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Study of Precipitation and Recovery Kinetics in a 6xxx Automotive Sheet Alloy

A.K. Gupta, C. Doutre, D.J. Lloyd

Alcan International Limited, Kingston Research and Development Centre
P.O. Box 8400, Kingston, ON K7L 5L9 CANADA

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Abstract

Aluminum sheet are increasingly used in the automotive industry to produce fuel efficient vehicles, it is necessary to have the ability to predict the final strength of a finished panel so that the right sheet gauge can be determined early in the design stage. This way it becomes easy to establish the maximum possible weight reduction, and realize the cost of manufacturing associated with aluminum panels with respect to steel panels. The final strength of a finished body panel is the net effect of three competing processes involving strain hardening, precipitation hardening and thermal recovery. The YS of a formed and painted part is determined experimentally using time-consuming and oversimplified simulations of the complex forming and multiple cycle paint cure operations. In this study, simple models to predict the final strength of the finished panel stamped from a 6xxx sheet alloy have been developed, and the strength predictions are confirmed with the measured values from a liftgate assembly.

1. Introduction

The dent resistance of a formed and painted outer body panel depends on many factors that are related to material parameters like strength, part geometry and its proximity to the support, the characteristics of the impacting object, and the rate of loading[1-2]. For aluminum body panels, the dent resistance is related inversely to the thickness of the sheet and directly to its yield strength (YS). The ability to predict the YS of a finished panel is the key to determine the right sheet gauge while assuring that the maximum weight reduction and the consequent fuel savings are realized. The YS of a formed and painted part is determined experimentally using time-consuming and oversimplified simulations of the complex forming and curing operations, however, for the most part, these simulations give a reasonable estimate of the strength of the finished part. The prediction of the YS of a formed and painted panel stamped from AA6111 sheet material has been successfully modeled previously[3]. Likewise, in this study, models have been developed for panels stamped from a 6xxx sheet alloy. Previous approaches used to develop a model have been simplified and the YS predictions of the models confirmed with measured values from a liftgate assembly stamped from a 6xxx sheet material.

2. The Material, Heat Treatments and Testing

A DC cast ingot of a 6xxx alloy containing Cu, Mg, Si, Fe and Mn was homogenized and hot and cold rolled to the final 1 mm gauge and solutionized at > 530°C in a continuous annealing and solution heat treatment line. Tensile specimens were prepared from this material and the ageing treatments were carried out in a laboratory furnace equipped with programmable temperature controllers. Some of the tensile samples were strained in a tensile machine by 5, 10 and 15% before ageing at 180°C. Tensile properties were determined in the transverse direction from triplicate specimens using a standard ASTM specimen with a crosshead speed of 2.54 mm/min to 0.025 strain followed by 12.7 mm/min to failure. Duplicate samples were used in the recovery study.

3. Modeling of a Formed and Painted Panel

The final strength of a formed and painted body panel is the result of three competing processes including strain hardening, precipitation hardening and thermal recovery. The flow stress, σ_{ij}, for any region of a formed part subjected to a given prestrain (ε_{ij}) and paint cure operation can be represented by the expression

$$\sigma_{ij}\ (\varepsilon_{ij}) = \sigma_i + \Delta\sigma_{S(,\varepsilon_{ij})} + \Delta\sigma_{P(t_i,T_,,\varepsilon_{ij})} - \Delta\sigma_{R(t_i,T_,,\varepsilon_{ij})} \qquad (1)$$

where σ_i and $\Delta\sigma_{S(\varepsilon ij)}$ are the initial strength and strain hardening components of the flow stress σ_{ij}, while $\Delta\sigma_{P\,(ti,\,Ti,\,\varepsilon ij)}$ and $\Delta\sigma_{R(ti,\,Ti,\,\varepsilon ij)}$ are the precipitation and recovery components for various strains following the cumulative exposure to different thermal cycles. The strain-hardening component, which usually varies significantly from one region to the other, can be predicted by finite element modelling. However, the strength components from precipitation and recovery cannot be predicted until appropriate models are developed from the experimental data. For uniaxial tensile deformation, the expression for the flow stress, σ_F, is reduced to

$$\sigma_F = \sigma_i + \Delta\sigma_{S(\varepsilon_i)} + \Delta\sigma_{P(t_i,T_,)} - \Delta\sigma_{R(t_i,T_,,\varepsilon_i)} \qquad (2)$$

The flow stress due to strain hardening, precipitation hardening and recovery is alloy dependent and can be determined as described in the following sections.

