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# A Simplified Empirical Model of Precipitation Strengthening in 6000 Al-Mg-Si Extrusion Alloys

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## Abstract

The strengthening behaviour in the 6000 series alloy group is commonly attributed to achieving a “balanced” alloy composition with respect to $Mg_2Si$, with strength being a function of alloy content and additional strengthening being related to “excess Si” beyond the balanced composition. Al-Mg-Si alloys with a wide range of Mg and Si contents were VDC cast as billet and extruded and the tensile properties in a T6 heat treatment condition were evaluated. In contrast to the traditional model of strengthening, it was found that the tensile properties are more simply related to the amount (volume fraction) of $Mg_xSi$ precipitates, with x close to one. This simplified model for alloy design shows that the total alloy content can be reduced and that an excess of Si (or Mg) has minimal effect on the tensile properties.

## 1. Introduction

6000 series Al-Mg-Si extrusion alloys are used in high volume architectural, structural and automotive applications. In general terms, the alloys are produced as billet using continuous casting (vertical direct chill, VDC, or horizontal direct chill, HDC). The billet is homogenised to eliminate segregation, to transform, break-up and spheroidise Fe-containing intermetallic phases and to generate evenly distributed precipitates that are readily dissolved during extrusion. Homogenised billet is preheated and extruded to final shape or for subsequent forming and fabrication. Extrudability, which can be expressed in terms of extrusion speed, break-out pressure or surface finish, is a key factor in production.

Heat-treatment of the extrusions typically consists of solutionising Mg and Si, which occurs at the maximum extrusion exit temperature, press-quenching, natural ageing, stretching and artificial ageing. Final application of the alloys requires adequate strength as defined in appropriate standards [1].

The strengthening precipitates in 6000 series alloys are magnesium-silicide phases. There are conflicting reports in the literature of the Mg and Si contents of precipitates and in particular the Mg:Si ratio in the precipitates [2,3]. These studies have been on widely different alloy compositions and heat-treatment conditions (varying from early cluster formation through to coarse over-aged precipitates). If, for a wide range of alloys, the Mg and Si content of precipitates is not in the atomic ratio of 2Mg:1Si as commonly accepted (based on the equilibrium phase $Mg_2Si$), then the traditional concept of a “balanced” alloy design [4] may no longer be useful and the description of an alloy having “excess Si” with respect to the balanced alloy design may be misleading.

Of practical interest is how to design 6000 series alloys for optimum mechanical properties in the peak-aged (T5/T6) condition, without compromising extrudability of the alloys. An experimental program was devised to investigate alloys with a wide range of Mg and Si contents. Minor alloying elements (e.g. Mn, Cr, Cu) were avoided to simplify the alloy comparisons, but typical Fe levels were used. From the results, a simplified empirical model of strengthening has been developed which explains the observed behaviour and which enabled the design and development of alloys with improved extrudability and strength [5,6].

## 2. Experimental Procedures

All alloy billet and extrusions were produced at Comalco Research and Technical Support. In the first stage eight alloys were VDC cast to $\phi$178mm billet. In the second stage a further three alloys were cast.  In each case, billet was homogenised for 2hours at 570°C, then machined down to $\phi$125mm for extrusion at a ratio of 56:1 to a 40x6mm solid rectangular section.

For trial 1 (alloys A1 to A8), extrusion billet was pre-heated within 1h to 450°C, the container and die temperature were 430°C and the extrudate speed was 40m/min with forced-air press-quenching. For trial 2 (alloys A1 to A4 and alloys B1 to B3), extrusion billet was induction heated and the extrudate speed was 20m/min with water press-quenching.

