PURDUE UNIVERSITY®

School of Materials Engineering

Development of Recovery Anneal Treatment for Steel Sheet to Achieve Property Targets

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The SDI Butler Senior Design Team been tasked with exploring the mechanical properties of partially annealed steel to meet the SS70 physical requirements as outlined in ASTM A653. Recovery annealing is a process in which the material is annealed, allowing for recovery, but is removed from the furnace before the recrystallization process can begin. Recovery annealing should allow for the recovery of some ductility but without a drastic loss of strength, allowing SDI to achieve the desired properties of SS70 steels. This project aims to explore the time-temperature conditions necessary to achieve recovery annealing and ultimately produce SS70 steel.

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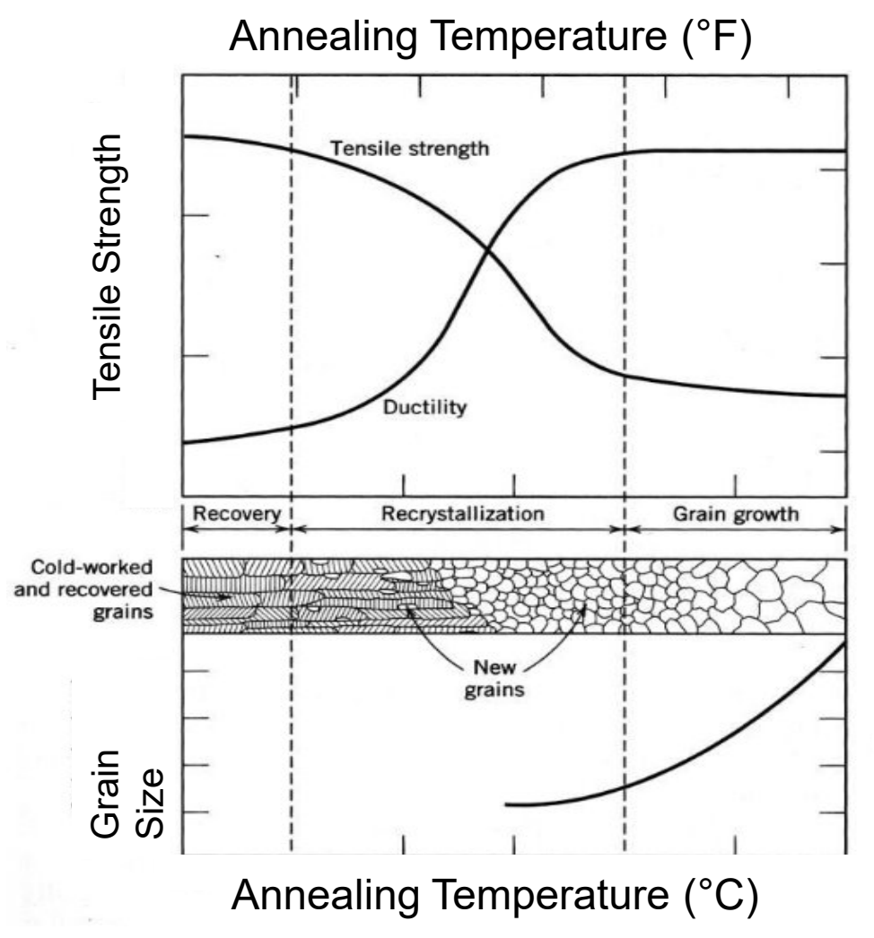
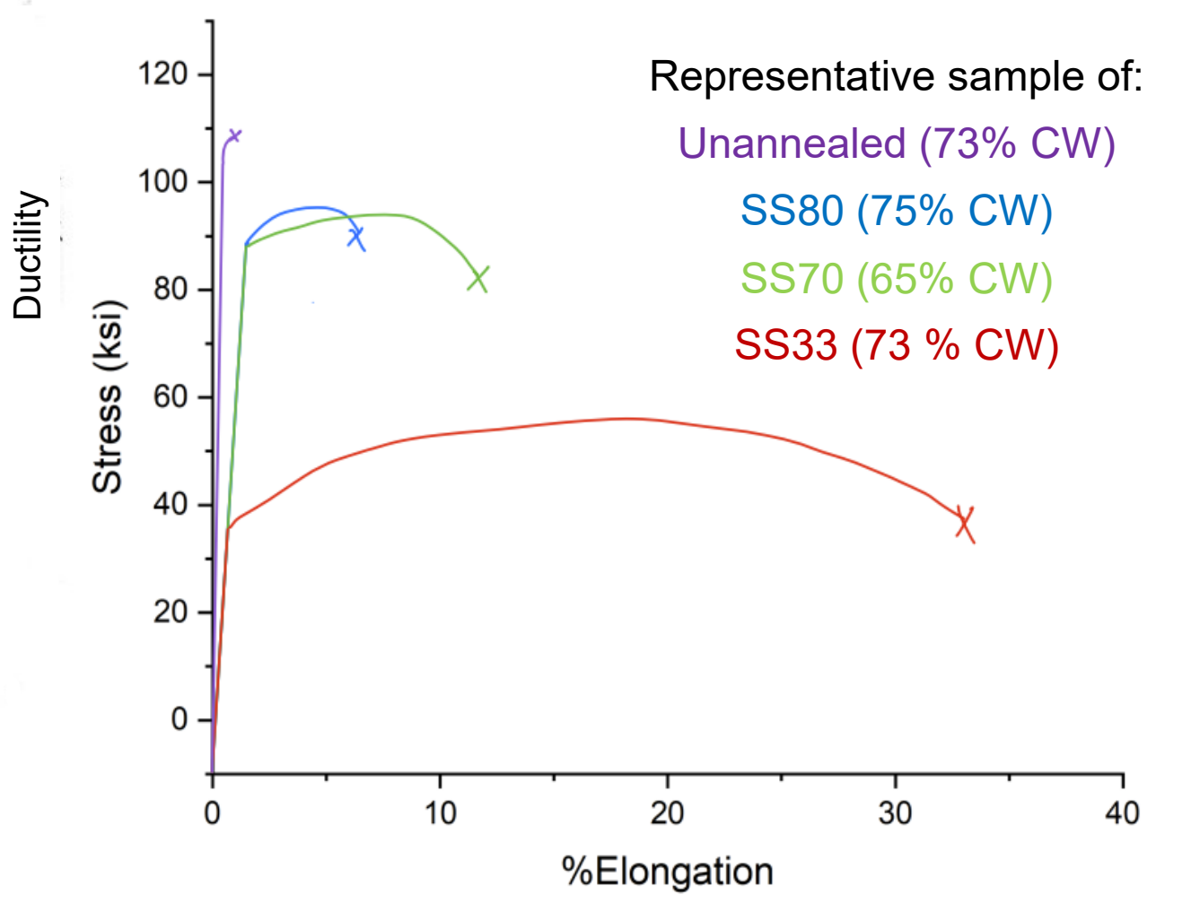
SDI