3.1 Strain Hardening

Figure 1 shows a typical true stress vs. true strain (σ vs. ε) plot of a 6xxx sheet material. The plastic deformation behavior in most aluminum alloys can be expressed by the modified Voce equation of the following type

$$\sigma = \sigma_s\left\{1-\left[\left(1-\frac{\sigma_i}{\sigma_s}\right)^{1-k} - \frac{\theta_0(1-k)(\varepsilon-\varepsilon_0)}{\sigma_s}\right]^{\frac{1}{1-k}}\right\} \qquad (3)$$

and

$$\sigma_e = \frac{\sigma}{(1+\varepsilon_e)} \qquad (4)$$

where σ_s is a saturation stress, σ_i is the yield strength, θ_o is the initial hardening rate, k is a constant, ε_o is the elastic plastic boundary strain, σ_e is the engineering stress and ε_e is the engineering strain. The true stress true strain plot in Figure 1 for a 6xxx material fits very well with equation (3) and an initial YS of ~ 122 MPa, with values of 386 MPa, 4795 MPa, and 1.9 for σ_s, $\theta_{o,}$ and k, respectively. The engineering stress can be calculated from true stress values for a given engineering strain using equation (4).

3.2 Precipitation Hardening Kinetics

3.2.1 Isothermal Ageing

Figure 2 shows the ageing curves of a 6xxx alloy at 100, 140, 160, 180 and 200°C. The alloy with an initial YS of ~ 122 MPa begins to strengthen almost immediately at ≥ 100°C ageing temperatures and acquires a peak value of ~ 280 MPa in 48 h @ 160°C. It is believed that the strengthening in this alloy is caused by the formation of the metastable precursors of equilibrium Mg_2Si and quaternary AlCuMgSi- Q phase.

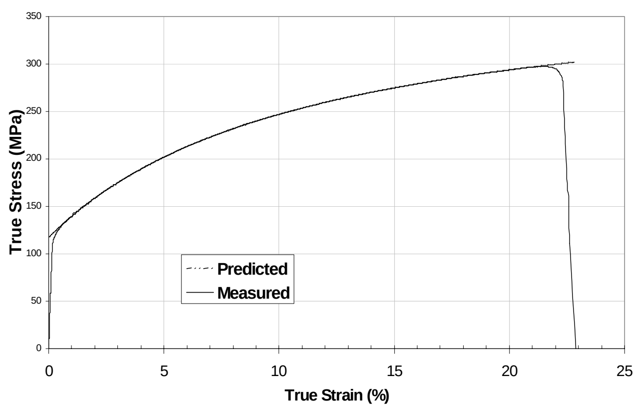

Figure 1: Measured and predicted true stress vs strain curves of a 6xxx sheet alloy in the transverse direction.

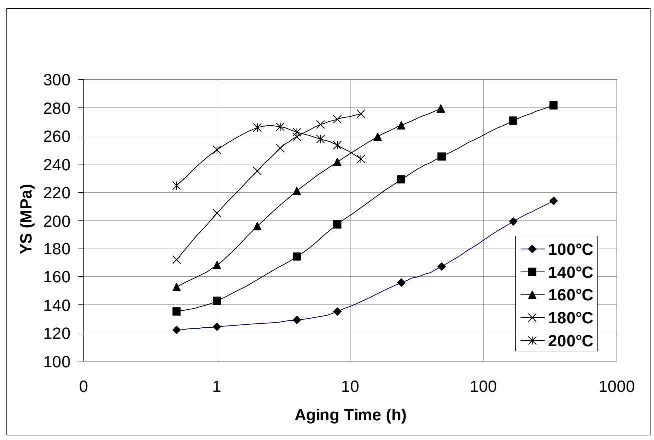

Figure 2: Ageing curves of a 6xxx sheet alloy.