For consistency, the extrusions were solution treated after extrusion and artificially aged to obtain T6 properties. Ageing curves (Rockwell H hardness for 160, 170, 185 & 200°C) were used to determine a convenient peak-ageing temperature and time for each alloy - 185°C was selected for T6 peak-ageing. For trial 1, samples for tensile testing were solution treated for 1h/520°C, cold water quenched, stretched to 0.5% within 1-2h, pre-aged for 24h and then artificially aged. The peak ageing time was selected as the mid-point of the hardness peak “plateau” and was found to generally increase with decreasing alloy content from between 7 to 12h (Table 1). For trial 2, samples were solution treated, quenched, pre-aged without stretching and then artificially aged. A single ageing condition (10h at 185°C) was used for all the alloys in trial 2.  Tensile testing was conducted at room temperature on all samples, according to AS1391-1991 (average of three tests each).

The compositions of the alloys are given in Table 1. Two nominal levels of Mg were used, 0.5 and 0.7wt%. The calculated atomic ratio of Mg:Si in Table 1 is firstly based on total alloy content and secondly, corrected for Si tied up in Fe-containing intermetallics. The Fe correction assumes a solid solubility of 0.01wt% and the remaining Fe tied up in intermetallics in the ratio 2Fe:1Si (assuming $\alpha$-$Al_8Fe_2Si$ is the predominant intermetallic type) [7].

Table 1: Alloy compositions, determined by wet chemical (ICP) analysis*, and T6 ageing conditions

| Alloy Number | Mg (wt%) | Si (wt%) | Fe (wt%) | Mg:Si (atomic)[1.] | Mg:Si (atomic)[2.] | Ageing time (h)[3.] | Ageing time (h)[4.] |
|---|---|---|---|---|---|---|---|
| A1 | 0.49 | 0.27 | 0.10 | 2.10 | 2.29 | 12 | 10 |
| A2 | 0.48 | 0.39 | 0.12 | 1.42 | 1.53 | 10 | 10 |
| A3 | 0.47 | 0.49 | 0.13 | 1.11 | 1.18 | 7 | 10 |
| A4 | 0.48 | 0.62 | 0.12 | 0.89 | 0.94 | 8 | 10 |
| A5 | 0.72 | 0.40 | 0.12 | 2.08 | 2.23 | 12 | - |
| A6 | 0.70 | 0.53 | 0.15 | 1.53 | 1.63 | 12 | - |
| A7 | 0.74 | 0.77 | 0.22 | 1.11 | 1.19 | 8 | - |
| A8 | 0.67 | 0.84 | 0.12 | 0.92 | 0.95 | 8 | - |
| B1 | 0.47 | 0.77 | 0.10 | 0.71 | 0.73 | - | 10 |
| B2 | 0.46 | 0.97 | 0.09 | 0.55 | 0.56 | - | 10 |
| B3 | 0.54 | 1.24 | 0.10 | 0.50 | 0.51 | - | 10 |

* Ti: 0.01-0.03; Mn, Cu, Ni <0.01; Cr, Zr<0.005; Sr<0.001

[1.] Based on total alloy content 2. Corrected for Si in Fe-containing intermetallics

3. Ageing time at 185°C for trial 1. 4. Ageing time at 185°C for trial 2.

## 3. Results and Discussion

The tensile properties of the T6 heat-treated extrusions from trials 1 & 2 are shown in Tables 2 & 3 respectively. The strong relationship between Si content and strength for a given Mg content is apparent in trial 1 (compare alloys A1 to A4 or A5 to A8). For trial 2, the repeat evaluations of alloys A1 to A4 with different extrusion conditions and slightly different ageing times are in good agreement with the results of trial 1. At very high Si contents (alloys B1 to B3) there is minimal effect of Si content on strength.

Table 2: T6 tensile properties for trial 1

| Alloy Number | UTS (MPa) | YS (MPa) | Elong (%) |
|---|---|---|---|
| A1 | 152 | 139 | 14.3 |
| A2 | 194 | 187 | 13.5 |
| A3 | 221 | 213 | 14.3 |
| A4 | 260 | 251 | 11.7 |
| A5 | 214 | 204 | 15.5 |
| A6 | 268 | 251 | 12.0 |
| A7 | 299 | 289 | 10.0 |
| A8 | 314 | 305 | 12.0 |

