Microstructural Fineness in Aluminum Castings

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ABSTRACT

In sand and permanent/semi-permanent mold casting processes, the hypoeutectic aluminum alloys of Al-Si-Mg and Al-Si-Cu-Mg solidify in a dendritic structure. It has generally been desired to have a fine dendritic structure for the best mechanical properties. The fineness of the dendritic structure is typically quantified by measuring the spacing between the secondary dendrite arms, referred to as the SDAS or DAS. While this is a widely accepted measurement technique no industry standard exists defining a consistent measurement process. This paper shows the variability identified between various laboratories and provides a method which significantly improves the repeatability in quantifying the fineness of the microstructure within these alloy systems and casting processes.

Keywords: aluminum, microstructure, secondary dendrite arm spacing, dendrite arm spacing, SDAS, DAS

INTRODUCTION

Aluminum castings are used in many different applications. As applied in structural applications designs must maintain a minimum factor of safety. This safety factor is often determined by comparing the resultant stresses as determined from finite element analysis (FEA) to the anticipated mechanical properties of the castings. Often however the highest resultant stresses from the FEA occur in areas of the castings where mechanical properties are difficult or even impossible to directly measure. It is the role of the Metallurgical Engineer to assist the Computer Aided Engineering (CAE) community in determining what mechanical properties to analyze with in these areas.

Castings by their very nature do not have homogeneous mechanical properties. The mechanical properties of aluminum castings are controlled by the local solidification rate, local chemistry, mold filling conditions, and subsequent post-processing activities such as heat treatment. The local solidification rate of a casting is most often characterized by the secondary dendrite arm spacing (SDAS) of the microstructure. This relationship is generally shown as Equation 1.[1, 2] Various permutations of the generalized equation have been developed to present this relationship.[3, 4, 5, 6] While this correlation is not the focus of this paper it is important to explain why the measurement of SDAS is important.

$$SDAS = kt_s^m \qquad \text{Equation 1}$$

Since the early 1950s the measurement of SDAS and its relationship with mechanical properties has been examined. Several papers have been published showing a general trend that as the SDAS increases the corresponding tensile properties decrease.[7, 8, 9, 10] However few papers have been published documenting the procedure for measuring SDAS. There are no known international industry standards documenting a standardized procedure for measuring SDAS. SDAS is commonly measured manually using a variation of the line intercept method. However, the start and end location of the line is not standardized which leads to variations in the overall length of the line which is subsequently divided by the number of eutectic/primary aluminum boundaries intersected. This technique is tedious and operator dependent; therefore, it cannot be easily applied over a large sample or a large number of samples and it makes comparing results between labs difficult. An automated technique was proposed by Crepeau, et.al. which utilized 5 concentric circles and an image analysis system.[11] This technique allows for easy measurement over large sample areas or of many samples however the resultant value is typically larger than the manually measured SDAS values in the same samples and has not been adopted as a typical measurement technique.

SDAS MEASUREMENT REPEATABILITY

SDAS has traditionally been specified in critically loaded regions of cylinder heads and engine blocks. However, with the lack of an international industry standard defining the procedure for measuring SDAS it is often up to the OEM's and foundries to agree upon the procedure. This has the potential to lead to low repeatability in the measurements.

A study was conducted to evaluate the repeatability of manual SDAS measurements. Four mounted and polished samples were evaluated by three different laboratories. Eight fields of view per sample were evaluated measuring the SDAS of ten different dendrites per field of view for a total of eighty measurements. A line was drawn to span at least three dendrite arms. The length of the line was then divided by the number of eutectic regions it intersected. Figure 1 shows an example of the measurements taken and Table 1 shows the corresponding SDAS calculations.
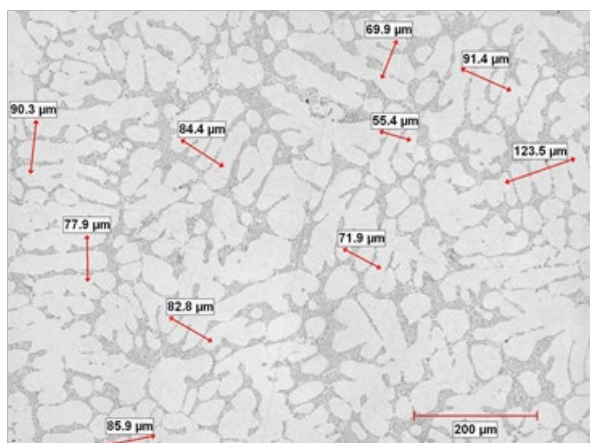
Figure 1. Example field of view showing 10 dendrite measurements.