Precipitation reactions in aluminum alloys are diffusion controlled and proceed by the process of nucleation and growth. For isothermal heat treatment, the reaction rate can be expressed by the following equations (4):

$$\frac{dY}{dt} = f(Y)k \tag{5}$$

$$k = k_0 \exp\left(-\frac{Q}{RT}\right) \tag{6}$$

where Y is the fraction transformed, f(Y) is a certain function of Y, k is the rate constant, k_0 is the pre exponential factor, Q is the activation energy, R is the gas constant, T is the absolute temperature and n is a numerical exponent. It is possible to deduce from equations (5) and (6):

$$\int_0^Y \frac{dY}{f(Y)} = \int_0^t k_0 \exp\left\{-\frac{Q}{RT}\right\} dt \tag{7}$$

For isothermal reaction,

$$F(Y) = kt, \tag{8}$$

where

$$F(Y) = \int_0^Y \frac{dY}{fY} \tag{9}$$

The function F(Y) can be expressed by the Johnson-Mel-Avrami equation:

$$F(Y) = \left[\ln\left\{\frac{1}{(1-Y)^{1/n}}\right\}\right] \tag{10}$$

Substituting for the function F(Y) from equation (10) into equation (8) and rearranging:

$$\ln \ln\left\{\frac{1}{(1-Y)}\right\} = n \text{ x } (\ln k + \ln t) \tag{11}$$

The value of Y is related to the YS as follows:

$$Y = \frac{(\sigma_t - \sigma_i)}{(\sigma_p - \sigma_i)} \tag{12}$$

where, σ_t is the YS at time t, and σ_p and σ_I are the peak and the initial YS respectively.

Equation (11) was used to establish the kinetics of precipitation a 6xxx alloy, and the values of kinetic parameters n, k_o and Q/R was found to be 0.63, 9.97 x 10^8 and 11397, respectively. The prediction of the YS up to peak strength from the model using equations (11) and (12) was within an average error of 3.3 MPa.

3.2.2 Multiple Cycle Ageing Treatments

The YS of a 6xxx material after multi-cycle ageing can be determined from the precipitation model developed above in the following manner(3):

Step 1 - Calculate the value of Y for the first ageing step using equations (11) and (12).

Step 2 - Determine time needed to obtain Y calculated in step 1 at the second ageing temperature from equations (11) and (12).

Step 3 - Add the desired ageing time at the second temperature to the time determined in step (2).

Step 4 - Calculate the values of Y and YS corresponding to the next ageing treatment by using equations (6), (11) and (12).

In one of the experiments, tensile samples of a 6xxx alloy were subjected to E-coat, primer and clear coat cure cycles, involving ageing typically at 163°C for 30 min, 130°C for 30 min, and 121°C for 24 min, with heating and cooling cycles between each step. The YS of the sample was found to be close to 161 MPa, which was in agreement with the prediction of the model described above. The above analysis is valid only up to peak ageing conditions and in situations where there is no change in basic precipitation mechanism.

3.3 Thermal Recovery Kinetics

The application of prestrains increases the strength of the material, and the contributions from strain hardening due to the inclusion of strains and precipitation hardening are additive. In the absence of recovery, equation (3) becomes:

$$\sigma_F = \sigma_i + \Delta\sigma_{S(\varepsilon_i)} + \Delta\sigma_{P(t_i,T)} \tag{13}$$

The strain and precipitation hardening components, $\Delta\sigma_{S(\varepsilon i)}$ and $\Delta\sigma_{P(ti,\,T)}$, for a given prestain, and ageing condition can be calculated from the strain hardening and precipitation models described in Sections 3.1 and 3.2. Figure 3 shows that the strength difference between the predicted and measured responses is quite significant particularly for longer ageing times. The measured strength is lower than predicted, which is caused by thermal recovery. The loss of strength due to recovery is higher with higher prestrains and ageing times.

