

The Natural and Artificial Aging Response of Semi-solid Metal Processed Alloy A356

H. Möller^{1,a}, G. Govender^{1,b} and W.E. Stumpf^{2,c}

¹Materials Science and Manufacturing, CSIR, Pretoria, South Africa

²Department of Materials Science and Metallurgical Engineering, University of Pretoria, South Africa

^ahmoller@csir.co.za, ^bsgovender@csir.co.za, ^cwaldo.stumpf@up.ac.za

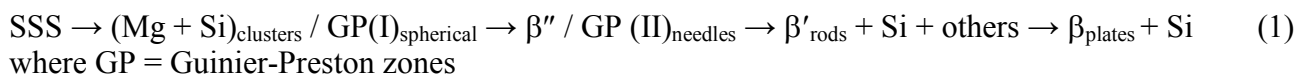
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Abstract

The heat treatment cycles that are currently applied to semi-solid processed components are mostly those that are in use for dendritic casting alloys. These heat treatments are not necessarily the optimum treatments for non-dendritic microstructures. For rheocast alloy A356, it is shown that natural aging prior to artificial aging causes the time-to-peak-hardness to be longer compared to the time when only artificial aging is used. Furthermore, a hardness plateau is maintained during artificial aging at 180°C between 1 and 5 hours without any prior natural aging. A natural aging period as short as 1 hour results in a hardness peak (rather than a plateau) to be reached during artificial aging after 4 hours at 180°C.

Introduction

The Al-Mg-Si alloy A356 is a casting alloy which is used in many applications due to its high strength-to-weight ratio. The castings are generally heat treated to obtain the desired combination of strength and ductility. However, the heat treatment cycles that are currently applied to semi-solid processed components are mainly those that are in use for dendritic casting alloys [1]. These heat treatments are not necessarily the optimum treatments for non-dendritic microstructures. The unique globular microstructure of semi-solid metal (SSM) processed components offers a shorter diffusion path (kinetic enhancement), and the thermal history of the components promotes enhanced dissolution of solutes before heat treatments commence (thermodynamic enhancement) [1]. In Al-Mg-Si alloys containing an excess of silicon, the decomposition of the supersaturated solid solution (SSS) is believed to occur as follows [2]:



where GP = Guinier-Preston zones

β = equilibrium Mg_2Si

β' and β'' = metastable precursors of β

The natural aging response of alloy A356 is considered to be due to GP zones and (Mg+Si) clusters. The precipitation hardening from natural aging alone produces the useful T4 temper. Peak hardening with artificial aging (i.e. from the T6 temper) results from the precipitation of the metastable and coherent β'' . Unfortunately, the cost and production time associated with the T6 heat treatment are substantial and shortening of this heat treatment cycle would, therefore, have a significant implication on the manufacturing cost and productivity [3]. The optimum solution treatment temperature would give the best compromise between time savings, lower risk of distortion, energy savings and maximum dissolution of alloying elements. It appears as if 540°C is the optimum temperature for alloy A356 in terms of the compromise between shortening heat treatment time as well as minimising the risk of blistering and distortion [3]. In the foundry industry, it is frequently stated that a dendritic A356 component should be solution treated at 540°C for 6 hours [4]. According to Rosso and Actis Grande [3], the shortest possible time for solution treatment of rheocast A356 at 540°C is much shorter at only 1 hour. A solution treatment of only 30

minutes caused the presence of brittle intermetallic phases due to an incomplete solution process. Previous work by the authors [5] confirmed that similar T4 and T6 tensile properties could be achieved by using solution treatment at 540°C of either 1 or 6 hours for Sr-modified A356.

The influence of prior natural aging time on the subsequent artificial aging response has not been studied in great detail for alloy A356. Dewhirst [1] varied the natural aging time of semi-solid processed A356 between 8 and 24 hours. He found that increasing the natural aging beyond 8 hours had a slight negative effect on the tensile properties of the material.