Table 1. Dendrite Arm Measurements

Measurement	Length	# of dendrites	SDAS
#1	90.3	2	45.2
#2	77.9	2	39.0
#3	85.9	3	28.6
#4	82.8	3	27.6
#5	84.4	3	28.1
#6	69.9	2	35.0
#7	91.4	3	30.5
#8	55.4	2	27.7
#9	123.5	4	30.9
#10	71.9	2	36.0

After all the measurements were completed by the three laboratories the results were summarized to show an average SDAS measurement per sample. The results revealed that for the samples provided and with the general guidance provided for how to perform the analysis the repeatability in the measurement was low as shown in Figure 2.

This repeatability study revealed that there were variations present that inherently drove variation in the results. It is interesting to note that the variation did not appear to be random as each laboratory either consistently read low, consistently read high, or consistently read in the middle. This trend indicated that a systemic bias existed between the laboratories. This would suggest the variation resided within differences between the measurement procedures which were likely confounded by the natural variation found within the samples. Further investigation to identify potential sources of this bias were not pursued.
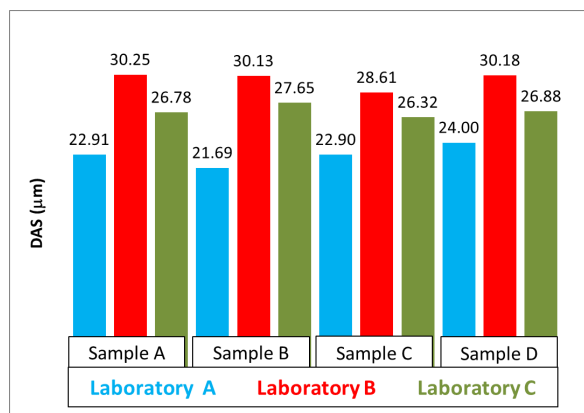

Figure 2. Summary graph showing the average SDAS measurement per sample by laboratory.

A study by Vandersluis and Ravindran evaluated five different SDAS measurement techniques.[12] Vandersluis and Ravindran also identified significant variation in the results between measurement techniques. The authors did provide a recommendation for which technique should be used by the industry and researchers to improve consistency between measurements.

A NEW SDAS MEASUREMENT METHOD

Since at least the mid-1990s, attempts have been made to automate the SDAS measurement using image analysis software.[11, 13] Some software packages include a DAS package however they still require manual selection of the dendrites and only automate the calculation. Building off of the work that Crepeau, et al. had performed Wang, et al. developed new measurement methodologies utilizing different image analysis measurements which can be fully automated and then combined to calculate the dendrite spacing.[14, 15] The new methodology measures the average distance between alpha aluminum dendrites accounting for the amount of eutectic and the average aspect ratio, α, of the dendrite cells as shown in Equation 2. The aspect ratio is determined by dividing the maximum Feret (caliper) diameter, F_{max}, by the minimum Feret diameter, F_{min} of the dendrite cell. This methodology results in a Mean Linear Dendrite Spacing (MLDS) of which the value is equivalent to the manually measured SDAS value. Advantages of the new methodology include speed of measurement and repeatability of the results.

$$DAS = \frac{(1-V_{eu})*DCS}{\sqrt{\alpha}} \qquad \text{Equation 2}$$

Validation of the new methodology included taking thirty measurements twice and comparing the first result to the second result. This was done using both the manual SDAS measurement technique and the new MLDS technique. The results were plotted on an isoplot to evaluate offset, skewedness, and discrimination. Skewedness is evaluated based on the slope of the best fit trend line of the data. If the slope is not equal to one, then measurement 1 to measurement 2 is skewed. Offset can be evaluated based on the y intercept and slope of the best

fit trend line. Zero offset with no skew would have a y intercept of zero. Discrimination is an evaluation of how well the measurement system can determine differences between readings. A high discriminating measurement system will have a high R-squared value.

