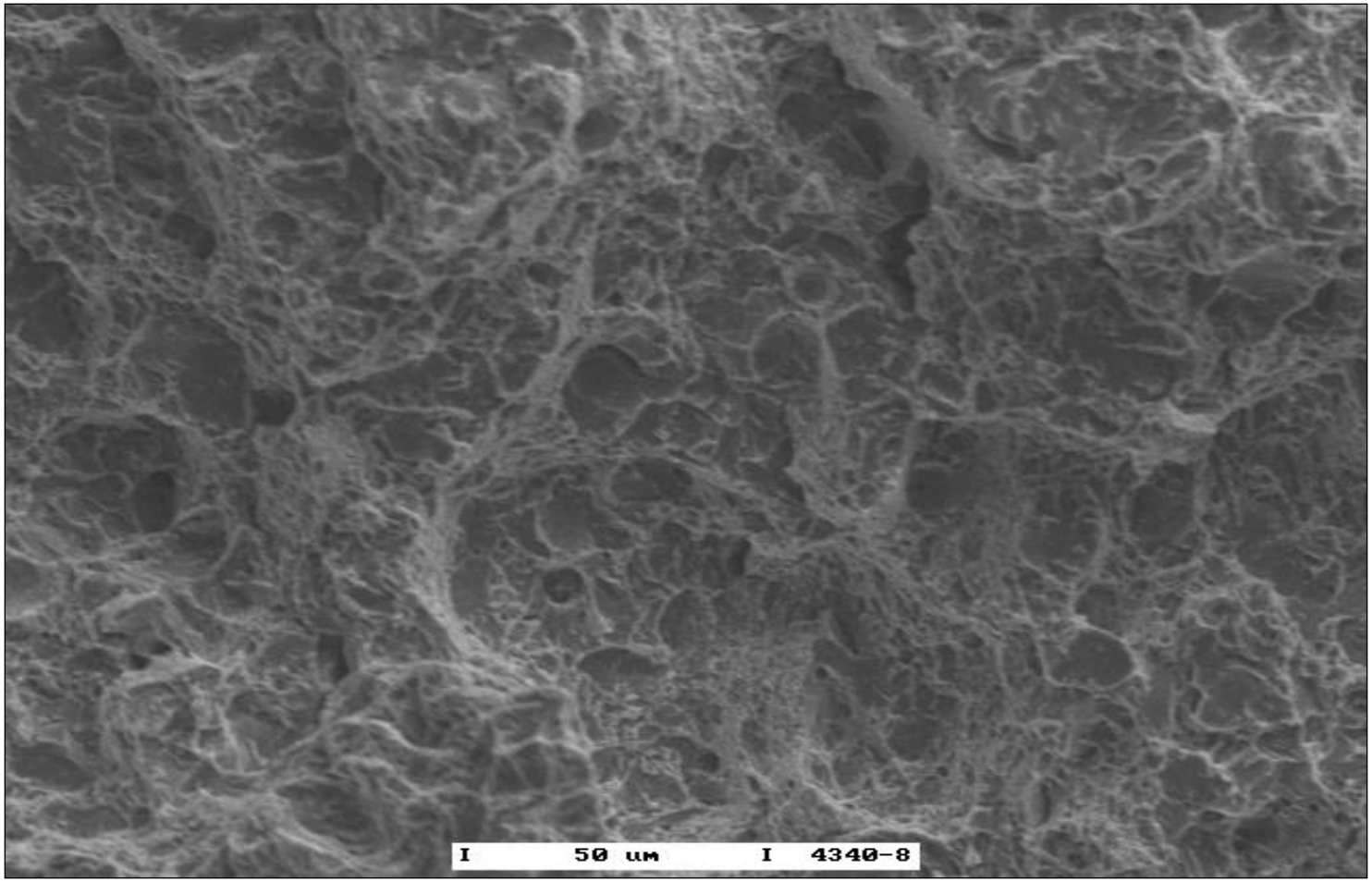


Figure: Sample Tempered at 621°C (1150°F), No Hydrogen

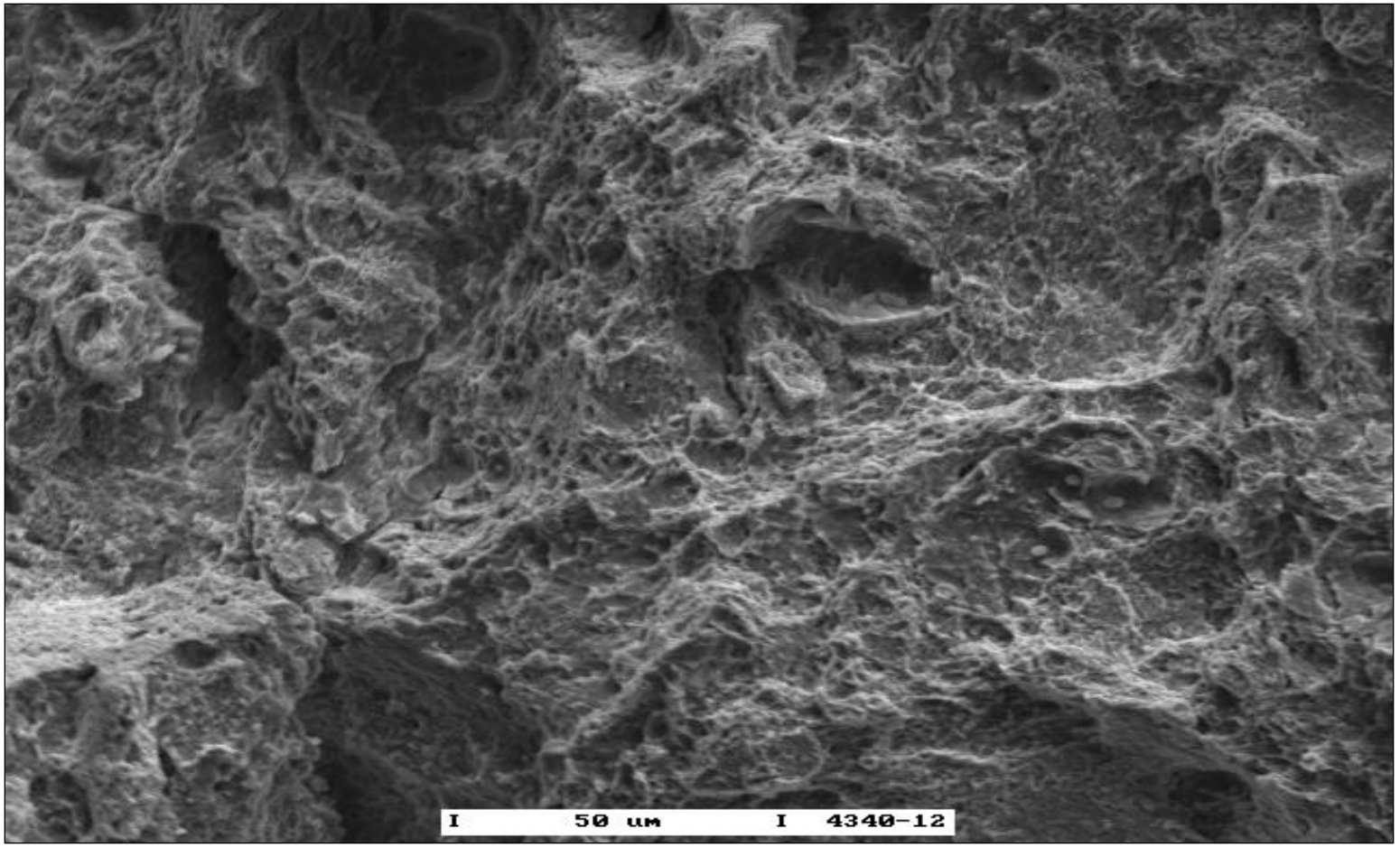


Figure: As-Charged Sample Tempered at 354°C (670°F)

