PURDUE
UNIVERSITY
Materials Engineering

Ductile to Brittle Transition in Casting Steels

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The purpose of this project was to help determine the feasibility of replacing welded wrought steel parts of tractor roll over protection structures (ROPS) with cast steel parts. ROPS materials must satisfy SAE and John Deere standards for low temperature impact energy among other properties. Charpy impact testing was performed to produce ductile to brittle transition plots which were used alongside other mechanical testing to determine which cast steel compositions and heat treatments met the mechanical requirements.

Work sponsored by John Deere, Waterloo, IA

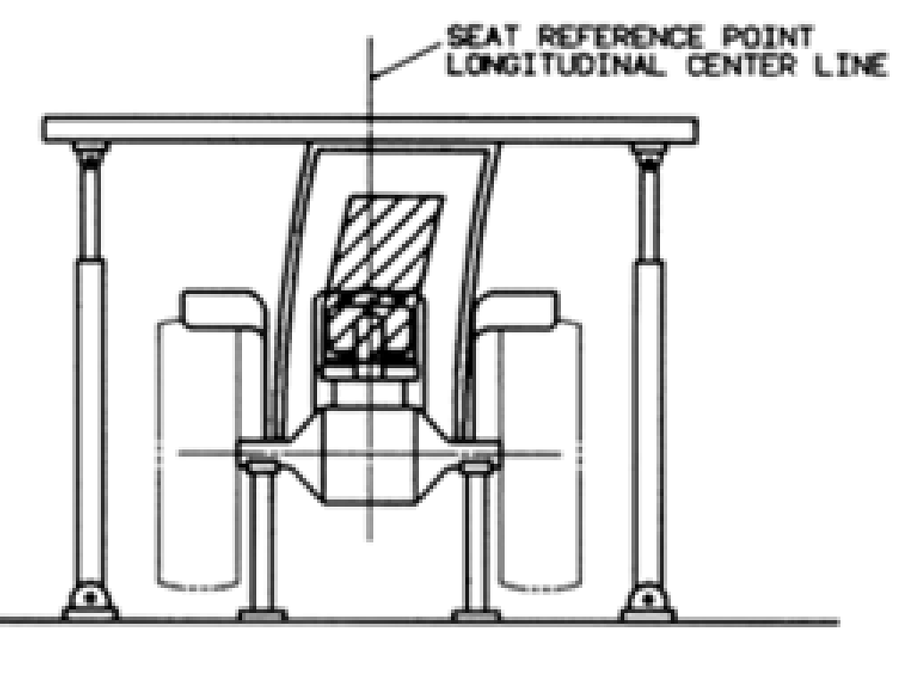
Project Background

Roll Over Protection Structures (ROPS)

- Mandated by SAE safety standards (J2194)
- Rigorous testing and mechanical strength specifications
- Protect operator in case of roll over

Weld vs Cast ROPS

- ROPS currently constructed from weldments
- Casting is a cheaper and more time effective alternative
- Cast steel grades must be investigated and proven to meet specifications



SAE J2194, *Roll-Over Protective Structures (ROPS) for Wheeled Agricultural Tractors*, SAE International

Testing Standards

SAE J2194 - ROPS for Wheeled Agricultural Tractors
SAE impact energy requirement ≥ 11J at -30°C
ASTM E23 - Notched Bar Impact Testing