Figure 3 shows the isoplot results for the manually measured SDAS. Figure 3 shows that the manually measured SDAS technique does not have the ability to discriminate between readings. There was also found to be significant skew in this measurement. These results indicate that the manually measured SDAS technique has a low degree of repeatability.
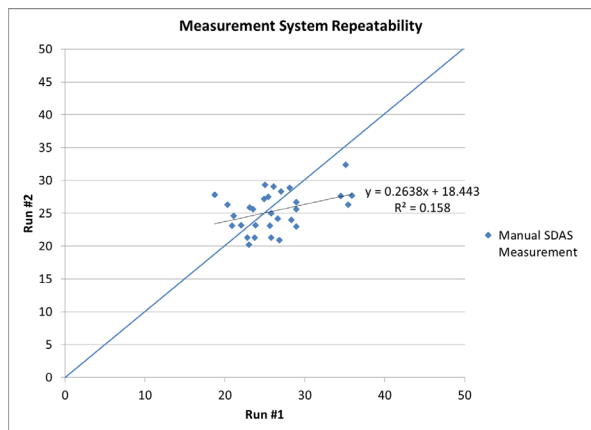
Figure 3. Isoplot for manually measured SDAS values showing a low degree of discrimination between results.

Figure 4 shows the isoplot results for the MLDS measurement technique. Figure 4 shows good alignment between the readings with very little skew, slope near 1, and good discrimination, R-squared value of 0.9. These results suggest that the new MLDS measurement technique has significantly better repeatability than the manual SDAS measurement technique. This study did not account for lab to lab variation, operator to operator, or image analysis system to system variation.

Figure 5 compares the results of the MLDS measurement process to the SDAS measurement process. This comparison included four different alloys as well as a couple of different casting processes. As can be seen the SDAS and MLDS measurement processes resulted in similar results. As a result of the poor repeatability of the manual SDAS measurement process however a strong correlation between the MLDS and SDAS measurement results could not be established.

INFLUENCE OF MICROSTRUCTURE ON MECHANICAL PROPERTIES

With an increased emphasis on computer aided design and ever-increasing demands on lightweighting for improved fuel economy the need to predict mechanical properties in all areas of a casting becomes crucial. One means of accomplishing this is to scale the mechanical properties in any region of the casting based on the
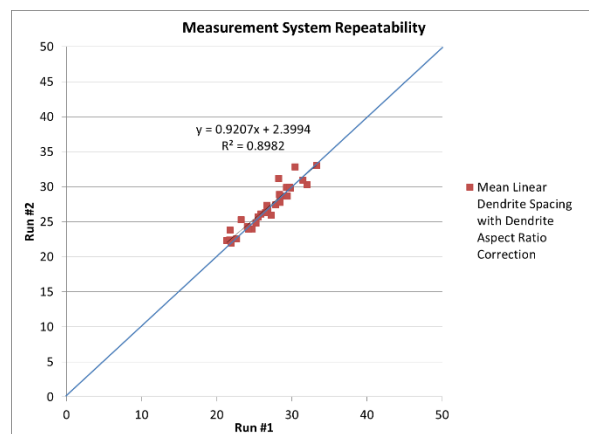