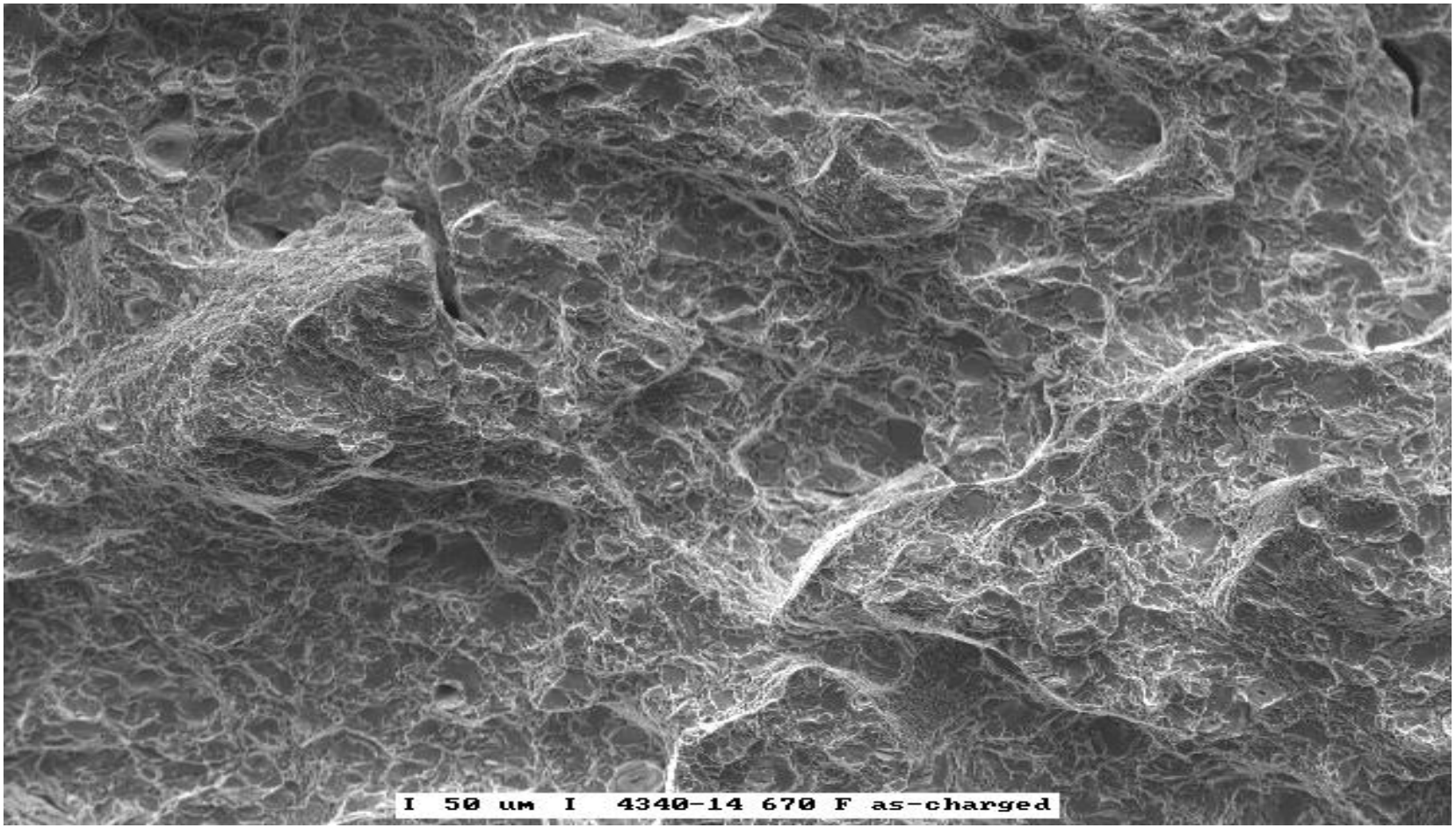
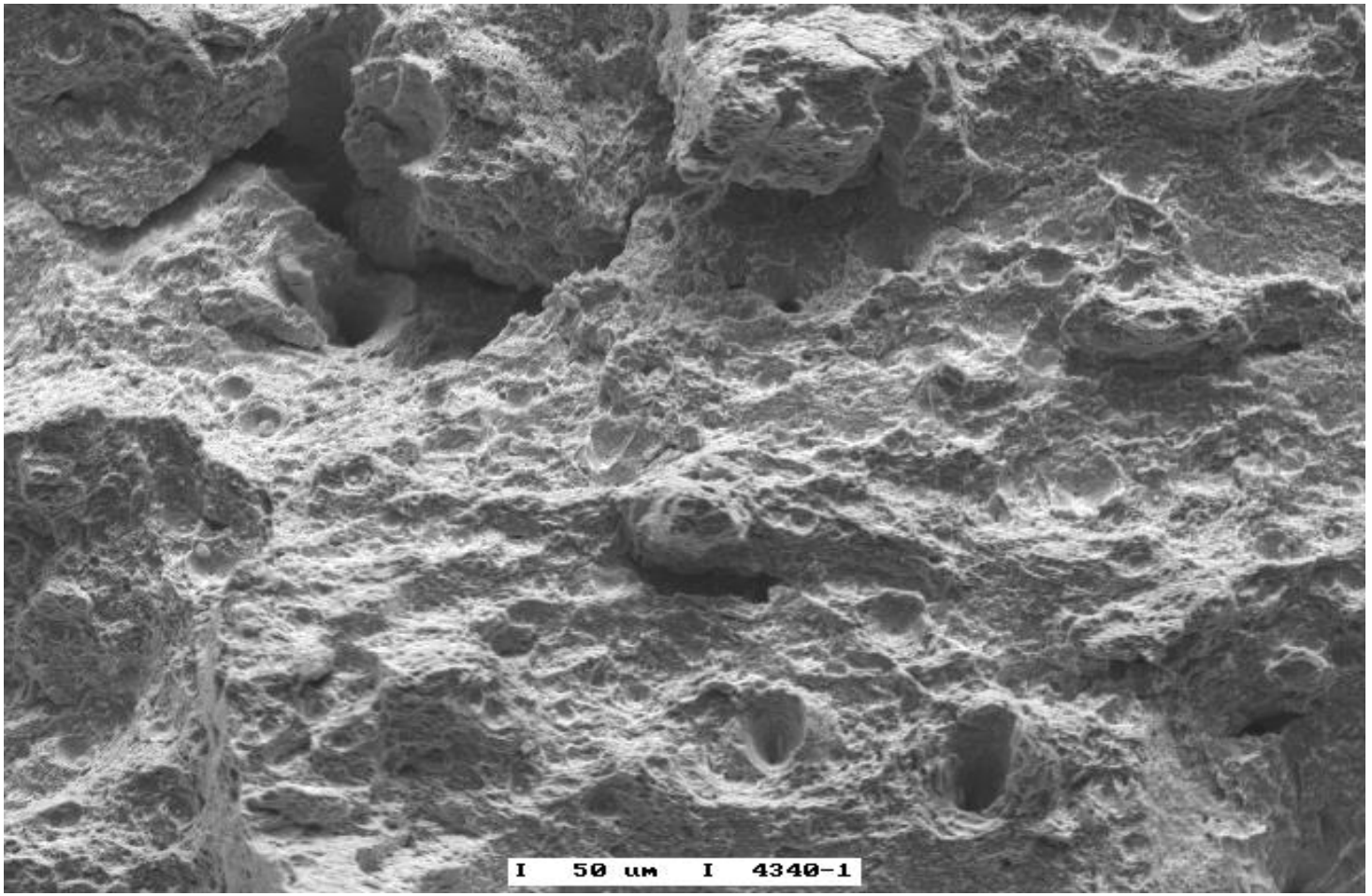


