Comparison of the ASTM Comparative Chart Method and the Mean Line Intercept Method in Determining the Effect of Solidification Rate on the Yield Strength of AA5182

By

Brad Peirson

School of Engineering
Grand Valley State University

Laboratory Module 9

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Section 1

Instructor: Dr. P.N. Anyalebechi

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Abstract

The purpose of this laboratory was to determine the effect of cooling rate on the yield strength of metals. The sample photomicrographs provided were of a single AA5182 sample cooled at various rates. Each photomicrograph was taken with polarized light at 50x magnification. First the photomicrographs were examined using the ASTM comparative chart method. Then each photomicrograph was examined using the mean line intercept method. The ASTM grain size was calculated for each photomicrograph using the results of both methods. The Hall-Petch Equation was then used to determine the yield strength of the metal at the points where the photomicrographs were taken. There were some slight discrepancies in the results using the different methods but both the ASTM comparative chart and the mean line intercept method show the same trends in the yield strength of the sample at the various cooling rates. Both methods show that as the cooling rate of the metal decreases the yield strength also decreases.

Introduction

The average size of the grains in a given metal sample is a critical value. Using the Hall-Petch equation the grain size can be used to determine the yield strength of a material. Before the Hall-Petch equation can be utilized the grain size must be determined. There are many ways that this can be accomplished. The simplest would be to calculate the area of each individual grain and determine their individual diameters. The average of these diameters would provide a very accurate average grain size diameter. The downfall is that this method would be extremely time consuming and prone to human error at nearly every stage of the analysis.

A more appropriate method of determining the grain size is by a method known as the mean line intercept method. This method involves dissecting the photomicrograph with multiple lines and counting the number of grains intersected by each line [2]. The ultimate goal of this method is to determine the grain size index. The following equation is used to find this value:

$$m = 2^{G_E + 3} \tag{1}$$

where m = number of grains per mm^2 at a magnification of 1x, G_E = grain size index.

This equation assumes that the photomicrograph was taken at 1x magnification. The area must also be expressed in mm^2. The following equation can be used to adjust the number of grains observed for any magnification:

$$m = \left(\frac{M}{1}\right)^2 g_m \tag{2}$$

where M = magnification of the photomicrogaph and g_m = number of grains per area in mm^2.

Another common method for determining the grain size is the ASTM comparative chart method. This method results in an ASTM grain size number for the photomicrograph.
The ASTM grain size number for a given photomicrograph can be found using:

$$N = 2^{n-1} \tag{3}$$

where N = the number of grains observed in an area of 1 in^2 on a photomicrograph taken at a magnification of 100 times (100x), and n = the ASTM grain size number [1].

This number can then be translated into an average grain diameter via

$$d = \frac{\sqrt{\dfrac{25.4^2}{2^{n-1}}}}{100^2} \times 1000 \tag{4}$$

where d = the average grain diameter in μm.

This equation also makes assumptions about the photomicrograph. In this case it is expected that the photomicrograph was taken at 1x magnification and the area is in mm^2. Equation 4 can be used to adjust the values to the required magnification.

$$N = \left(\frac{M}{100}\right)^2 g_i \qquad (5)$$

where M = magnification of the photmicrograph and g_i = number of grains per area in in^2.

Once the average grain diameter is known the yield strength of the material can be determined per the Hall-Petch equation:

$$\sigma_y = \sigma_0 + \frac{K}{\sqrt{d}} \qquad (6)$$

where σ_y = yield strength of the material and d = the diameter of the material. K and σ_y are constant values for a given material.

The constants K and σ_0 can be solved for the given metal using a chart similar to that shown in Figure 1. By choosing two points on the curve for the material in question two equivalent expressions can be set up and solved. This will give K and σ_0 for the material. Once these constants are known only the average grain diameter of the material is necessary to determine its yield strength. Therefore if care is taken during the ASTM comparative chart and mean line intercept stages calculating the corresponding yield strengths is a rather systematic process.
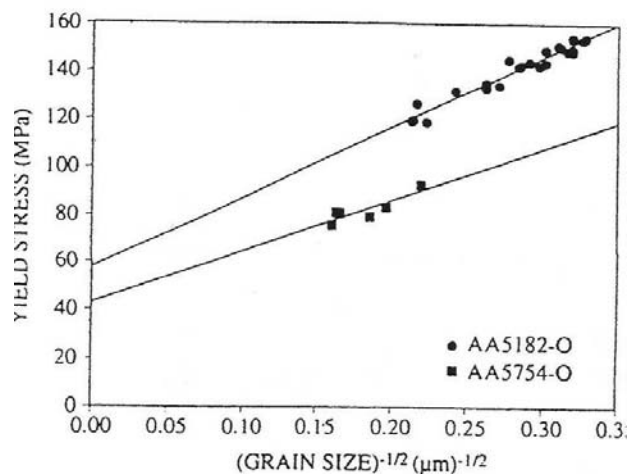

