Analysis of Boiler Steel from 1880 Historic Train

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Abstract

This paper endeavors to make a brief analysis of the boiler steel that is used in the steam engines in the 1880 Train, and compare this steel to the modern standard for pressure vessels, ASTM A516. Since 1957 the 1880 Train has operated three steam locomotives from the 1920s as a tourist attraction in the Black Hills of South Dakota. The importance of this investigation is undeniable, given the safety implications present when operating antique pressure vessels, and their documented history of catastrophic failure. A sample of boiler steel was donated by the 1880 Train for analysis which included tensile testing, charpy V-notch impact testing, fracture toughness testing, and metallography. The results of this physical analysis, especially the tensile testing, indicated that the steel performs at its specifications, and is adequate to operate in its current capacity. The fracture toughness testing allows for maintenance recommendations that should improve the overall safety of the boiler. The metallography revealed a relatively clean and fine grain structure, and served to corroborate the results of the physical testing. This of course offers a great relief all those who are concerned with the safety of the train, including those who operate and maintain it, as well as those who ride it.

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Introduction

The Black Hills Central Railroad, also known as the 1880 Historic Train, operates steam locomotives as a tourist attraction from Hill City to Keystone in the Black Hills of South Dakota. The line was originally developed as means to transport mining cargo, but since 1957 the 1880 Train has been hauling its enthusiastic passengers as an historical recreation. The 1880 Train operates three steam locomotives and two diesel locomotives as well as a dozen cars. Of particular interest in this paper are the steam locomotives, numbers 7, 104, and 110 which date from 1919, 1926, and 1928 respectively. In order to better understand the locomotives structural strength, a section of boiler plate was donated by the 1880 Train for analysis. This plate was cut out from the boiler because it contained several serious flaws in the form of deep gouges, and holes for pressure gauges. Samples from this steel were then subjected to mechanical tests of tensile, impact, and fracture toughness, as well as microscopic examination for the purposes of determining the microstructure and composition of the steel. The results of these tests were then compared with ASTM A516, a modern grade of steel used in pressure vessels. This comparison should be eminently useful to the mechanics in determining maintenance requirements especially with regard to replacement of boiler sections, since this would require the use of the new steel as well as the original.

Broader Impact

Because the locomotives are so old and their method of operation so different from modern locomotives a host of mechanical and maintenance issues cause significant problems. What should be noted most significantly is the presence of a power boiler that creates the potential for a catastrophic failure. According to the Hartford Steam Boiler Inspection and

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Insurance Company, from 1880 to 1919 (the same year that locomotive #7 was built) over 14,281 boiler explosions occurred, resulting in the deaths of 10,638 people [1]. A more recent example of the dangers associated with power boilers occurred in 2001 when an antique steam tractor exploded at a county fair killing 5 people. To be sure many of these incidents can be attributed to operator error, the most common of which would be failing to maintain an appropriate water level in the boiler; however improper maintenance, as well as material and design flaws also contributed. That said most currently operating steam engines are subjected to such critical inspections and continuous maintenance that they can be considered perfectly safe.

The designs of all currently operating locomotives have been analyzed and found to be satisfactory to a considerable factor of safety. Therefore after eliminating operator error as a cause of failure as it cannot be easily avoided by engineering means, the only other method of failure for a locomotive would have to be related to maintenance issues. Since the boilers are so old, the original quality of the material cannot be taken for granted, and the deterioration of the steel over 80+ years of service is an unknown quantity. Therefore this paper will analyze the properties of the boiler plate used in the 1880 Train's locomotives, and compare them to the standards at the time of their manufacture, and to modern pressure vessel steel. The purpose of this examination is to determine the quality of the steel currently being used, and to offer operating and maintenance suggestions based on the findings.

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Procedure

Sample Preparation

The boiler plate was taken from the top back of the boiler (the corner between the flat face of the firebox, and the longitudinal length of boiler). As supplied by the 1880 Train the plate was approximately 35 inches long and 6.5 inches wide, by .5 inches thick (fig. 1). Unfortunately because of the location from which it was cut, the plate was curved in two directions making it difficult to obtain samples for testing. Further compounding the problem were the surface flaws and irregularities found on the inside of the plate. Nonetheless four samples for each test were cut by water jet from the boiler plate; two samples each from the longitudinal direction and from the circumferential direction (see figure 1). Because of the curvature and dimensions of the plate it was necessary to use a modified ASTM sub sized tensile specimens. All dimensions of the tensile test coupons remain identical to the ASTM E8 standard for sub sized specimens except the grip length which was reduced from 1.25” to 1 in. For the same reason some of the tolerances on the fracture toughness samples could not be achieved, however they were met as closely as possible, and none of the discrepancies should affect the results.

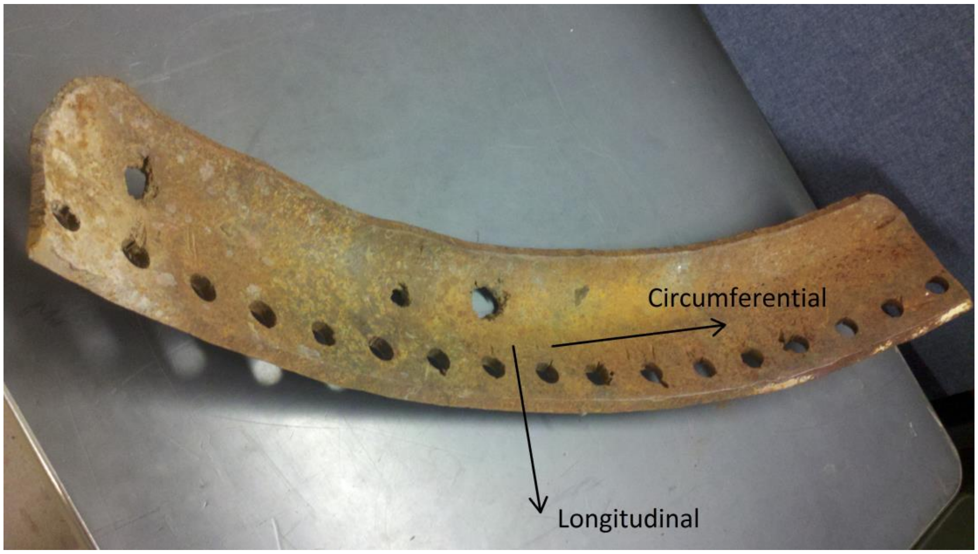

Figure 1: Boiler plate as received

Because of the curvature of the plate it was necessary to machine the samples considerably thinner than their original .5 in. order to obtain a flat specimen. This was done by milling the tensile and fracture toughness samples to a thickness of .250 in. After the outside dimensions of each sample were met the notches for the charpy V-notch and fracture toughness samples were machined using a chevron notch for the fracture toughness samples.