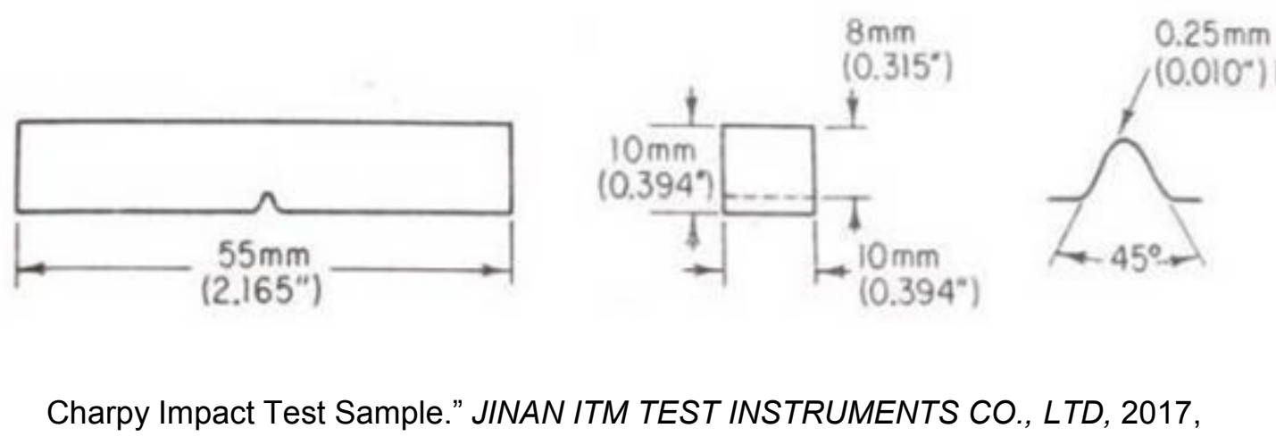
Experimental Procedure

Sample	Grade	Heat Treatment
A	ASTM A 148 GR 80-40	Anneal 1700°F
B	Modified 4135	Anneal 1700°F
C	ASTM A 352 GR LCB	Water Quench & Temper (1650°F/1250°F)
D	ASTM A 216 GR WCC	Normalize & Temper (1700°F/1150°F)
E	ASTM A 216 GR WCB	Anneal 1700°F
F	4120	Water Quench & 2x Temper (1650°F/1200°F)
G	8620	Water Quench & 2x Temper (1650°F/1200°F)

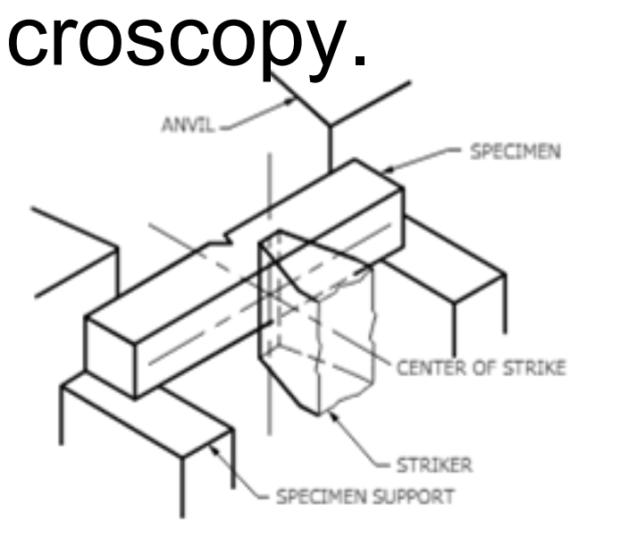
Various compositions and heat treatments were selected to provide several influential factors on the ductile to brittle impact temperatures.

Sample	C	Si	Mn	P	S	Ni	Cr	Cu	Mo	Al	V	Zr
A	0.295	0.445	1.335	0.013	0.01	0.070	0.135	0.085	0.025	0.060	0.007	0.020
B	0.340	0.420	0.870	0.016	0.011	0.060	0.740	0.090	0.420	0.064	0.009	0.021
C	0.230	0.470	0.840	0.012	0.010	0.060	0.110	0.080	0.020	0.069	0.008	0.018
D	0.247	0.440	0.945	0.013	0.010	0.073	0.247	0.083	0.092	0.065	0.007	0.019
E	0.257	0.453	0.891	0.013	0.009	0.088	0.169	0.118	0.050	0.062	0.008	0.017
F	0.240	0.423	0.758	0.011	0.014	0.165	0.840	0.153	0.218	0.034	0.008	-
G	0.243	0.413	0.760	0.011	0.013	0.675	0.568	0.173	0.268	0.045	0.006	-

Mechanical testing consisted of Charpy impact testing, tensile testing, and hardness measurements. Fractography consisted of optical microscopy.



Charpy Impact Test Sample." *JINAN ITM TEST INSTRUMENTS CO., LTD,* 2017, www.impacttestingmachine.com/new/charpy-impact-test-sample.html.



