Age hardening response of AlSiMg foundry alloys

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Abstract

The well-accepted description of a T6 condition consists of a solid solution heat treatment followed by rapid cooling and artificial age hardening. The solid solution heat treatment temperature must be above the solvus temperature, and the time must be sufficient to ensure complete dissolution of Mg-containing particles.

The paper demonstrates that T6-properties (defined by age hardening 8 hrs at 160 °C) may vary significantly even though the above requirements are fulfilled. A correspondingly strong effect of cooling rate after the solid solution heat treatment is observed, comparing cooling rates all of them higher than the critical one for precipitation during cooling.

Keywords: AlSiMg, foundry, heat treatment, vacancies, mechanical properties

1. INTRODUCTION

AlSi7Mg foundry alloys offer good castability with the possibility of obtaining high strength applying a T6 heat treatment. In order to optimise the material properties, it is necessary to have a fundamental understanding of the mechanisms of major importance for the increased strength achieved by the heat treatment.

The age hardening curve of AlSiMg foundry alloys is primarily determined by the Mg-content. However, the following parameters are also important:

- The solid solution heat treatment temperature
- The cooling rate from this temperature
- The room temperature storage before artificial ageing

The main goal of this work is to clarify and quantify the interaction between Mg and these three additional parameters.

2. EXPERIMENTAL

2.1 Alloys

Three DC-cast billets with composition given in table 1 have been used for the studies.

Table 1. Alloy composition (wt%)

Alloy	Si	Fe	Mg	Sr	Ti	B
0.14 Mg	7.3	.09	.14	.039	.052	.0005
0.24 Mg	7.1	.10	.24	.027	.004	.0001
0.43 Mg	7.0	.11	.43	.028	.004	.0001

DC-cast billets are a high quality material with minimal porosity and a secondary dendrite arm spacing (DAS) in the range 10-15 μm. All alloys reveal a fine grain structure, despite the fact that only one (0.14 Mg) is grain refined.

2.2 Heat treatment

The solid solution heat treatment was carried out in an air circulation furnace as follows:

- 12 hrs. at 490 °C
- 3 hrs at 550 °C

The age hardening was done in oil at 160 °C. Age hardening was carried out immediately after the solid solution heat treatment for one set of the samples, while another set was stored 7 days at room temperature.

In order to achieve different cooling rates after the solid solution heat treatment, different cooling media were applied. A thermocouple was mounted in the centre of a 15x15x15-mm3 sample, corresponding to the sample used for hardness measurements. Table 4 shows the resulting cooling rates.

Table 2. Cooling procedures and resulting cooling rates. The indicated cooling rate is the average cooling rate for the temperature interval 550-350 °C in the centre of the cubic 15x15x15 mm^3 sample.

Cooling sequence	Description of cooling medium	Cooling rate
1	Water	~200 °C/s
2	Oil	~25 °C/s
3	Air stream from cooling fan 10 mm from the sample	~3 °C/s
4	Air	~1 °C/s

2.3 Mechanical testing

All samples for hardness testing were 15x15x15 mm^3. After heat treatment the samples were cut in two and measured in the middle, in order to avoid any effect of Mg-evaporation during the solid solution treatment. 5-10 indentation values were used, and the typical standard deviation was 2HV.

The tensile samples were cylindrical with diameter 6.25 mm, gauge length 30 mm and the test speed was 2 mm/min ($d\varepsilon/dt = \sim 10^{-3} s^{-1}$). Three parallels have been used in all trials.

3. RESULTS

3.1 The effect of solid solution temperature and room temperature storage

As observed in fig.1, the strength of the alloys after artificial ageing increases markedly when the solid solution heat treatment temperature increases from 490 to 550 °C. The increase in yield strength is 91, 102 and 80 MPa for 0.14, 0.24 and 0.43 wt% Mg, respectively. A corresponding increase in ultimate tensile stress and hardness is also observed. The fracture elongation is only slightly affected by the solid solution heat treatment temperature; i.e. the strength increase is not achieved at the expense of ductility.