Table 3: T6 tensile properties for trial 2

| Alloy Number | UTS (MPa) | YS (MPa) | Elong (%) |
|---|---|---|---|
| A1 | 160 | 142 | 19.8 |
| A2 | 192 | 181 | 15.2 |
| A3 | 215 | 209 | 15.9 |
| A4 | 255 | 243 | 13.2 |
| B1 | 265 | 253 | 9.2 |
| B2 | 280 | 263 | 9.9 |
| B3 | 264 | 254 | 10.5 |

A representation of the tensile strength results from trial 1 based on the traditional model of “balanced” alloys with respect to $Mg_2Si$ is shown in Figure 1. The linear correlation of strength and wt%$Mg_2Si$ is poor (note wt% is used which is equivalent to volume fraction under the assumption of a fixed density). In the traditional model, the variation would be interpreted as due to an effect of “excess Si”. Further calculations were conducted by varying the assumed composition (or stoichiometric ratio) of precipitates (i.e. $Mg_xSi$). The correlation of strength versus amount of precipitate is maximised when the assumed ratio “x” is close to one. The results are shown in Figure 2, for x=1 as an example. In this simplified model, the variation in strength is largely accounted for ($R^2$=0.94) by the calculated amount of $Mg_xSi$ precipitate and no reference to “excess Si” is required to explain the results.

| Alloy | Atomic Ratio of Mg:Si | Excess Mg / Si | Excess at% | $Mg_2Si$ wt% |
|---|---|---|---|---|
| A1 | 2.29 | Mg | 0.07 | 0.68 |
| A2 | 1.53 | Si | 0.08 | 0.76 |
| A3 | 1.18 | Si | 0.18 | 0.74 |
| A4 | 0.94 | Si | 0.30 | 0.76 |
| A5 | 2.23 | Mg | 0.08 | 1.02 |
| A6 | 1.63 | Si | 0.09 | 1.10 |
| A7 | 1.19 | Si | 0.28 | 1.17 |
| A8 | 0.95 | Si | 0.41 | 1.06 |

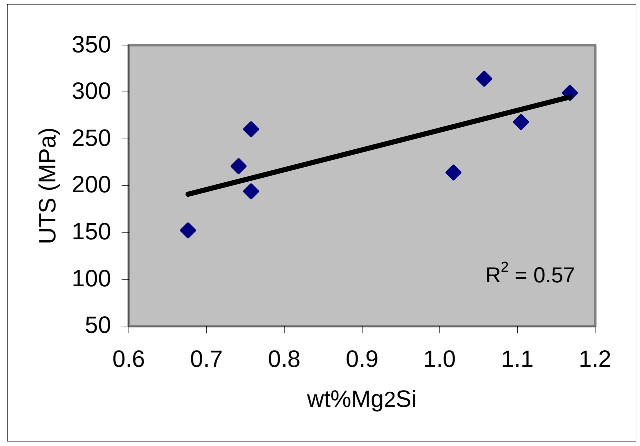


Figure 1: The traditional model of strengthening based on $Mg_2Si$ gives a low correlation with the tensile strength results from trial 1 and suggests an effect of excess Si.

| Alloy | Atomic Ratio of Mg:Si | Excess Mg / Si | Excess at% | $Mg_1Si$ wt% |
|---|---|---|---|---|
| A1 | 2.29 | Mg | 0.31 | 0.46 |
| A2 | 1.53 | Mg | 0.18 | 0.68 |
| A3 | 1.18 | Mg | 0.08 | 0.86 |
| A4 | 0.94 | Si | 0.04 | 1.03 |
| A5 | 2.23 | Mg | 0.44 | 0.69 |
| A6 | 1.63 | Mg | 0.30 | 0.92 |
| A7 | 1.19 | Mg | 0.13 | 1.34 |
| A8 | 0.95 | Si | 0.04 | 1.44 |