Tensile Testing

Tensile testing for all samples, longitudinal and circumferential, was conducted at room temperature using a MTS 810 tensile tester with a one inch gauge length extensometer. The samples were tested with a cross head speed of .05 in. per minute.

Fracture Toughness Testing

The fracture toughness testing for all four samples, two from each direction, was conducted at room temperature using the same machine as the tensile testing. Several practice samples were tested before testing the boiler steel so that the procedure could be confirmed. For the first sample the pre-crack was initiated by a fatigue test cycling at first between a load 550 +/- 450 lbs., with a frequency of 15 Hz, then increasing the loading by 15% every 10,000 cycles until crack initiation was observed, or the loading reached 1100 +/- 900 lbs. For subsequent samples the same procedure was followed except the initial loading was increased to 825 +/- 675 lbs., to

Figure 2: Fracture toughness testing setup

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speed up the process. When the crack reached its minimum required length the loading was lowered to 825 +/- 675 lbs. and cycled for another 10,000 cycles. The fracture toughness test itself was conducted immediately after the fatigue pre-cracking, without removing the samples from the testing fixture. The loading rate of for the fracture toughness testing was 2000 lbs./min.

Impact Testing

Charpy V-notch (CVN) impact testing for all samples was conducted at room temperature with a 60 lb. pendulum.

Metallography

The samples for metallographic examination were sectioned from the interior of the plate well away from any thermally or mechanically disturbed regions. Three samples were taken such that each direction, longitudinal, circumferential, and in plane could be observed in cross section. These samples were then prepared by grinding, polishing, and etching using 4% nital in accordance with standard metallographic procedures. The samples were viewed under optical magnification on a Nikon Epiphot 200 up to 1000x and a Zeiss Supra 40 VP scanning electron microscope.

Results

Tensile Testing

Values for yield strength, ultimate strength, and elongation are tabulated below. The average tensile strength is 57700 psi. The yield points were determined by the obvious yielding,

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and the subsequent decrease in load that can be observed on the stress strain plots of all four samples. The average yield strength for all four specimens is 35000 psi.

Table 1: Tensile results

	Yield Strength (psi)	Ultimate Strength (psi)	Percent Elongation
Specimen 1 (Longitudinal)	36,000	60,200	23.5%
Specimen 2 (Longitudinal)	36,500	58,800	20%
Specimen 3 (Circumferential)	34,200	56,800	19.7%
Specimen 4 (Circumferential)	33,600	55,100	23.5%

During the testing of specimen 1 a crack developed in the grip section (originating from a welding flaw), causing the test to be paused briefly. Even with a crack in the grip section the sample still failed inside the gauge length, and was otherwise unremarkable. This caused the strain data to be clouded, however valid yield strength, ultimate strength, and even initial, and total elongation were obtained. The initial elongation up to 2% was obtained by the extensometer, and the total elongation measured after the test by measuring the extension of the gauge punch marks; neither method was affected by the crack.

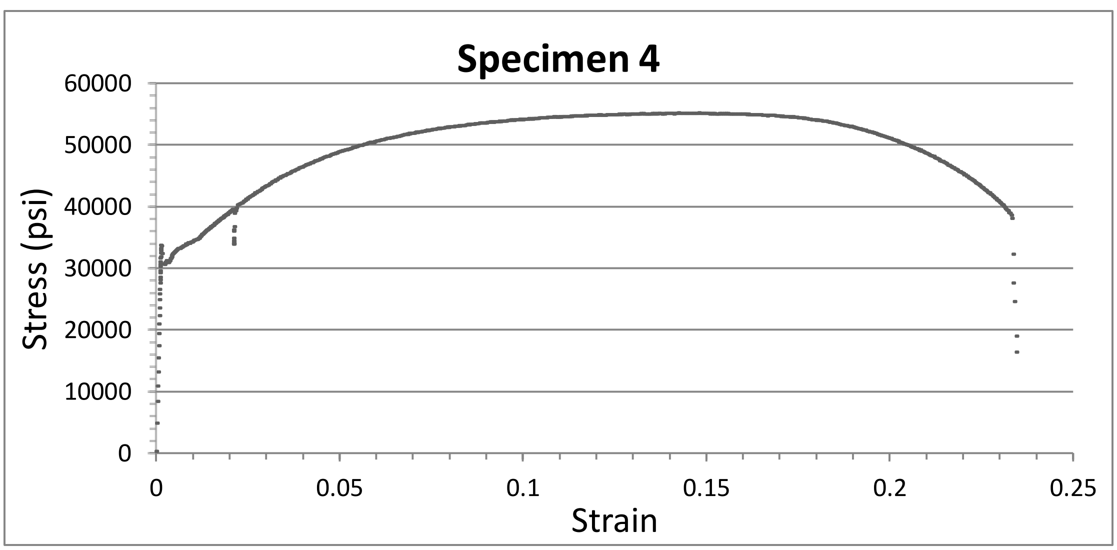

Figure 3: Stress strain curve for tensile specimen 4

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Specimens 2-4 were tested uneventfully. A stress strain plot for specimen 4, which is characteristic of all the samples, is shown in figure 3. Plots for the other samples can be found in the appendix. The noise at 2% strain is caused by the extensometer reaching its saturation point.

Fracture Toughness Testing

Fracture toughness testing was accomplished on two specimens with great difficulty. Software problems destroyed two specimens (numbers 1 and 3) during the fatigue pre-cracking. While fatigue cycling the tensile machine would not keep up with the command loading at any reasonably high frequency. To compensate for this the command signal was raised significantly in order to obtain the proper actual signal, however when the test was paused the frequency effectively dropped to zero very quickly, allowing the machine to reach the input loading, thus destroying the specimens. This was remedied by lowering the command signal to zero before stopping the fatigue test.