Figure 1: Effect of grain size on the yield strength of aluminum alloys 5182 and 5754 [1]

3

Table 1: Average grain diameter for each of the common ASTM grain sizes [1]

ASTM Grain Size	Grain Diameter (μm)
0	359
1	254
2	180
3	127
4	90
5	64
6	45
7	32
8	22.4
9	15.9
10	11.2
11	7.94
12	5.61
13	3.97
14	2.81

Experimental Procedure

Ten polarized light photomicrographs were obtained from the instructor. The material in the photomicrographs was known to be AA5182 – O-Temper. Each of the photomicrographs was known to be taken at 50x magnification. The number of grains contained in each of the photomicrographs was counted. Those grains that contacted the outer border of the photomicrograph were counted as ½ grain. These counts are shown in Table 2. The area of each of the photomicrographs was identical and is also recorded in Table 2.

Next the grain size index was calculated. Prior to using equation (1) to calculate the index the measurement required adjusting to fit the format for the equation. In order to use equation (1) the magnification has to be 100x. Equation (2) accounts for the adjustment from any magnification, 50x in this laboratory. The corrected grain size indices are listed in Table 2.

Equation (5) was used to adjust the magnification to 1x in order to calculate the ASTM grain size. This adjustment was then substituted into equation (3) to calculate the

ASTM grain size. Once the ASTM grain size was calculated it was used to determine the average grain diameter for each of the separate cooling rates.

Equation (6) was then used to calculate the yield strength of the different solidification rates. *K* and σ_y are were first found for this material using Figure 1 and used in all subsequent calculations involving equation (6). These yield strengths are shown in Table 3.

Once the ASTM comparative chart method procedure was completed the mean line intercept method of grain size determination was performed. For this portion of the laboratory a total of ten lines were drawn on each of the ten photomicrographs: four vertical, four horizontal and two diagonal. The number of grains intersected by each line was counted. Those grains that contacted the outer border of the photomicrograph were counted as ½ grains.

After the grains were counted the average grain size for each photomicrograph was calculated. This was done by dividing the length of each line by the number of grains it intersected. This value was divided by 50 to adjust for the 50x magnification of the photomicrographs. A simple statistical analysis was performed on the ten separate values (one for each line) for each photomicrograph. The results are given in Table 4.

The average grain diameters calculated in Table 4 were used to find the ASTM grain sizes for the ten photomicrographs. The ASTM grain sizes were estimated using Table 1. Finally, equation 5 was used to calculate the yield strength of the material in each of the ten photomicrographs.

Experimental Results

The results of the first portion of the ASTM comparative chart method are given in Table 2. Figures 2 and 3 show grain size index versus average solidification rate and ASTM grain size versus average solidification rate respectively. Figure 2 shows that for these ten solidification rates the grain size index decreases as the solidification rate increases. Figure 3 shows a similar trend in the ASTM grain size. The trend in Figure 2 demonstrates that a large grain size index translates to a greater number of grains and

thus a smaller grain size. Figure 3 seems to demonstrate the convention that a larger ASTM grain size translates to smaller grains via a fast solidification rate.