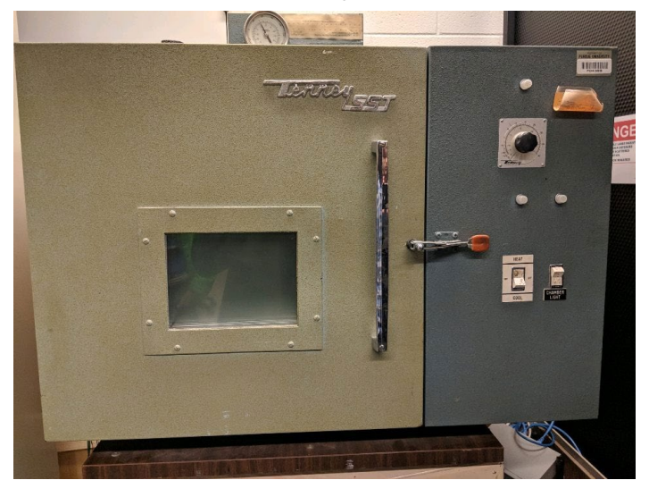
ASTM E23-18

Temperature Control

Range: -60°C to 100°C ± 1°C
Elevated: hot plate and water bath
Chilled: isopropyl alcohol bath undercooled in Tenney environmental chamber.

Charpy Impact Tester

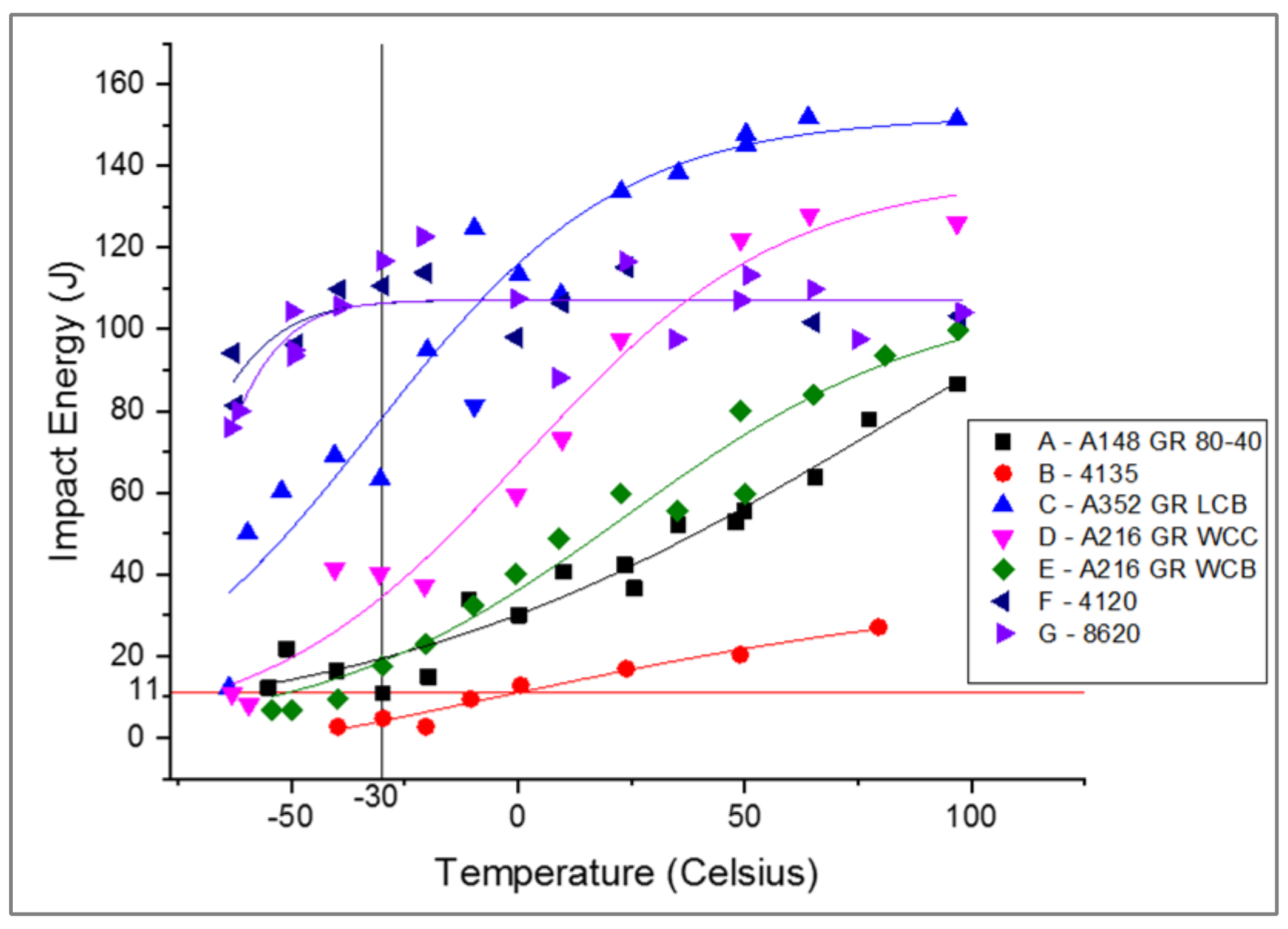
In order to ensure the samples were within ± 1°C, the isopropyl bath was kept in a thermos when outside the chamber. Once removed from the bath, the sample had to be tested within 5 seconds according to the ASTM E23 standard.