Two samples were successfully tested and their data record is presented below in figures 4 and 5. In order to obtain the critical loading P_Q, or load at which stable tearing occurs, a line with slope equal to 95% of the slope of the initial linear region as determined by a linear curve fit, was constructed through the origin. The intersection of this line with the loading curve is P_Q. For specimen 2, P_Q was found to be 1315 lbs. (fig. 3), and for specimen 4 it was determined to be 1304 lbs.

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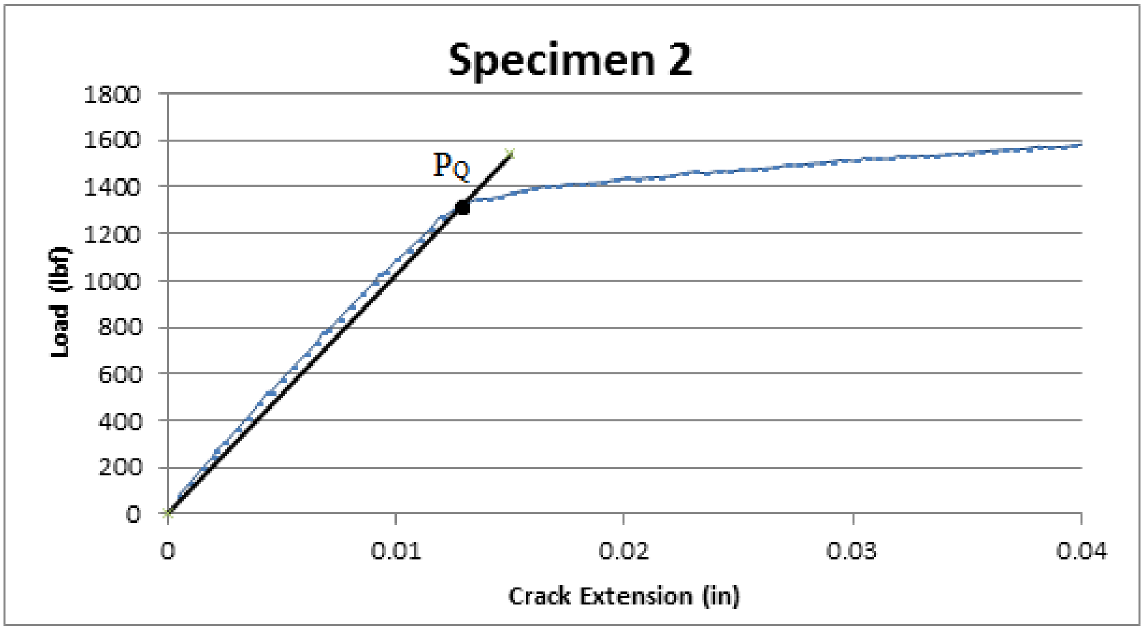

Figure 4: Load vs. crack opening displacement, specimen 2

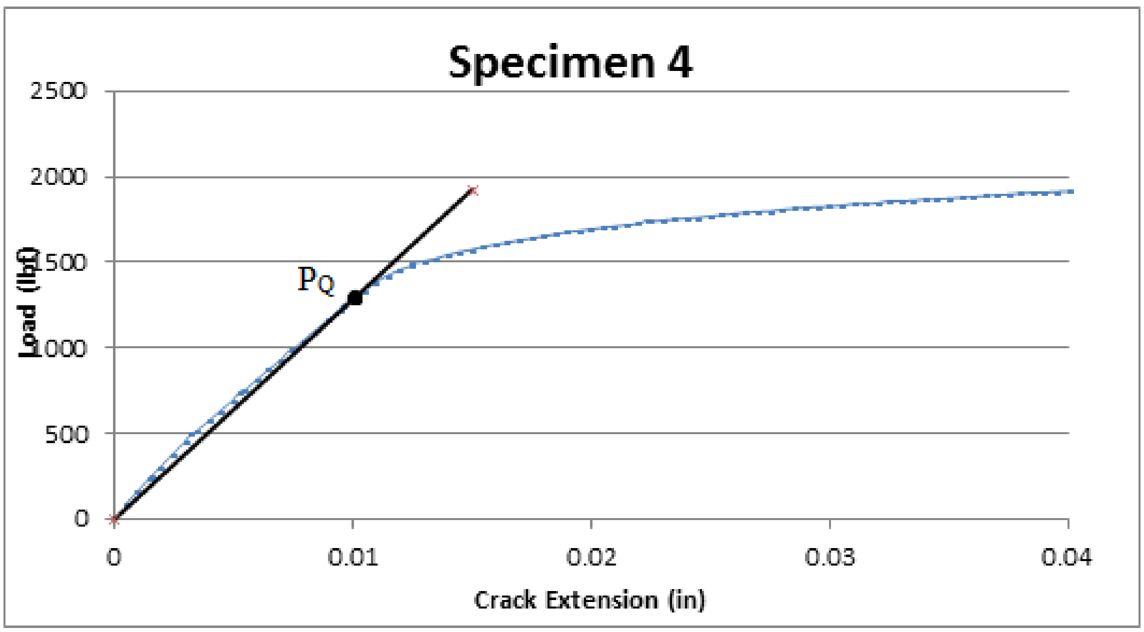

Figure 5: Load vs. crack opening displacement, specimen 4

The K_Q value is then found by $$K_Q = \frac{P_Q}{B\sqrt{W}} * f(a/W) \quad (1)$$

Where $$f(a/w) = \frac{(2+ a/W).886+4.64*a/W-13.32(a/W)^2+14.72(a/W)^3-5.6\,(a/W)^4)}{(1-a/W)^{3/2}} \quad (2)$$

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a= pre-crack length

B= sample thickness

W= width from edge to pin center

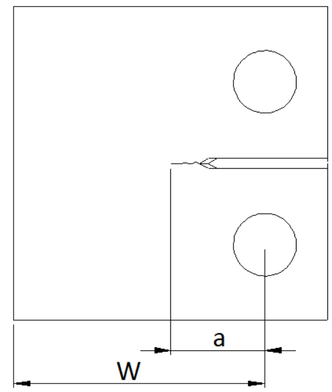

Figure 6: Compact tension fracture toughness sample

Using this method a K_Q value of 40,500 psi$\sqrt{\text{in}}$ was found for specimen 2 and 37,700 psi$\sqrt{\text{in}}$ for specimen 4. It should be noted that the samples were too thin to obtain a K_{IC} value, and so K_Q is used exclusively.