Table 2: Data obtained from 10 polarized light photomicrographs of AA5182 samples taken at 50x magnification using the ASTM comparative chart method

Average Solidification Rate (K/s)	# Grains Observed	Area of Photomicrograph (in^2)	Area of Photomicrograph (mm^2)	Area Density (grains/in^2)	Area Density (grains/mm^2)	Corrected Area Density (grains/in^2 @ 100x)	Corrected Area Density (grains/mm^2 @ 1x)	Grain Size Index	ASTM #
14.1	184.5	19.25	8652	9.5844	0.0213	2.3961	53.3114	2.7364	2.2607
7.5	169.5	19.25	8652	8.8052	0.0196	2.2013	48.9771	2.6140	2.1384
6.0	130.5	19.25	8652	6.7792	0.0151	1.6948	37.7080	2.2368	1.7611
2.9	121.5	19.25	8652	6.3117	0.0140	1.5779	35.1075	2.1337	1.6580
1.6	113	19.25	8652	5.8701	0.0131	1.4675	32.6514	2.0291	1.5534
1.2	103	19.25	8652	5.3506	0.0119	1.3377	29.7619	1.8954	1.4197
0.8	79	19.25	8652	4.1039	0.0091	1.0260	22.8271	1.5127	1.0370
0.6	70.5	19.25	8652	3.6623	0.0081	0.9156	20.3710	1.3484	0.8728
0.2	52	19.25	8652	2.7013	0.0060	0.6753	15.0254	0.9093	0.4337
0.1	34.5	19.25	8652	1.7922	0.0040	0.4481	9.9688	0.3174	-0.1583

Table 3 was created using equation 5. This table shows the relationships between ASTM grain size number, grain diameter and yield strength. The data in Table 3 is represented graphically in Figures 4 and 5. These figures show that a lower solidification rate leads to a larger average grain size. The figures also show that a lower solidification rate leads to a lower yield strength. This suggests that as the grain size increases the yield strength of a metal decreases.
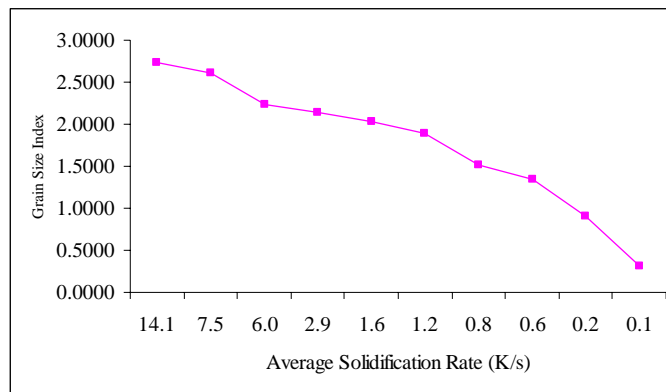

Figure 2: Comparison of the average solidification rate and the grain size index of ten samples of AA5182
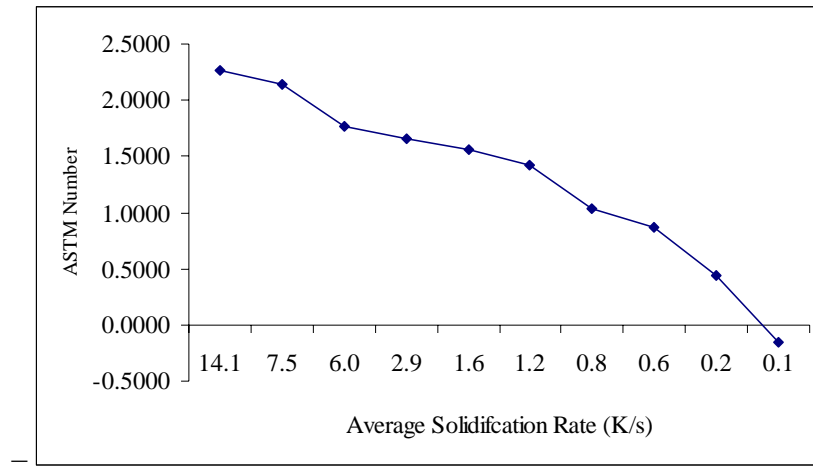
Figure 3: Comparison of the average solidification rate and the ASTM grain size of ten samples of AA5182

Table 3: The average solidification rate and it effect on ten AA5182 samples via the ASTM comparative chart method

