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*Research Note*

# Evaluation of Quality Index of A-356 Aluminum Alloy by Microstructural Analysis

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In this paper, the effect of morphology, size and volume fraction of the most important microstructural constituents of cast A356 aluminum alloy on its main mechanical properties has been studied. The investigated variables consist of Dendrite Arm Spacing (DAS) of $\alpha$ aluminum phases, spheroicity of silicon particles in eutectic areas and 2-D micro porosity areas. The variations of Quality Index (Qi) with DAS and spheroicity of eutectic silicon particles follow a linear relationship. For the micro-porosity area of a polished section of the studied samples, two linear relationships were found, one for values less than 1.25% and another for higher values. As the basis for a quantitative analysis of the microstructure, some relationships have been proposed to estimate the quality index, which is, for the most part, a compromising result of three mentioned components of the microstructure.

## INTRODUCTION

Hypoeutectic Al-Si-Mg casting alloys are used in an extremely wide spectrum in different industrial domains, such as car manufacturing, aerial and military industries [1]. In order to select the most favorable conditions that better fulfill the requirements of the components, industrial designers need an effective indicator to evaluate the essential properties of material. Microstructural quantitative and qualitative analysis has been introduced as a helpful indicator to evaluate the mechanical properties of engineering materials. In the same way, the mechanical and metallurgical properties of 356 aluminum cast alloy are a result of compromising between different microstructural constituent effects, such as the dendrite arm spacing of soft $\alpha$-primary aluminum, a brittle eutectic silicon phase, different iron, magnesium and other alloying element containing phases, as well as gas or shrinkage microporosity. Casting conditions (solidification rate, pouring temperature etc.), as well as a set of appropriate processes, like inoculation and grain refining, can affect strongly the final mechanical results.

Solidification rate is a very important factor in optimizing the mechanical properties of casting [2-6] by the reduction of Dendrite Arm Spacing (DAS), modification of the morphology of $\beta$-silicon phase particles and iron containing phases (for example, $Al_5FeSi$, needle-like iron containing phase converts to Chinese script and $Al_{15}(Fe,Mn)_3Si_2$, with a modified morphology that provides less stress concentration). Heat treatment can also affect the mechanical properties of alloy by influencing both the size and the morphology of the silicon eutectic phase or, together by developing $Mg_2Si$ precipitates that contribute to strengthening. However, rapid solidification is not the only way for grain refinement or silicon phase modification. These results can be amplified by using proper grain refiners like Ti-B or modifiers like Sb, Na or Sr. All supporting treatments, like grain refinement, silicon phase modification by modifiers or by rapid solidification, are thought to influence mechanical properties indirectly through their influence on feeding characteristics during solidification [1].

This investigation proposes to determine the feasibility of using microstructural measurements to predict the casting's potential to meet the mechanical properties requirements, without destroying the casting. As the mechanical properties of alloy depend on the volume, size, shape and distribution of different microstructural constituents, one should measure each of these parameters one by one and calculate individual influences on final mechanical properties. Many efforts have been made to use certain of these parameters, like DAS [2,3,5,6], microporosity [7,8] or other microstructural constituents, to predict the

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mechanical properties of the alloy. However, as these properties are the result of a combination of all of them, the proposed models haven't predicted different conditions of casting and further treatments. Also, some other microstructural details, such as formation and growth of $Mg_2Si$ precipitates, which strongly affect mechanical properties, cannot be measured directly by ordinary techniques. Other studies used the continuum mechanics analysis to determine the iso-relative ductility parameter, $q$, lines, but the agreement obtained between experimental results and calculated data can only be fortuitous, because it must be borne in mind that the variations in strength and ductility, with aging, are the result of changes in the micro mechanics of deformation and damage generation of the material and not to continuum mechanics analysis [5].

The initiation and propagation of the cracks is highly dependent on the size, morphology and distribution of the brittle constituents of the microstructure, such as the silicon eutectic phase, inclusions, iron, manganese, copper, magnesium and other intermetallic phases. This effect can be related to easy initiation of micro cracks at microporosity sites in the microstructure. The effect of higher cooling rates, which has been shown by the decreasing of the dendrite arm spacing, has a strong influence on the spheroicity of silicon particles. This effect restrains the nucleation and propagation of the crack under strain. Although the castings were modified by strontium addition, at lower cooling rates, the decrease of spheroicity was remarkable. Morphology of the silicon phase is also strongly influenced by the solidification rate, but the addition of some additional agents, such as strontium, sodium, antimony and etc., can modify this eutectic phase [9].

