# Influence of quench rate on the artificial ageing response of an Al-8Si-0.4Mg cast alloy

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## Abstract

The aim of the study is to present the influence of quench rate on the artificial ageing response of Al-8%Si-0.4%Mg cast alloy in terms of Brinell hardness and yield strength. The investigated material was produced by a gradient solidification technique and exhibited a microstructure that corresponds to the one of gravity die castings, with a dendrite arm spacing of approximately 25 µm. The study comprises two solution treatment temperatures, five quench rates and artificial ageing times exceeding 100 hours at 170 and 220 $^{0}$C. The microstructure and concentration profiles of Mg and Si were evaluated using energy and wavelength dispersive spectroscopy. Microstructural examination reveals an increment of solutes in the Al-matrix when higher solution treatment temperatures accompanied with high quench rates are applied and shows how both Si and Mg atoms have diffused towards the eutectic during quenching. Consequently, i.e. by increasing the levels of solutes and vacancies, the highest strength levels were realized. The study confirmed that quench rates above 2 $^{0}$C /s do not offer substantial strength improvement while quenching at lower rates resulted in a lower peak hardness and longer times to peak.

## Introduction

A T6 heat treatment is often conducted to obtain an increase in strength of cast Al-Si-Mg alloys. A T6 heat treatment consists of a solution treatment, a quench and an artificial ageing. The objective of quenching is to suppress precipitation upon cooling of the casting from the high solution treatment temperature to room temperature. A fast quench results in a high supersaturation of solute and vacancies and a high strength after ageing. If the cooling is slow, precipitates or second phases will form heterogeneously on dislocations or grain boundaries during cooling, which results in a reduction in supersaturation and concomitantly a lower strength after ageing. A high supersaturation as well as a high diffusion rate are needed for the precipitation to take place. These two properties have opposite temperature dependence and the highest nucleation and growth rates thereby occur at intermediate temperatures between 450 °C and 200 °C for most Al-alloys [1-4]. The time spent in this temperature region during quenching should therefore be as short as possible to avoid precipitation.

Cast aluminium alloys are more quench sensitive, i.e. more prone to form precipitates during quench, compared to wrought alloys [2,5]. This is explained with the presence of eutectic Si particles in casting alloys [2]. The concentration of Si in solid solution in the matrix is reduced with reduced quench rates due to diffusion of Si atoms to eutectic Si particles. Further, the Mg concentration is reduced by nucleation of β-$Mg_2Si$ phase on eutectic Si particles. Another effect of the eutectic Si particles is a higher dislocation density formed during quench, due to the difference in thermal expansion between Si and Al, on which precipitates can nucleate [2]. Loss of Mg due to precipitation during quench obviously affects the fraction of β'' phase formed during ageing and thereby the strength. Loss of Si also has an influence on strength after ageing as the concentration of Si in excess influences the composition of the β'' phase [6] and thereby the volume fraction of β' precipitates formed. The influence of quench rate on yield strength for some Al-Si-Mg casting alloys is summarized in Figure 1. All samples were aged 6-8 h at 170 °C after quenching, i.e. more or less peak aged. The slope of the curves in Figure 1 is a measure of the quench sensitivity of the alloy. At low quench rates (below 1 °C/s), the yield strength increases linearly with the logarithm of the quench rate and does not seem to depend on the composition of the alloy. At quench rates between 1 and 4 °C/s the quench sensitivity is alloy dependent, and quench sensitivity increases with increasing Mg concentration. At higher quench rates (above 4 °C/s), the quench sensitivity is independent of the Mg concentration and much lower.