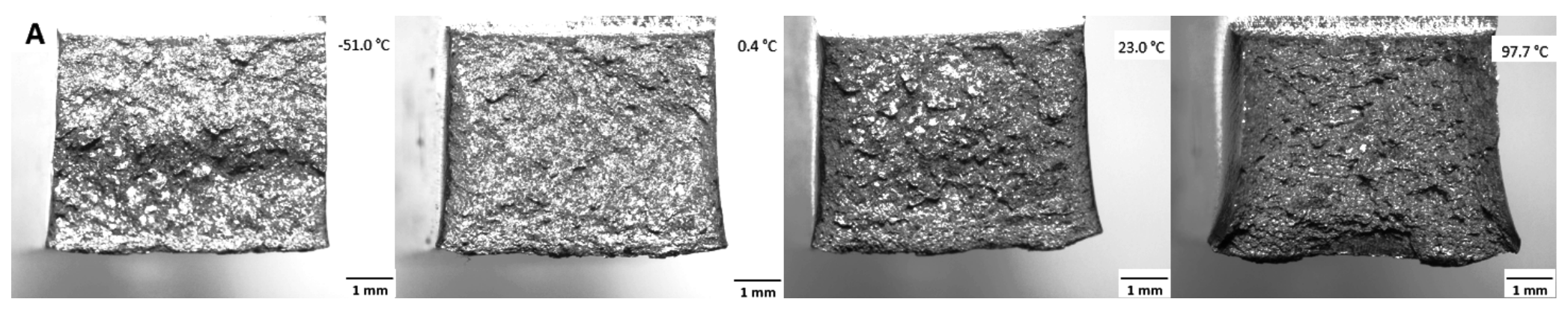
Tenney Environmental Chamber

Results

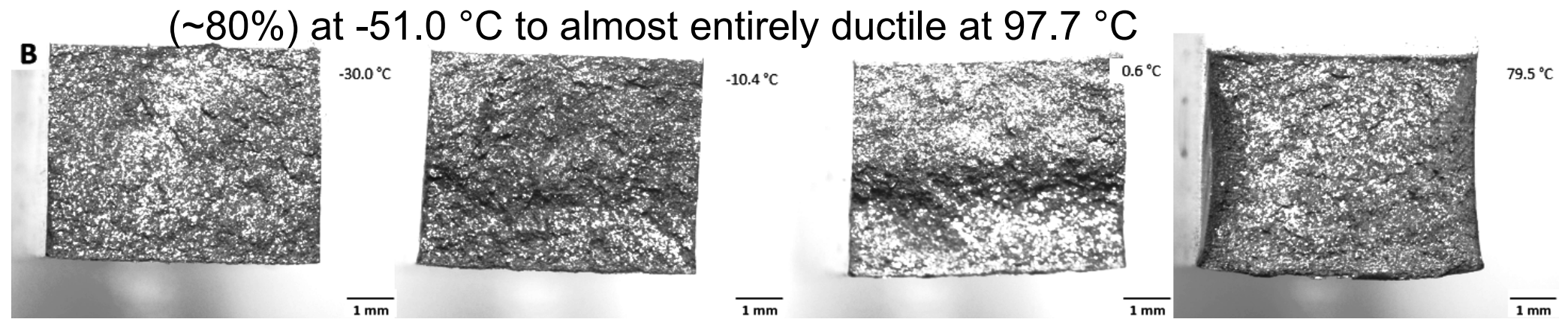
We verified the Charpy machine with NIST low energy verification samples before and after testing. All tests were within the tolerance of 15 ± 1.4 J at the testing temperature of -40 ± 1°C.



