Estimation and correlation of strengthening components to the evolution of microstructure following cold work and artificial aging in AA6111 aluminium

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ABSTRACT
In this study, the contributions of the various strengthening components following the application of cold work and precipitation in AA6111 has been evaluated and correlated by means of tensile testing and transmission electron microscopy (TEM). The results show a considerable improvement in yield and tensile strength with increasing level of cold work. The component of strength developed from cold work and precipitation respectively increases with increasing level of cold work. The recovery strength (softening) also increases with increasing level of cold work. TEM showed a strong interaction of strengthening precipitates with dislocations. The density of dislocation tangles is shown to increase with increasing degree of cold work.

1. INTRODUCTION
In the automotive industry, the use of aluminum alloys has increased over the years as manufacturers strive to design lighter vehicles as part of an overall goal to meet the North American Corporate Average Fuel Efficiency (C.A.F.E) Standards. These standards seek to improve fuel efficiencies and reduce vehicular emissions into the atmosphere while meeting governmental and international targets set in regulations such as the Kyoto Protocol. Heat treatable AA6111 has emerged as one of the most prominent materials employed in outer body panels of cars and light trucks.

There has always been the desire to have some way of estimating the yield strength of a part following forming and/or heat treatment operations. For a formed and painted automobile panel, the yield strength involves combining strength components arising from cold work, strain aging, precipitation, and recovery. The challenge over the years has been to find a method of quantifying each of these strengthening components. The conflicting demand of low yield strength alloy and high yield strength components in the 6xxx series alloys containing Cu are partially addressed through the aging response promoted through the automotive paint bake cycle. Unfortunately, only a small fraction of the full aging potential inherent in the alloy is exploited due to the relatively low temperatures as well as short duration of most commercial paint bake cycles. The need for rapid strengthening response in today’s finishing lines has led researchers to impose thermo-mechanical process histories along with variation in alloy compositions on 6xxx series aluminum alloys with the view to improving the strengthening characteristics as well as kinetics of these alloys [1-5]. In the present investigation, the contributions of the various strengthening components following the application of cold work and artificial aging in AA6111 has been
evaluated with a view to estimating the overall yield strength of a formed part under the paint bake cycle of the alloy.

2. EXPERIMENTAL PROCEDURE
Tensile test specimens of 1mm sheet AA611 (composition in wt % 0.8Mg, 0.6Si, 0.7Cu, 0.25Fe, 0.2Mn, 0.05Cr, 0.06Ti, and balance Al) were machined according to the ASTM E-8 standard and solution heat treated (SHT) at 560°C for 30 minutes in an air furnace and rapidly quenched in 20°C water. The samples were then kept at room temperature for two hours to stabilize them after which some were given 2%, 5% or 10% cold work by stretching and then artificially aged at 180°C for various lengths of time followed by tensile testing measure the yield stress. Samples of AA6111 aluminum at the simulated paint bake cycle of 180°C for 30 minutes as well as overaged samples strained to various levels were examined in a Hitachi 2200 FE STEM at 200kV.

3. RESULTS AND DISCUSSION
Figure 1 (a) shows the variation of yield strength as a function of aging time at 180°C for various levels of cold work. It can be observed that as the aging time increases at each level of cold work, the yield strength values increase up to a peak value after which they decrease with further aging time. The significant increase in yield strength is attributed to the increase in dislocation density, due to cold work, piling up to form tangles and hence increasing the strength of the material [6,7]. The time to attain peak strength for all levels of cold work occurred after about 10 hours of aging.

Figure 1: (a) Variation of yield strength with aging time at various levels of cold work on AA6111, (b) change in yield strength following SHT (σ − σ_{ss0}) versus aging time for various levels of cold work on AA611

3.1 Quantifying the Strengthening Components
Aluminium alloys such as AA6111 strain harden quite rapidly during the forming process, and, for a highly strained panel the yield strength can almost double. However, the increased strength due to forming will recover, and hence soften to some extent due to exposure to the elevated temperatures associated with the paint bake. As such, the strength of the final part is the net effect of cold work, precipitation and recovery. Figure 1 data was used in quantifying the contribution of strength components for cold work, precipitation and recovery under the paint bake temperature. Let us designate σ_y as the net yield stress, σ_{ss0} as the initial strength of the material after solution heat treatment, σ_{cw} as the strength due to cold work, σ_{ppt} as the strength component due to precipitation, and σ_{rec} as the component resulting from recovery. To estimate the strength component following cold work, the yield strength values were normalized with the strength following solution heat treatment σ_{ss0}. Figure 1(b) presents the change in yield strength following SHT, (σ − σ_{ss0}) versus aging time for various levels of cold work at 180°C. The contribution of
strength components for 2%, 5% and 10% cold work ($\sigma_{cw}$), were respectively 56.2MPa, 98.2MPa and 141.6MPa, showing an increase in strength due to the level of cold work.