Figure: As-Charged Sample Tempered at 621°C (1150°F)



Conclusions

Results of the Charpy impact tests indicate that there was only a significant difference in the energy values when the tempering temperature exceeded 468°C [875°F]. There was no significant change in impact energy when tempered below 468°C [875°F].

Conclusions Continued

The results were explained by the model which proposes that hydrogen can be transported more rapidly by mobile dislocations to the fracture site.

Conclusions Continued

- SEM fracture surfaces in both the ductile region 621°C [1150°F] and the brittle region 354°C [670°F] indicated that the charged surfaces were populated by microvoids of finer size compared to the hydrogen-free surfaces.

Phase 2:

Can Charpy Impact testing quantitatively detect hydrogen charging [presence of hydrogen] in different cadmium plating thicknesses?

Acknowledgements











Phase 2 Publication

- Effect of Cadmium Plating Thickness on the Charpy Impact Energy of hydrogen-Charged 4340 Steel
  - Co-Authors: O. S. Es-Said, J. Guerra, E. Jones, A. Dominguez, M. Hahn, N. Ula, L. Zeng, B. Ramsey, H. Mulazimoglu, Young-Jun Li, M. Miller, J. Alrashaid, S. Kalnaus, E. W. Lee and W. E. Frazier
  - JMEPEG, in press

- In the previous work, the tempering was performed between 354 °C and 621 °C. In

- In phase 2 tempering was done between 257 °C -593 °C.

Changes between Phases 1 and 2

In this work, two changes were implemented:

1. The specimens were re-austentized (1,000°C for 1 hour) and water quenched to form martensite prior to tempering. The oxide layer was removed prior to mechanical testing.

Changes between Phases 1 and 2



Figure 1: Removing scale from Charpy impact specimens.
Figure 2: Removing scale from tensile specimens. Lower picture shows the effect after etching 8 hours in 25% HCl solution

Changes between Phases 1 and 2

2. Three levels of cadmium plating were evaluated (0.00508mm (0.2 mils), 0.00762mm (0.3 mils), and 0.0127mm (0.5 mils))

Tensile and Charpy Impact Samples

- Tensile and Charpy impact samples were separated into one group of uncharged and three groups of hydrogen charged samples

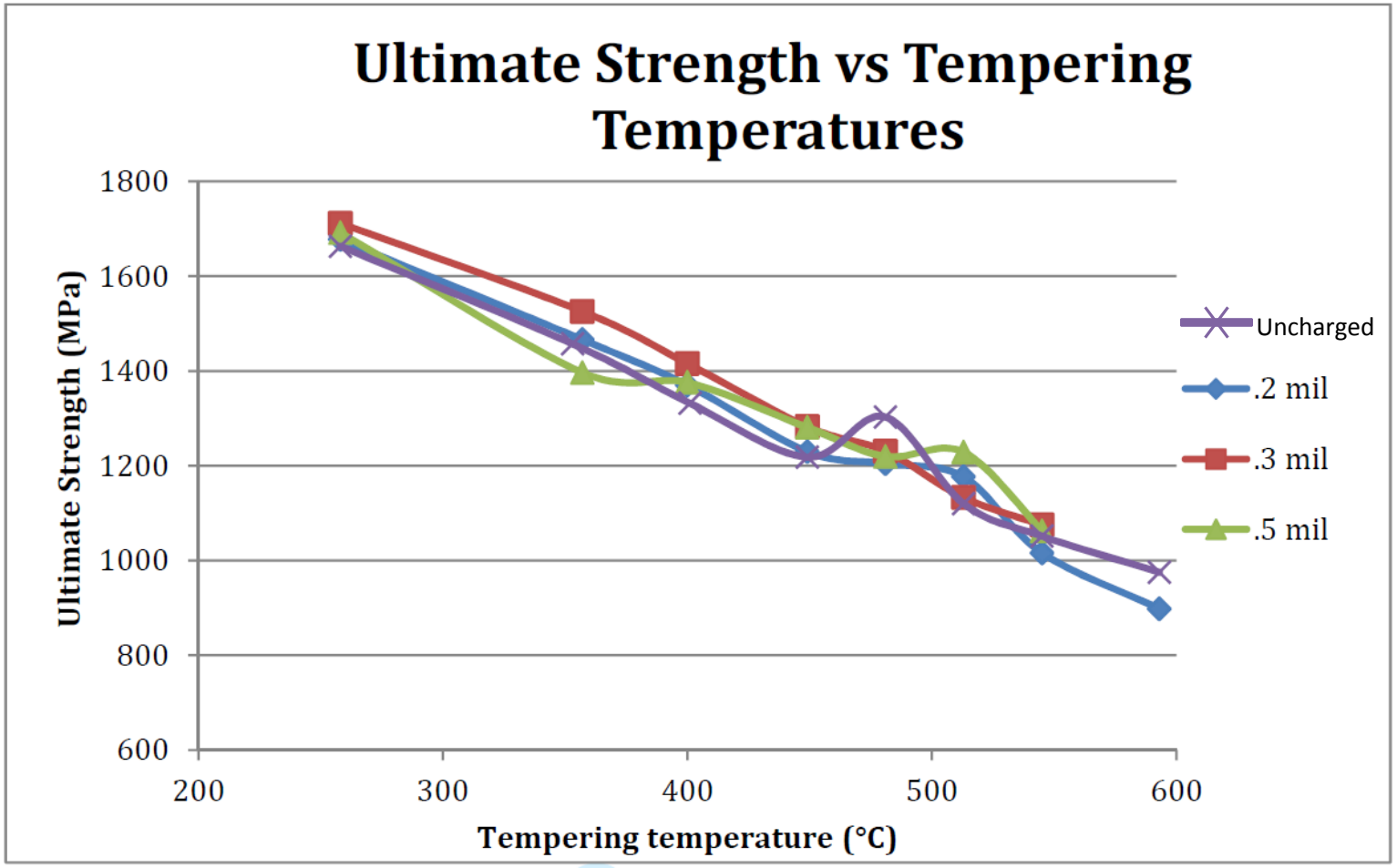
- The hydrogen charged samples were Cadmium plated with 0.00508 mm (0.2 mils*), 0.00762mm (0.3 mils), and 0.0127 mm (0.5 mils).