Accepted artificial aging treatments for both globular and dendritic alloy A356 are either 6 hours at 160°C [3] or 6 hours at 170°C [3]. Both Dewhirst [1] and Rosso and Actis Grande [3], however, have proposed that the optimum artificial aging treatment for rheocast alloy A356 is 4 hours at 180°C. Previous work by the authors [6] has shown that artificial aging of rheocast A356 at 160°C produces only slightly higher peak hardnesses compared to artificial aging at 180°C. However, the time-to-peak hardness is unfortunately increased significantly due to the slower diffusion.

Experimental

Semi-solid metal slurries of alloy A356 (chemical compositions given in Table 1) were prepared using the CSIR rheocasting process [7]. Plates (4 mm × 80 mm × 100 mm) were cast in steel moulds with a 50 tons high pressure die casting (HPDC) machine. Solution heat treatment was performed at 540°C for 1 hour, followed by a water quench (25°C). The samples were then naturally aged (NA) at 25°C for either zero hours (artificial aging only), 1 h, 20 h (before reaching the stable T4 temper), or 120 h (stable T4 temper), before being artificially aged (AA) at 180°C to determine artificial aging curves. Vickers hardnesses (VHN) were determined (using a 20 kg load) from the average of at least four readings per sample. The average hardness values were found to be reproducible within ± 3 VHN for all heat treatment conditions tested. Tensile samples (sub-standard size) were machined from the plates [6]. A total of 5 tensile tests were used for each heat treatment condition.

Table 1: Chemical compositions (wt%) of alloy A356 used in this study

	Si	Mg	Fe	Cu	Mn	Zn	Ti	Sr
Batch 1	7.14	0.36	0.10	0.01	0.01	0.01	0.07	0.02
Batch 2	7.08	0.40	0.10	0.01	0.01	0.01	0.08	0.02

Results

Microstructure. Figure 1(a) shows an optical micrograph of the as-cast A356. Solution treatment at 540°C for 1 h results in spheroidisation of the eutectic silicon particles (Fig. 1(b)).

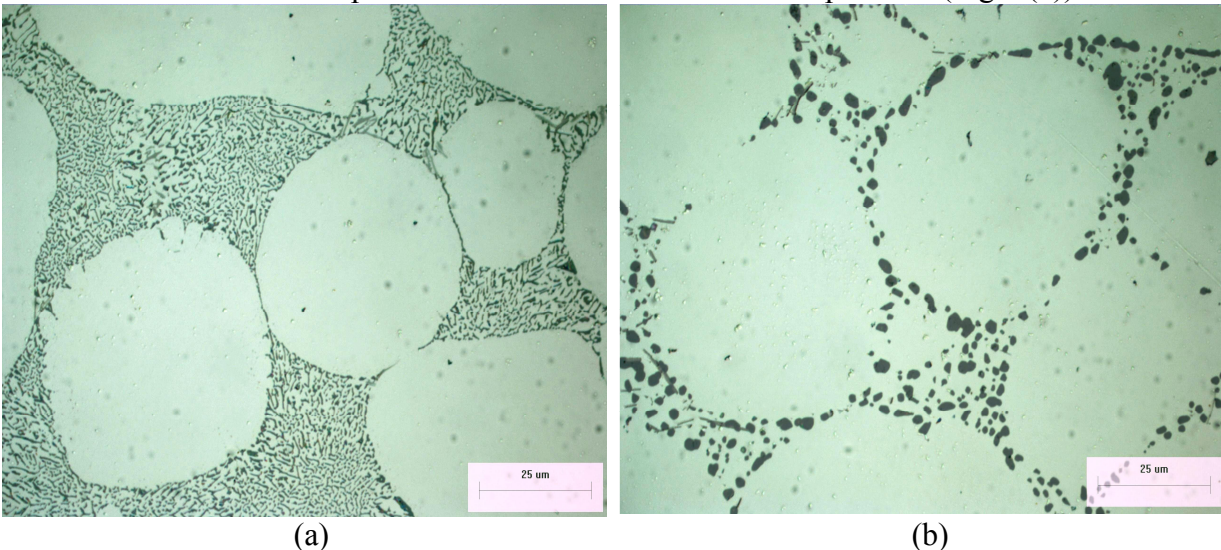


Figure 1. Optical micrographs of (a) as-cast alloy A356 and (b) after solution treatment at 540°C for 1 h

Natural aging. The natural aging curve for rheocast alloy A356 (0.36 wt% Mg) is shown in Fig. 2. The alloy is relatively soft directly after quenching (VHN = 52), but the hardness increases rapidly in the first hour. The hardness levels out after about 120 hours (VHN = 78 in T4 temper).