However, some authors believe that microporosity (gas or shrinkage) is the greatest contributing factor to ultimate tensile strength, elongation and fatigue strength [7,8,10]. Anyway, as the mechanical properties of a casting alloy are the result of the contribution of each of its main constituents, one can estimate the mechanical properties by qualitative analysis of microstructural constituents. This is not very simple, because the contribution of each component to final resulted mechanical properties is not the same. Some authors have presented some relationships to predict the final mechanical properties of casting, using only one of these constituents [2,3,7,11], but none of these equations can be perfectly reliable, unless assuming the exact influence of all microstructural constituents.

This study is an effort to predict the mechanical properties of A356 alloy in as cast conditions, by analysis of the most predominant microstructural constituents. This alloy is perhaps the most widely specified Al-Si-Mg casting alloy for premium quality sand and permanent mold casting [1]. For simplicity, the alloy has been studied under its cast condition to prevent the strengthening effect resulted from aging. The effect of aging cannot be measured directly on the microstructure.

The most important microstructural components, including Dendrite Arm Spacing (DAS), silicon phase morphology, as well as size and quantity of gas porosity and micro shrinkage, were measured quantitatively to determine their effect on the resulted mechanical properties of the cast alloy. Among the mechanical properties, the maximum tensile strength, yield strength, relative elongation percentage and quality index have been examined.

## EXPERIMENTAL METHODS

A356 aluminum alloy was cast in a wedge model accompanied by a copper chill block (Figure 1). A sufficient volume of riser insured the soundness of the castings. Series A and C of the samples were obtained at two different solidification rates using 5 cm and 2 cm chill blocks, respectively (four castings for each one).

The molds were made by a $CO_2$-silica sand molding process. The temperature of the inserted chill block was 25°C and type $K$ thermocouples were installed along the axis of the mold cavity. About 500 kg of A356 melting (Table 1) was prepared using a reverberatory furnace with a graphite crucible and transferred to a smaller one for further treatment. Degassing of the melt was carried out in the crucible by an argon rotary degassing installation (15 min) [12].

The modification of the melt is made by Al-%10 Sr at the 13th minute of the degassing process to prevent strontium fading during melt degassing. The

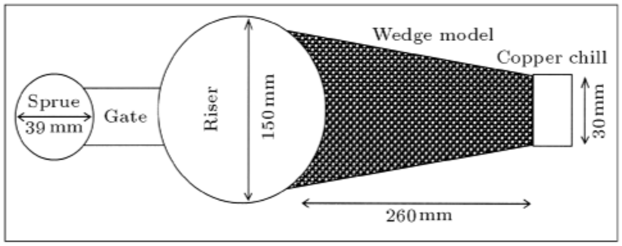

**Figure 1.** Schematic illustration of wedge model.

**Table 1.** Chemical composition of test alloy castings.

| **Element** | Si | Fe | Cu | Mn | Mg | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| **Wt%** | 6.63 | 0.23 | 0.18 | 0.02 | 0.34 | 0.008 | 0.18 | Bal. |

**Table 2.** mechanical and microstructural results of the experimental castings.

| Sample | | | Mechanical Properties | | | | Microstructural Measurements | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Distance from Edge (mm)** | **Solidification Time (Sec)** | **YS (Mpa)** | **UTS (Mpa)** | **El (%)** | **Quality Index (Mpa)** | **DAS ($\mu$m)** | **Spheroicity of Si Particles** | **Micro Porosity (%)** |
| A1 | 15 | 92 | 79.75 | 153.97 | 7.09 | 281.56 | 43 | 0.81 | 1.45 |
| A2 | 45 | 395 | 76.53 | 136.63 | 4 | 226.94 | 80 | 0.59 | 1.31 |
| A3 | 140 | 986 | 74.47 | 119.41 | 2.72 | 184.54 | 112.5 | 0.30 | 2.48 |
| A4 | 210 | 1465 | 67.47 | 112.04 | 2.22 | 164.00 | 131.34 | 0.23 | 2.50 |
| A5 | 240 | 1842 | 61.23 | 103.73 | 1.99 | 148.55 | 140.30 | 0.203 | 3.575 |
| C1 | 15 | 21 | 85.16 | 165.03 | 10.19 | 316.23 | 25.93 | 0.783 | 0.084 |
| C2 | 45 | 110 | 79.86 | 161.10 | 6.30 | 284.32 | 49.44 | 0.628 | 0.271 |
| C3 | 75 | 244 | 78.53 | 152.53 | 4.58 | 249.88 | 63.40 | 0.491 | 1.093 |
| C4 | 105 | 695 | 78.23 | 145.47 | 2.80 | 212.54 | 95.5 | 0.352 | 0.969 |
| C5 | 135 | 775 | 70.41 | 142.95 | 2.65 | 206.1 | 100.84 | 0.296 | 1.138 |
| C6 | 165 | 1320 | 75.53 | 136.75 | 3.74 | 227.58 | 129.48 | 0.254 | 1.266 |