Figure 4. Isoplot for the MLDS measurement technique showing a high degree of discrimination and good repeatability between the results.
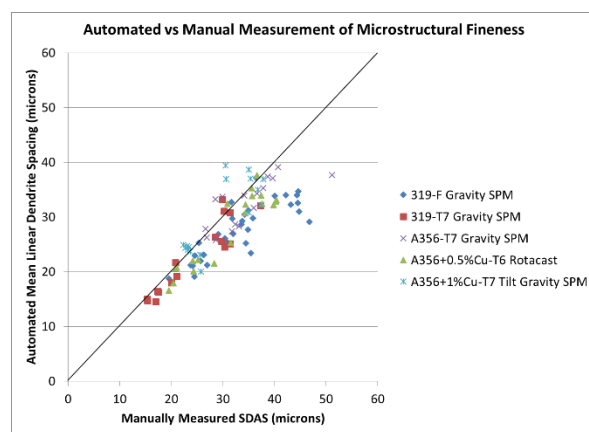

Figure 5. Comparison of the MLDS and SDAS measurement methods showing that in general both measurement techniques result in similar results.

solidification results. Thus, the mechanical properties need to be correlated to the solidification results. The effect of SDAS on the mechanical properties of aluminum castings has been documented for several decades.[7, 8, 9, 10] In general, the ultimate tensile strength (UTS) and elongation at fracture are found to decrease with increasing SDAS. While the trends from all the previous research seems to be similar the exact values tend to vary.

In the present research, the authors evaluated tensile bars from various aluminum alloys, casting processes, and heat treatments utilizing the MLDS method discussed in the previous section. Metallographic mounts of tensile bar cross sections were prepared from immediately behind the fracture surfaces. An image analysis system was utilized to evaluate as much of the cross-sectional area of the test bar as possible. The average MLDS of the cross-sectional area was determined for each tensile bar. The UTS, 0.2% offset yield strength (YS), and plastic elongation were plotted against the average MLDS for each tensile bar.

Figure 6 shows the results of plotting the UTS versus the average MLDS of the tensile bars. The UTS was shown to

decrease with increasing MLDS value. The relationship was found to be different depending on the alloy and heat treatment condition evaluated. The correlation as shown by the R-squared value was above 0.8 for all conditions evaluated.
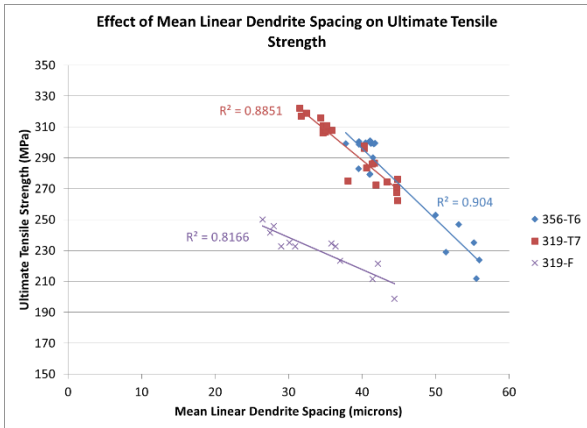

Figure 6. Effect of MLDS on the UTS of 319 and 356 aluminum alloys.

Figure 7 shows the results of plotting the YS versus the average MLDS of the tensile bars. In the case of the 319-T7 and 356-T6 samples, the YS was shown to decrease while the 319-F samples showed little influence of the MLDS on YS. YS was not expected to show a significant correlation with MLDS. The high correlation between YS and MLDS for the 356-T6 samples was unexpected.
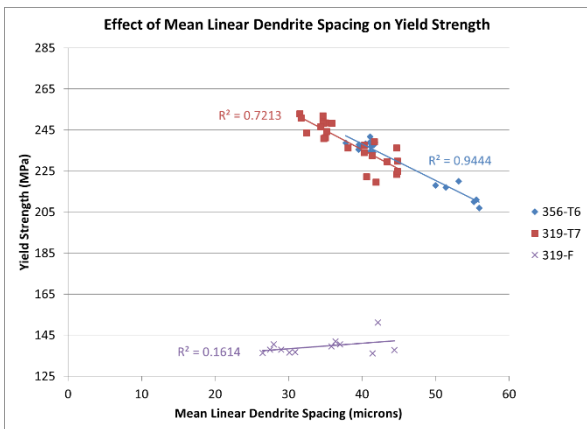

Figure 7. Effect of MLDS on the YS of 319 and 356 aluminum alloys.