The kinetics of recovery can be expressed by a general equation

$$R = 1 - S \times \ln\left(1 + \frac{t}{t_0}\right) \tag{14}$$

where R the fraction of residual hardening, S is dependent on the annealing temperature but assumed to be independent of prestrain, t is the recovery time in seconds and t_o is a relaxation time. The residual hardening can be determined from the underlying data in Figure 3 using the following expression

$$R = \frac{(\sigma_t - \sigma_p)}{(\sigma_s - \sigma_i)} \tag{15}$$

and

$$\Delta R = (1 - R) \times (\sigma_s - \sigma_i) \tag{16}$$

where σ_t is the flow stress after a prestrain and recovery for time t, σ_p is the flow stress due to precipitation in the unstrained specimen after ageing time t, σ_s is the flow stress after a prestrain but before any recovery and ΔR is the recovery during ageing of a prestrained part.

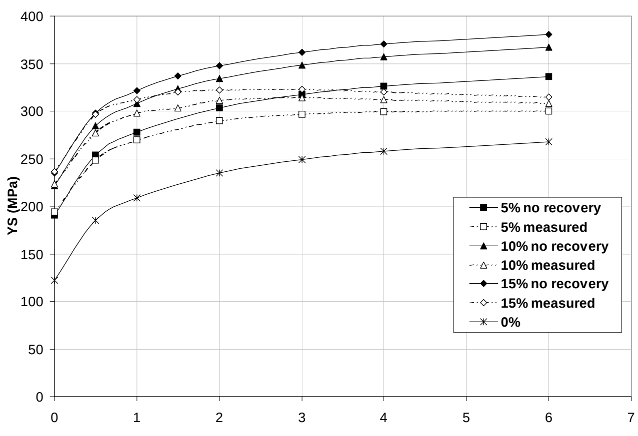

Figure 3: Measured and predicted ageing response of the prestrained 6xxx sheet at 180°C.

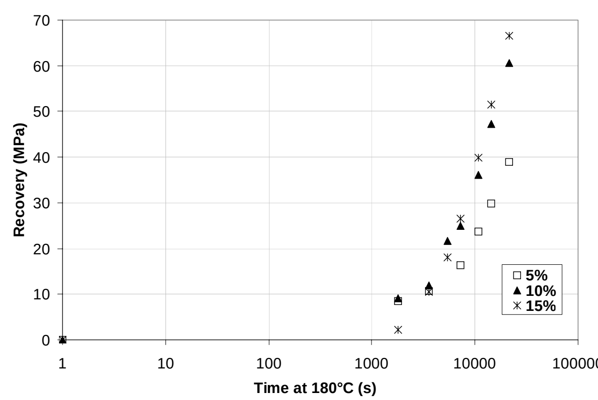

Figure 4: Variation in recovery with time for different strains at 180°C.

The data shown in Figure 3 can be transformed to the extent of recovery, as shown in Figure 4. The same data can also be converted to the fraction of residual hardening and fitted to equation (13) as shown in Figure 5. Equation (14) fits well within an average error of ~ 3 MPa with the experimental data when values of S and t_o are 0.38 and 6910 s, respectively.

A pair of liftgate assemblies stamped with a 6xxx alloy was considered in this study. One of the liftgates was subjected to a simulated E-coat, primer and coloring coat cure process involving ageing at 163°C for 30 min, 130°C for 30 min and 24 min at 121°C, respectively. The heating and cooling operation between each cycle is performed typically at a rate between 10 to 15°C/min. The heating profile during the ageing process was monitored by attaching thermocouples at twelve different locations of the assembly. The recorded thermal profiles from each location are shown in Figure 6, and the tensile properties from each locations were determined from both heat treated and as-received assemblies.