Average Solidification Rate (K/s)	ASTM Grain Size	Grain Diameter (μm)	Yield Strength (MPa)
14.1	2.2607	164.0895	80.9433
7.5	2.1384	171.1962	80.4394
6.0	1.7611	195.1074	78.9513
2.9	1.6580	202.2046	78.5613
1.6	1.5534	209.6717	78.1725
1.2	1.4197	219.6142	77.6859
0.8	1.0370	250.7642	76.3536
0.6	0.8728	265.4511	75.8084
0.2	0.4337	309.0846	74.4247
0.1	-0.1583	379.4631	72.7185

The results of the mean line intercept method are given in Table 4. This table seems to show the same trend as the results of the ASTM comparative chart method. Using this method the average grain size still seems to increase as the solidification rate decreases. Likewise the yield strength seems to decrease as the solidification rate decreases.
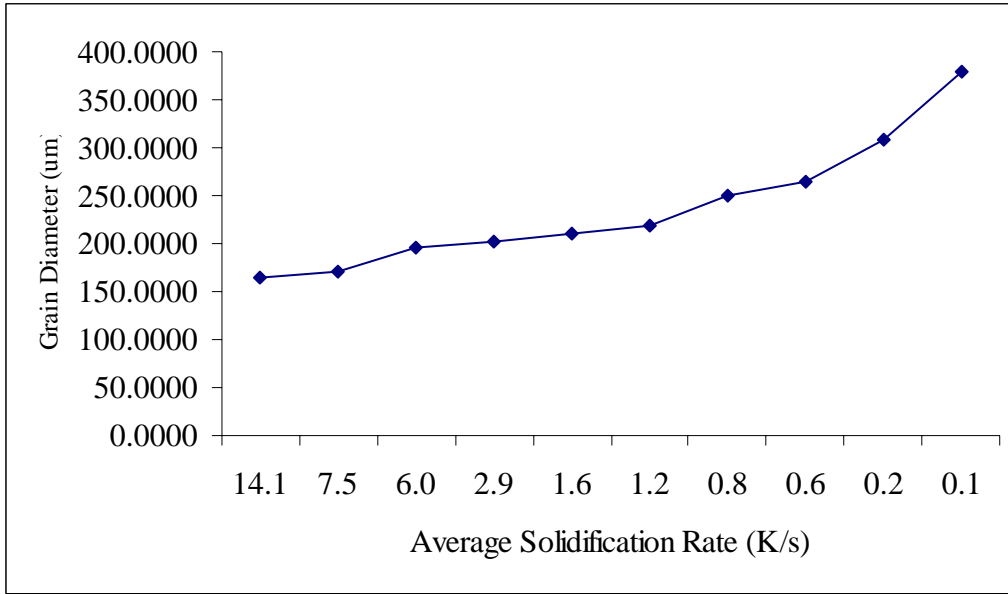
7

Figure 4: The relationship of average grain diameter and average solidification rate of ten AA5182 samples via the ASTM comparative chart method
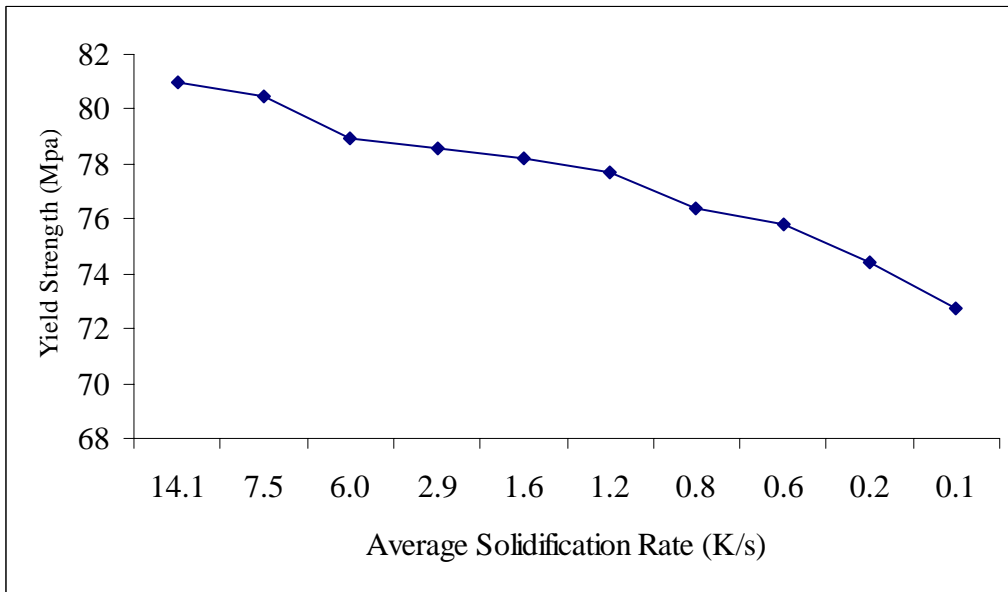