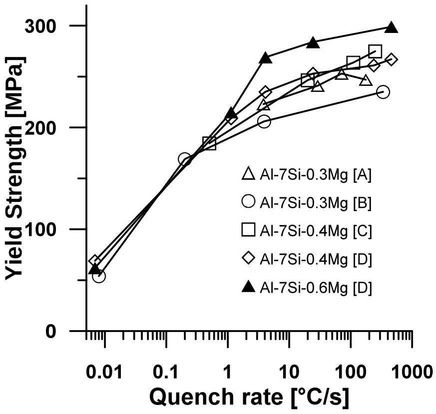



**Figure 1 Influence of quench rate on the yield strength where [A] Emadi et al. [7], [B] Seifeddine et al. [8], [C] Zhang and Zheng [5], [D] Rometsch and Schaffer [4].**

Peak ageing is often used to study the influence of quench rates on the hardness. It has however been shown by Zhang and Zheng [5] that the time to peak hardness is increased for slow quench rates. The aim of the work is to study the influence of quench rate on the shape and position of the ageing curve (hardness versus ageing time). The influence of the solution treatment temperature, i.e. supersaturation of solute and vacancies, is also included.

## Experimental

The composition of the alloy is given in Table 1. An Al-10Sr master alloy was used for Sr modification. Cylindrical rods (length 16 cm, diameter 1 cm) were cast in a preheated permanent mould. The rods were remelted with the gradient solidification technique which gives samples with a low content of porosity defects thanks to the good feeding. The gradient solidification technique allows the control of solidification rate, and hence the coarseness of the microstructure. Rods with secondary dendrite arm spacings (SDAS) of approximately 25 μm were produced, which corresponds to a coarseness of the microstructure obtained for gravity die casting.

**Table 1 Alloy composition in wt. %.**

| | Si | Mg | Fe | Al | Sr [ppm] |
|---|---|---|---|---|---|
| Al-Si-Mg | 7.4 | 0.39 | 0.09 | Bal. | 258 |

Solution treatment was conducted in an electrical furnace at a temperature of 530°C. A solution treatment time of 3 h was used as earlier studies have shown that this time is enough to achieve complete dissolution and homogenization [9]. 15 min for heating of the sample to the solution treatment time was added. The samples were quenched in five different medias: 60 °C water, 100 °C water, sand, insulation material and furnace. A hole of 1.5 mm diameter and 10 mm length was drilled in a test sample and a thermocouple was fixed to log the temperature decrease during quench. The samples were removed from the quench media at a temperature of 100 °C and directly placed in the furnace for artificial ageing at 170°C. A heating time of 20 min to the artificial ageing temperature is excluded from the reported ageing times.

A second solution treatment temperature of 550°C followed by quench in 60 °C water was used to study the influence of supersaturation of solute and vacancies on the age hardening response. A second artificial ageing temperature of 210°C was used for sand quenched samples.

The heat treated samples were ground and polished for hardness tests and microscopic analysis. For the samples aged less than 20 h, the hardness tests were performed just after cooling; for ageing time equal to or higher than 20 h the samples were placed in a refrigerator to avoid microstructural modifications. Nevertheless, the hardness tests were done as soon as possible. Hardness was measured using the Brinell test with a test load of 40 Kgf, equivalent to 392.4 N, an application time of 10 s and a spherical penetrator with a diameter of 2 mm. Two diametrical perpendicular measurements are needed to calculate the hardness value according to the norm EN 10003-1 [10]. In some cases, the shape of the indentations was not perfectly circular and four measurements for each indentation were therefore taken, three on the diameter and one on the circumference, from which an average diameter was calculated. Three indentations were made on each sample and the average diameter was used to calculate the hardness, *HB*, according to Eq. 1, where *F* is the applied load, *D* the diameter of the sphere and *d* the measured diameter of the imprint. The yield strength, *YS*, was calculated using Eq. 2 derived by Rometsch and Schaffer [11], where *n* is the strain hardening exponent.

$$HB = \frac{2F}{\pi D\left(D - \sqrt{D^2 - d^2}\right)} \qquad (1)$$

$$YS = 2.95HB(0.065)^n \qquad (2)$$

The concentration of Mg and Si in the α-Al dendrites after quench and peak ageing at 170°C was measured using wavelength dispersive spectroscopy (WDS). The acceleration voltage was set on 10 kV and pure elements were used as standards. Three dendrites on each sample were selected and five measurements were taken on each dendrite, moving along the dendrite width.

## Results and Discussion

The logged quench curves are shown in Fig. 2 and the average quench rates within the temperature range of 450 °C to 200 °C are given in Table 2.