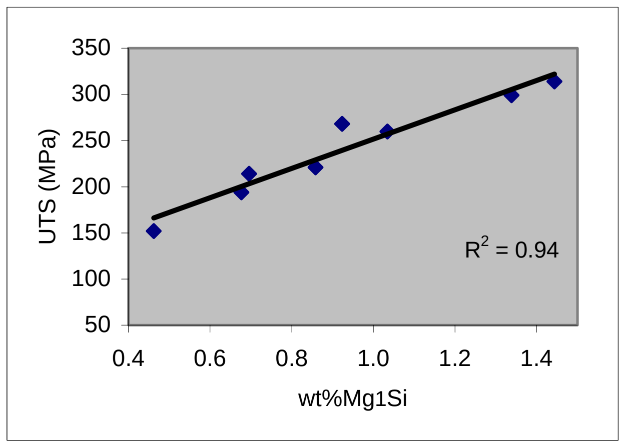


Figure 2: The simplified model of strengthening based on $Mg_xSi$, with x=1, gives a high correlation with the tensile strength results of trial 1.

Given the effectiveness of the simplified model in explaining the observed behaviour it seems reasonable to assume that the most effective hardening phase would have a composition with Mg:Si ratio close to (or on average) one. In the T6 heat treatment condition, the predominant phase is usually considered to be β". This phase has been recently determined as $Mg_5Si_6$ [8], that is, with a Mg:Si ratio of 0.83. The alloy studied (Al-0.5Mg-0.5Si-0.2Fe, in wt%) has a corrected atomic ratio of 1.2. In a 6061 alloy (Al-0.80Mg-0.79Si-0.18Cu-0.22Fe, in wt%) which has a corrected atomic ratio of 1.25, the Mg:Si ratio of strengthening precipitates was reported by atom-probe as 1.1 to 1.2 [9]. Further work on alloys with a wide range of Mg:Si ratios, tested under similar T6 heat-treatment conditions [10] has confirmed the strengthening precipitate compositions are largely independent of alloy composition. In contrast to this, atom-probe work on a range of alloys [11] indicates clearly that the composition of solute clusters and GP zones (early stages of precipitation) do vary depending on alloy composition.

A number of corrections or refinements are possible to the model calculation of amount of Mg and Si available to form strengthening precipitates. The corrections for solubility of Fe and for Si in the Fe-containing $\alpha$-$Al_8Fe_2Si$ intermetallics were made for Figures 1 & 2. Different intermetallic forms could be included depending on the alloy and homogenisation conditions. Equilibrium $Mg_2Si$, formed or retained when the solution treatment temperature does not exceed the solubility limit, is another possible correction. Potentially more significant corrections include the room temperature solid solubilities of Mg and Si [7], assuming that one or both of these elements is retained in solution following artificial ageing. A sensitivity analysis was performed on the calculation of correlation for strength versus wt%$Mg_xSi$ by including estimates for the above factors, but this did not alter the conclusion that "x" close to one (0.9-1.1) best explains the observed behaviour.

A simple illustration of the various contributions, which accounts for the Mg and Si contents in the alloys, is shown in Figure 3. The alloy is typical of those designed based on the traditional model of strengthening with respect to $Mg_2Si$, with an excess of Si for improved strength. However, based on the simplified model, the alloy already has an excess of Mg over that required to be balanced with respect to $Mg_xSi$, with x=1. Increasing the Si content of the alloy would be expected to increase strength by forming more precipitates with the available Mg. Reducing the Mg content would be expected to have little effect on the strength but have potential advantages from the reduced total alloy content (e.g. reduced alloy costs, improved extrudability and conductivity [5,6]).