Figure 5: The relationship of yield strength and average solidification rate of ten AA5182 samples via the ASTM comparative chart method

Table 4: Results of the mean line intercept method for ten samples of AA5182

Average Solidification Rate (K/s)	Mean Average Grain Size (mm)	Standard Deviation Average Grain Size (mm)	Max Average Grain Size (mm)	Min Average Grain Size (mm)	Range Average Grain Sizes (mm)	ASTM Grain Size	Yield Strength (MPa)
14.1	0.1302	0.0271	0.1920	0.1018	0.0902	2.8	83.8884
7.5	0.1209	0.0162	0.1400	0.0958	0.0442	3.1	84.901
6.0	0.1329	0.0145	0.1461	0.1018	0.0443	2.6	83.6178
2.9	0.1424	0.0106	0.1527	0.1212	0.0316	2.4	82.7075
1.6	0.1552	0.0223	0.1920	0.1288	0.0633	2.6	81.6232
1.2	0.1760	0.0263	0.2060	0.1373	0.0687	2.1	80.1194
0.8	0.1968	0.0290	0.2585	0.1585	0.1000	1.7	78.8565
0.6	0.1981	0.0285	0.2400	0.1585	0.0815	1.6	78.7828
0.2	0.2359	0.0448	0.3055	0.1585	0.1470	1.4	76.9566
0.1	0.3972	0.1037	0.5760	0.2585	0.3175	-	72.3623

There appears to be one exception to the previous trends in the data set given in Table 4. However, overall the aforementioned trends appear to present in this data set. It appears as if a decreasing solidification rate increases the average grain size and decreases the yield strength.
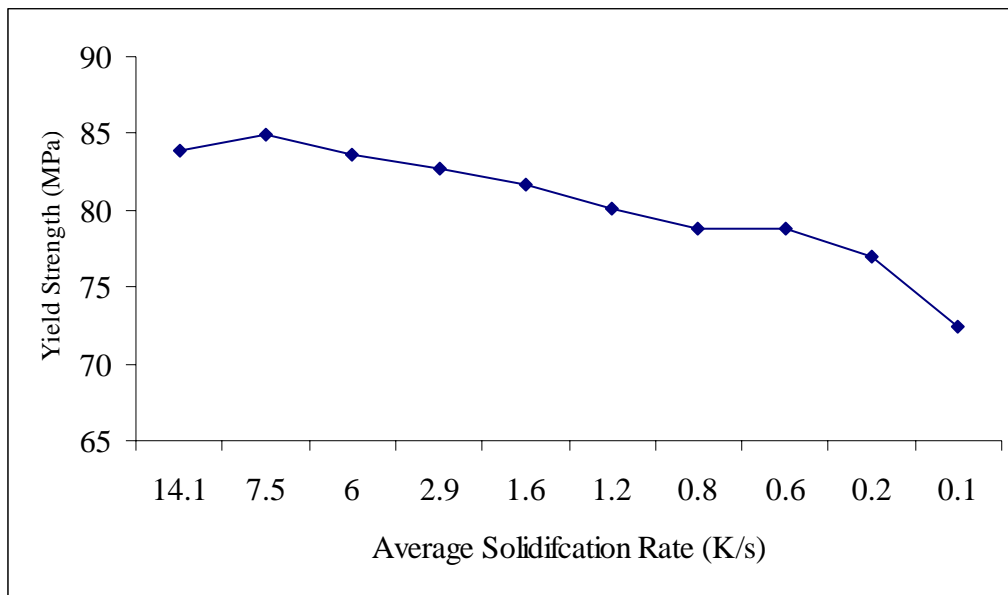