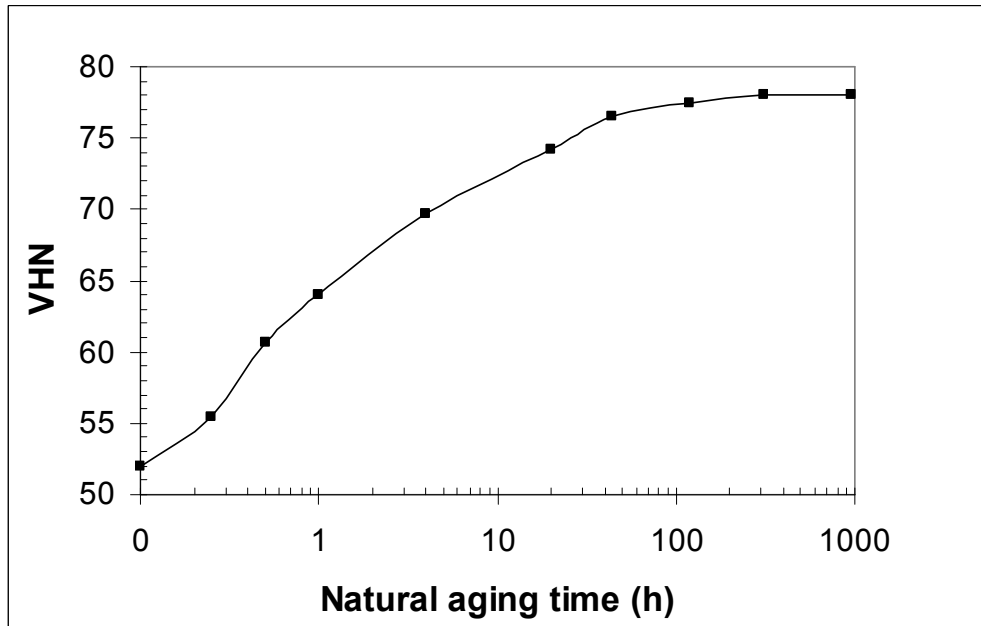


Figure 2: Natural aging curve for rheocast alloy A356 (0.36 wt% Mg)

Artificial aging. Artificial aging curves at 180°C for alloy A356 (0.36 wt% Mg), following natural aging periods of either 0, 1, 20 or 120 hours, are shown in Fig. 3. When no prior natural aging is applied, the initial artificial aging response is rapid. The converse is also true - when natural aging is employed, the subsequent artificial aging response is sluggish. Natural aging of only 1 hour decreases the artificial aging response of this alloy significantly. It has been shown that natural aging following the solution treatment reduced the age hardenability of Al-Mg-Si wrought alloy AA6016 [2], especially in the under-aged condition. This was attributed to solute clustering during natural aging, and the subsequent dissolution of these clusters during artificial aging. The extent of the loss was, however, recovered by precipitation of β'' particles upon further aging [2].

