# Effects of Ageing on the Formability of Aluminium Alloy AA 6063

R. Gao<sup>1</sup>, K. Stiller<sup>2</sup>, A. Oskarsson<sup>1</sup>

<sup>1</sup> Sapa Technology, 612 81 Finspång, Sweden <sup>2</sup> Chalmers University of Technology, 412 96 Gothenburg, Sweden

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#### Abstract

The effects of ageing on the formability (in terms of uniaxial elongation) of aluminium alloy AA 6063 were studied. It was found that long natural ageing preceding artificial ageing has some positive effects on both the strength and the formability of AA 6063 at tested temperatures. The formability decreases with increasing ageing time and increasing ageing temperature until peak ageing is reached. At the peak ageing the formability was found to be independent of ageing temperature, even though the strength increases with decreasing ageing temperature. The obtained results are discussed in light of the precipitation reactions in the alloy.

#### 1. Introduction

Being lightweight and age hardenable, the 6000 series Al-Mg-Si alloys are gaining increasing popularity in a wide array of engineering applications. Many of such applications involve forming operations. Consequently, the formability of these alloys is also becoming a topic of interest in the aluminium research arena. In the current paper, uniaxial elongation to fracture from tensile test is used to evaluate the formability of AA 6063. The aim of this work is to study the effects of ageing on the formability of AA 6063.

#### 2. Experimental

2.1 Sample Materials:

Were taken from extruded 2.x mm thick profiles of a commercial AA 6063. The chemical composition of the alloy is listed in Table 1.

Table 1: Composition of the sample alloy (wt%).									
Si	Fe	Mn	Mg	Ti	Al+other				
0.56	0.17	0.03	0.51	0.02	98.71				

Т	able 1: Cor	nposition	of the sam	nple alloy ( <sup>,</sup>	wt%).	
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The processing history of the alloy consists of 3 hours soaking at 585 °C, then extrusion and guenching by forced air to room temperature, with a guenching rate of around 25  $^{\circ}C$  / second. Samples were divided into three groups undergoing three different pre-ageing treatments: 288 h natural ageing (herein referred to as material A), 3 h natural ageing (as material B) and 3 h natural ageing + 5 h ageing at 80  $^{\circ}$ C (as material C).

The latter is often referred to as stabilising ageing. Subsequently the samples were artificially aged for different durations ranging from 0.25 hour to 64 hours at three different temperatures: 165°C, 185°C and 205 °C.

#### 2.2 Tensile Tests:

Were performed after ageing according to standard EN 10 002-1. Elongation value A50 was used as an indicator to evaluate the formability.

#### 2.3 Microstructural Studies:

Were performed using a transmission electron microscope (TEM) Jeol 2000FX operating at 200 kV. TEM foils were obtained by electro-polishing in a 1:4 solution of nitric acid and methanol, at -35 °C and 20V, using a Tenupol jet polisher [1]. TEM foil thickness was estimated using converging beam electron diffraction (CBED) technique [2]. The determination of foil thickness, measurement of precipitates' sizes and their number density were confined to rectangular areas of 440nm x 590 nm (to which a TEM image in this study corresponds) on the foil. It was assumed that TEM foils were wedge-shaped (i.e. had a linearly increasing thickness) so that the thickness measured at the centre of the investigated area could be used as the average thickness of the whole analysed volume.

#### 3. Results

3.1 Uniaxial elongation as a function of ageing time, tensile strength and ageing temperature

The results of uniaxial elongation to fracture are plotted as a function of ageing time, tensile strength and ageing temperature in Figures 1-3. The figures show that the highest elongation value for each material type/pre-ageing condition was obtained immediately after pre-ageing treatment. The values are 19.5%, 21.7% and 20.1% for materials A, B, and C respectively (see Figure 1). The strength-elongation curves in Figure 2 shows that long natural ageing (material A) shifts the curves to the upper right of the diagram and gives higher elongation for the same strength. The second best result was obtained using the stabilising ageing (material C). It is worth mentioning that this ranking is valid for all three tested ageing temperatures: 165°C, 185°C and 205°C. Figure 3 shows that the elongation is independent of the ageing temperature at peak ageing.