Figure 6: Comparison of the yield strength and average solidification rate of ten AA5182 samples via the mean line intercept method
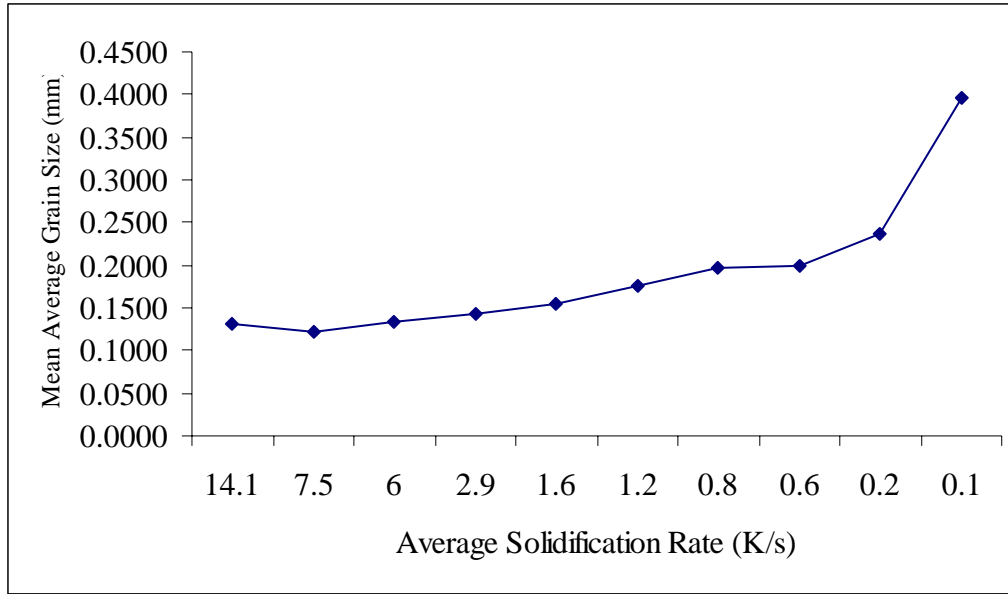
Figure 7: Comparison of the average grain size and solidification rate of ten AA5182 samples via the mean line intercept method

The final data comparison was performed between the two test methods. The comparison shows that the trend in the yield strength does exist in both data sets. Figure 8 shows that the yield strengths found using the mean line intercept method are generally higher than those found using the ASTM comparative chart method. Though this discrepancy exists both sets of yield strengths decrease as the solidification rates decrease.

Table 5: Comparison of the yield strengths calculated using both the ASTM comparative chart method and the mean line intercept method

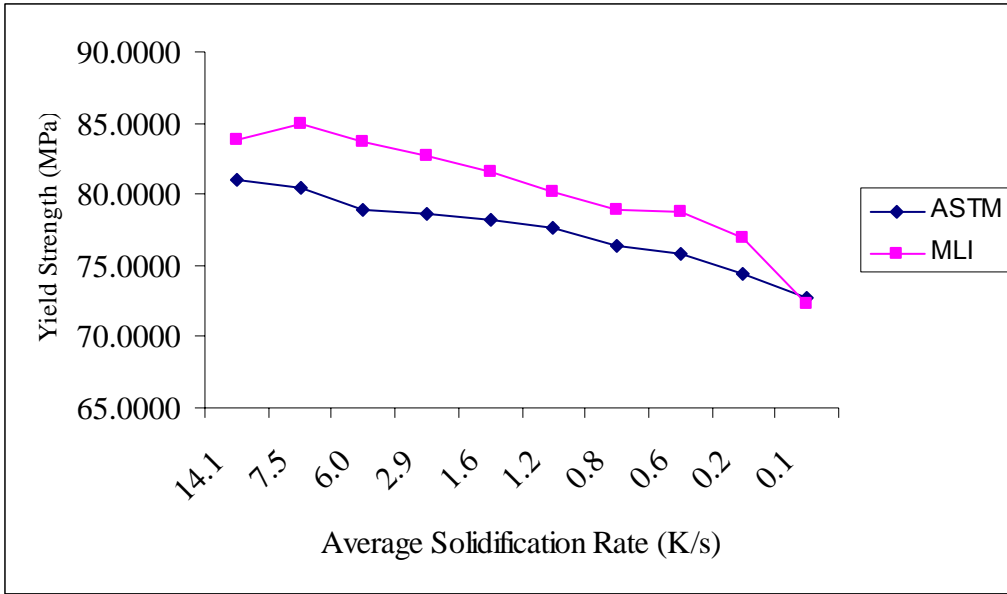| Average Solidification Rate (K/s)	Yield Strength – Comparative Chart Method (MPa)	Yield Strength – Mean Linear Intercept Method (MPa)
14.1	80.9433	83.8884
7.5	80.4394	84.9010
6.0	78.9513	83.6178
2.9	78.5613	82.7075
1.6	78.1725	81.6232
1.2	77.6859	80.1194
0.8	76.3536	78.8565
0.6	75.8084	78.7828
0.2	74.4247	76.9566
0.1	72.7185	72.3623