The plastic elongation was also plotted against the average MLDS of the tensile bars as shown in Figure 8. The plastic elongation was shown to decrease as the MLDS increased for all alloys and heat treatment conditions evaluated. The general trends for UTS, YS, and plastic elongation were found to be consistent with previous research.
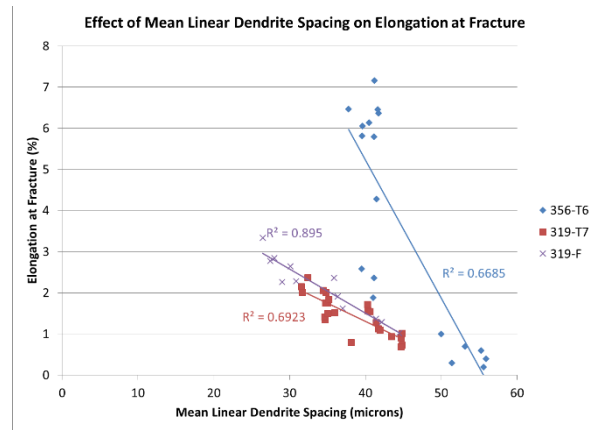

Figure 8. Effect of MLDS on the elongation at fracture for 319 and 356 aluminum alloys.

While the trends for UTS, YS, and plastic elongation are consistent with previous research the comparison of each back to dendrite spacing may be somewhat misleading. Each result is treated as if it were independently related to MLDS or SDAS, depending on the research being evaluated when in fact the three measurements are inter-related.[16] The inter-relationship between the plastic elongation, the UTS, and the YS is driven by strain hardening and how each point is determined from a tensile curve. Thus, it might stand to reason that if a given alloy and heat treatment yields consistent strain hardening parameters then the plastic elongation / strain could be related to the spread between the 0.2% offset yield strength and the UTS. A plot of this relationship for the three alloys and heat treat conditions evaluated in this study is shown in Figure 9. It is found that as the spread or delta between the UTS and YS increases the plastic elongation also increases. The increase occurs at different rates depending on the alloy and heat treat condition. Considering this relationship and the corresponding R-squared values from Figures 6 through 8 it is expected that the MLDS most directly influences the UTS.
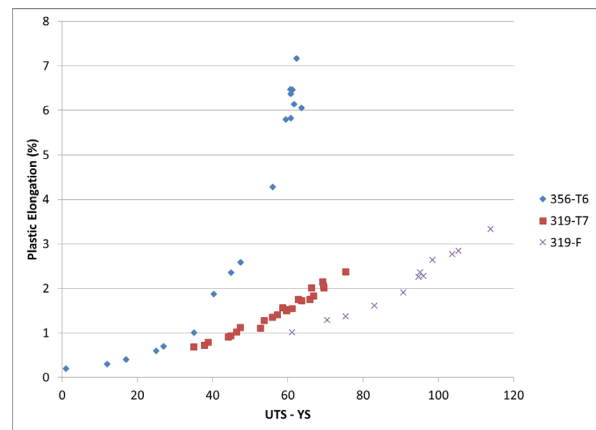

Figure 9. Plastic elongation as a function of the spread or delta between the UTS and YS for 319-F, 319-T7, and 356-T6 alloys.

The maximum pore size and volume percent porosity were also measured on all the tensile specimens. No strong correlations were found between the maximum pore size and the tensile results although in general as the maximum pore size increased the UTS results decreased as shown in Figure 10 and the plastic elongation results decreased as the volume percent porosity increased, as shown in Figure 11.
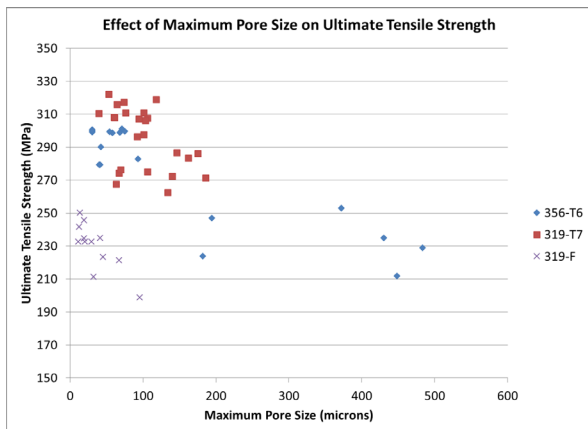