melt was treated also by about 0.02% Ti for grain refining using Al-5%Ti-1%B master alloy. Care was taken to minimize turbulence during pouring to avoid gas pickup and entrainment of inclusions. The pouring temperature of the samples was 700 ± 5°C [13].

After solidification, wedge samples were cut to smaller blocks from the top to the bottom. After cutting and machining procedures, the tensile samples were prepared according to the standard of ASTM-13577M (12.5 mm gage length). The tensile test samples were tested by the Instron machine Model 4486 (2mm/min tensile rate). All samples were microstructurally studied by a light optical microscope (Leitz- Aristomet ME1). Dendrite arm spacing and the morphology of the silicon component and micro porosity area were evaluated by image analysis software (SIS analysis imaging C). If the investigated surface of the sample is sufficiently large, one can obtain, statistically, a good estimation of the total volume of the porosity from 2-D results [14].

In this study, the samples have been studied in two groups with different solidification rates and microporosity contents. As each microstructural constituent affects the others during the solidification process, the final mechanical properties of the alloy will be a result of compromise between these multiple effects. For example, a reduction of dendrite arm spacing by increasing the solidification rate can change both the spheroicity of the silicon particles and the microporosity volume and its distribution. Therefore, the individual influence of each single component of the microstructure on resulted mechanical properties cannot be revealed directly. For this reason and considering the various solidification characteristics at each position along the samples, a "quality index" has been used to relate the mechanical properties of the alloy with different microstructural conditions. The "quality index" correlates the tensile strength rate and the increasing percent of elongation, as well as the contribution of different microstructural constituents on the mechanical properties [5,15]. This parameter is defined as follows:

$$Q = UTS + K \log \text{(Elongation)}. \tag{1}$$

In this equation, the constant $K$, for the alloy A356, is equivalent to 150 Mpa [5,15].

Minitab statistical software (release 13.32) has been used for analyzing experimental data using a multiple regression analysis for fitting general least squares models. Multiple regression gives output from multiple regression, i.e., regressions with two or more predictors. The model is $Y = bo + b1X1 + b2X2 + \cdots + bkXk + e$. The analysis of variance table on the output includes the sequential sums of squares.

## RESULTS AND DISCUSSION

The mean mechanical and microstructural results of samples are reported in Table 2. Figure 2 shows the variations of the spheroicity of silicon particles, regarding dendrite arm spacing as an indicator of the solidification rate. A proportional relationship may be resulted for the spheroicity of silicon particles. Some authors believe that DAS is the most important factor, which determines the characteristic mechanical strength of aluminum casting alloys [2-4], but some others believe that the effect of eutectic silicon phase morphology [1], volume, size and morphology of micro porosity [13], have the same or more importance. DAS has often a proportional relationship with the solidification rate [3,4,9]. It is also roughly proportional to the resulted mechanical properties [2,4] by improvement of ultimate tensile and yield strength, as well as elongation percentage (Table 2). Alloy chemical composition has generally been found to influence the spacing, although the effect is usually small compared with that obtained by solidification time [4].

The increasing of dendrite arm spacing increases the micro porosity 2-D area (Figure 3), followed by a consequent reduction of the quality index of the alloy (Figure 4). The influence of dendrite arm spacing on the mechanical properties of alloy has been presented by Figures 5 and 6. Equation 2 can describe this dependence by the following simple linear equation $(S = 19.90, R \quad Sq = 87.0\%, R \quad Sq(\text{adj}) = 85.5\%)$:

$$\text{Qi} = \quad 1.25(\text{DAS}) + 338, \tag{2}$$

where Qi is the quality index (Mpa) and DAS is dendrite arm spacing (micron).

The eutectic silicon phase morphology has also an important influence on the resulted mechanical properties of casting (Figures 7 and 8). This effect has been presented by the following linear relationship $(S = 24.26, R \quad Sq = 80.6\%, R \quad Sq(\text{adj}) = 78.5\%)$:

$$\text{Qi} = 210(Sp) + 133, \tag{3}$$

where $Sp$ is area percent of spheroicity.