The effect of 7 days room temperature storage before age hardening is modest when solid solution heat treating at 550 °C. The reduction in T6-strength is ~ 0 for 0.14 Mg, 3HV/5MPa for 0.24 Mg and 5HV/12MPa for 0.43 Mg. As expected, the fracture elongation values are also quite similar.

The ageing curves in fig.2 demonstrate that the age hardening response is much faster if the solid solution heat treatment is performed at 550 °C. As a consequence, when ageing 48 hrs at 160 °C, the difference in hardness between 490 and 550 °C is less than after 8 hrs. The effect of intermediate room temperature storage, fig.3, is that the time to peak hardness is increased.

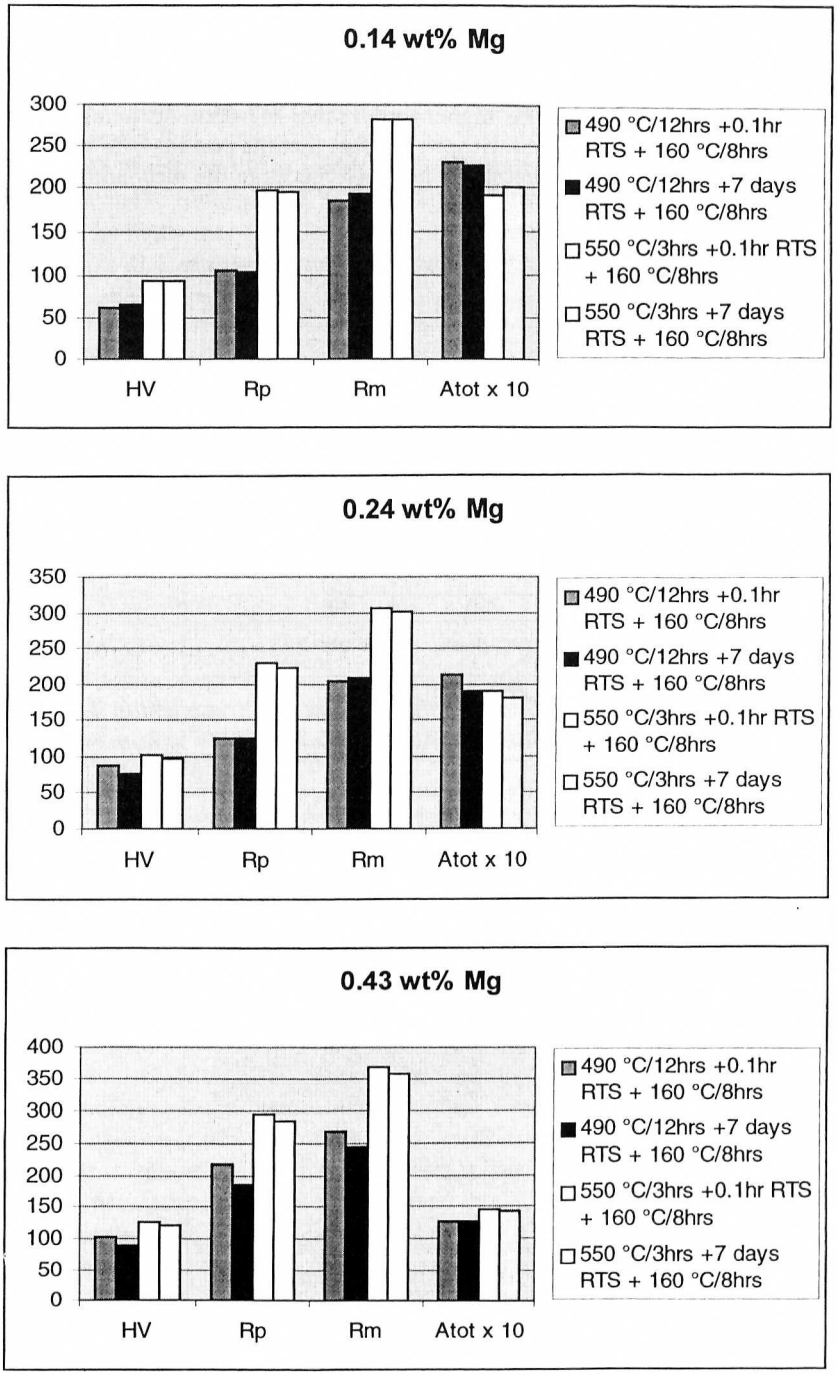

Fig.1 The effect of solid solution heat treatment temperature and intermediate storage time before age hardening on mechanical properties in the T6-condition.