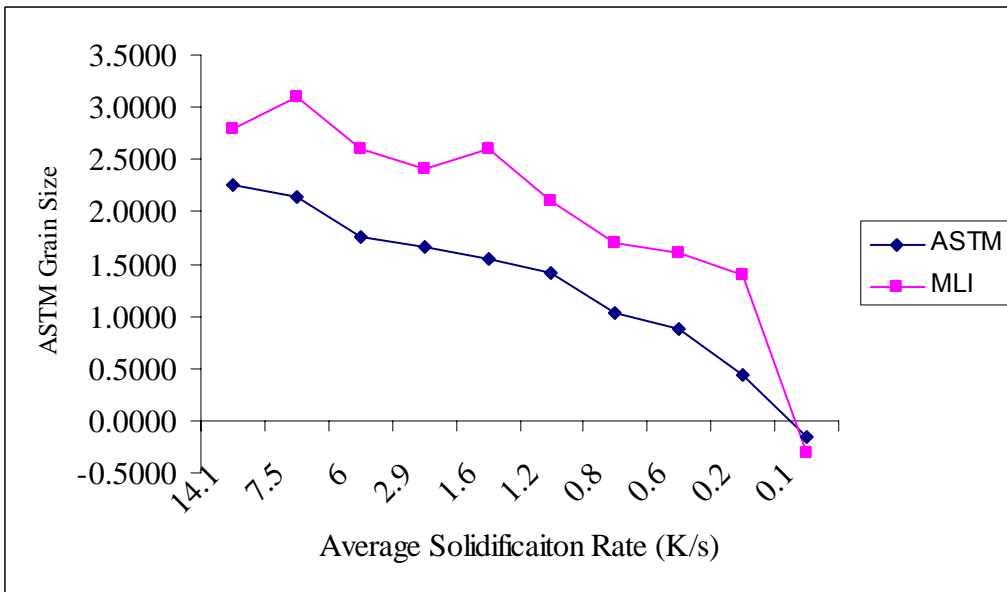Figure 8: Graphical comparison of yield strengths of ten samples of AA5182

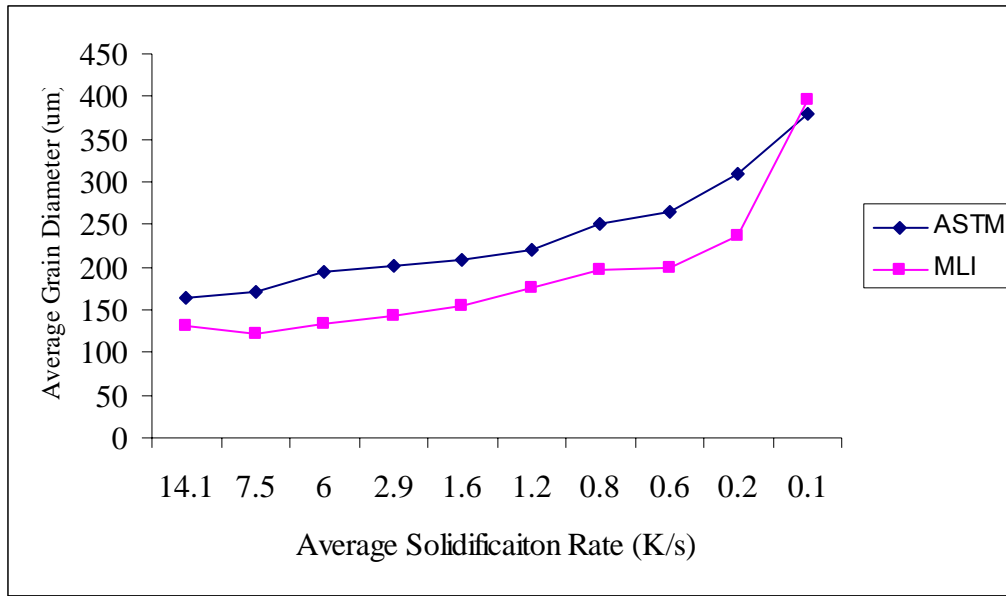Figure 9: Graphical comparison of ASTM Grain Size of ten samples of AA5182