Background & Objectives

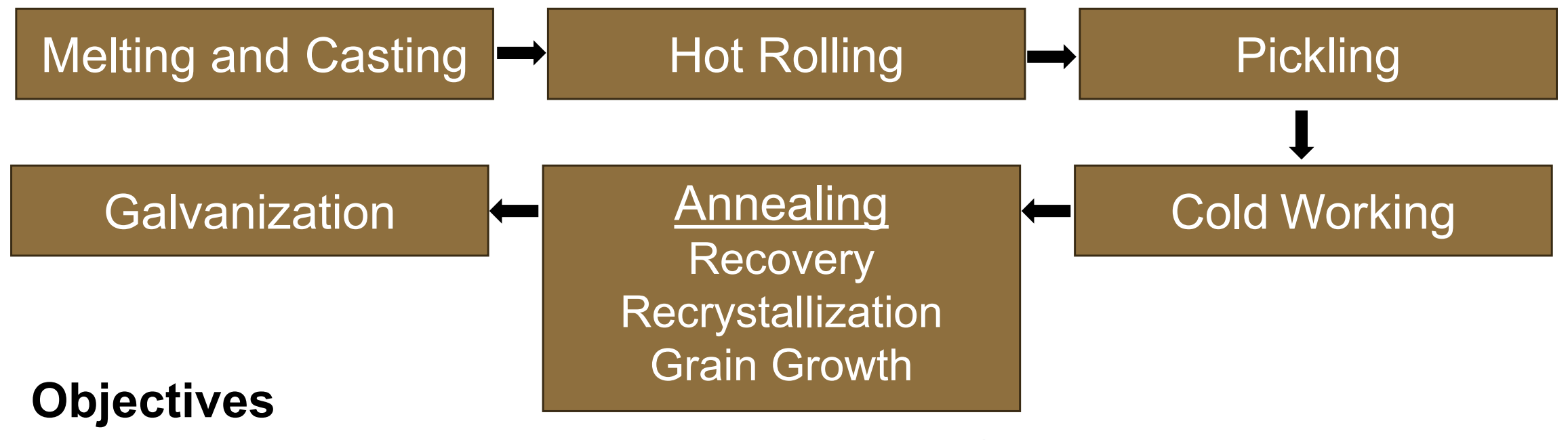
Project Background

- Sheet steel is a form of steel that has been rolled into thin, flat sheets that are rolled into large coils for storage. Applications include automotive bodies, construction, roofing, and packaging.
- SS70 steel requires a minimum yield strength of **70 ksi** and a minimum elongation of **9%;** SDI has previously run trials of SS70.
- Annealing is a process used to soften steel, returning ductility while sacrificing strength. Steel Microstructure is directly related to this process.
- SDI utilizes a continuous annealing furnace, with adjustable temperatures and line speeds.
- The steel spends 50-60 seconds in the continuous annealing furnace, but only 15-20 seconds at annealing temperatures.





SDI's Steel Making Process



Melting and Casting → Hot Rolling → Pickling ↓ Cold Working ← **Annealing**: Recovery, Recrystallization, Grain Growth ← Galvanization

Objectives

- Develop a time-temperature combination for a recovery annealing cycle for SS70 properties that would allow SDI to sell their steel for new applications to new customers.
- Provide SDI with annealing kinetics data gathered at Purdue and a way to correlate it to their annealing line.
