Modelling of the Pre-Strain Dependent Age Hardening Response in AA6000 Series Aluminium Alloys

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Abstract. The usual application of AA6000 series aluminium alloys in the automotive industry consists of forming the material in a soft T4 temper and applying a post-forming heat treatment, artificially ageing the material to achieve a higher final component strength. The strengthening response of a given AA6000 alloy has been found to depend on the heat treatment parameters as well as the amount of plastic deformation the material has undergone during the forming process. As a consequence, an inhomogeneous distribution of mechanical properties occurs over the finished component. In this work, a method of modelling the pre-strain dependant age hardening response of the material to be used in finite element simulations on the component level is presented. A microstructural model of the precipitation process has been applied to predict the material properties after age hardening as a function of the thermal exposure as well as the accumulated plastic deformation in the material. The results of the microstructural model are then implemented into a finite element analysis to determine the behaviour of components produced in this manner under high levels of plastic deformation (e.g. automotive crash simulation). Initial validation of the method is carried out on the example of a uniaxial tensile test; final validation is conducted using top–hat type tubes under axial crushing.

1. Introduction
Heat treatable AA6000 series aluminium alloys can provide a significant advantage in component manufacture and design over non heat treatable aluminium alloys in that they can be formed in a ductile, soft condition and later on heat treated to achieve the required mechanical strength [1]. This is a further advantage if the heat treatment is already an integral part of the product manufacturing process, as for example in automotive body-in-white production, where the assembled and painted car body undergoes thermal treatment to cure the paint.

There are, however, challenges associated with designing parts that take advantage of the age hardening capabilities of these materials. The level of strength increase during the heat treatment process is dependent on several factors, one of which is the amount of plastic deformation accumulated in the material from previous forming operations [2]. This in turn means that the heat treatment changes the mechanical properties of the material in a non-uniform manner. Since finite element simulation is an integral part of many design processes, there is a clear need for a mathematical description of this effect and an implementation into a finite element model.
In this work, an approach for modelling the non-uniform material strength distribution across a formed and heat-treated component, taking into account the effects of deformation from previous process stages, is presented. A constitutive model extension has been developed in the form of an extended hardening law and implemented into a commercial finite element modelling software package.

2. Age-hardening of AA6000 series aluminium alloys
A typical age hardenable AA6000 series aluminium alloy contains specific levels of Si, Mg and sometimes Cu which, with proper processing, create a microstructure that enables a strength increase of the material through time and heat treatment. In aluminium processing, the process of strengthening is called age hardening or simply ageing. If ageing occurs at ambient temperature it is called natural ageing and if it is conducted at elevated temperatures it is called artificial ageing [3].

A typical age hardenable alloy is produced by ingot casting, hot rolling and cold rolling as any other aluminium sheet metal. Following the rolling process, a heat treatment step called solutionizing is carried out on the sheet. In this step, the material is heated to a temperature close to the solidus line (~540-570°C) and then quenched to ambient temperature. The heating step anneals the material and dissolves the soluble alloying element into solid solution. The quenching then subsequently freezes the dissolved elements into the aluminium matrix, so that they can form precipitates later on in the ageing process.

The age hardening process in AA6000 series alloys consists of precipitation of the dissolved alloying elements out of solid solution to form precipitates. The formed precipitates present obstacles to dislocation movement, inhibiting the dislocation from freely propagating through the crystal lattice, thus resulting in an overall increase in material strength on the macroscopic level.

The rate and density of precipitate formation is strongly dependant on the ageing temperature as well as on other aspects of the materials microstructure. If the material is plastically deformed prior to ageing, the resulting dislocations act as nucleation sites for precipitate formation. Moreover, dislocation accelerate the growth of the precipitates by providing faster diffusion of the solute elements through the dislocation. Therefore, for a given ageing time and temperature, plastic deformation in the material increases the final strength achieved after ageing.

3. FEA implementation of pre-strain dependence
To account for the change in material strength after artificial ageing, the hardening law of the constitutive model is defined as a 3 dimensional flow surface where the effective flow stress of the material is a function of the current effective plastic strain ($\varepsilon_{pl}$) and the accumulated effective plastic strain from the previous forming steps ($\varepsilon_{PRE}$), denoted here as pre-strain (equation 1).

$$\sigma_f = f(\varepsilon_{pl}, \varepsilon_{PRE})$$

A flow rule of this sort is implemented into the finite element simulation on an integration point level, as shown on Figure 1 below. In the current implementation, the 3 dimensional flow surface is input as a discrete (i.e. tabulated) function with linear interpolation between the values.