Figure 10: Graphical comparison of average grain diameters of ten samples of AA5182

Discussion

Figures 9 and 10 show that both methods are closely related as far as the trends shown in both the ASTM grain sizes and the average grain diameters. Both methods produce results that show an increase in ASTM grain size as the solidification rate decreases. They also show that the grain size diameter increases as the solidification rate decreases. This holds with the basis of the ASTM grain size scale, which is the larger the ASTM size the smaller the actual grain diameter. There is a slight discrepancy between the sets of data for both measurements. The mean line intercept method seems to produce higher ASTM grain size numbers than the ASTM comparative chart method. The opposite relationship exists for the average grain diameter. The main source of this discrepancy is likely the mean line intercept method.

The mean line intercept method has a major downfall over the ASTM comparative chart method. This pitfall is its lack of coverage of the photomicrograph. The lines used in counting the grains have gaps between them. This means that there are likely grains between lines that do not get accounted for. This would account for the larger average grain size because of the fewer number of grains counted. There is another downfall of the mean line intercept method that can be attributed to human error.

This method allows for misinterpretation of what defines a grain intersection. The count could vary greatly if the reference lines just contacted grain boundaries and not counted as intersections. The ASTM comparative chat method's downfall lies also in interpretation. Even though the photomicrographs were generated using polarized light there were minute gradient differences within what appeared to be single grains. If these slight differences in shade were indeed separate grains and were not counted the calculations would be off. Overall the mean line intercept method seems to be the faster and simpler approach. This method would likely be best employed in situations that require in-process checks of the material being used. The ASTM comaparative chart method is more time consuming and seems to have more potential for error via a miscount. However this method logically seems more likely to produce accurate results if care is taken. This method would be best reserved for failure analyses.

Despite these differences between the two methods they do show the same trends in grain size and yield strength. Both sets of data show that as the solidification rate decreases the grain size increases. A lower solidification rate also seems to result in a lower yield strength. This trend suggests that the maximum yield strength would be obtained by cooling the metal as quickly as possible. This also means that as a result of the rapid cooling the grains would be smaller.

This trend in the yield strength can be directly attributed to the cooling rate. The data shows similar trends in both the ASTM grain size and the grain size index. As the solidification rate decreases so does the yield strength. The data also shows that a decrease in the solidification rate also leads to a decrease in both the ASTM grain size and the grain size index. This suggests that large ASTM grain sizes and large grain size indices will result in higher yield strengths. This also means that all three properties can be maximized by cooling the metal as quickly as possible.

Conclusions

1.   Both the ASTM comparative chart and the mean line intercept methods produce the same trends in ASTM grain size, grain size index and yield strength.

2.   While there are discrepancies between the two methods the differences may be negligible depending on the application.

3.   The ASTM comparative chart method seems to produce more accurate results but has a higher risk of human error associated with it. Its time requirements make it suitable for a failure analysis tool as opposed to an on-line check.

4.   The mean line intercept method is quicker and easier than the ASTM comparative chart method but has a higher potential for uncounted grains. Its ease makes it more suitable for an in-process inspection.

5.   The results show that as the solidification rate decreases the yield strength, ASTM grain size and grain size index all decrease.

References

1. Dr. P.N. Anyalebechi: "Materials Science and Engineering Laboratory Manual," School of Engineering, Padnos College of Engineering and Computing, Grand Valley State University, January 2005, pp. 98-101.

2. Dr. P.N. Anyalebechi: "Essentials of Materials Science and Engineering (EGR 250)," School of Engineering, Padnos College of Engineering and Computing, Grand Valley State University, May 2005, pp. 226-229.