*** 1 mil = 0.001 in = 0.0254 mm**

Table 1: Desired UTS and the obtained UTS after tempering at the specified temperatures for uncharged specimens

Temper (°C)	Uncharged Desired UTS (ksi)	Uncharged Desired UTS (MPa)	Uncharged Obtained UTS (ksi)	Uncharged Obtained UTS (MPa)	Percent Difference
593	145	1000	142	976	2%
545	160	1103	153	1052	5%
513	170	1172	163	1120	4%
481	180	1241	184	1266	-2%
449	190	1310	177	1219	7%
401	205	1413	193	1333	6%
353	220	1517	211	1458	4%
257	250	1724	241	1664	3%

Figure: Ultimate Strength Vs Tempering Temperature for Uncharged and Charged Specimens



Average impact energy vs tempering temperature for uncharged and charged specimens

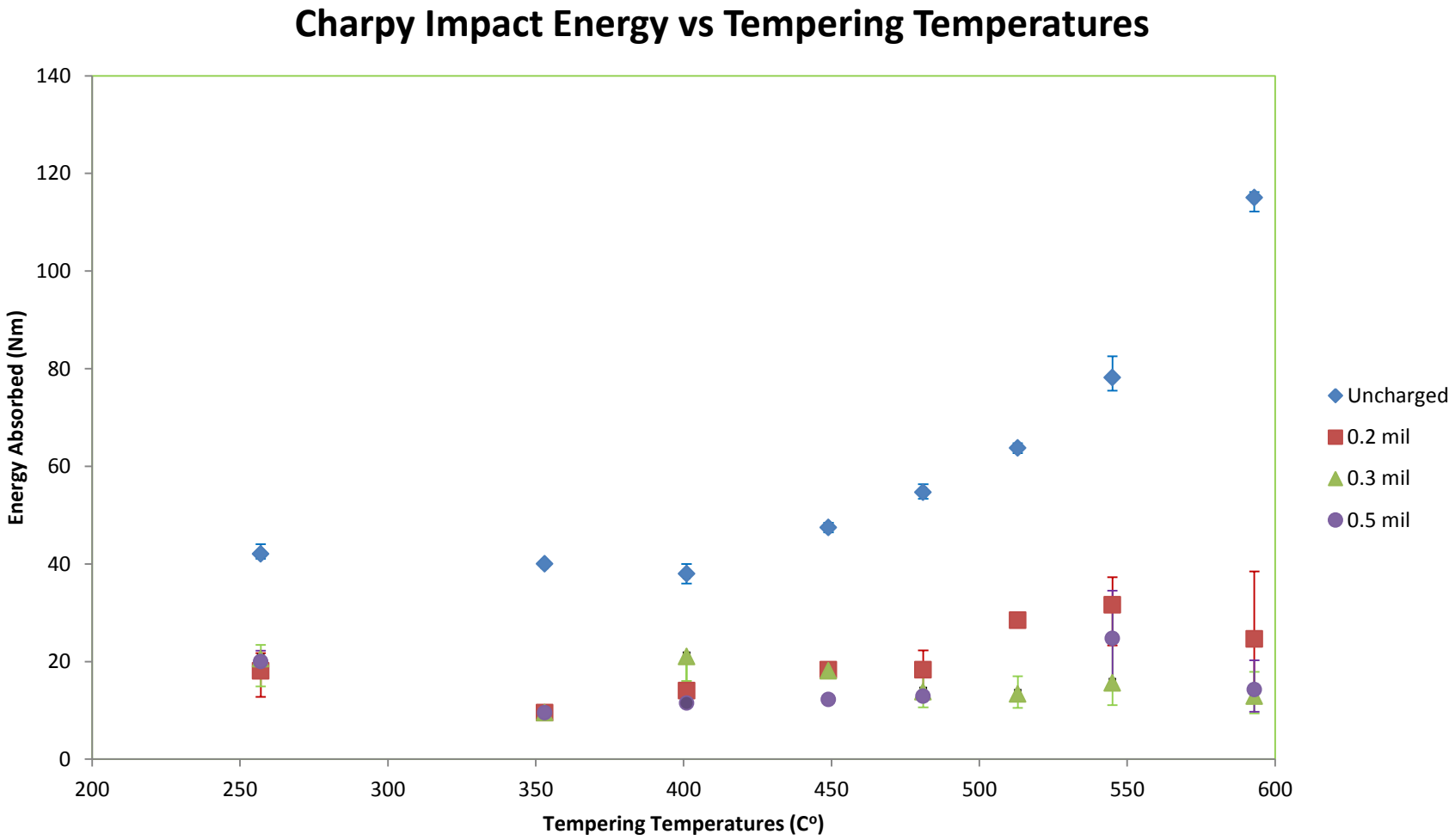


Figure: Charpy Impact vs Strength for Uncharged and Coated Samples

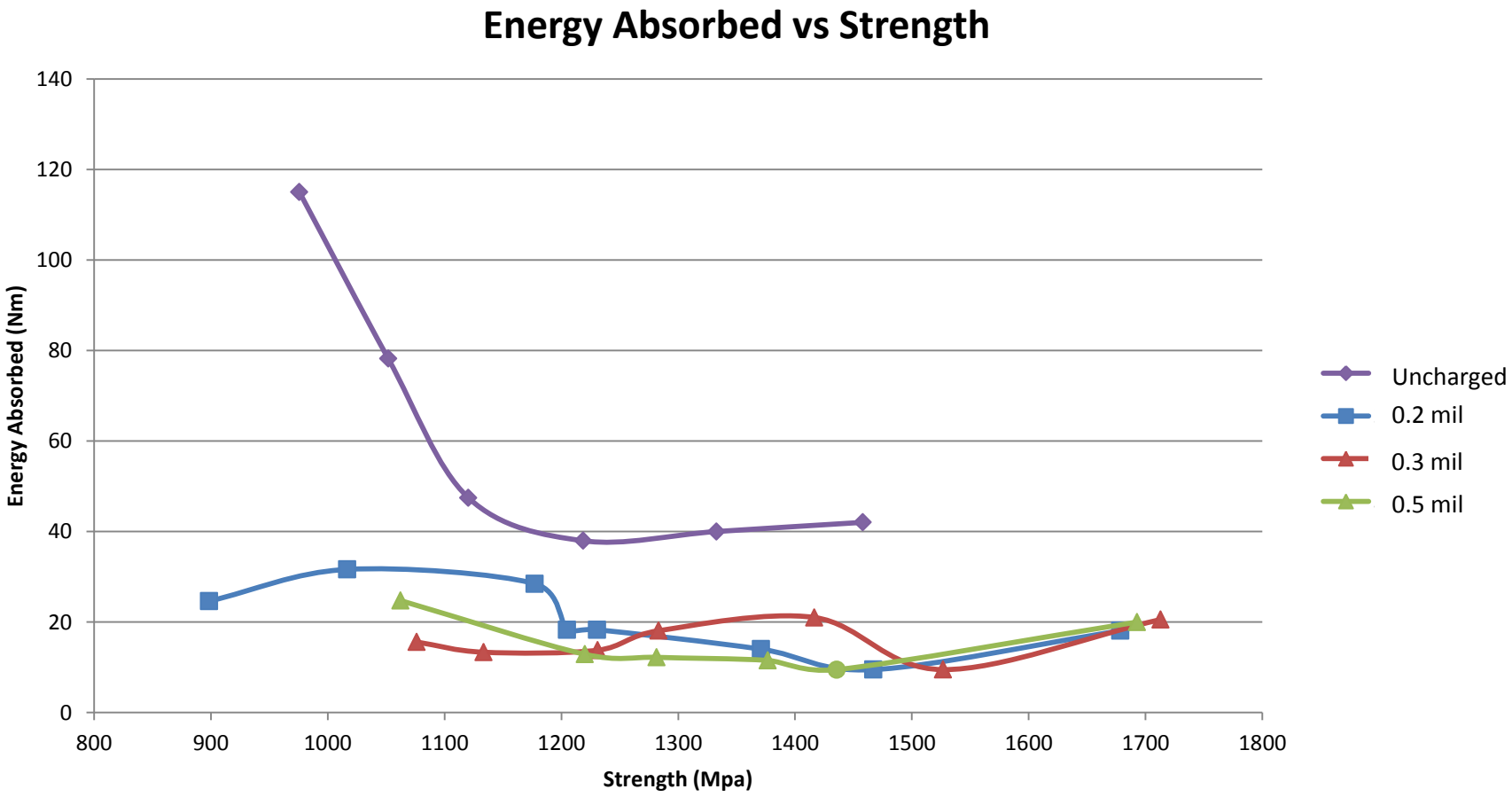
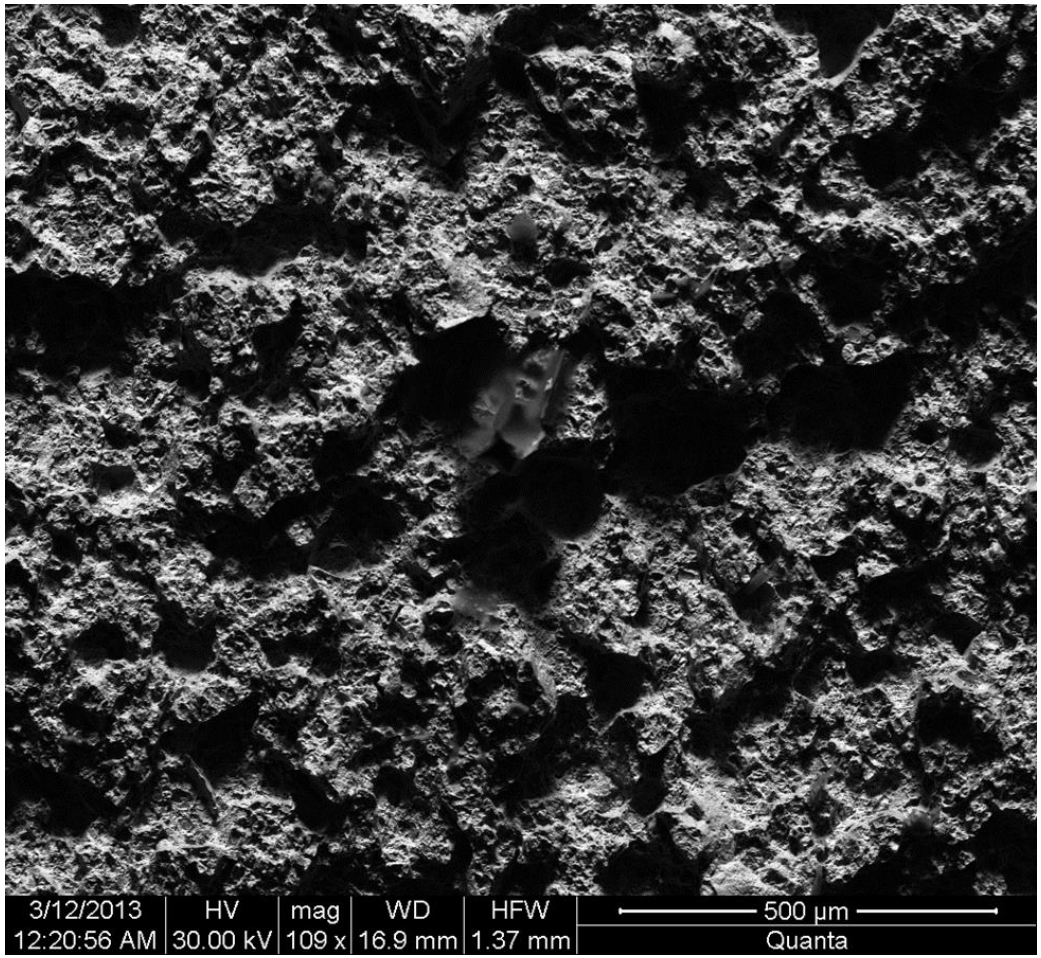


Figure : As received after being austenitized, oil quenched, and tempered at 232 °C



Average impact energy vs tempering temperature for uncharged and charged specimens