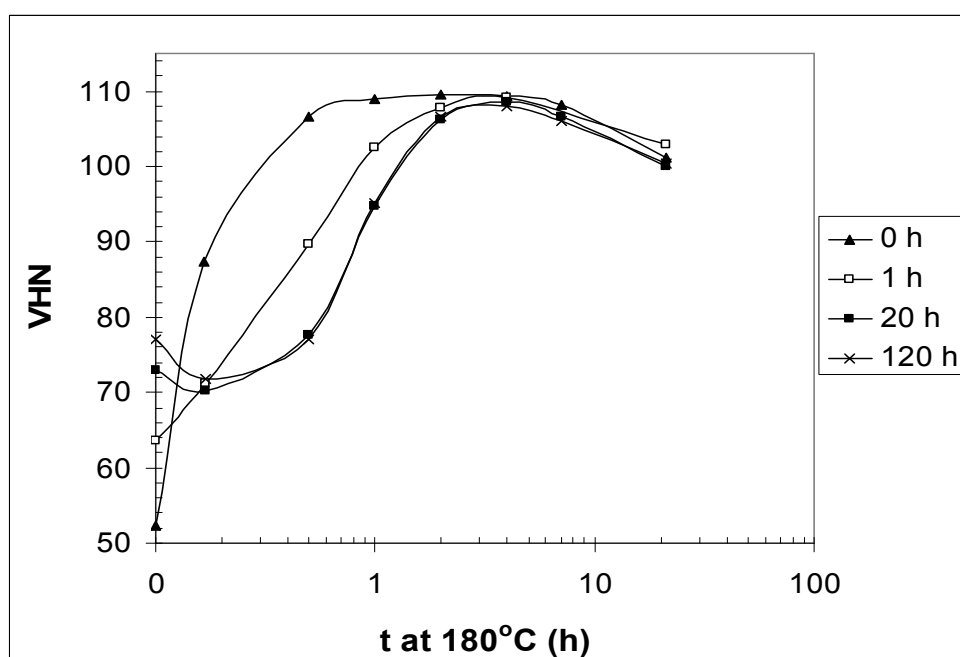


Figure 3: Artificial aging curves at 180°C after natural aging for times of 0, 1, 20 and 120 hours respectively for A356 with 0.36 wt% Mg

Considering Fig. 3, it is seen that for naturally aged alloy A356, initial softening occurs, but that the hardness values are also recovered with further artificial aging. It is therefore concluded that reversion of the solute clusters is probably also responsible for the slow artificial aging response in naturally aged alloy A356. When no natural aging is employed, a plateau is maintained once the maximum hardness is reached during artificial aging after about 1 to 5 hours. This differs from when natural aging is used, when a hardness peak is observed after approximately 4 hours. In all cases, the maximum hardness (T6 temper) is $VHN = 109$. The tensile properties (yield strength (YS), ultimate tensile strength (UTS) and % elongation) as a function of the artificial aging time within the hardness plateau (with no prior natural aging) were determined (Table 2 and Fig. 4). It is seen that the ultimate tensile strengths of the samples are similar (which is to be expected, as they have similar hardness values – Fig. 3). However, the yield strength of the 1 hour artificially aged sample is significantly lower than the rest of the samples. This concurrently leads to a slightly higher % elongation (see Table 2). Once natural aging occurs, a hardness plateau is not maintained during the subsequent artificial aging. Instead, a hardness peak is reached after approximately 4 hours (Fig. 3). The tensile properties as a function of natural aging time after artificial aging for 4 hours at 180°C are shown in Table 2 and Fig. 5. In this case, no significant differences are seen in either the yield strength or ultimate tensile strength. The influence of any natural aging prior to artificial aging can therefore be removed by a 4 hours, 180°C artificial aging treatment. It is seen from Fig. 3 that, while artificial aging at 180°C for 1 h causes maximum hardening in rheocast A356 that was not naturally aged, under-aging is achieved in samples that were naturally aged prior to artificial aging. The tensile properties of 0.40wt% Mg-A356 were determined under these conditions (1 hour artificial aging at 180°C for samples that were naturally aged for 0 h, 20 h and 120 h). The negative influence of natural aging on the initial stages of artificial aging can clearly be seen in Table 2 and Fig. 6. To determine whether the process of natural aging could be impeded by low temperatures, A356 samples were stored in a freezer at -18°C for 20 h after quenching, before artificial aging at 180°C for 1 h. The tensile properties (Table 2, Fig. 6) indicate that this treatment was indeed successful. The artificial aging response of the samples that were kept in the freezer was the same as the samples that were not naturally aged at all.

Table 2: Yield strength, UTS and % elongation of rheocast A356 samples. The standard deviation from five values for tensile properties is also indicated in brackets. “540-1,0NA,180-1” implies a T6 heat treatment cycle consisting of a solution treatment at 540°C for 1 hour, 0 h natural aging and artificial aging at 180°C for 1 hour. All samples were quenched in water at 25°C after the solution treatment.