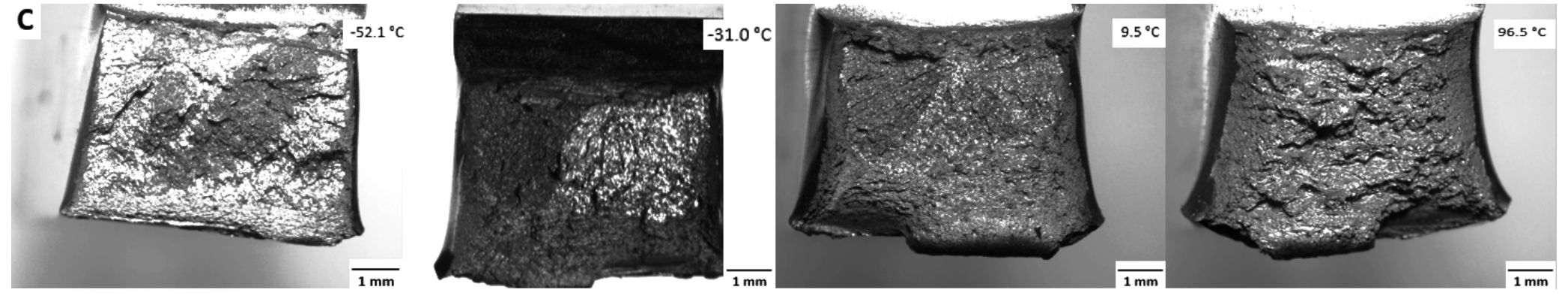
This graph displays the charpy impact energies with respect to the temperature. The values required by SAE J2194 are marked (-30 C, 11 J). If multiple tests were performed at the same temperature, the impact energy results were averaged for the sake of this plot.



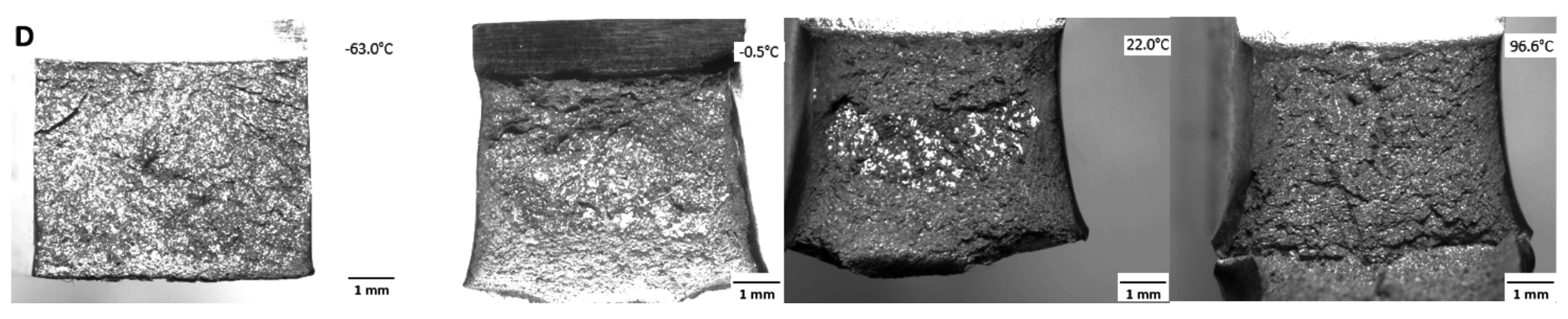
The fracture surface for set A displays a shift from largely brittle (~80%) at -51.0 °C to almost entirely ductile at 97.7 °C