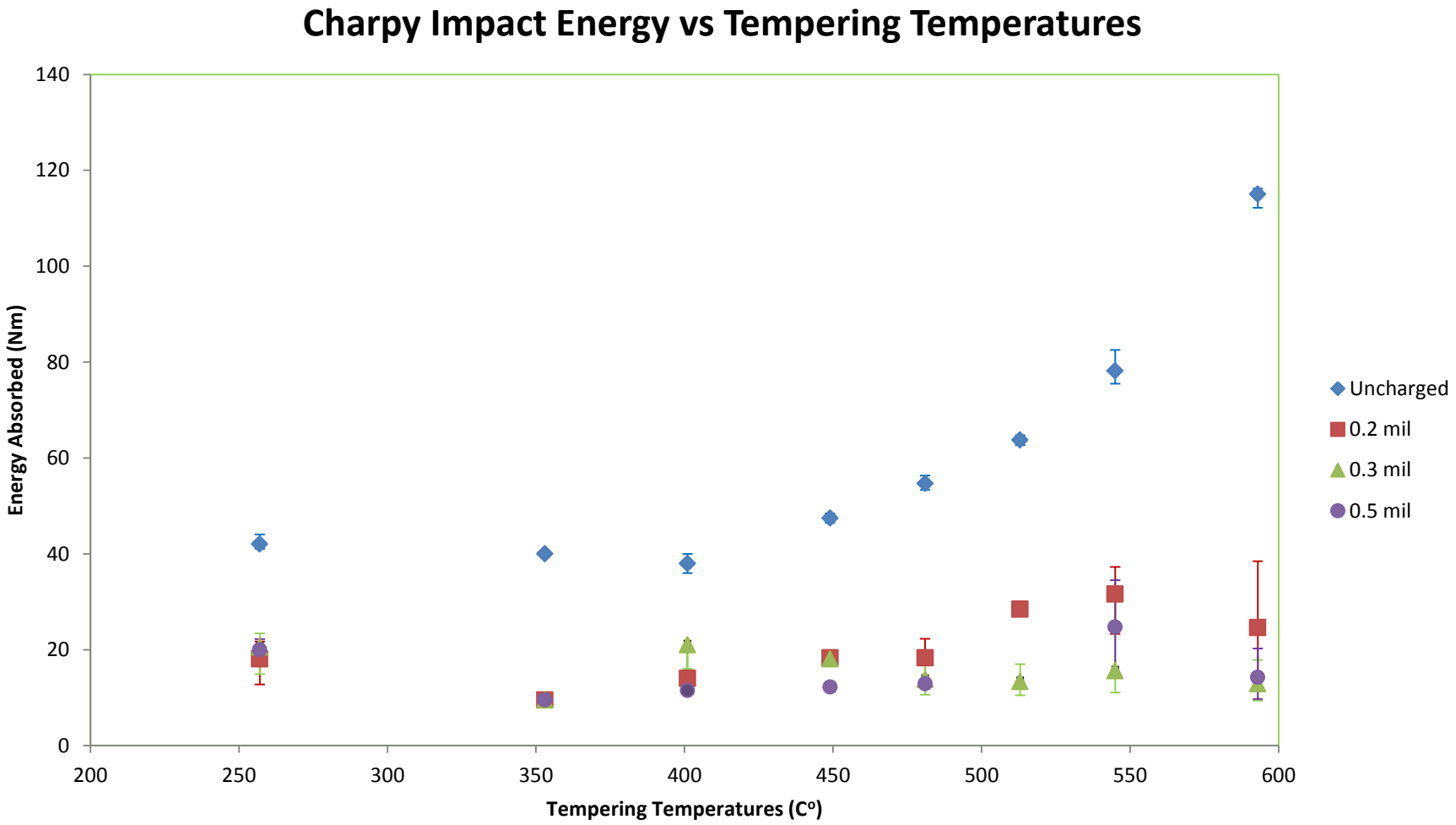


Figure: Specimens Tempered at 257 °C to produce a target strength of 1724 MPa (250 ksi) (uncharged)

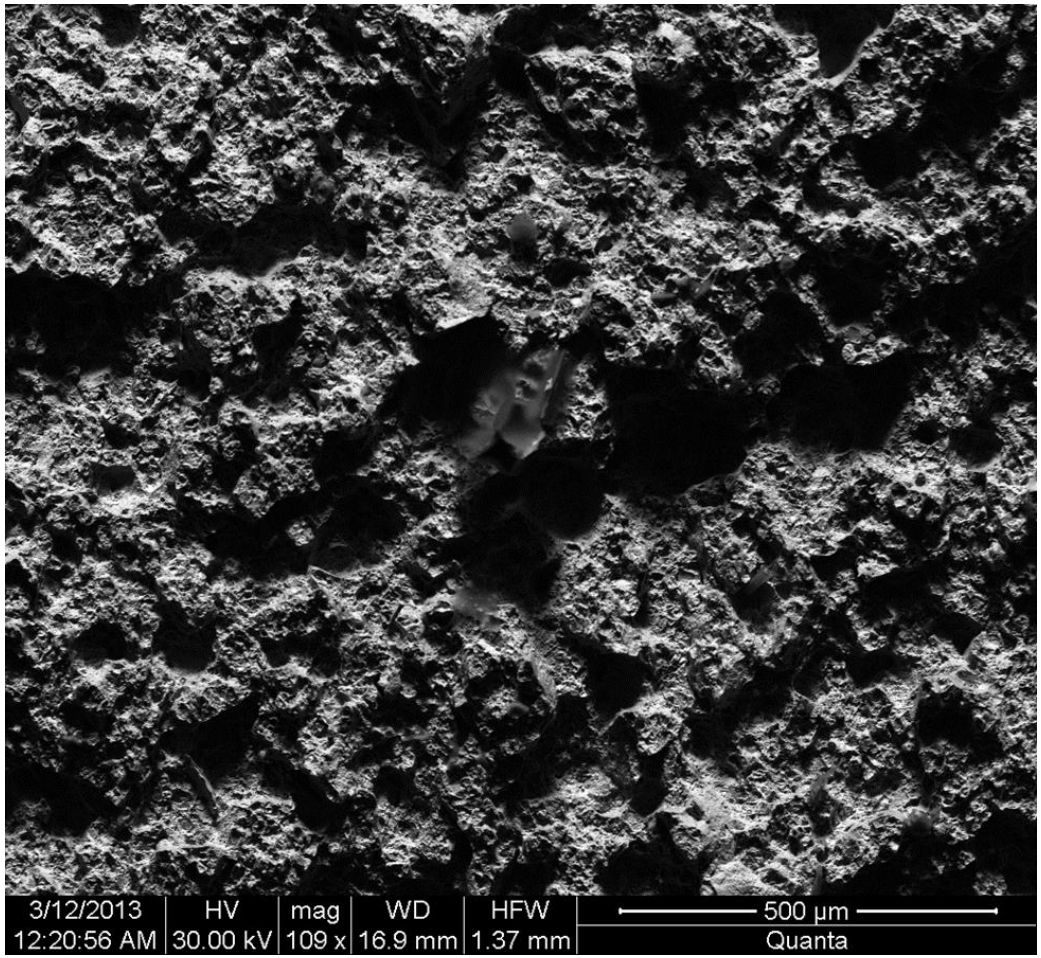


Figure: Specimens Tempered at 257 °C to produce a target strength of 1724 MPa (250 ksi) (0.00508mm (0.2 mils))