#### 3.2 Microstructure Evolution during Ageing

Figures 4, 5 and 6 show the evolution of precipitates in materials A and C during ageing at 185°C for 0.5, 2 and 8 hours respectively. All of the images were taken with the electron beam parallel to one of the <100> directions of the AI matrix. This orientation has been reported [3] to be the best viewing direction for examination of the needle-shaped  $\beta$ " precipitates that are known [3, 4] to be largely responsible for the peak hardening in AI-Mg-Si alloys. Precipitates become increasingly visible from 0.5 hour to 8 hours of ageing. In material C, the presence of precipitates after 0.5h ageing is revealed by the occurrence of small dots [4] (indicated by arrows) in Figure 4b. Such contrast is hardly visible in Figure 4a showing the microstructure of material A after the same ageing time. In Figure 5, after 2 hours ageing, needle-shaped precipitates identified by selected area diffraction patterns (SADP) to be  $\beta$ " [3, 4, 5] are nearly visible. At this stage, the difference in microstructure

between the two materials is not very pronounced. On the other hand, after 8 hours ageing (Figure 6) the length of precipitates is much larger in material C than in material A (56nm versus 38nm).

A close examination of the cross-sections of the precipitates revealed the presence of two different precipitate morphologies. After 2 hours ageing all the cross-sections of the precipitates are circular, which is consistent with the presence of  $\beta$ " precipitates. However, after 8 hours ageing, a significant portion of oval-shaped cross-sections is observed in both materials. In material C the precipitates with the oval-shaped cross-sections account for 75% of all the precipitates, whereas in material A only 53% of the precipitates have oval cross-sections. According to an investigation by Marioara [3] the precipitates with the oval cross-sections are probably ribbon-shaped  $\beta$ ' precipitates. The diffraction patterns of the  $\beta$ " and  $\beta$  precipitates were proved to be difficult to differentiate [3]. Also, no difference in the average length of the two types of precipitates could be observed.



#### 4. Discussions

## Figure 1: Uniaxial elongation as a function of ageing time at (a)185°C and (b) 205 °C.

The positive effects of long natural ageing and stabilising ageing, observed in this study, can probably be explained by the differences in microstructure (Figures 4-6) among the three pre-ageing conditions. Earlier studies [5, 6, 7] have shown that solute atom clusters start to form in Al-Mg-Si alloys immediately after solution treatment. These clusters transform with time to GP zones which have solvus temperature well above the quenchbath and ageing temperatures for many Al-Mg-Si alloys [8]. As a result, GP zones can be formed easily at room temperature or at 80°C.

The average size of GP zones increases with the pre-ageing time (natural or stabilising ageing) [9], making them more resistant to a possible dissolution during the subsequent artificial ageing at high temperature. The longer the natural ageing time, the higher the number of clusters/GP zones that will pass the critical size to become stable for certain artificial ageing temperatures. It was also suggested [7, 8] that these stable GP zones, formed during pre-ageing, can act as the nuclei for subsequent precipitate phases to be formed during artificial ageing.

4.1 Effect of Pre-Ageing Conditions

In the present investigation different pre-ageing conditions lead to different amounts and different sizes of such nuclei at the beginning of artificial ageing. Obviously, long time natural ageing gives the highest number of small GP zones while the stabilising ageing results in a smaller amount of GP zones with larger sizes. This statement is supported by the TEM observations revealing a higher amount of visible precipitates in material C than in material A after 0.5 h of ageing at 185°C which implies larger size of the GP zones in this material before artificial ageing. Fine and densely distributed precipitates increase more effectively the strength as well as the toughness of the material. This is probably why long natural ageing has the best combination of elongation and strength.



#### 4.2 Effect of Ageing Time



Figure 3: Uniaxial elongation as a function of ageing temperature.