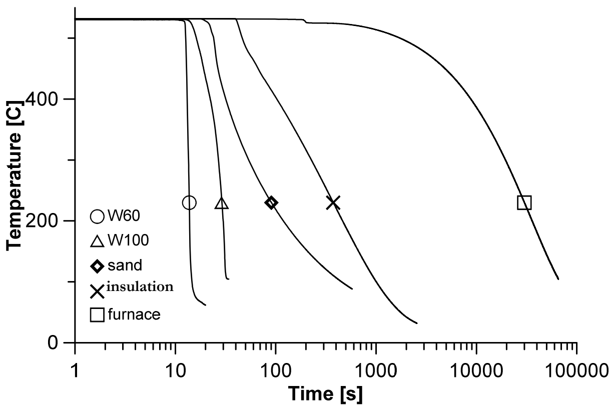



**Figure 2 Quench curves for different quench media.**

The temperature decrease for quench in sand and insulation material is observed to be non-linear due to heating of the quench media because of its low thermal conductivity.

**Table 2 Average quench rates.**

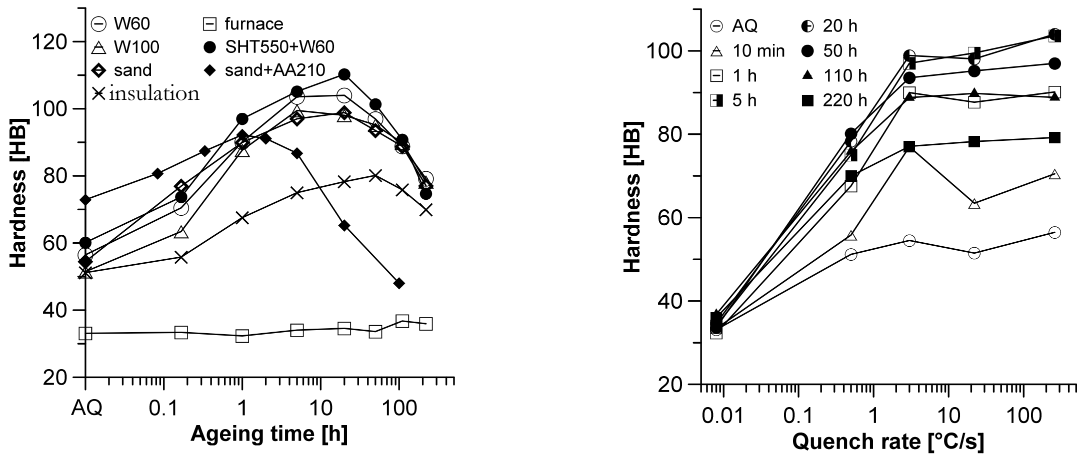
| Quench media | 60 °C water | 100 °C water | Sand | Insulation material | Furnace |
|---|---|---|---|---|---|
| Quench rate [°C/s] | 260 | 22 | 2 | 0.6 | 0.008 |

Ageing curves at 170 °C and 210 °C (where indicated for the latter ageing temperature) for different quench media and heat treatments are shown in Figure 3a. Ageing curves for quench in 60°C water, 100°C water and sand are similar, while quench in insulation media resulted in a lower peak hardness and a longer time to peak. A tiny increase in hardness is obtained for furnace quenched samples, indicating that most solute precipitates during quench. The as quenched hardness in Figure

3b is similar for all quench rates except furnace quenching. The influence of quench rate on the hardness obtained after ageing increases with ageing time and shows a maximum around peak ageing to decrease again upon overageing. An influence of the ageing condition on the quench sensitivity has earlier been reported by Zhang and Zheng [5] and Newkirk et al. [12]. Ageing curves in Figure 3a show good agreement with those presented by Zhang and Zheng [5] for an Al-7Si-0.38Mg alloy.

Solution heat treatment at 550°C results in a higher hardness with a similar appearance of the ageing curve, see Figure 3a. A higher supersaturation of solute and vacancies are obtained after quenching from the higher solution treatment temperature, which is expected to result in a higher peak hardness as it is observed, but also in a shorter time to peak, which is not observed, see Fig. 3a.