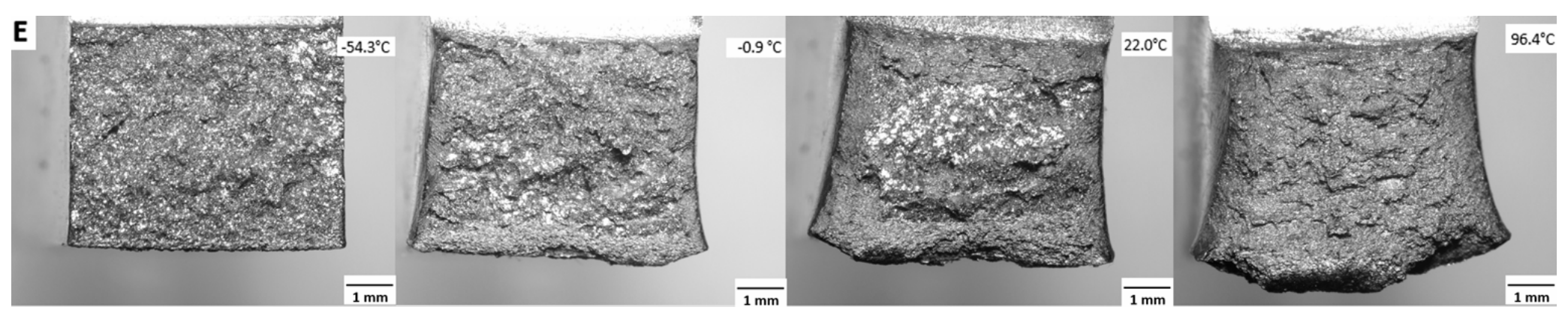
The fracture surface for set B remains largely brittle across the temperature range. Unsurprisingly, it does not meet the standard.



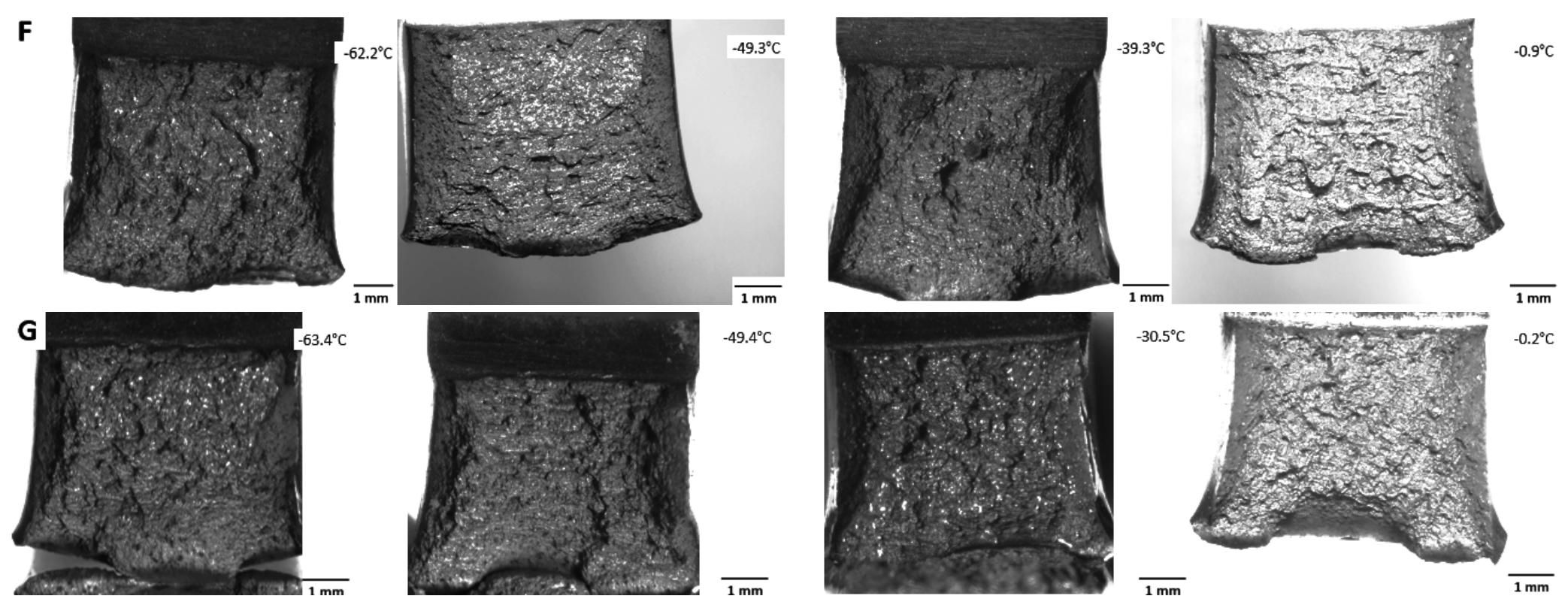
The fracture surface for set C shifts towards greater amount of brittle fracture at low temperatures, but does not become fully brittle even at -52.1°C.