Impact Testing

Impact testing results show significant scatter, but clearly indicate decently tough steel with an average of 28.25 ft-lbs. The visual inspection of the broken specimens indicates that the fracture was approximately 50% brittle for all 4 specimens.

Table 2: Charpy V-notch results

Charpy V Notch	
Specimen 1 (Longitudinal)	25.5 ft-lbs
Specimen 2 (Longitudinal)	22.25 ft-lbs
Specimen 3 (Circumferential)	45 ft-lbs
Specimen 4 (Circumferential)	20.25 ft-lbs

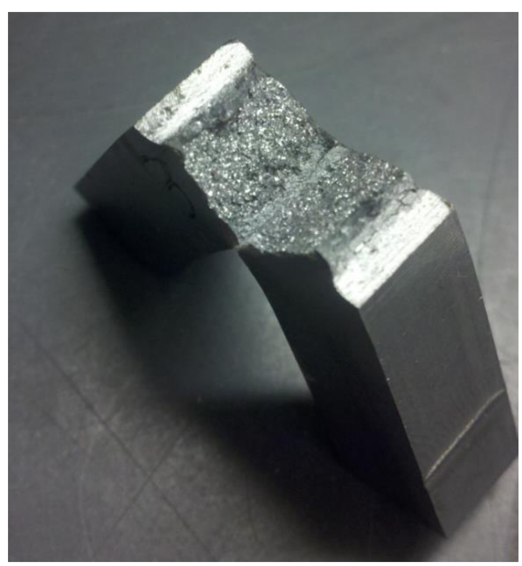

Figure 7: CVN specimen 3

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Metallography

The metallography confirmed that the steel is indeed a low carbon steel with little alloying. The majority of the microstructure consists of ferrite, with lesser amounts of pearlite. The grain size in all three directions is approximately 30 µm, and appears to be more or less uniform throughout all of the samples, indicating that there is no discernable rolling direction. All three samples contain small inclusions; a micrograph showing these inclusions is given in figure 8. SEM analysis using energy dispersive spectroscopy revealed that the majority of the inclusions are manganese sulfide (B in figure 8), and some silicon oxide (A in Figure 8).

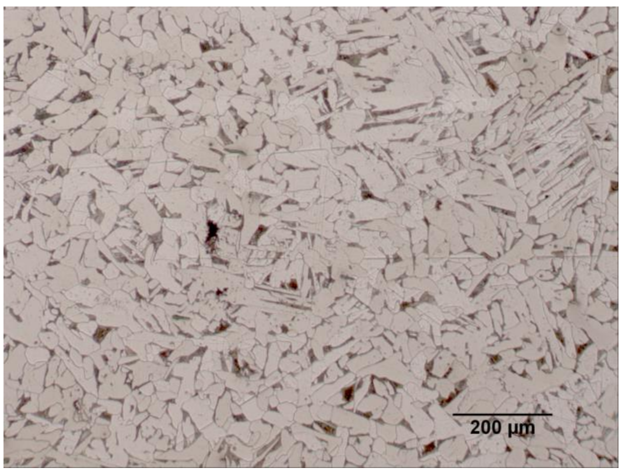

Figure 8: Circumferential cross section (OM)

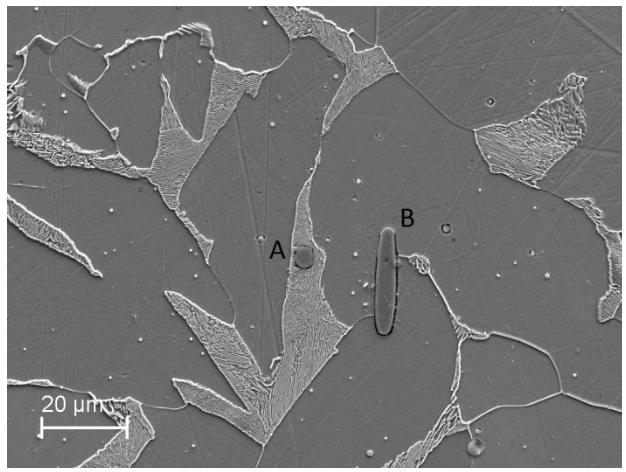

Figure 9: Circumferential Cross section (SEM)

Discussion

The mechanical testing for the most part confirmed the expectations of the original steel. None of the results seemed to be out of the ordinary, and in fact with the exception of one charpy test, they all fall together with decent precision. A complete comparison of all the physical properties relevant to this study can be found in table 3.

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Table 3: Property comparison

	Yield Strength (psi)	Ultimate Strength (psi)	Percent Elongation	Charpy V notch (ft-Lbs)	Fracture Toughness (Psi $\sqrt{in}$)
ASTM A516-70	38,000 (min)	70,000 (min)	21%	15	178,000 (K_{IC}) [7]
Original Specifications [2]	27,500 (min)	55,000 (min)	25 %	N/A	N/A
Specimen 1 (Longitudinal)	36,000	60,200	23.5%	25.5	N/A
Specimen 2 (Longitudinal)	36,500	58,800	20%	22.25	40,500 (K_Q)
Specimen 3 (Circumferential)	34,200	56,800	19.7%	45	N/A
Specimen 4 (Circumferential)	33,600	55,100	23.5%	20.25	37,700 (K_Q)

Tensile Testing

The tensile data confirms that the steel performs to its original specifications. Tensile and elongation specifications from the period require the boiler steel to have a minimum strength of 55 ksi, a yield strength of at least half the tensile strength, and approximately 25% elongation.[2] All four samples tested exceeded the tensile requirements, even if only slightly, and the elongation though not quite as high as specified is still relatively close. The yield strengths for all the samples are high, being only slightly lower than that of the A516 especially when compared to the considerable difference in ultimate tensile strength between the two steels.