- Provide HRB hardness measurements taken at Purdue with a way to correlate to the HRB that was taken at SDI.
- Provide visual characterization on the microstructural composition of SDI's steel.

Materials & Methods

Methods

- Steel coupons 0.034" thick of various degrees of cold work were annealed, varying with time and temperature. To achieve near-instantaneous heat transfer, our samples were submerged in molten tin held at a steady annealing temperature. To prevent deposition of tin into the steel, our samples were first coated in white-out containing titanium oxide.
- Rockwell B hardness testing (HRB) was performed. HRB was followed by Vickers micro-indentation hardness testing (HV) as a proxy for yield strength (YS) with the correlation seen in equation [1].

$$[1]\quad \boldsymbol{YS\,(MPa) = -90.7 + 2.876(HV)}$$

- 10 Vickers indentations were made at each time interval for a larger sample size.
- Optical microscopy was utilized to capture the microstructure of our samples to determine the visual extent of annealing.

Steel Chemistry

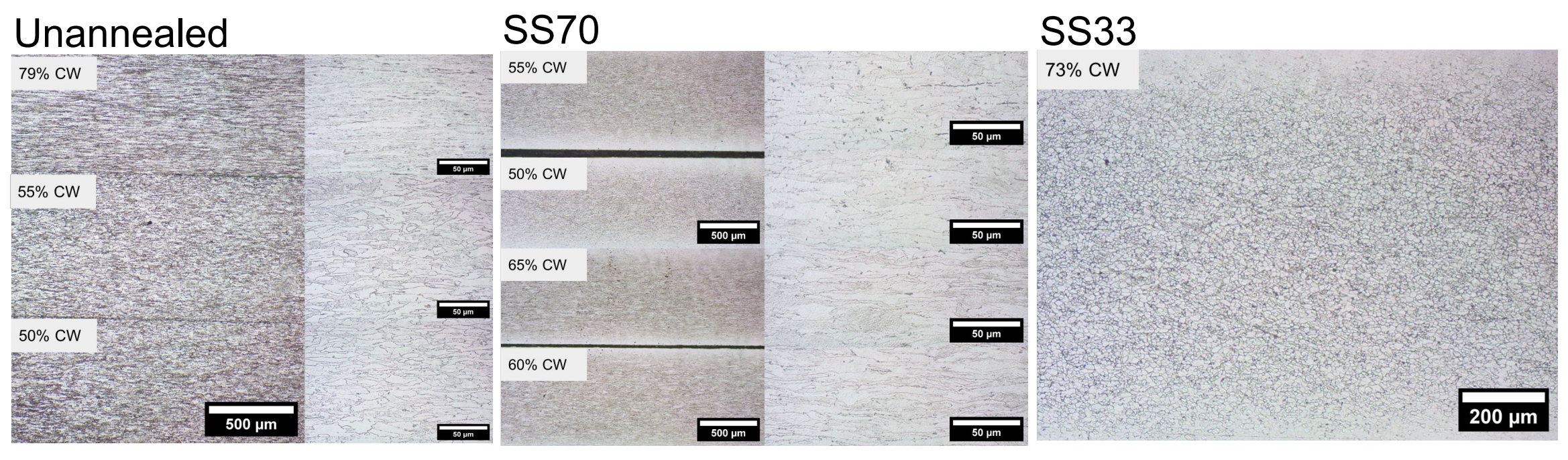
C	Mn	P	Si	Al	Cu	Ni
0.03	0.23	0.014	0.03	0.018	0.17	0.05
Cr	**Mo**	**N**	**V**	**Nb**	**Ti**	**B**
0.07	0.02	0.009	0.001	0.001	0	0.0054