Quality index variations versus the 2-D microporosity area have been presented by Figures 9 and 10. The following equation presents experimental data in

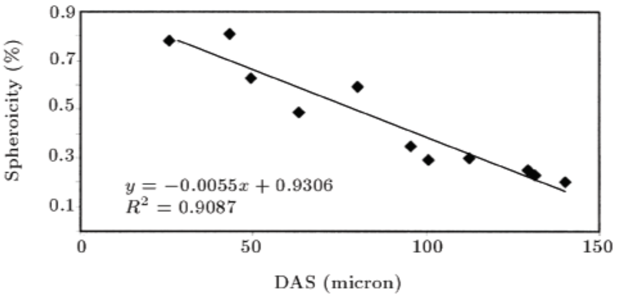

**Figure 2.** Spheroicity of eutectic silicon particles versus dendrite arm spacing.

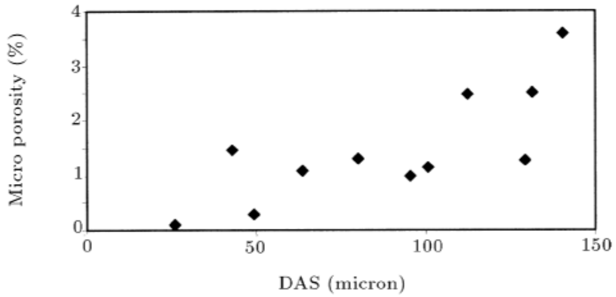

**Figure 3.** 2-D microporosity area percentages versus dendrite arm spacing.

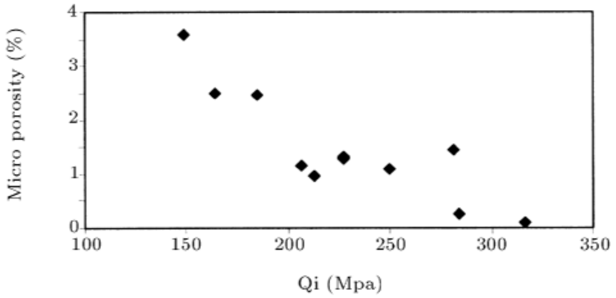

**Figure 4.** Variations of quality index with 2-D microporosity area.

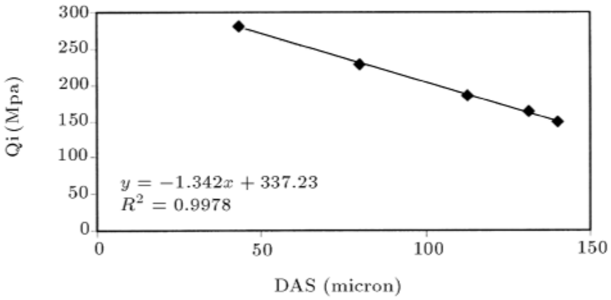

**Figure 5.** Quality index versus dendrite arm spacing for series A of the samples.

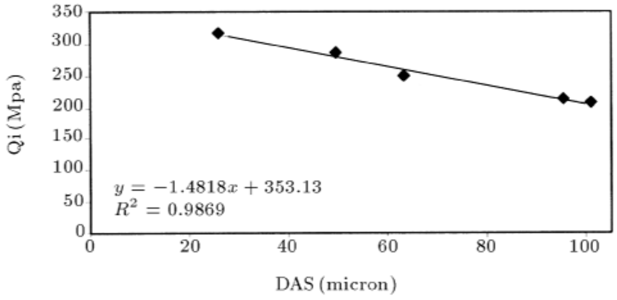

**Figure 6.** Quality index versus dendrite arm spacing for series C of the samples.

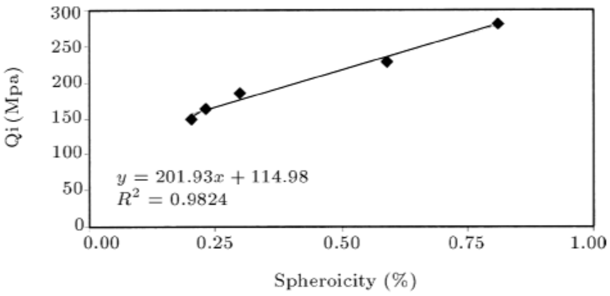

**Figure 7.** Quality index versus spheroicity of eutectic silicon particles for series A of the samples.

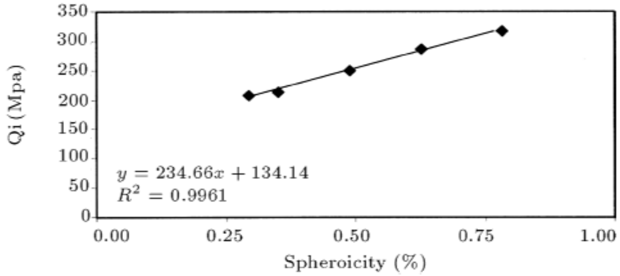

**Figure 8.** Quality index versus spheroicity of eutectic silicon particles for series C of the samples.

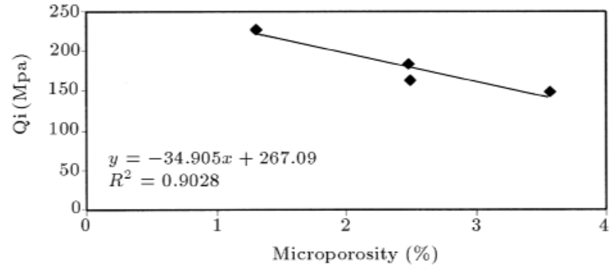

**Figure 9.** Quality index versus 2-D area of microporosity for series A of the samples.

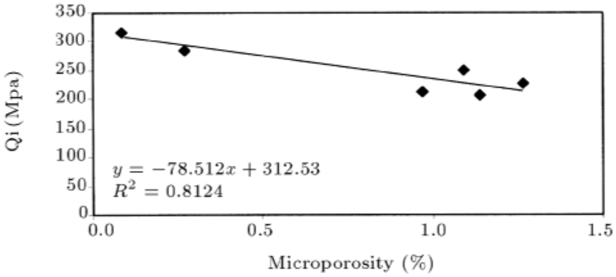

**Figure 10.** Quality index versus 2-D area of microporosity for series C of the samples.

the form of a linear equation ($S = 27.83, R \quad Sq = 74.5\%, R \quad Sq(\text{adj}) = 71.7\%$):

$$\text{Qi} = \quad 44.1(MP) + 292, \tag{4}$$

where $MP$ is 2-D microporocity area percent.

As the final mechanical properties of cast alloy are assumed to be resulted from the sharing effect of three mentioned microstructural major components, a linear relationship can be obtained by regression analysis of quality index versus DAS, spheroicity and the 2-D microporosity area ($S = 15.01, R \quad Sq = 94.2\%, R \quad Sq(\text{adj}) = 91.7\%$) as follows:

$$\text{Qi(Mpa)} = 213 \quad 0.081\ \text{DAS}(\mu\text{m}) + 126\ \text{spheroicity} \quad 24.0\ \text{porosity}(\%). \tag{5}$$

Figure 11 shows residuals versus the fitted values of experimental data compared with calculated values. It seems a rather good compatibility of experimental data with Equation 5 (less than about 10%).

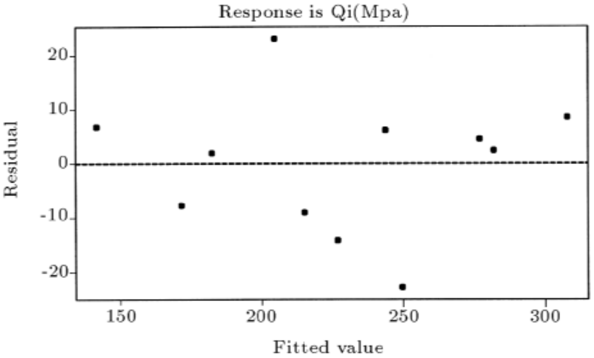

**Figure 11.** Residuals versus the fitted values of experimental data comparing the calculated values.

However, the effect of heat treatment on other alloying elements (Fe, Mn and Mg) have not been investigated in this study. For example, the aging of the alloy can change its mechanical properties without any quantifiable variation of microstructural aspects. Furthermore, for high iron contents, the quantitative effect of iron intermetallics should be taken into account. The principle aims of future studies are to predict the mechanical behaviors of more complicated microstructures and, also, to evaluate other microstructural susceptible mechanical properties, such as high cycle fatigue and low cycle thermal fatigue.

## CONCLUSIONS

The effect of three important microstructural constituents of hypoeutectic A356 cast aluminum alloys on its mechanical properties has been investigated. Variations of the quality index with dendrite arm spacing, the spheroicity of silicon eutectic particles and the 2-D microporosity area have been presented using a regression analysis of experimental data. However, for more complicated situations, such as with high iron, manganese and other alloying elements or different heat treatment conditions, more detailed experiments should be provided.

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