Values from samples taken in the longitudinal direction are slightly higher than those from the circumferential direction. When a two sample T-test is performed on the ultimate tensile strengths, with the null hypothesis being that the longitudinal samples are stronger, a p-value of .044 is obtained. This is enough to conclude that at the 95 % confidence interval the longitudinal samples are indeed stronger. However only two samples in each category is an exceptionally small sample size, and with no supporting evidence from the metallography this result should be taken with a grain of salt. Additionally since there is no way to know that the plates were arranged in the same direction during the construction of the boiler, it does not even

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matter. The fact that the tensile data meets specifications is a hugely significant result because these previously unconfirmed values have been used when conducting design analysis on the boiler. A value of 50 ksi had been assumed when conducting the regular analysis of the boiler. Had the steel underperformed this analysis would have to be repeated, and operating conditions adjusted to accommodate the difference.

Impact Testing

Charpy impact data revealed that the steel possesses good toughness, and its ductile to brittle transition temperature is below room temperature. Though charpy specifications for the original steel could not be found, when compared to ASTM A516 the old boiler steel actually performs better by a good margin.

Fracture Toughness

The fracture toughness values represent a K_Q, not a K_{IC}, because the thickness of the plate did not allow for true K_{IC} determination. Using the K_Q and yield strengths found, the samples would have to have been over 3 in. thick ($\text{thickness} > 2.5 * \left(K_Q/\sigma_y\right)^2$), in order to fulfill ASTM standards for plain strain fracture toughness.[6] However since K_Q decreases as the sample thickness increases, asymptotically approaching K_{IC}, a useful comparison to the ASTM A516 can still be made. This is to say the K_{IC} value of the 1880 Train steel will be lower than the K_Q value that was experimentally determined, which means that it would still be significantly lower than the K_{IC} for A516.

The fracture toughness results present an excellent opportunity to apply the data to practical circumstances. When the boiler plate was received it contained numerous flaws, most

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of which can be attributed to repeated welding, and patching. In fact it was documented that several pressure gauges had been removed from the plate, and their holes filled in with weld material. Figure 10 shows a cross section of what appears to be an accidental cut with a plasma torch that penetrates about two thirds the way through the material. This is of course nearly the exact parameter that the fracture toughness characterizes, so an imminently useful analysis can be conducted.

Figure 10: Boiler plate surface gash

In the interest of making practical suggestions for safety and maintenance a rough estimate of critical flaw size can be made by conducting a brief analysis. Since this is by no means an exhaustive analysis, but rather a simple application of the fracture toughness results several simplifications shall be applied: the boiler shall be assumed to be a cylindrical thin walled pressure vessel, the weight of the water is negligible, and the only significant stresses on the boiler are due to the pressure of the steam, which shall be assumed to be 200 psi. The boiler would be under stress around its circumference (hoop stress), and its length (longitudinal stress), however since there is no shear stress, these stresses represent the principal stresses, and thus only the greater of the two, the hoop stress, need be considered. Hoop stress is defined in eqn 3.

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$$\sigma_H = \frac{P\,r}{t} = \frac{200*15}{.5} = 6000 \text{ psi} \qquad (3)$$

Where P = the gauge pressure (200 psi)
r = radius of cylinder (15 in)
t=thickness of the wall (.5 in)

Then using a simplified stress intensity equation (eqn. 4), which has been modified to account for the plate being of finite thickness, the average K_Q as determined experimentally, and a factor of safety of 4.0, a critical flaw size can be determined.

$$K = F.S. * f\sigma_H \left(\frac{t}{t-a}\right) \sqrt{\pi a} \qquad (4)$$

$$39133 = 4 * 1.12 * 6000 \left(\frac{.5}{.5-a}\right) \sqrt{\pi a} \qquad (5)$$

a=.216 in

f =geometry factor (1.12)
a= crack length
t=plate thickness (.5)

This is an overestimation because the experimental K_Q was used instead of a K_{IC}, and the K_{IC} is always lower than a K_Q. A crack this large should be easily detected by eye, or if necessary by magnetic powder, dye penetrant, or eddy current inspections, which are carried out regularly by the maintenance staff.

Metallography

The metallography revealed that the microstructure is much cleaner than expected. Small inclusions of manganese sulfide and silicon oxide can be found throughout the samples, however they are relatively small, on the order of 10 µm across. Additionally very little porosity or other defects were observed. This of course is in line with the mechanical testing which showed that the material performed quite well, at least meeting its specifications. The grain size is also

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reasonably fine, averaging around 30 μm which is impressive given the age of the material and the manufacturing processes available at the time.

The composition of steel is mostly ferrite with pearlite colonies interspersed throughout, confirming that it is a low carbon steel. Because of the uniformity of the grains, their relatively small size, the nature of the pearlite, and the lack of a rolling direction it can be reasonably deduced that the steel plates have been normalized. This was standard procedure at the time of the boilers manufacture, and remains common practice for modern boilers. Normalizing would give the steel good strength as well as excellent ductility, and a uniform microstructure, properties highly desirable in pressure vessel applications.

Conclusion

The mechanical testing corroborated by the metallography shows that the steel performs as well as one could expect, and indeed it is of surprisingly good quality given its date of manufacture. This is especially significant with respect to the tensile data, because any design analysis which is critical for safe operation, would require accurate tensile strengths. After finding that the steel is indeed as strong as it should be, we can have much more confidence in the analysis, and safety of the boiler. Consequently as far as the scope of this project is concerned, i.e. material properties and concerns, it can be concluded that the train is operating under no false assumptions and is as safe as could be expected.

The fracture toughness results provide a basis for determining maintenance requirements, as related to surface defects. The rough calculations presented above offer a decent estimate of the tolerance the boiler plate has for cracks and surface damage. The estimated critical crack length, approximately .216 in. is large and would be easy to detect, certainly much larger than

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would be allowed by the maintenance crews who operate the train. This result again reinforces the conclusion that the boiler is operating appropriately.