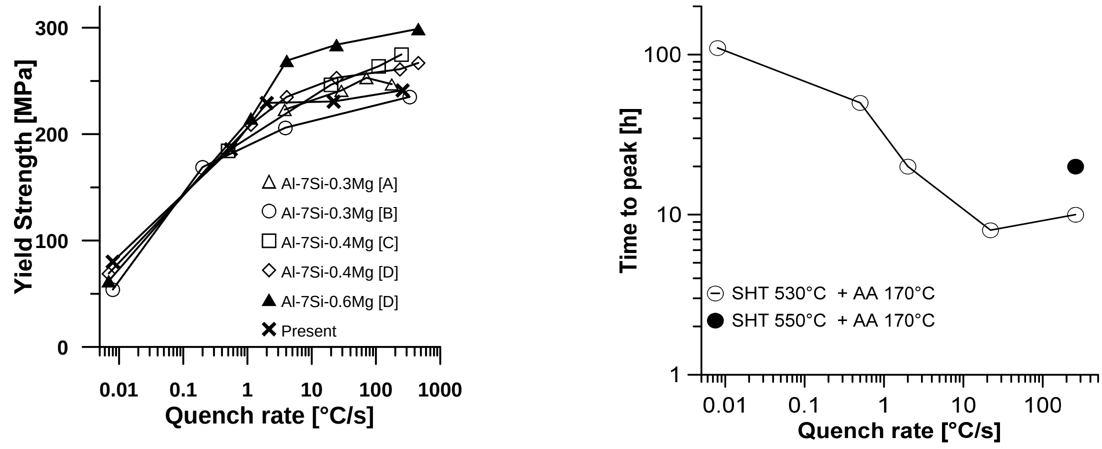
Ageing at 210°C after a sand quench results in a lower peak hardness compared to ageing at 170°C. Earlier measurements [13] on an Al-8Si-0.40Mg alloy quenched in water and directly aged at 170°C or 210°C showed similar peak yield strengths. A lower hardness at a higher ageing temperature has however been reported in the literature [11] for an Al-7Si-0.40Mg alloy quenched in water and directly aged at 170°C or 210°C. It can therefore not be concluded if the lower hardness at 210°C is a result of an increased sensitivity to the ageing temperature for material quenched slowly or if it is just a matter of the measurement type, i.e. hardness compared to yield strength.




**(a)** **(b)**

**Figure 3 a) Ageing curves for various quench rates. b) Quench sensitivity for various ageing conditions at 170°C.**

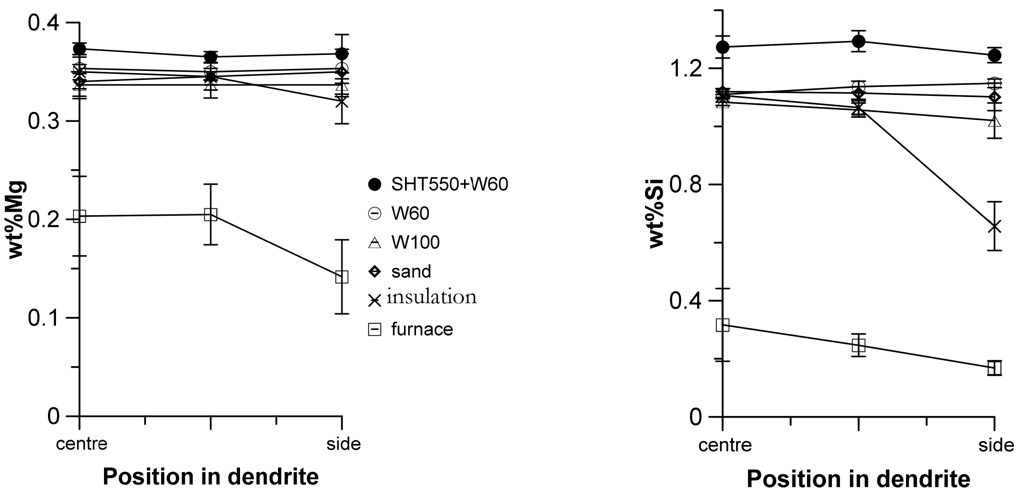
A low quench sensitivity is observed for quench rates above 2°C /s, which is in agreement with data reported in the literature for similar alloys, see Figure 4a. The present investigation however shows a lower quench sensitivity compared to other investigations. Two comments can be made with help of data from Zhang and Zheng [5]. Both hardness and yield strength were measured for ageing 6 h at 170 °C after quenching. Firstly, the hardness data from Zhang and Zheng [5] shows higher quench sensitivity compared to the present investigation. Secondly, the quench sensitivity is lower for calculated yield strengths using Eq. (2) compared to measured yield strengths. Note that the data shown in Figure 4a are for measured yield strengths, with the exception for the present investigation. The lower quench sensitivity of the present alloy can thereby be explained by the measurement method, hardness instead of yield strength, but the quench sensitivity is still lower compared to hardness measurements made by Zhang and Zheng [5].