Heat treatment	Yield strength (MPa)	UTS (MPa)	% Elongation
0.36 wt% Mg			
540-1,0NA,180-1	255 (4.8)	330 (6.4)	10.4 (2.5)
540-1,0NA,180-2	269 (8.5)	334 (6.8)	7.5 (1.9)
540-1,0NA,180-4	273 (6.5)	333 (8.4)	8.4 (2.1)
540-1,0NA,180-5	273 (3.1)	328 (6.9)	7.7 (3.1)
540-1,1NA,180-4	269 (5.8)	325 (4.6)	10.3 (3.4)
540-1,20NA,180-4	270 (4.7)	325 (2.8)	9.3 (1.7)
540-1,120NA,180-4	270 (5.5)	328 (5.8)	8.0 (2.2)
0.40 wt% Mg			
540-1,0NA,180-1	266 (7.5)	341 (9.5)	7.8 (1.8)
540-1,20NA,180-1	224 (7.5)	315 (3.4)	12.5 (1.4)
540-1,120NA,180-1	233 (8.2)	318 (5.2)	10.0 (2.7)
540-1,-18°C for 20h,180-1	266 (6.7)	343 (4.7)	9.1 (1.9)

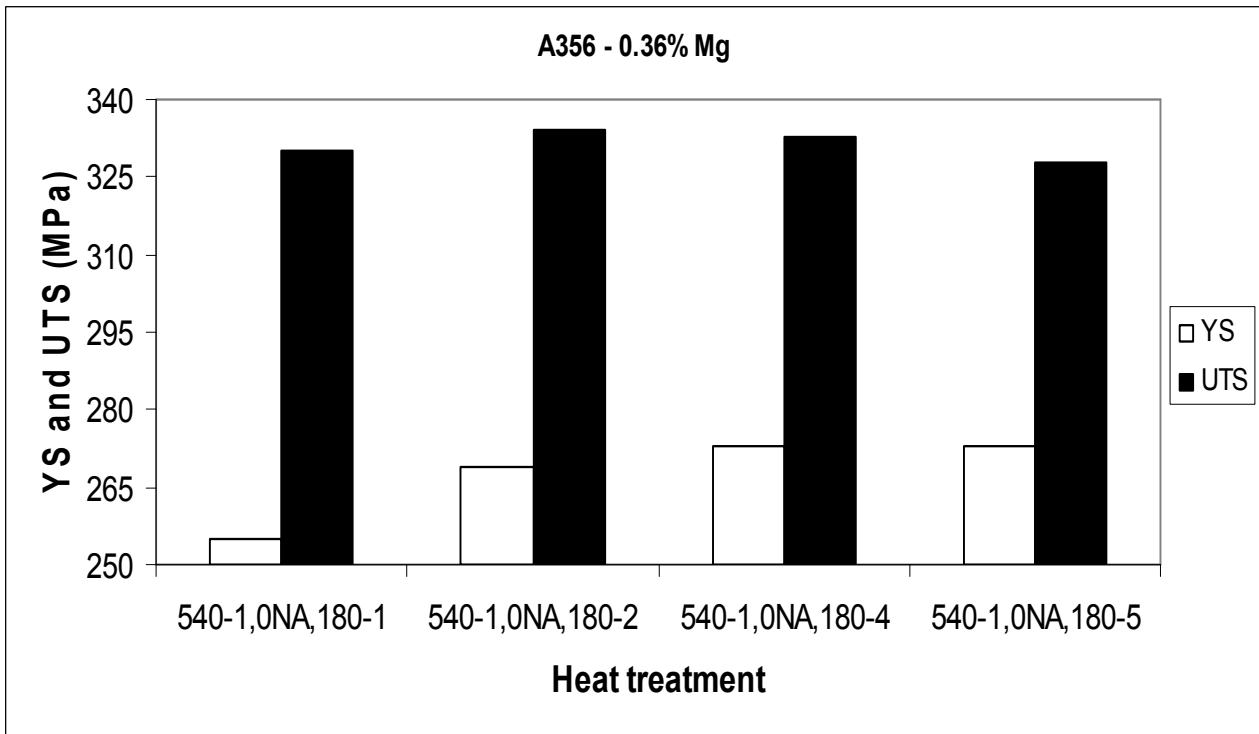


Figure 4: Tensile properties of rheocast alloy A356 (0.36wt% Mg) heat treated at 180°C within the hardness plateau for either 1 h, 2 h, 4 h or 5 h. The samples were not naturally aged prior to artificial aging.