The tensile results, and design analysis allow us to conclude that the boiler as it sits right now is perfectly safe; while the fracture toughness results allow the maintenance crews to insure that the boiler continues operating safely, and effectively. This being said, it should be noted that this paper does not present a comprehensive design analysis, nor is it even a complete study of the boiler steel. In order to get a complete picture more samples from different locations, and different trains should be taken, and much more testing needs to be done. Additionally an analysis and characterization of the welds on the boiler should be undertaken to insure their strength. Some of the welding that was seen on this boiler plate sample was less than perfect, and contained flaws that are detrimental to the boilers performance and safety.

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Appendix

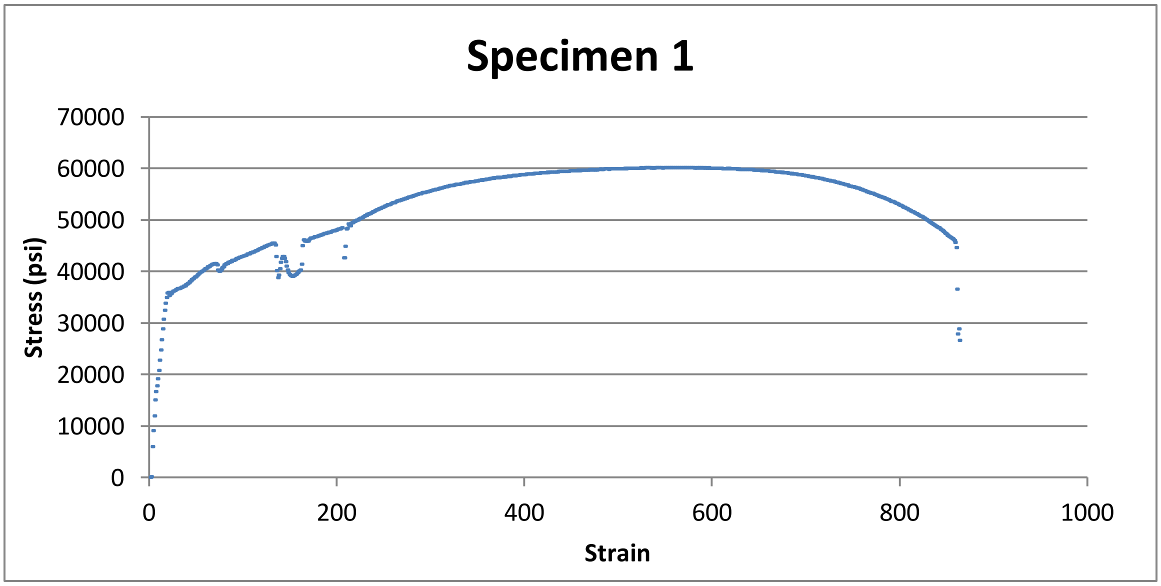

Figure 11: Specimen 1 stress strain curve

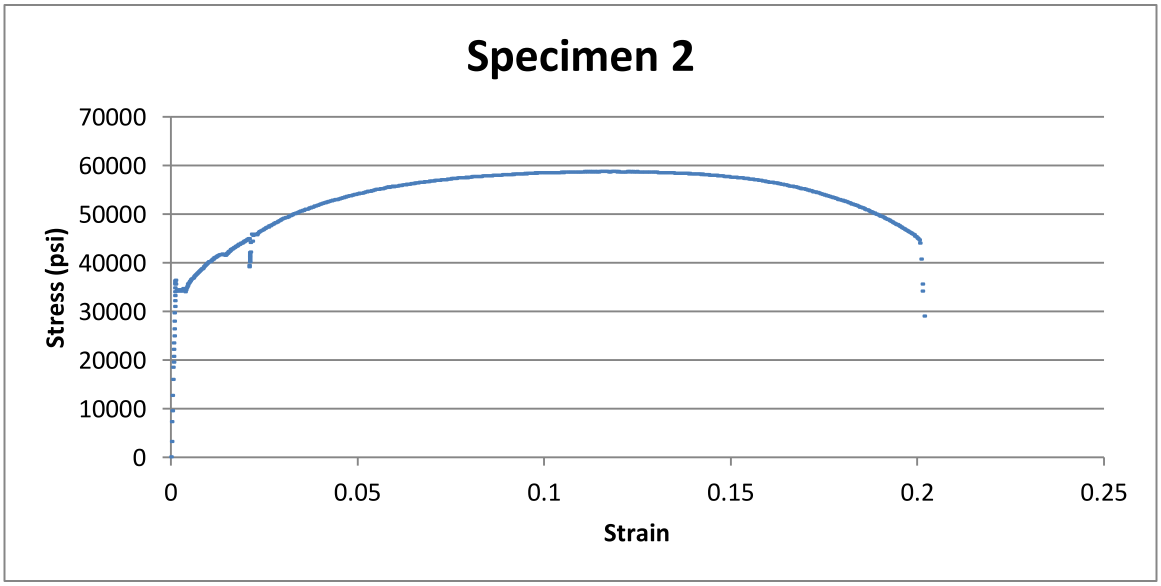

Figure 12: Specimen 2 stress strain curve

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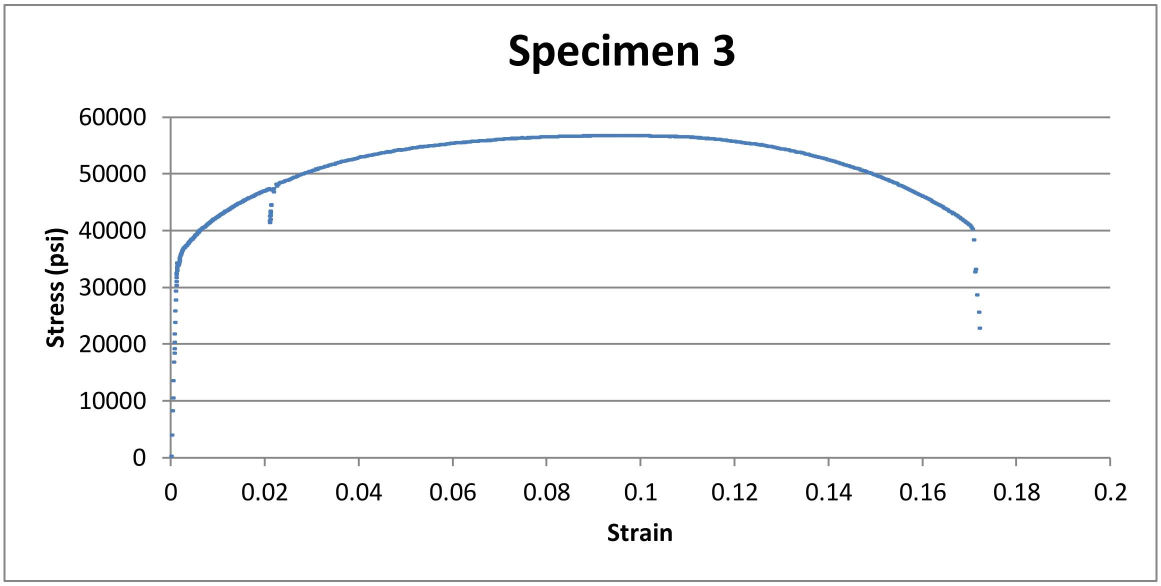