- The average chemistry of the 19 different alloys sent from SDI is shown in the table above, showing an ultra low carbon, plain composition.
- No element relevant to strengthening varied more than 5/100th of a weight percent.
- Utilizing an established correlation between yield strength and chemistry sensitivity,[2] with the maximum and minimum alloy compositions, a 2 ksi (~15 MPa) variance in strength can be attributed to variance in chemistry.
- 2 ksi is within the margin of error for the equation and will be neglected.

$$[2]\quad Y\,(\pm\,31\text{ MPa}) = 88 + 37(\text{wt\%Mn}) + 83(\text{\%Si}) + 2918(\text{\%N}) + 15.1(d\text{ (mm)}^{-1/2})$$

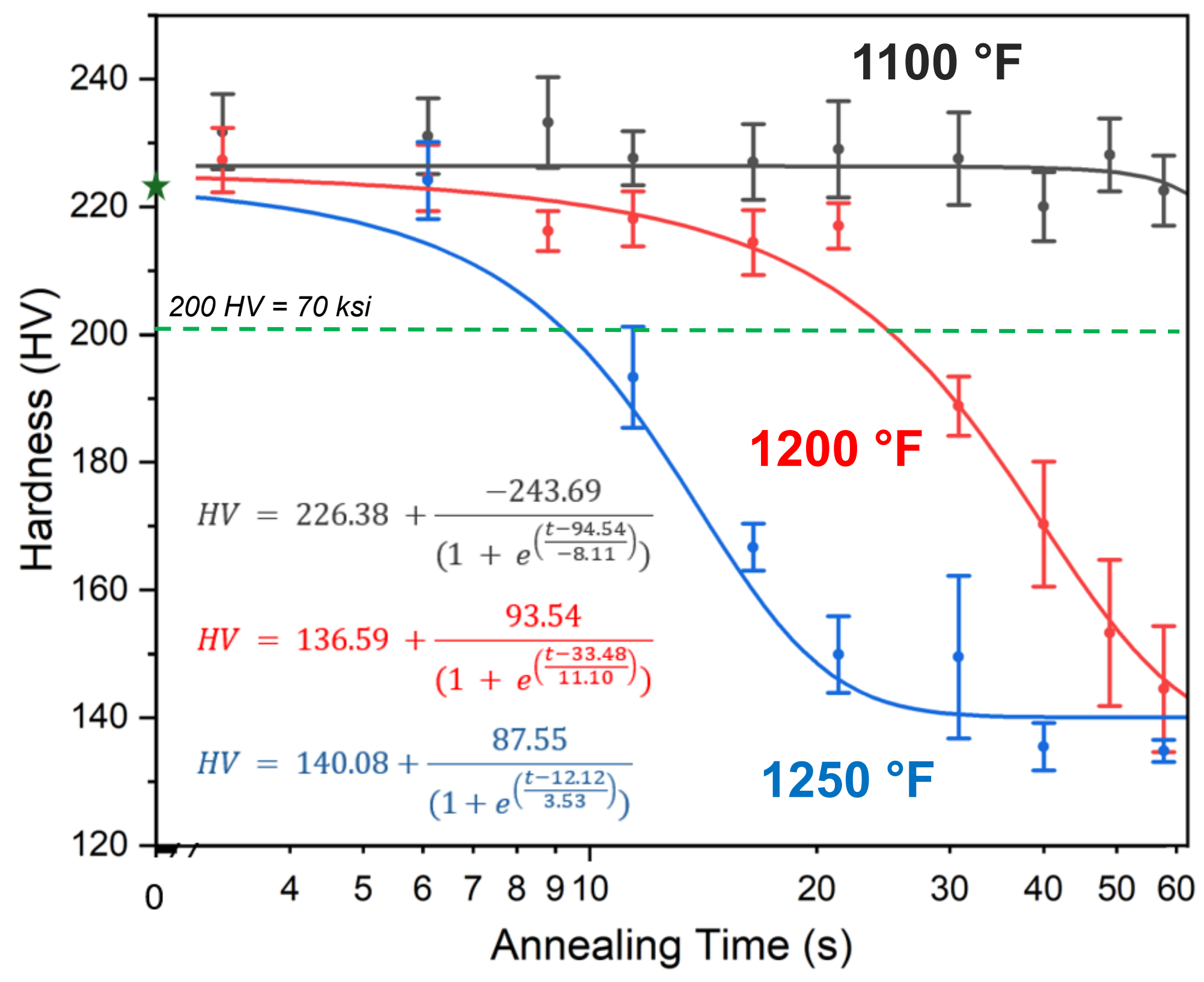