3.2 Reduced cooling rate after the solid solution heat treatment

In the same way as a lowered solid solution heat treatment temperature causes a significant strength reduction in the T6-condition, a lowered cooling rate has the same effect. The water-quenched samples are typically 25HV/70 MPa higher for all three Mg-contents compared to the samples oil-cooled, van-cooled and air-cooled. Despite the fact that the cooling rate varies with a factor 25 between the 3 latter cooling sequences, no clear differences in the mechanical properties are found.

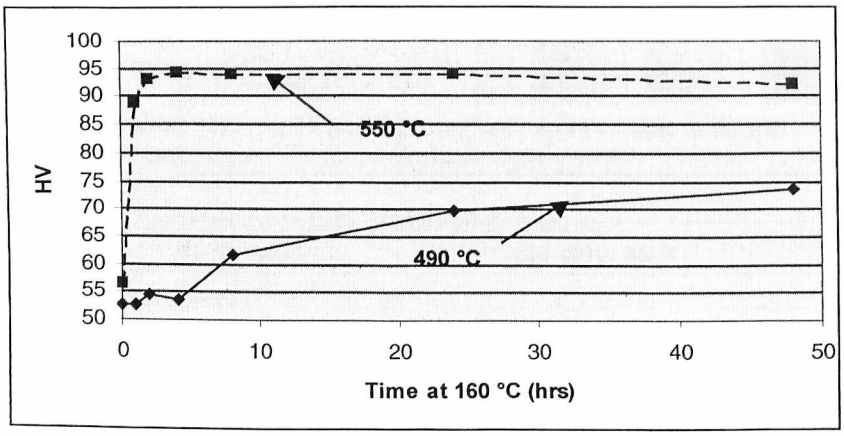

Fig.2. Age hardening curves for 0.14wt% Mg after solid solution heat treatment at 490 and 550 °C, respectively. All Mg is in solid solution prior to the age hardening in both cases.

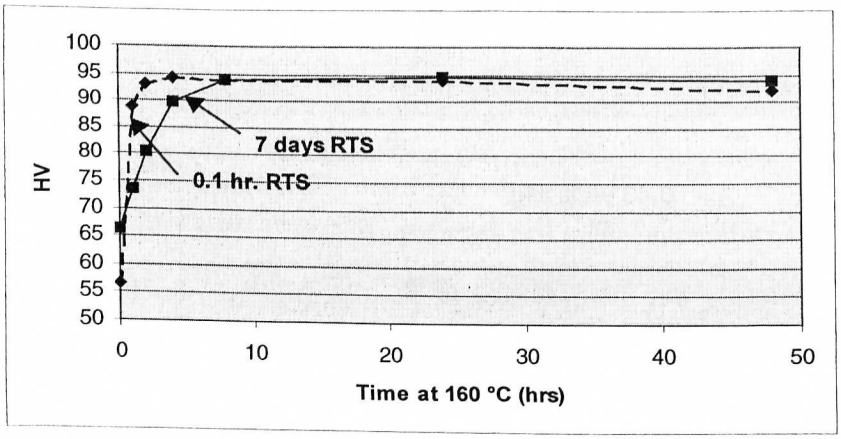

Fig.3. Age hardening curves for 0.14 wt% Mg after solid solution heat treatment at 550 °C and Room Temperature Storage (RTS) for 0.1 hr. and 7 days, respectively.

4. DISCUSSION

In order to explain the results, the solubility variation of magnesium with temperature is obviously important. Phase diagram results from calculations by ThermoCalc [1] for the AlMgSi-system are shown in fig.4, indicating a maximum solubility of Mg equal to 0.35 wt% at 490 °C and 0.60 wt% at 550 °C. Results from Phillips [2] are additionally shown, revealing a higher

solubility of Mg. Some preliminary results indicate that ThermoCalc is more correct for predicting the maximum Mg-solubility. At present we are not able to say whether adding Fe to the system reduces the Mg- solubility. We know, however, that additional Mg must be added in order to compensate for the Mg tied up in the π-AlMgFeSi-phase ($Al_{18}Si_{10}Mg_7Fe_2$ according to our measurements).