![Figure 1. Schematic implementation of the pre-strain dependence into a simulation process.](image-url)
After the final forming simulation step, the effective plastic strains for each integration point are written into a history variable as pre-strain. At the start of the performance simulation, the pre-strain is initialized and the post-ageing material model is invoked. This effectively prescribes a unique yield stress and hardening curve to each integration point, which is then used in the performance simulation.

4. Flow surface characterization and validation
To measure the necessary material hardening data, a multi-step tensile test, combined with an artificial ageing heat treatment, was carried out. The validation of the constitutive model was then carried out on a numerical simulation of this same testing procedure. A representative AA6000 series alloy sheet was used in all investigations, with a thickness of 2.5 mm.

4.1. Tensile testing
The testing procedure was designed to emulate a real-life use case for an age-hardenable AA6000 series aluminium alloy. The material was solution heat treated, pre-strained, artificially aged and then tested to determine its material properties in the in-service condition, as outlined on Figure 2. Pre-strain levels were chosen such that no localized necking was apparent on the samples at the highest pre-strain level.

![Figure 2. Tensile testing procedure for pre-strain effects characterization.](image)

The ISO 6892-1 norm was followed as closely as possible in all tensile testing; 5 samples per condition were tested and the gauge used length was 50 mm. Only deviation from the standard was in stopping the measurement before failure to achieve pre-strain. An extended Voce fit (equation 2) [4] was used to extrapolate the results to high strains for use in a hardening law. The extended Voce fit was found to describe the behaviour of aluminium alloys well [5].

\[
\sigma_{\text{f,PRE}}(\varepsilon^{\text{pl}}) = A + (B + K \cdot \varepsilon^{\text{pl}})^c \left[1 - \exp\left(-c/B \cdot \varepsilon^{\text{pl}}\right)\right]
\]  

(2)

The resulting flow surface is shown on Figure 3 below. The effect of pre-strain is significantly stronger at lower levels of strain it is than in the saturated linear region. Initial yield stress of the material increases by approximately 45 MPa at 12% pre-strain when compared to no pre-strain, versus an increase of approximately 10 MPa in the saturated linear region.

![Figure 3. Measured and extrapolated pre-strain dependant flow surface.](image)
4.2. Tensile test simulation

All simulations were carried out using a developer version of the commercial finite element software LS-DYNA. To re-create the physical testing outlined above in a numerical model, a multi-step simulation workflow was created, as represented on Figure 4:

![Figure 4. Tensile test simulation procedure for pre-strain validation.](image)

The model used for the tensile test simulation is shown on Figure 5. Quarter symmetry was utilized and fully integrated quadrilateral shell elements with a characteristic edge length in the reduced section of 0.625 mm were used.

![Figure 5. Finite element model of the tensile test.](image)

A Barlat 89 [6] yield locus was used in conjunction with the pre-strain dependent hardening law. The material input data for the age-hardened flow surface was derived from the measured tensile test data after pre-straining as described in Section 4.1.

4.3. Tensile test validation results

Figure 6 shows the resulting engineering stress-strain curves, both for the physical testing as well as the numerical simulation. One representative curve from the 5 repeats of the physical test is shown here for clarity.

![Figure 6. Tensile testing and simulation results.](image)

Results of the physical testing (solid lines) clearly show the effect of pre-strain on the level of strengthening achieved during the artificial ageing process. The yield stress increases considerably from
approximately 210 MPa with no pre-strain, to over 255 MPa at 12 % pre-strain. Also of note is the significant reduction in ductility of the material.

The simulation results (dashed lines) correlate well to the physical tests. The constitutive model is able to accurately reproduce the stress-strain response in simple uniaxial tension, at least up to the onset of localized necking, and is consistent with the input data. The non-physical softening post necking is an artefact of the shell element formulation and is not the subject of the present work.

5. Axial crush
As a more complex validation case on the component level, a quasi-static axial crush test of a top-hat type tube was carried out. Three material states, listed in Table 1, are considered to evaluate the performance of the material model.

| Sample | Temperature (°C) | Hold time |
|--------|------------------|-----------|
| T4     | /                | /         |
| PB     | 180              | 20 min    |
| T6     | 180              | 10 hours  |

5.1. Physical testing
The tube geometry and test set-up are shown on Figures 7 and 8 respectively. The tubes consist of a channel produced by bending a flat sheet and a flat bottom plate bolted to the channel.