Results & Discussion

Microscopy



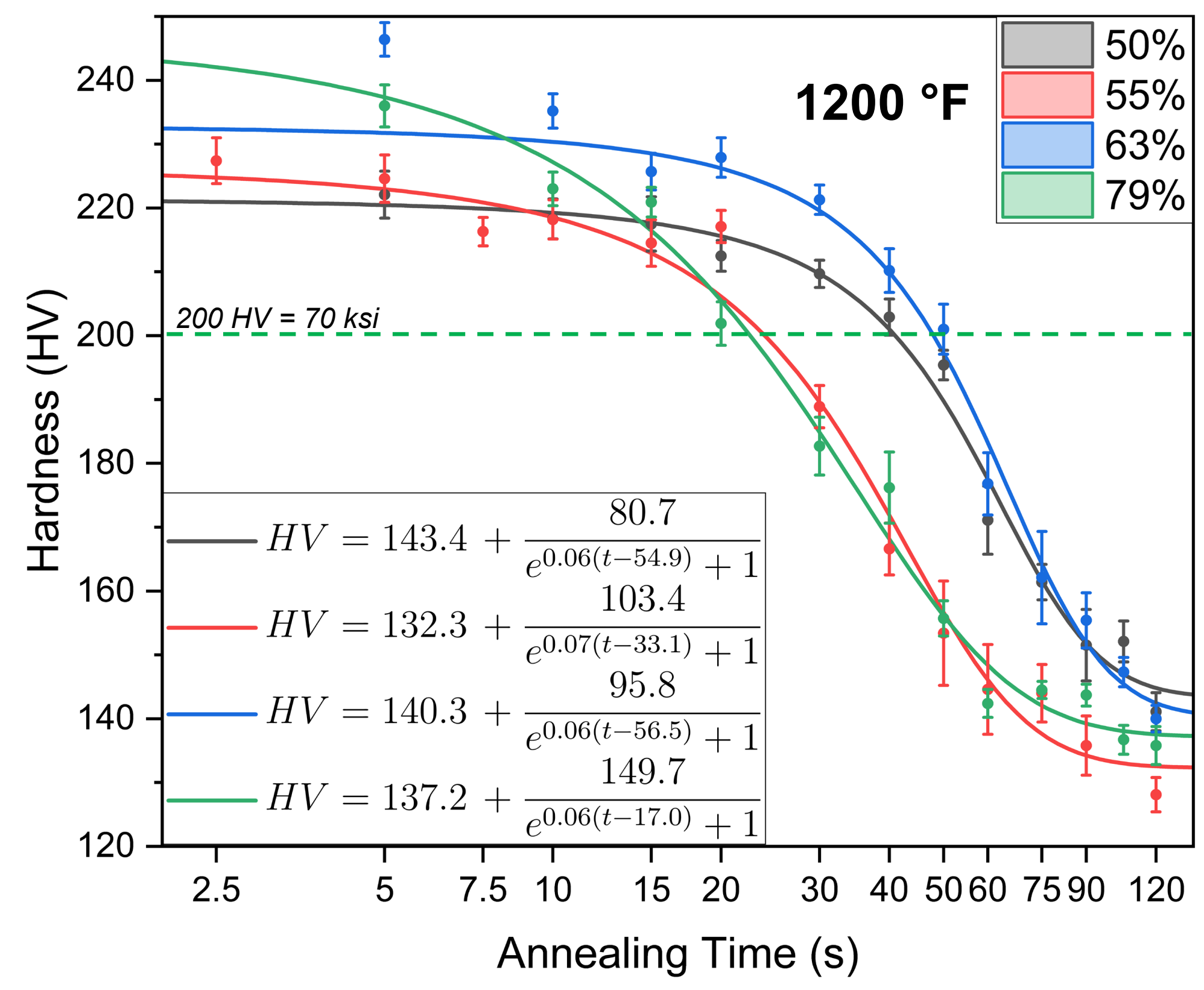
- Microscopy of unannealed, SS70, and SS33 steel samples sent directly from SDI was completed, presented above from least to most annealed moving from left to right.
- All conditions show a very uniform and plain microstructure.
- For unannealed, three different % cold works (CW) are shown. The grains start very elongated and become flatter as CW increases.
- For SS70, four different % cold works (CW) are shown. All images show elongated grains, suggesting little to no recrystallization occurs.
- For SS33, an equiaxed structure is seen, suggesting the recrystallization stage has been completed, as elongated grains are no longer seen.