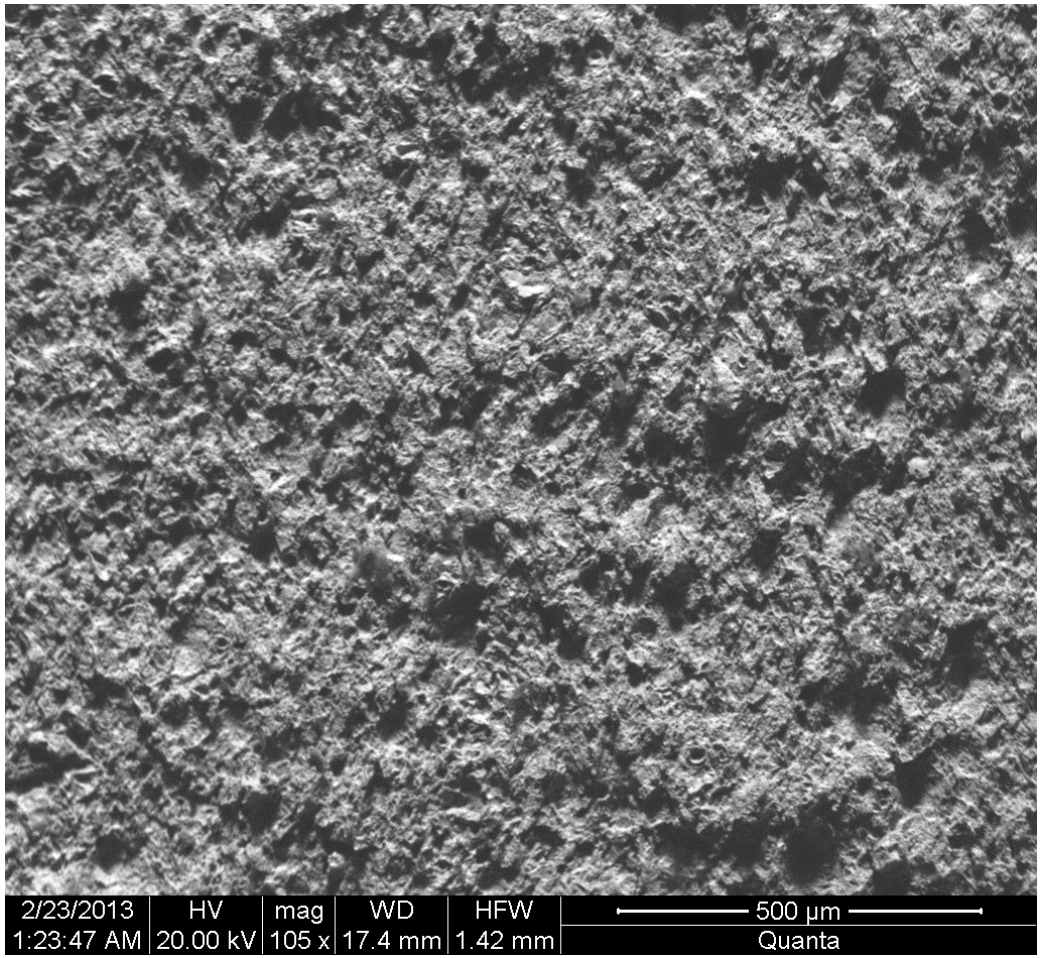


Figure: Specimens Tempered at 257 °C to produce a target strength of 1724 MPa (250 ksi) (0.00762mm (0.3 mils))