The fracture surface for set D is fully brittle at -63.0 °C and fully ductile at 96.0 °C. The sample at -0.5 °C is about 25% ductile and the sample at 22.0 °C is about 75% ductile.



The fracture surface for set E also transitions from largely brittle at -54.3 °C to largely ductile at 96.4 °C.



The fracture surface for sets F and G remain largely ductile even at low temperature. At room temperature and above, the Impact Energy was so great some samples stopped the hammer entirely.

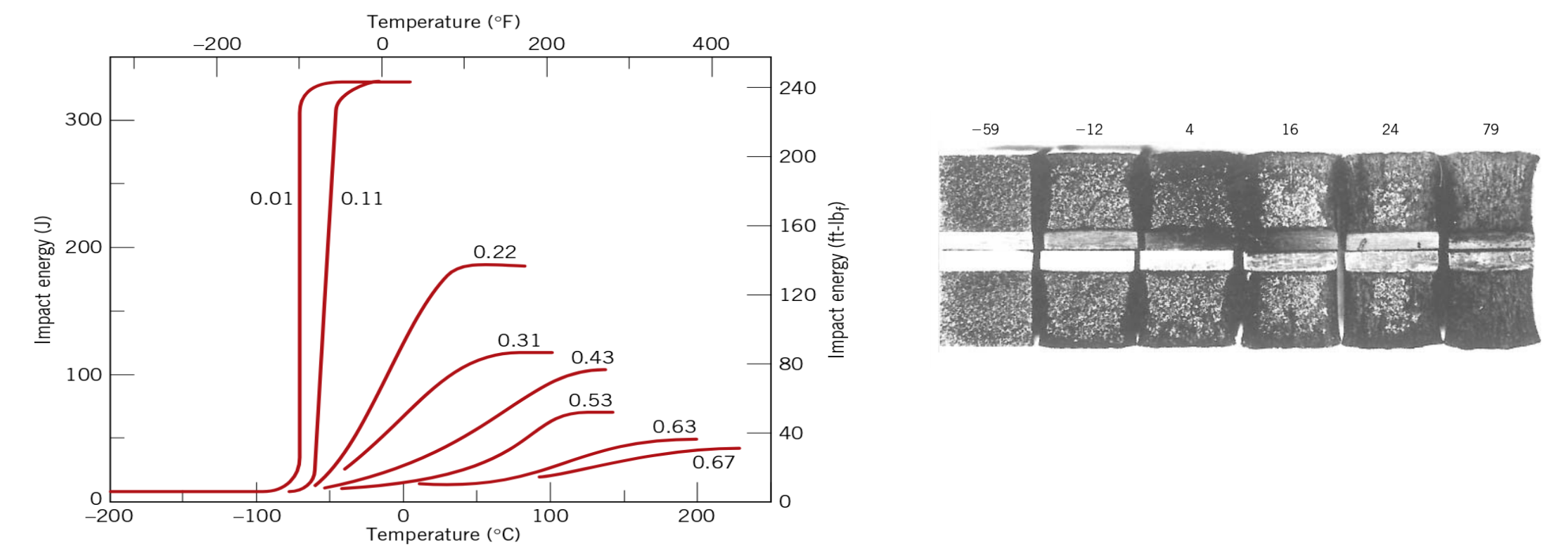
Sample	UTS (MPa)	σ_{UTS}	σ_y (MPa)	$\sigma_{\sigma y}$	Hardness (HRB)	σ_{HRB}	Impact -30C (J)	σ_{Impact}	% elongation	$\sigma_{\%el}$
A	608	8	328.0	10.3	86	2.8	10.85	4.89	26.8	1.2
B	761	13	362.0	8.8	93	1.6	4.75	1.17	15.2	2.8
C	591	30	412.9	-	89	1.6	63.27	10.73	30.6	3.7
D	594	29	369.3	2.6	84	1.1	40.22	5.48	32.7	2.0
E	529	6	291.1	3.7	78	2.0	17.63	5.91	30.2	1.1
F	729	13	593.5	30.0	95	0.7	110.67	1.50	29.0	3.7
G	716	30	522.4	30.6	100	2.2	116.77	5.43	26.2	0.2

Tensile testing was performed on a 300 kN load cell with an 1” extensometer attached until shortly after yield. Ultimate tensile strength (UTS) was measured using the maximum load reported and gauge section dimensions measured before the tensile test.Additional hardness testing using Rockwell B (HRB) and Rockwell C (HRC) scales was performed on the pristine sections of the tensile bar grips