Annealing Trials – Selecting a Temperature



- Annealing Trials of 55%CW samples at various temperatures is shown above with lines of best fit included.
- A green line highlights an equivalent yield strength of 70 ksi[1].
- 1100 °F showed minimal recovery and recrystallization for the times presented.
- 1200 °F and 1250 °F showed recovery around 19 and 9 seconds respectively.
- This data suggested that **1200 °F** is the ideal temperature candidate for our recovery annealing trials to show the effect of varying %CW.

Annealing Trials – Degree of Cold Work

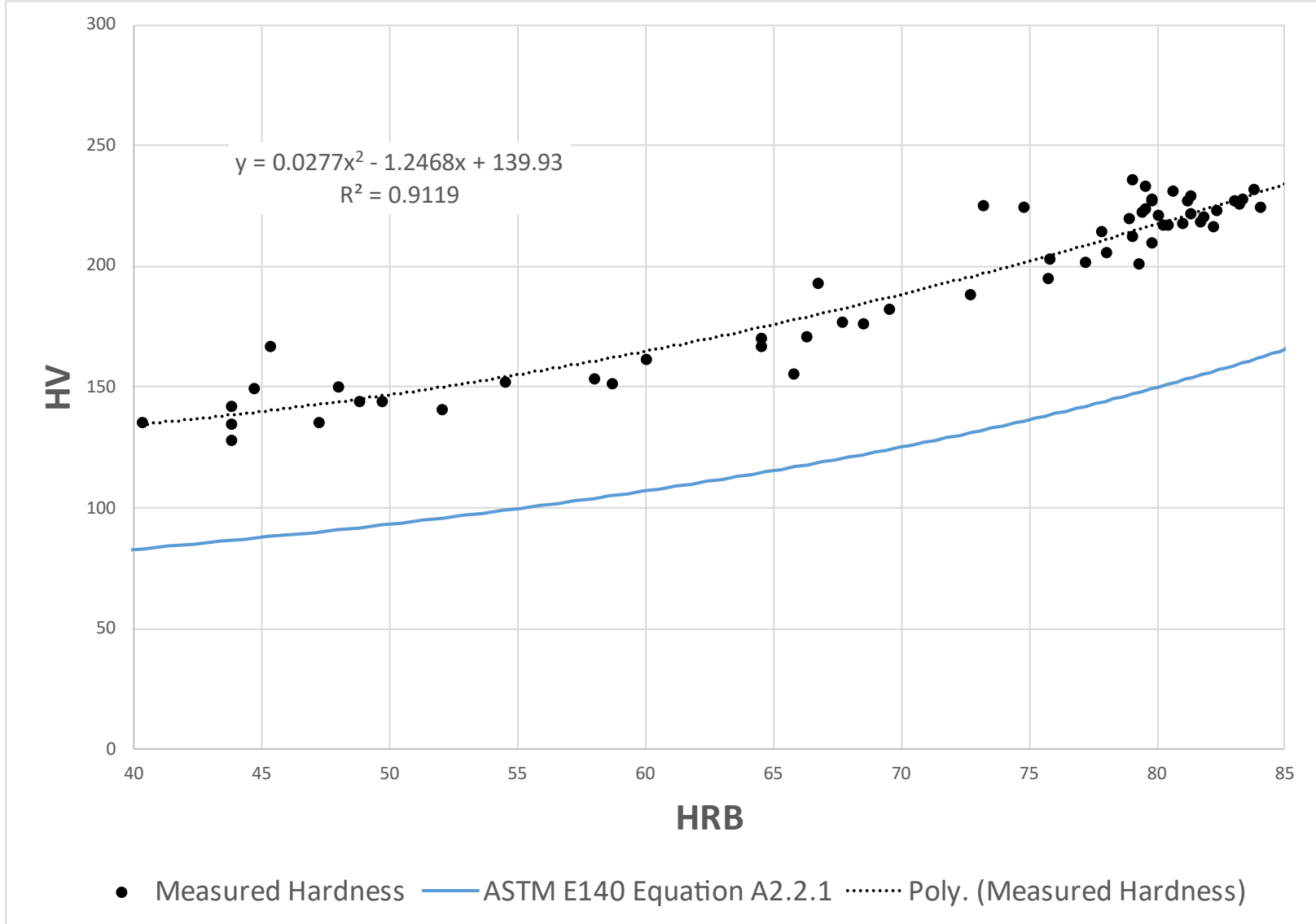


- Annealing Trials of samples ranging from 50-79% CW at 1200°F is shown above with lines of best fit included.
- A dotted green line highlights an equivalent yield strength of 70 ksi[1].
- Time to begin recovery is inversely proportional to the amount of cold work, with times to recovery ranging from 40 seconds to 20 seconds for 79%CW to 50%CW respectively.
- The lower cold works demonstrate a rapid drop in strength during the recrystallization phase.

Results & Discussion Cont.

HRB Data

- HRB is the method used by SDI as a "quick check" on their steel as it is non-destructive, fast, and can be completed on site. As such, HRB was run on our trials before they were mounted and Vickers tested.



50%CW	
Measurement Taker - Type	**HRB**
SDI - Unannealed	88.5
SDI - SS70	87.8
Purdue - Unannealed	76.0

55%CW	
Measurement Taker - Type	**HRB**
SDI - Unannealed	90.3
SDI - SS70	88.9
Purdue - Unannealed	78.7

- The graph above showcases our empirical correlation between HRB and our measured HV for our samples. This data should be helpful for pinpointing the HRB range needed to achieve the desired yield stress of 70 ksi.
- The lower line represents the expected hardness values according to ASTM E140 Equation A2.2.1 for non-austenitic steels:

$$HRB = 1.14665 \times 10^{2} + 8.82796 \times 10^{-2}(HV) - 1.41855 \times 10^{-4}(HV)^{2} - 6.69528 \times 10^{3}(HV)^{-1}$$