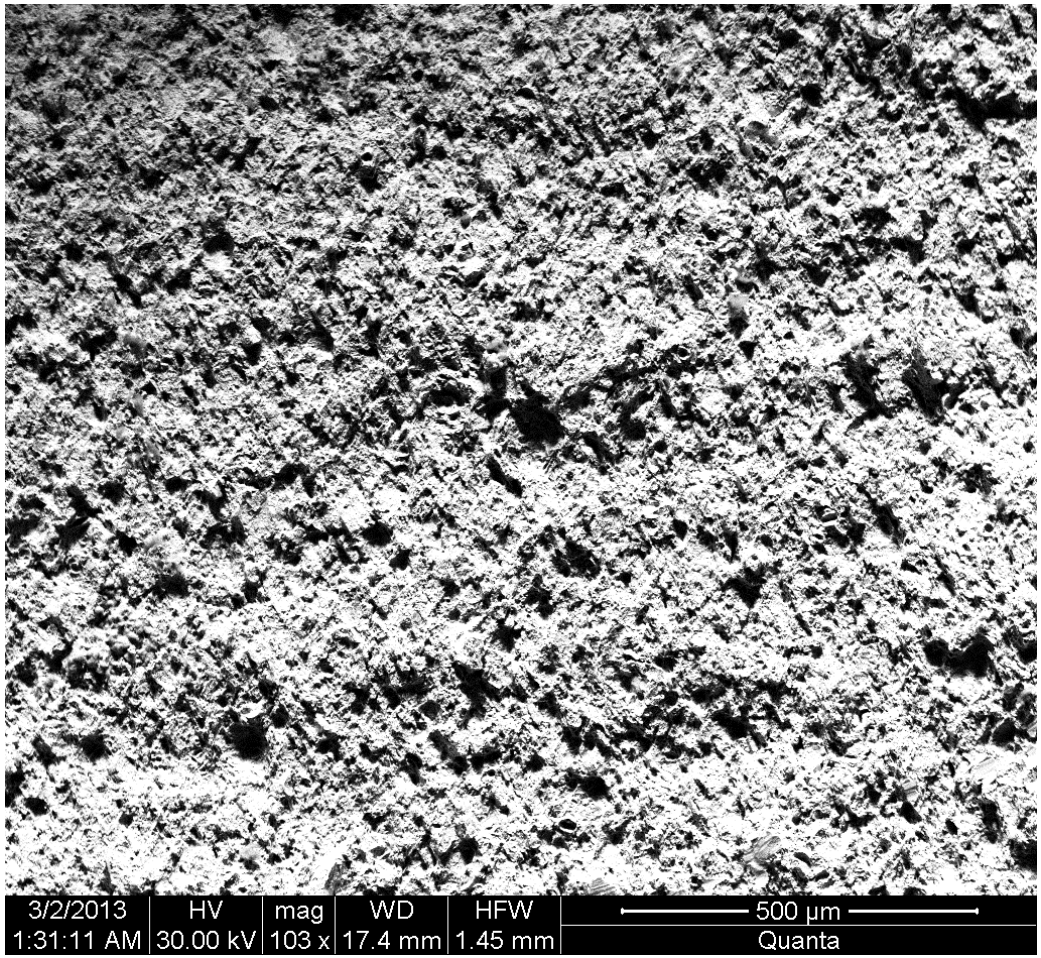
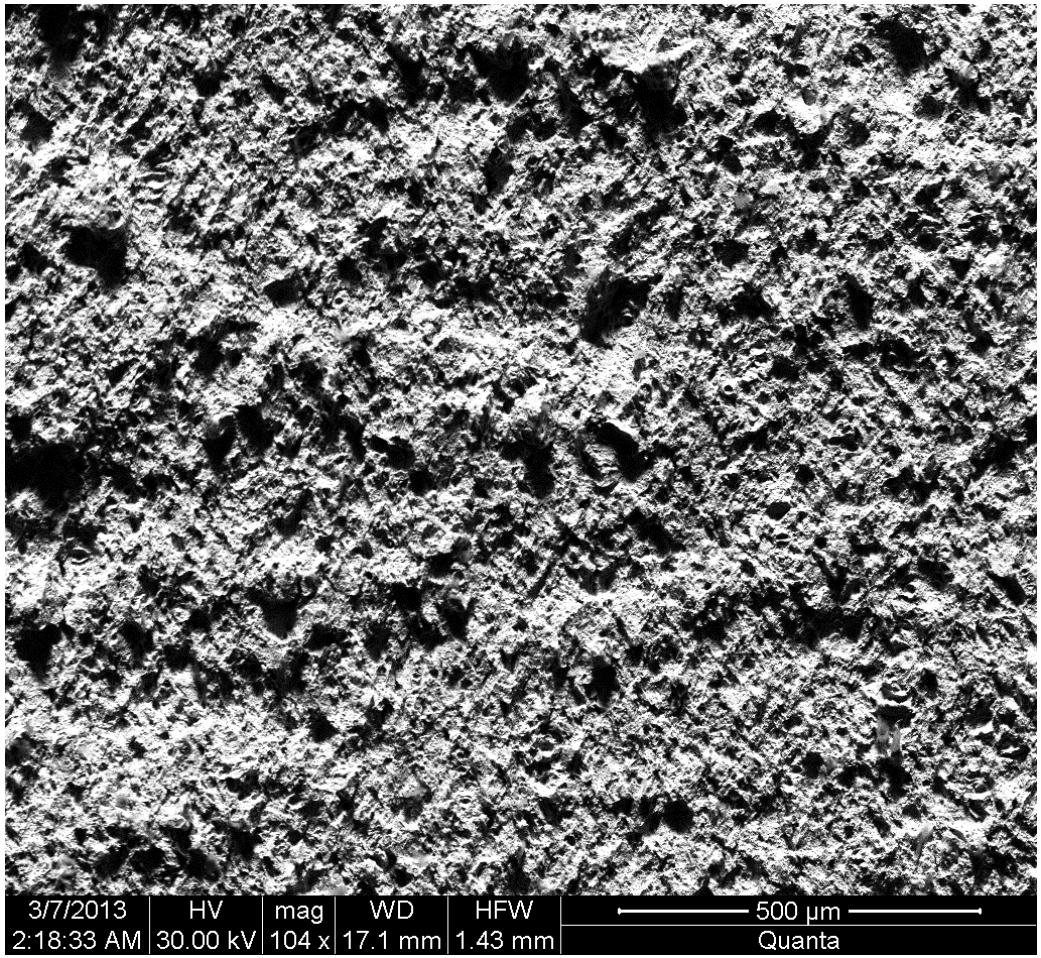


Figure: Specimens Tempered at 257 °C to produce a target strength of 1724 MPa (250 ksi) (0.0127mm (0.5 mils))



Phase 2 Conclusions

Results of Charpy impact tests indicate that this technique can clearly distinguish hydrogen charged specimens as compared to uncharged specimens in the range of all the tempering temperatures tested. This could be a very useful simple way of detecting hydrogen in steel alloys across the whole strength range.

Phase 2 Conclusions Continued

All the cadmium plated specimens had very low Charpy impact values irrespective of the tensile strength values

Phase 2 Conclusions Continued

SEM results again indicated that charged surfaces were populated by fine numerous microvoids, as compared to hydrogen-free values.

Phase 3:

Can Charpy Impact testing predict fracture toughness (K_{Ic}) values?

Charpy Impact Testing vs. Fracture Toughness in a Single Equation [Hertzberg 1995]

TABLE 9.3 Fracture–Toughness–Charpy Energy Correlations[24]

Material	Notch	Test	Temperature Range	Range of Charpy Results (J)	σ_{ys}(MPa)	Correlation[a]	Reference
A517D 4147 HY130 4130 12Ni–5Cr–3Mo 18Ni–8Co–3Mo	V-Notch	Impact	Upper Shelf	31–121 (23–89 ft-lb)	760–1700 (110–246 ksi)	$\left(\frac{K_{IC}}{\sigma_{ys}}\right)^2 = 0.64\left(\frac{\text{CVN}}{\sigma_y} - 0.01\right)$ $\left[\left(\frac{K_{ID}}{\sigma_{ys}}\right)^2 = 5\left(\frac{\text{CVN}}{\sigma_{ys}} - 0.05\right)\right]$	21,25
A517F A3202B ABS-C HY-130 18Ni (250) Ni–Cr–Mo–V Cr–Mo–V Ni–Mo–V	V-Notch	Impact	Transition	4–82 (3–60 ft-lb)	270–1700 (39–246 ksi)	$\frac{K_{IC}^2}{E} = 0.22(\text{CVN})^{1.5}$ $\left[\frac{K_{IC}^2}{E} = 2(\text{CVN})^{1.5}\right]$	25
A533B A517F A542	V-Notch	Impact	Transition	7–68 (5–50 ft-lb)	410–480 (60–70 ksi)	$K_{IC} = 14.6(\text{CVN})^{0.5}$ $[K_{IC} = 15.5(\text{CVN})^{0.5}]$	26
ABS-C A305-B A517-F	V-Notch	Impact	Transition	2.7–61 2–45 ft-lb)	250–345 (36–50 ksi)	$\frac{K_{ID}^2}{E} = 0.64\ \text{CVN}$ $\left[\frac{K_{ID}^2}{E} = 5\ \text{CVN}\right]$	27
		Slow Bend				$\frac{K_{IC}^2}{E} = 0.64\ \text{CSB}$ $\left[\frac{K_{IC}^2}{E} = 5\ \text{CSB}\right]$	

Conclusion

- **Possibility of correlating fracture toughness and Charpy Impact value.**
  - **Work in progress in the brittle region.**

Phase 4:

- The concentration of hydrogen will be measured in atomic percent versus the cadmium coating thicknesses.

- The Charpy Impact values will be correlated to the cadmium coating thicknesses values in terms of hydrogen concentration content.

Phase 4 Continued

- The transition from ductile to brittle behavior of hydrogen charged samples at coatings of different thicknesses of cadmium will be derived. This will be done at different strength levels and at different temperatures.

- These studies will be repeated for different steel and titanium alloys

Thank You