Figure 13: Specimen 3 stress strain curve

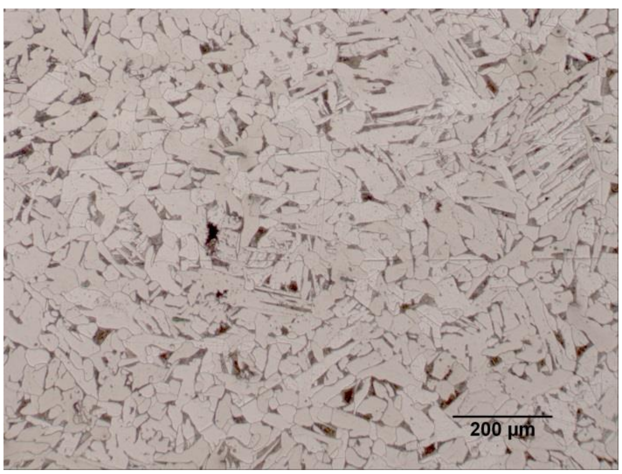

Figure 14: Circumferential cross section 100x

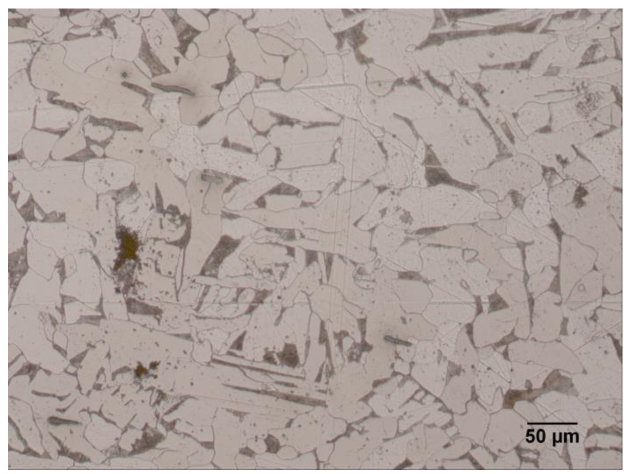

Figure 15: Circumferential cross section 200x

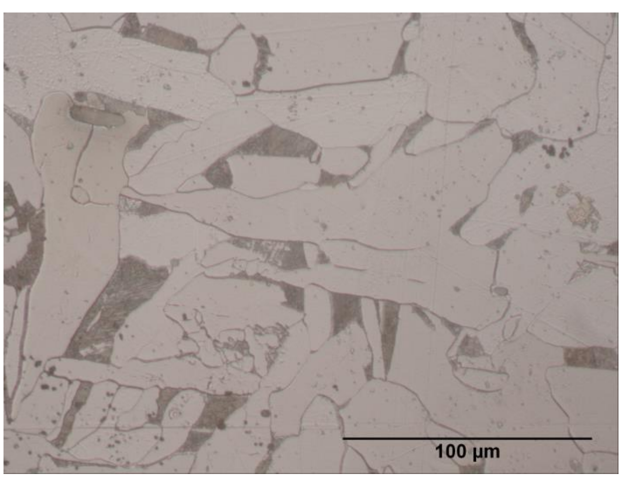

Figure 16: Circumferential cross section 500x

Figure 17: Circumferential cross section 1000x

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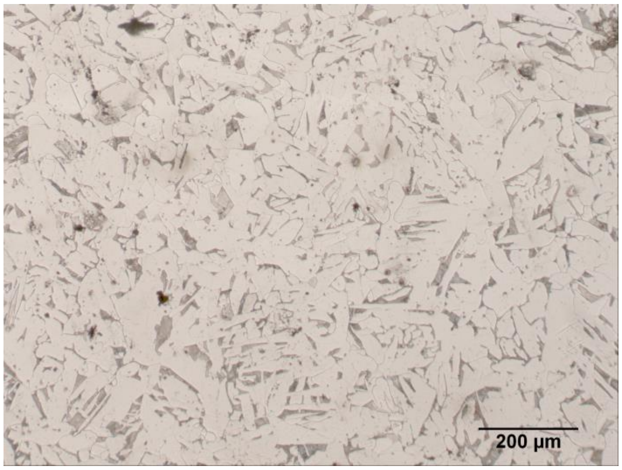