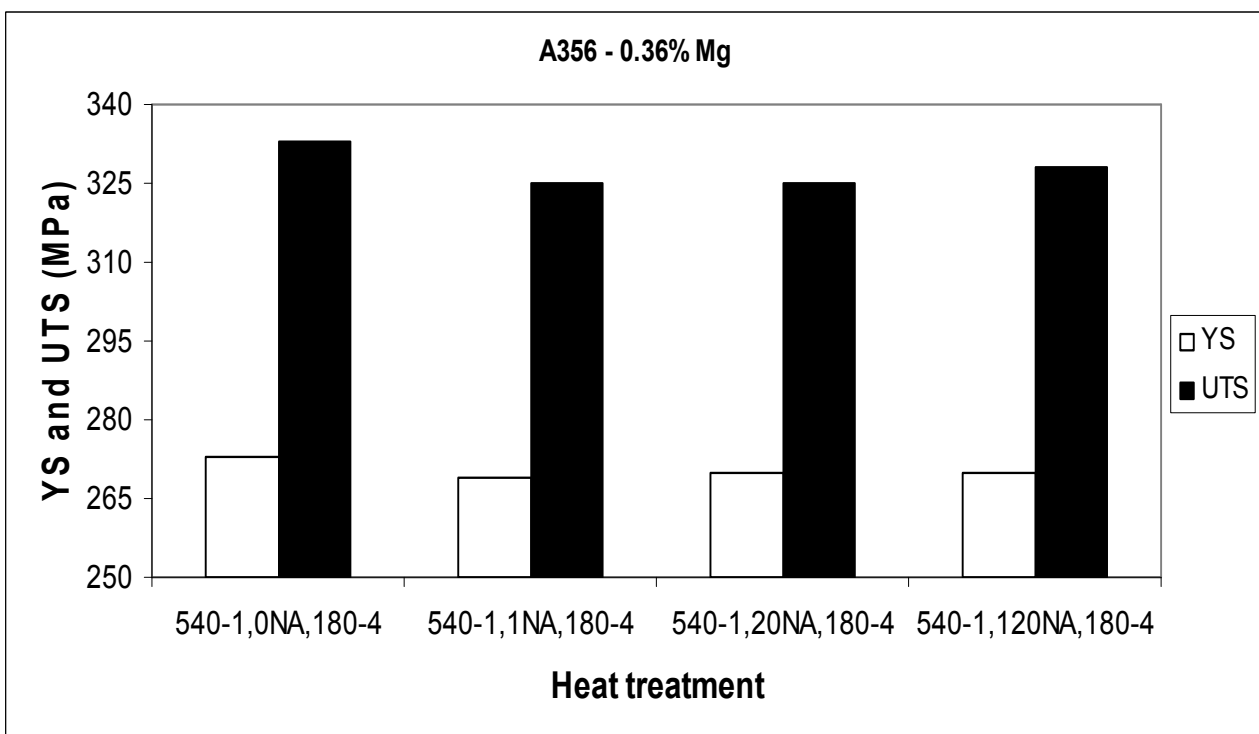


Figure 5: Tensile properties of rheocast alloy A356 (0.36 wt% Mg) heat treated at 180°C for 4 hours. The samples were naturally aged for either 0 h, 1 h, 20 h or 120 h prior to artificial aging.