![Graph](image1)

**Figure 2:** (a) Variation of ($\sigma - \sigma_{cw}$) with aging time at 180°C (b) Variation of Recovery strength with aging time at 180°C.

For strength components due to precipitation and recovery ($\sigma_{ppt}$ & $\sigma_{rec}$), the change in flow stress with yield strength of the cold worked sample prior to artificial aging, ($\sigma - \sigma_{cw}$) at 180 °C was used. Figures 2(a) presents the variation of ($\sigma - \sigma_{cw}$) with aging time at 180°C. Cold work is known to affect the precipitation process in two ways: (1) heterogeneous nucleation can occur on dislocations [8] and (2) the growth and/or coarsening rate of precipitates on dislocations can be accelerated as a result of dislocation core diffusion [9]. Figure 2(a) shows that there is a decrease in the ($\sigma - \sigma_{cw}$) flow stress values with increasing levels of cold work. This decrease is a result of recovery, a softening process, occurring at elevated temperatures. The difference between the ($\sigma - \sigma_{cw}$) flow stress values of the unstrained sample and those for the various levels of cold work gives an indication of the amount of recovery experienced in the material at the various levels of cold work at 180°C and attributed to the effect of dislocation core diffusion [9], the results of which are presented in Figure 2(b). A close look at the graph shows an increase in recovery with increasing level of cold work at 180°C. Under the paint bake condition of 180°C for 0.5 h, it can be observed that the level of recovery experienced by the material is minimal, indicating that the material retains a good amount of its strength under this condition. Figures 3(a) and (b) show the bright field TEM micrographs of AA6111 samples given 0 and 2% cold work, respectively, following the simulated paint bake cycle. It can be observed in Figure 3(a) that the unstrained sample consists mainly of widely spaced helical dislocations, which are pinned by solute clusters that formed after quenching. Figure 3 (b), on the other hand, shows substantial increase in

![Graph](image2)

![Micrograph](image3)

**Figure 3:** Bright field TEM micrographs of AA6111 samples subjected to the simulated paint bake cycle following (a) 0% cold work and (b) 2% cold work.

dislocation density with increasing level of cold work, thus confirming that the increase in
strength of cold worked material is due, in part, to the increased amount of dislocation tangles in addition to precipitates. A closer look at the strained sample again reveals dotted spots in the microstructure which are believed to be needle heads of strengthening precipitate particles. To establish the link between the strength properties of the alloy along with the phases responsible for them, an unstrained sample and a 10% cold worked sample were heavily overaged at 315°C for 2 hrs and TEM analysis done. Figures 4 (a) and (b) show the bright field TEM micrographs of heavily overaged samples of 0% and the 10% cold work respectively. Figure 4(a) shows that the unstrained sample comprises precipitates distributed randomly in the matrix. Figure 4 (b) on the other hand shows precipitates formed in a regular pattern, believed to be previous lines of dislocation generated by cold working. This shows that the increase in strength of the cold worked sample is due, in part, to increased amount of dislocations serving as high energy sites for the nucleation of precipitate phases. As well, the dislocations enhance the diffusion rates due to pipe diffusion by increasing the rate of solute diffusion through short circuit diffusion paths.

Figures 4 (a) and (b) show the bright field TEM micrographs of overaged samples at 0% and the 10% cold work respectively.

4. CONCLUSION
The overall strength of pre-strained and aged samples of AA6111 aluminum alloys can be estimated by determining and assembling the various strength components from their precipitation profiles. The component of strength developed from cold work increases with increasing level of cold work. The strength due to precipitation decreases with increasing level of cold work, the loss in strength is attributed softening in the alloy at the paint bake temperature. The loss of strength due to recovery also increases with increasing level of cold work.

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