Figure 18: Longitudinal cross section 100x

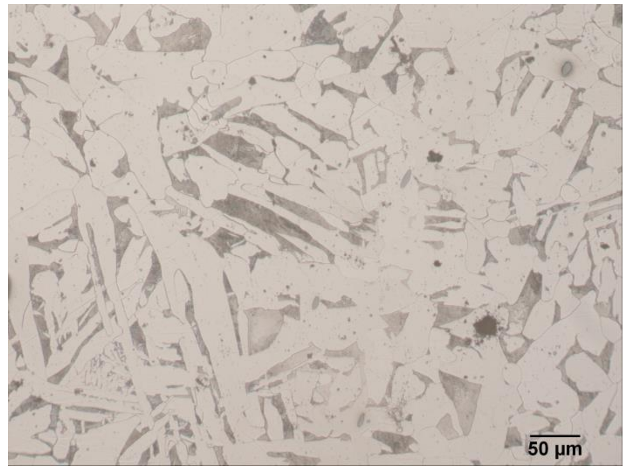

Figure 19: longitudinal cross section 200x

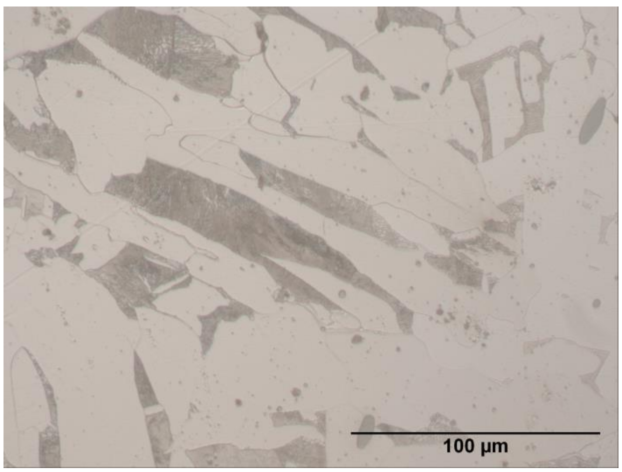

Figure 20: Longitudinal direction 500x

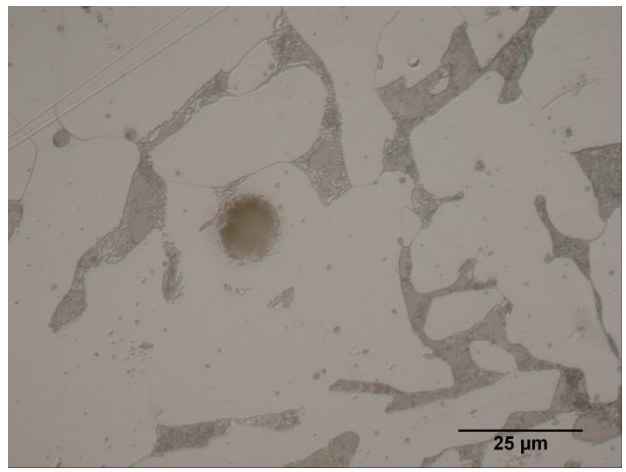

Figure 21: Longitudinal direction 100x

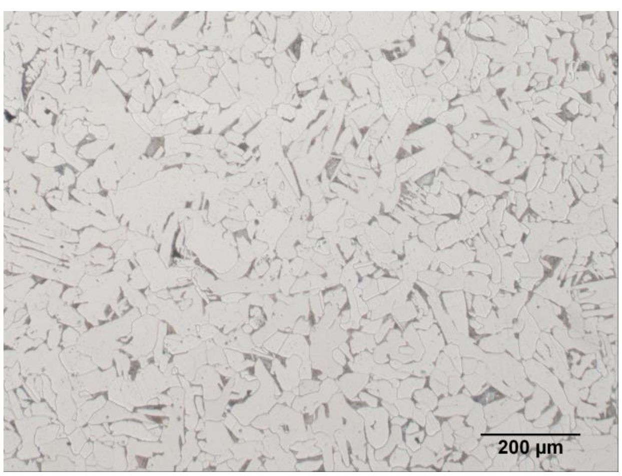

Figure 22: In plane cross section 100x

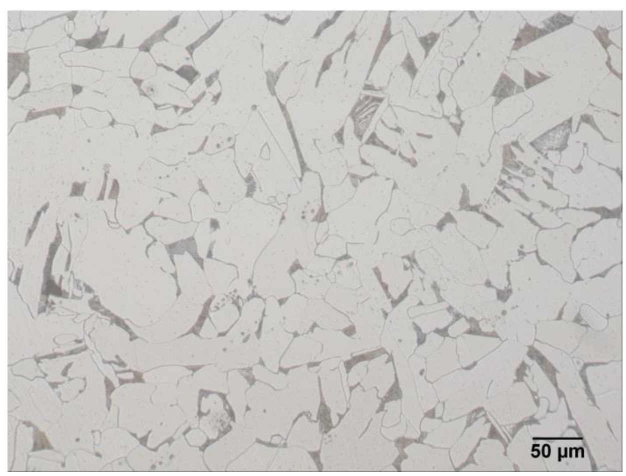

Figure 23: In plane cross section 200x

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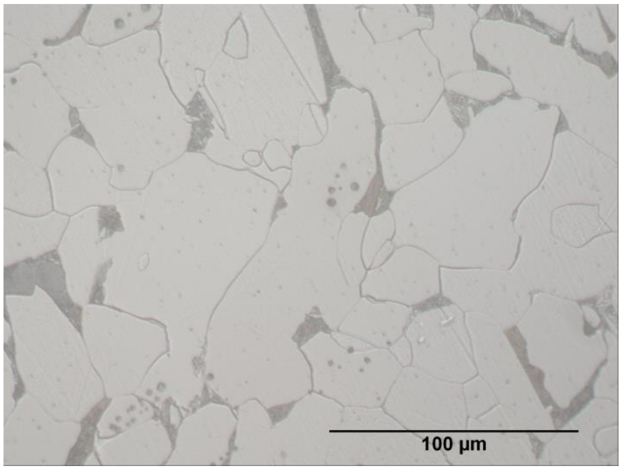

Figure 24: In plane cross section 500x

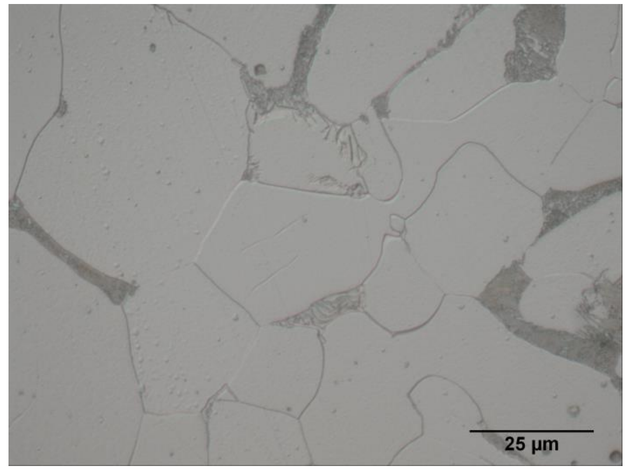

Figure 25: In plane cross section 1000x

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