Theory

Ductile to Brittle Transition Temperature

- As T↓, Impact Energy↓ and % Brittle fracture ↑
- Affected by microstructure, phase, impurity segregation, grain size and, composition



Callister and Rethwisch, Wiley, 9th ed., pp. 268-9

Hall Petch Relationships

- d ↓, yield stress ↑, fracture stress ↑↑, DBTT ↓
- Provides guidance for improving mechanical and DBT properties through grain refinement

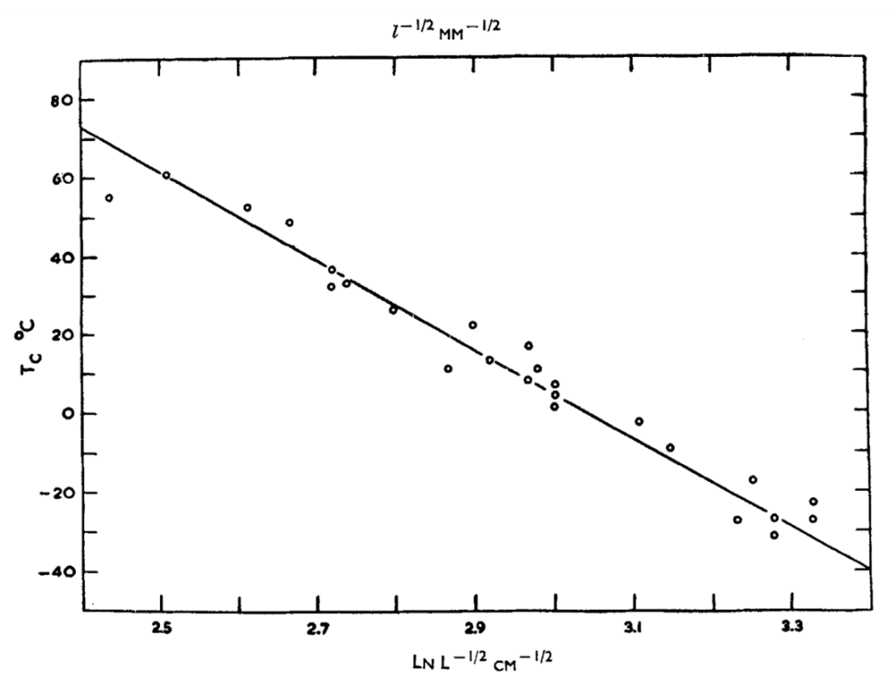
$$\sigma_y = \sigma_0 + K_y d^{-1/2}$$

$$\sigma_f = K_f d^{-1/2}$$

$$T_B = T_0 - K_B d^{-1/2}$$

$$\dots$$

$$K_B = -\left[\frac{d\sigma}{dT}\right]^{-1} (K_f - K_y)$$



Heslop and Petch, Pil. Mag., 3:34, 1128-1136 (1958)

Discussion

Our Charpy impact tests show that samples C, D, E, F, and G meet SAE standard for impact energy at -30°C. They also show that the transition regions of most of the samples are large, spanning at least 100°C and often more. This made it difficult to measure the upper and lower shelves of the DBT curve because of the temperature abilities of our testing equipment. Nevertheless, many of our samples show nearly the whole transition curve, which is useful for John Deere’s decision of material. Tensile testing adds useful information about ultimate tensile stress, yield stress, and percent elongation at failure which augment the picture of material properties given by the Charpy impact data. The three tests show strong correlations among the different properties and with the compositions and heat treatments of the samples. To quantify these relationships, ordinary least squares regression models were used. Total alloy composition in wt. % is a significant predictor of improved hardness (+13 HRB / wt. % @ 90%) and UTS (+161 MPa / wt. % @ 95%). Heat treatment is a significant predictor of Charpy impact energy at -30°C, showing +85 J at 95% confidence compared to air quench or anneal. Taken together, these results allow us to make confident recommendations to John Deere about the materials we tested and how to proceed.

Recommendations

Samples C, D, E, F, and G meet SAE standard for impact energy at -30°C. Future examination of how heat treatments affect the impact energy would provide insight into why sample sets F and G proved sturdy throughout the entire temperature range. Additional EBSD and other composition analysis could clarify the role of alloying elements.

MSE 430-440: Materials Processing and Design