The tubes were fabricated by press-break bending a sheet of material in the as produced, T4 condition into the specified channel geometry, then the bottom plate was attached using bolts through pre-drilled holes. Tubes prepared in this manner were then heat-treated as specified. To ensure consistent buckling behavior, a buckling initiator was added to the top of the tube by manually bending the top, bottom and sides. The bends run up to approximately 25 mm from the top edge of the tube and are approximately 5 mm deep at the edge. The top and bottom are bent downwards and the sides outwards. The test were conducted in an instrumented hydraulic press at a constant cross-head velocity of 10 mm/s.
5.2. Simulation
The model is constructed with assumed strain thick shell elements [7], two layers were used through the thickness to maintain a reasonable aspect ratio. The in-plane element size was approximately 2 x 2 mm and half symmetry was applied to save computational time. The material model used was as described in Section 4.2. All tube preparation steps were followed closely in the simulation procedure (Figure 9).

![Diagram of simulation procedure]

**Figure 9.** Simulation procedure for the axial crush test.

Channel bending was carried out using rigid tools to introduce the two necessary bends into a flat plate and create the pre-strain. The channel was then joined to the bottom plate using beam elements with a pre-load to achieve the desired contact pressure. A penalty contact with a constant coefficient of friction was used between the two parts. The bend initiators where then formed at one end of the channel using rigid tools, followed by a dynamic relaxation springback step. The channel after forming and springback is shown on Figure 10. As with the tensile test simulations, the material model was changed for the axial crush simulation to emulate the desired material state after ageing. Finally, the axial loading simulation was carried out using a rigid plate with a prescribed constant velocity.

![Image of top-hat tube model]

**Figure 10.** Top-hat tube model after bending, joining and bend initiator forming.

5.3. Results
Basic results of the axial load tests and simulations are summarized in Table 2.

| Sample | Peak load (kN) | Average load (kN) | Total absorbed energy (kJ) |
|--------|----------------|-------------------|---------------------------|
| Test   | Simulation     | Test              | Simulation               | Test          | Simulation |
| T4     | 94.3           | 104.6             | 43.5                      | 38.4          | 7.9        | 7.0        |
| PB     | 101.1          | 110.4             | 46.1                      | 43.4          | 8.3        | 7.9        |
| T6     | 133.9          | 152.4             | 55.5                      | 55.3          | 10.6       | 10.2       |
The simulations somewhat over-predict the initial peak load for all cases, while under-predicting the average load and total absorbed energy for the T4 and paint bake (PB) material conditions. The effects of material strengthening are clearly visible on the force-displacement and the energy absorption diagrams (Figures 11 and 12 respectively). The solid lines represent the test results and dashed lines the simulations.

**Figure 11.** Force-displacement response during axial crush for all material states, test vs simulation.

**Figure 12.** Energy absorption during axial crush curve for all material states, test vs simulation.

While the model is adequately accurate for the peak aged T6 condition, the T4 and PB conditions show poorer agreement with the test, under-predicting both the forces as well as the energy absorption. What is more, the difference between the T4 and PB conditions is over-estimated by the model. These two observations could possibly be attributed to some amount of natural ageing of the samples that has not been accounted for while calibrating the constitutive model as this would both increase the initial strength of the material as well as decrease the strength increase during ageing.

The initial peak load in the simulations, while being an important aspect of the axial crush test in practical terms, it is also significantly geometry dependent [8]. The initial peak could possibly be
affected by the geometry of the bend initiator, random perturbations in the physical samples that are not present in the simulations or inaccuracies in determining the initial yield point of the material.

It is also worth noting that the buckling behavior of the simulations is somewhat different to the experimental results, which can be seen on Figure 11 as well as below on Figure 13, showing the crush tube geometry at the end of the test vs. end of simulation. Notably, the buckling frequency is somewhat higher, resulting in one more fold initiating on the final geometry.

Figure 13. Comparison of fold geometry after crush for the three material states a.) T4, b.) Paint bake and c.) T6.

6. Conclusions and discussion
The results presented in this work clearly demonstrate the importance of accurately describing the age hardening process and its effects on the mechanical properties of the material in finite element simulations. The constitutive model presented here can accurately capture the effects of pre-strain on the strengthening response of the material during artificial ageing, as was shown with the tensile test validation case.

The axial crush case study demonstrates how such a simulation workflow, including the artificial ageing aspect, could be implemented into the performance evaluation of components made from age-hardened AA6000 series aluminium alloys. The experimentally observed trends in loads and energy absorption during crushing were captured well, even if a high level of accuracy was not achieved in absolute terms.

The top-hat tube example presented here was chosen for its simplicity, but is perhaps not the ideal demonstrator for this kind of material model. Firstly, the amount of plastically deformed material in the tube is quite limited, confined only to the bent portions of the channel. A more complex part produced by deep drawing would likely show significantly more influence. And secondly, the buckling behaviour is in itself difficult to accurately reproduce, possibly masking the contribution of the material model through other influences as discussed previously in Section 5.3.

In future work, the effects of the time-temperature exposure history of the material during heat treatment should be considered and the model expanded to account for such phenomena.

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