(a) (b)

**Figure 4 a) Peak strength, where [A] Emadi et al. [7], [B] Seifeddine et al. [8], [C] Zhang and Zheng [5], [D] Rometsch and Schaffer [4], X is present study, while b) shows time to peak as a function of quench rate.**

As for the ageing time needed to reach peak hardness, the current investigation shows that it increases with decreasing quench rate, see Figure 4b. The decrease in supersaturation of solute elements and vacancies with decreasing quench rate leads to a lower number density of precipitates, see complementary data in Fig. 5. This means that atoms need to diffuse a longer distance for the precipitates to grow and it will thereby take longer time for the concentration in the matrix to reach its equilibrium value.




(a) (b)

**Figure 5 Concentration of a) Mg and b) Si in the dendrites after quench.**

The concentration of Mg and Si in the dendrites for various quench rates are shown in Figure 5. Using WDS it is not possible to distinguish between concentrations in solid solution or in precipitates and observed in Figure 5 is a mixture of the two. It can however be observed and confirmed that diffusion of both Si and Mg atoms takes place towards the eutectic during quenching. Si atoms are added to the eutectic Si particles, while Mg precipitates either on the Si particles or on dislocations in the eutectic. Quenching in 60°C water, 100°C water and sand results in high concentrations of Mg and Si in the matrix as the time for diffusion to the eutectic is short. A decrease in Mg and Si concentrations is observed for the slower quench rates, i.e. insulation and furnace. As depicted in Fig. 5a, solution treatment at 550°C results in a slightly higher Mg concentration. A solution treatment temperature of 530°C should be enough to dissolve all phases containing Mg according to the phase diagram [14]. The increase in Mg seen for solution treatment at 550°C indicates that 3 h at 530°C was not long enough to dissolve all Mg containing phases. This was confirmed using EDS analysis, where a better dissolution of π-$Al_9FeMg_3Si_5$ particles were observed for the higher solution treatment temperature. It is worth mentioning that the level of Mg obtained in the matrix when solution heat treating at 550 °C corresponds well with the Mg content of the alloy shown in Table 1. A higher Si concentration is also obtained at 550°C, see Fig. 5b. The Si concentrations obtained after a 60°C water quench are in accordance with phase diagram [14], which are 1.25 wt.% at 550°C and 1.05 wt.% at 530°C. Quench in 60°C water, 100°C water and sand results in high concentrations of Mg and Si in the matrix and the corresponding hardness is high. It should however be kept in mind that measured high concentrations of Mg and Si does not ascertain that no precipitation takes place during quenching, but only that there was no diffusion to the eutectic. The insulation quench, 0.6°C/s, resulted in a small decrease in Mg concentration and a larger decrease in Si concentration and a loss in hardness as a consequence. Both the Mg and Si concentrations decreased drastically for the furnace quench as well did the hardness.

## Conclusions

1. Ageing curves at 170 °C for materials solution heat treated at 530 °C and quenched at rates above 2 °C/s are similar, while quenching at lower rates resulted in a lower peak hardness and a longer time to reach the peak.
2. Solution heat treatment at 550°C resulted in higher Mg and Si concentrations in the Al-matrix and consequently higher hardness.
3. Both Si and Mg atoms are diffused towards the eutectic during quenching.

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