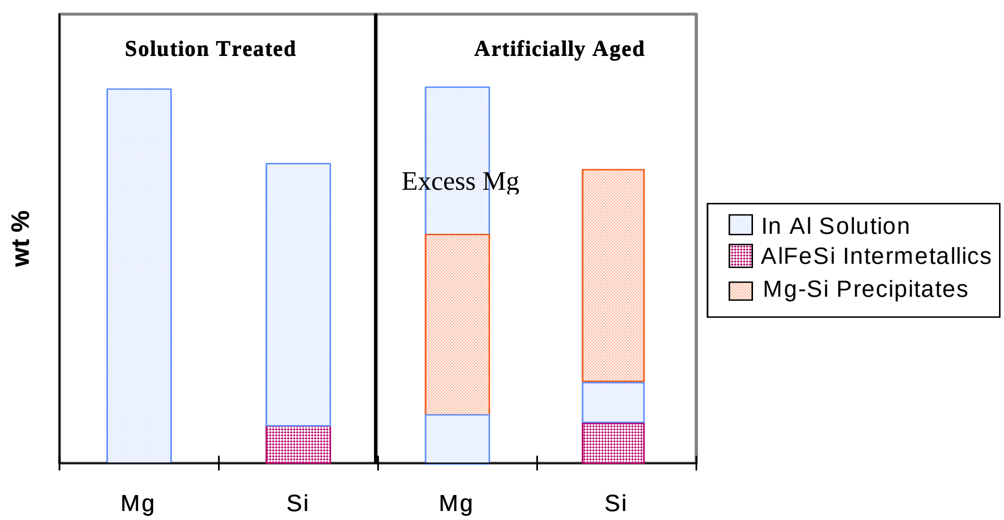


Figure 3: Schematic illustration of the phases containing Mg and Si in alloy A2 (0.5wt%Mg, 0.4wt%Si), based on the simplified model of strengthening, with respect to $Mg_xSi$, with x=1, and T6 heat treatment.

The tensile results for trial 2 provide further support for the simplified model of strengthening (Figure 4). The tensile results are plotted against Si content since the alloys compared all have about the same Mg content (nominal 0.5wt%). Alloys B1 to B3 have clearly "excess Si" but the additional Si has little effect on the tensile strength (Figure 4).

Alloy A4 is close to optimum for this Mg level, given that it is the closest to being "balanced" with respect to $Mg_xSi$, with x=1 (see Figure 2) and has the highest strength with the lowest possible alloy content (no excess Si).

| Alloy | Atomic Ratio of Mg:Si | Excess Mg / Si | Excess at% | $Mg_1Si$ wt% |
|---|---|---|---|---|
| A1 | 2.29 | Mg | 0.31 | 0.46 |
| A2 | 1.53 | Mg | 0.18 | 0.68 |
| A3 | 1.18 | Mg | 0.08 | 0.86 |
| A4 | 0.94 | Si | 0.04 | 1.03 |
| B1 | 0.73 | Si | 0.20 | 1.01 |
| B2 | 0.56 | Si | 0.40 | 0.99 |
| B3 | 0.51 | Si | 0.57 | 1.06 |

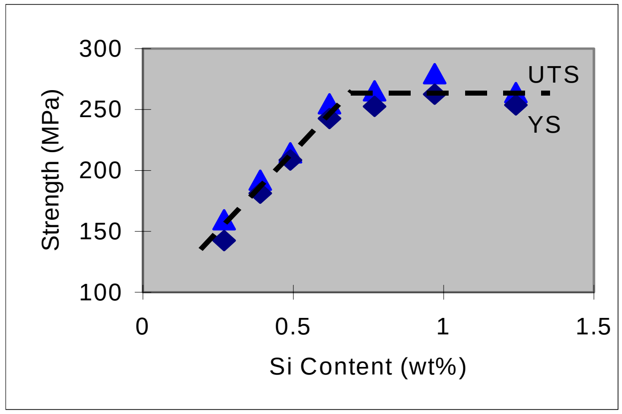


Figure 4. Calculations of excess Mg or Si and amount of precipitate based on the simplified model ($Mg_xSi$, with x=1) for trial 2 alloys with nominal 0.5wt%Mg. Tensile (UTS) and yield strength (YS) for the T6 heat treated condition are shown (lines drawn are schematic only).

## 4. Conclusion

A simplified empirical model of strengthening in 6000 series alloys has been proposed which explains the observed tensile results in T6 heat treated extrusions for a wide range of alloys. The model assumes that strength depends on the volume fraction of a single precipitate composition ($Mg_xSi$). When the assumed ratio x is close to one a good correlation with the experimental results is obtained and the model provides a basis for alloy optimisation. An excess of Si with respect to this alternate balanced alloy design has minimal effect on strength.

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