Not able to rely on the available phase diagram, the presence of Mg-containing particles was looked for in the microprobe. K_α Mg-mapping images were obtained with a Cameca SX100 microprobe. The method is capable of pointing out remaining particles, but can not be used to quantify the size and volume fraction of the particles.
The results can be summarised as follows:

- At 490 °C Mg-containing particles were only found in the 0.43 wt% Mg-sample.
- When cooling at different cooling rates from 550 °C, Mg-containing particles were not found at any cooling rates for the 0.14 or 0.24 wt% Mg-samples. For the 0.43 wt% Mg-sample only the water-quenched sample showed no precipitation of Mg-containing particles.

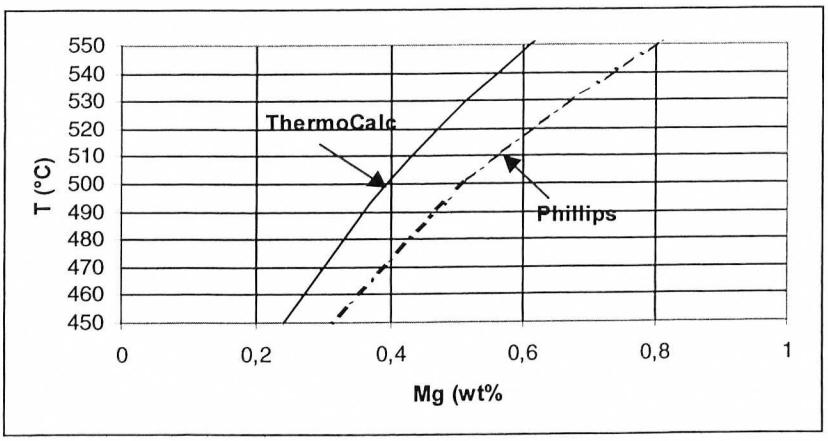

Fig.4 The solubility of Mg in the ternary eutectic Al+Si+Mg_2Si in the AlSiMg-system after ThermoCalc [1] and Phillips [2]. Adding Fe to the system means that additional Mg must be added to achieve the indicated solubility, in order to compensate for Mg bound in the π-AlMgFeSi-phase ($Al_{18}Si_{10}Mg_7Fe_2$). Some preliminary results indicate that ThermoCalc is more correct for predicting the maximum Mg-solubility.

It is quite clear that the significant difference between 490 and 550 °C for the 0.14 and 0.24 wt% Mg-samples cannot be explained by different amounts of Mg in solid solution. The equilibrium solubility of vacancies increases rapidly with temperature, according to Mondolfo [3] with a factor 10 pr. 100 °C, typically. When quenching the material (as in the trials discussed so far), the supersaturation of vacancies probably causes a high density of Si-vacancy pairs, more effective clustering of Si/Mg-atoms and a more efficient age hardening. The higher solubility of Si at 550 °C may also contribute positively. This solubility is approximately 1.30 wt% at 550 °C (0.75 wt% at 490 °C), meaning one Si atom pr. 750 aluminium atoms. The vacancy concentration is probably of the order 10^{-4}, [3], i.e. a shortage of vacancies compared to Si-atoms in relation to the process of pair formation. This indicates that the quenched-in vacancy concentration is the critical parameter.

5. CONCLUSIONS

T6-strength depends strongly on the solid solution heat treatment temperature. For low magnesium content (0.14 wt%) only insignificant age hardening response is observed after 8 hrs at 160 °C when the solid solution heat treatment temperature is 490 °C, while 100 MPa higher yield strength is obtained when the temperature is raised to 550 °C. At both temperatures all Mg is in solid solution prior to the age hardening.

The observed differences in strength can only be explained by a quenched-in vacancy mechanism. Consequently, the cooling rate after solid solution heat treatment is also important, even within that regime where no Mg-precipitation takes place during cooling.

Room temperature storage before artificial age hardening delays the age hardening response, but the peak value is very little influenced.

References

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