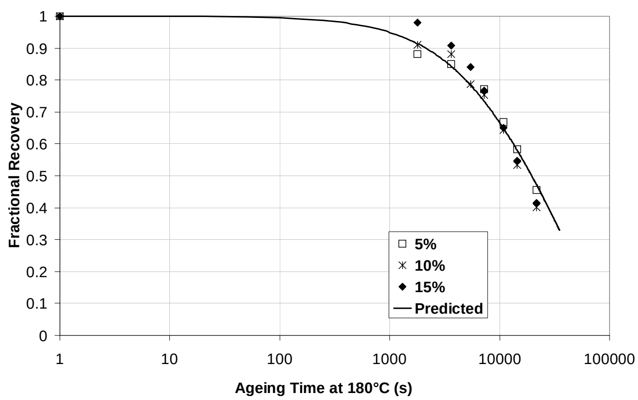

Figure 5: Fractional recovery with time for different strains at 180°C.

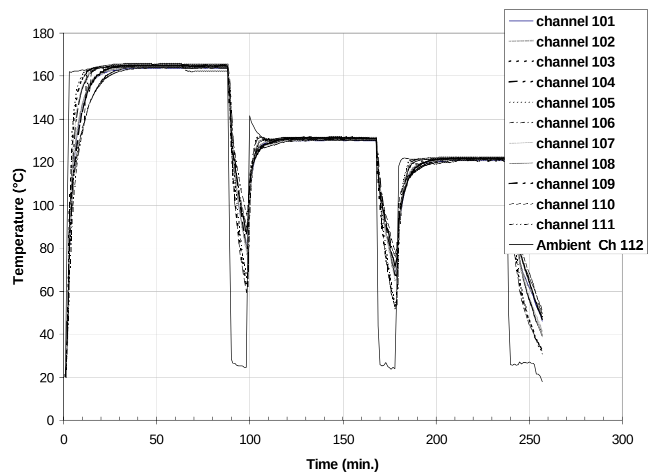

Figure 6: Heating curves recorded during the paint bake simulation treatment of a 6xxx liftgate assembly.

4. Practical Example

The initial strength of a 6xxx sheet before stamping was 130 MPa. Table 1 summarizes the YS of the samples sheared from each location of the heat treated and non heat treated liftgate assemblies. The predicted YSs for each location was determined by inputting the heating profile to a 6xxx precipitation model described by equations (6), (11) and (12). It should be noted that the three cycle ageing treatment used to heat treat the liftgate assembly was converted to the equivalent one step ageing using the method described in Section 3.2.2. In this study, the three step ageing treatment was equivalent to ageing for 18 min at 180°C, and the predicted YS for this treatment was 176 MPa.

The residual hardening calculated from equation (14) is ~ 95%, and the YS at each location of the liftgate using equations (14) and (15) are listed in Table 1. The predicted values at each locations are very close to the measured values and the average error is ~ 2.5 MPa, which is within acceptable limits.

Table 1: Yield strength of the liftgate assembly.

Location	As-Received YS, MPa	After Paint Bake YS, MPa	Predicted YS, MPa Precipitation Hardening Only	Predicted YS After Recovery, MPa	Error MPa
Initial Strength of Sheet Before Stamping 130 MPa					
1	165.8	214.3	175.6	209.4	4.9
2	163.6	210.3	175.9	207.6	2.7
3	151.7	207.7	178.0	198.5	9.2
4	164.7	213.5	178.9	211.7	1.8
5	162.3	209.7	179.5	210.0	0.3
6	169.3	212.7	175.8	212.8	0.1
7	159.0	207.6	178.9	206.4	1.2
8	160.3	205.6	176.4	205.0	0.6
9	167.4	211.2	177.1	212.4	1.1
10	159.7	207.6	176.8	204.9	2.7
11	163.0	209.8	174.7	205.9	3.9
12	157.2	202.4	178.8	205.5	2.1

5. Conclusions

The strength of uniaxially stretched and aged samples of a 6xxx sheet alloy can be successfully predicted using strain hardening, precipitation hardening and recovery models. These models can be used to predict the YS of material subjected to multiple paint cure cycles used in automotive finishing lines. A similar approach can be used to develop models for other 6xxx series alloys.

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