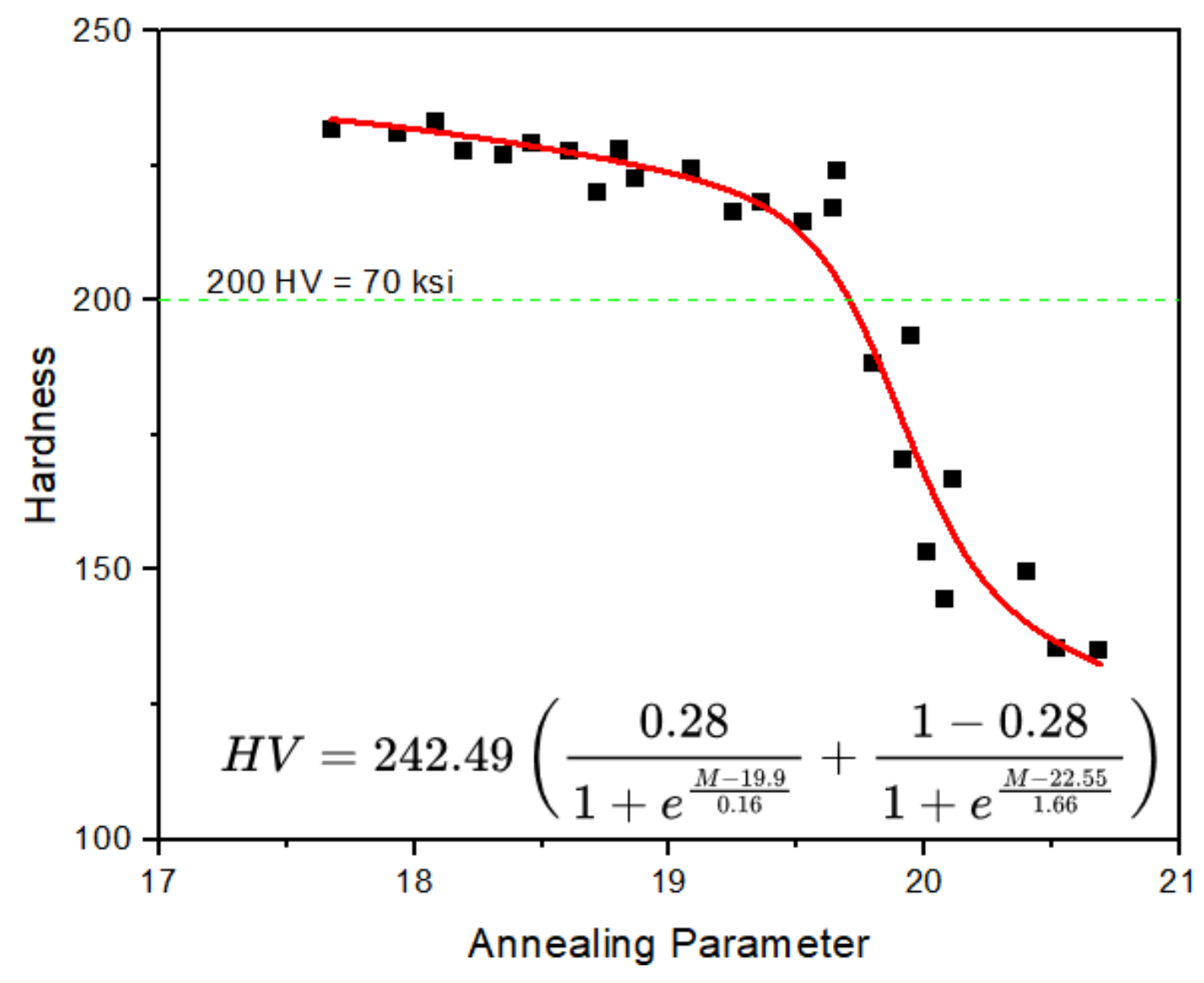
Recovery & Recrystallization

- The Larson-Miller relation is used to approximate Recovery and Recrystallization kinetics using the Larson-Miller parameter as the annealing parameter M shown below[3]

$$[3]\qquad M = T(\log(t) + C) * 10^{-3}$$

Where T is the temperature in Kelvin, t is time in seconds, and C is a constant with a value of 20. This relationship is plotted against Vickers hardness below.

- This data originates from our 55%CW annealing trials.



The fit of the graph follows a double Boltzmann relationship and suggests that the material will be at 70 ksi after an annealing parameter of 19.7.

Conclusions & Future Work

Conclusions

Through our trials, our team was able to conclude that the optimal temperature range for our testing configurations is 1200 – 1250 °F in order to achieve the desired physical properties of SS70 steel within the desired timeframe of SDI's continuous annealing furnace.

Future Work

Although our work provides data on yield strength, we lack any information on elongation, which is the second crucial specification. To gather this data, identical annealing trials would need to be performed on dog-bone samples, allowing tensile tests to be completed for the elongation data. Additionally, the relationship between our testing conditions and the real-world conditions should be explored to better utilize our data for real-world applications.

Acknowledgements & References

Acknowledgments

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References

[1] Pavlina, E.J. and Van Tyne, C.J. (2008) Correlation of Yield Strength and Tensile Strength with Hardness for Steels. Journal of Materials Engineering and Performance, 17, 888-893. https://doi.org/10.1007/s11665-008-9225-5.
[2] Pickering, F. B. (1978). Physical Metallurgy and the design of Steels. Applied Science.
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