Figure 10. In general, as the maximum pore size increases the ultimate tensile strength decreases however a strong relationship between UTS and the maximum pore size does not exist.
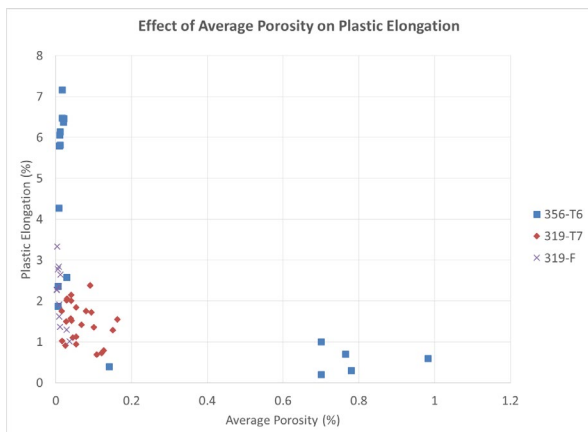

Figure 11. The percent plastic elongation is shown to decrease quickly as the average percent porosity increases.

The maximum pore size was plotted as a function of the MLDS, shown in Figure 12. As expected, the maximum pore size was found to increase as the MLDS increased however a strong correlation between the two did not appear to be present.

CONCLUSIONS

This paper introduced a new method to quantify the microstructural fineness of hypoeutectic aluminum-silicon-magnesium and aluminum-silicon-copper-magnesium alloys produced using the sand, permanent-mold, and semi-permanent mold casting processes. This new method, MLDS, was compared to the traditional manual SDAS quantification method and was shown to be more repeatable due to the elimination of the operator dependent selection of dendrites to measure. The repeatability of the MLDS method between laboratories and software packages were not evaluated in this study.
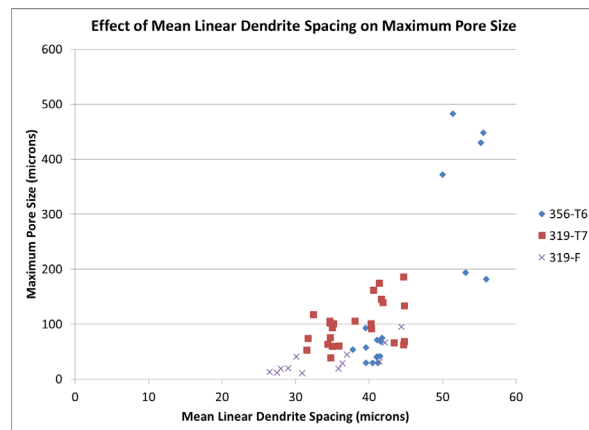

Figure 12. Maximum pore size is seen to increase as the MLDS increases.

The MLDS method improves over previously proposed automated measurement methods by accounting for the volume percent porosity, the percent eutectic in the sample, and the aspect ratio of the dendrite cells. These three adjustments to the DCS measurement brings the MLDS measurement results in-line with traditionally measured SDAS. This method enables an entire metallographic sample to be analyzed instead of only select dendrites and thus provides a better average representation of the overall sample.

Establishing a definitive correlation between mechanical properties and microstructural fineness has been an elusive goal. While general trends can be shown and are consistent between researchers the mechanical properties are not solely controlled by the microstructural fineness. The chemistry and the processing of the material also influence the mechanical properties. Variations in heat treatment parameters can significantly change the resulting mechanical properties.

ACKNOWLEDGEMENTS

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