The elongation of AA 6063 decreases with increasing ageing time (up to peak ageing) at all of the three tested ageing temperatures. After peak ageing the elongation remains nearly constant or even shows some increase (Figure 1). The sharp drop of the elongation in the beginning of ageing is probably due to the rapid growth of the coherent GP zones created during pre-ageing and also perhaps due to the nucleation and growth of the new zones.

According to TEM investigations after 0.5 h of ageing at 185°C the precipitates are still very small and spherical which could be a sign of their coherency with the matrix. Such small precipitates impede movement of dislocations that can pass them by shearing. Later on semi-coherent or incoherent precipitates (such as  $\beta$ " and  $\beta$ ) start to form. The resistance to dislocation movement offered by the coherent precipitates is then replaced by the resistance of semi- or incoherent precipitates and increases accordingly. While the precipitates grow larger it becomes more difficult for dislocations to pass them by shearing. Instead they will by-pass the precipitates through a different mechanism called Orowan looping.

Kelly and Nicholson [10] showed that the transition point between shearing and Orowan looping in the dislocation-precipitate interaction process is associated with a certain critical precipitate size and inter-precipitate spacing. This point often corresponds to the peak age hardening of the alloy. Thus, according to this model, shearing of precipitates by dislocations should be the dominant mechanism up to the peak ageing while by-passing is dominant for the over-aged materials. However, recently Donnadieu et al [11] showed that

Orowan by-passing may become an important interaction mechanism in an AI-Mg-Si alloy AA6061 even before peak ageing is reached.

The precipitation reaction during over-ageing is nevertheless dominated by the coarsening of precipitates. While the precipitates' volume fraction is almost constant, their interspacing becomes larger. This makes the dislocation movement easier which may explain the increase of elongation after prolonged ageing a t 205°C (Figure 1b).



Figure 4 Microstructure of (a) material A and (b) material C after 0.5 hour ageing at 185°C, small dots indicated by arrows reveal the existence of small spherical precipitates



Figure 5 Microstructure of (a) material A and (b) material C after 2 hours ageing at 185°C, note that the faint visible in both SADPs.



Figure 6 Microstructure of (a) material A and (b) material C after 8 hours ageing at 185°C, note that the faint visible in both SADPs.

#### 4.3 Effect of Ageing Temperature

The effect of ageing temperature on elongation is illustrated in Figure 3. It shows that for the same ageing time the elongation decreases with increasing ageing temperature. This is valid until peak ageing is reached. At peak ageing the elongation is nearly independent of the ageing temperature. Moreover, the rate of elongation drop is the most drastic within the first 0.5h of ageing at all tested ageing temperatures. The relatively lower initial elongation drop for materials A and C than for material B is a consequence of the short natural ageing time of material B which produces a material almost free from precipitates i.e. with the highest supersaturation of solute atoms prior to the artificial ageing.

The effect of ageing temperature on elongation is closely related to the diffusion rate of the solute atoms which is higher at higher temperatures. Faster diffusion gives a faster course of events during the precipitation process at higher temperatures and therefore faster elongation drop during the initial stages of precipitation. An interesting feature shown in Figure 3 is that the elongation value of the same material at peak ageing is nearly independent of ageing temperature.) Such an observation of a constant elongation value at the peak ageing is not well understood at the moment and deserves further investigation. On the other hand, the higher strength at lower ageing temperature can be easily explained in terms of finer and denser distribution of precipitates. This is due to the lower diffusivity of the solute atoms and higher driving force for precipitation, even though the volume fraction of precipitates at the peak ageing is similar for all temperatures.

### 5. Conclusions

Long natural ageing preceding artificial ageing has positive effects on both the strength and formability of AA 6063 at tested ageing temperatures. At the same pre-ageing condition, formability decreases with increasing ageing time and ageing temperature until peak ageing is reached. At the peak ageing, the formability of the same material is independent of the ageing temperature. The mechanical properties of the materials are closely related to their microstructure. A good combination of strength and formability is associated with a high density of finely distributed small coherent precipitates. At the peak ageing (for materials aged at 185°C) two types of precipitates,  $\beta$ '' and  $\beta$ ' were found using TEM.

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