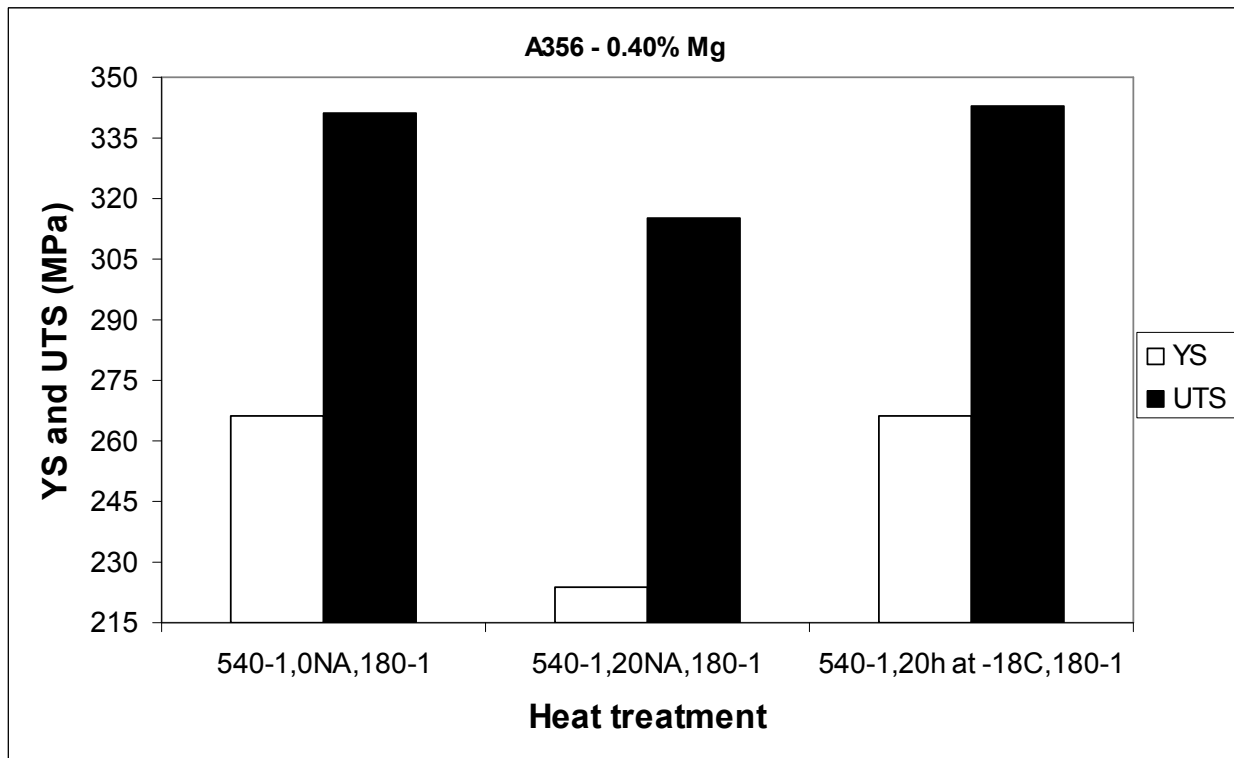


Figure 6: Tensile properties of rheocast alloy A356 (0.40 wt% Mg) heat treated at 180°C for 1 hour after different natural aging treatments

Also note that higher strength is achieved for the 0.40 wt% Mg alloy than the 0.36 wt% Mg alloy (Table 2, compare the “540-1,0NA,180-1” heat treatments). A higher wt% Mg should, firstly, lead to a higher volume fraction of the second phase β , and in all probability also of β' and β'' but, secondly, may change the thermodynamic characteristics of the precipitates by increasing the driving force for nucleation, leading to a higher nucleation rate and thus providing a differently sized distribution [6].

Conclusions

- Natural aging of rheocast alloy A356 occurs rapidly: from VHN = 52 directly after quenching to VHN = 78 after about 120 h for 0.36 wt% Mg-containing A356.
- Artificial aging of rheocast alloy A356 is influenced significantly by prior natural aging. Maximum hardness is reached after only 1 hour at 180°C with no prior natural aging. This time increases to 4 hours in all naturally aged samples.
- Maximum yield strength and ultimate tensile strength in the T6 condition can be achieved after 2 hours at 180°C with no prior natural aging, and after 4 hours at 180°C with prior natural aging.

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Semi-Solid Processing of Alloys and Composites X

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