Improved Model to Predict Properties of Aluminum Alloy Products after Continuous Cooling

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Previous models of quench sensitivity of age-hardening alloys have been extended to include loss of toughness as well as loss of yield strength upon postquench aging. Loss of toughness on slow quenching was modeled by the loss of solute to grain-boundary precipitates that promote intergranular fracture. The phenomena are modeled using differential equations, and the model includes temperature-dependent values of the minimum toughness and strength expected after extended isothermal hold times. Time-temperature-property (TTP) curves for the postaging yield strength and toughness were used to provide empirical kinetic and property data for fitting the proposed relationship. The model was tested against experimental data, both nominally isothermal and truly continuous cooling, for an Al-Cu-Li alloy plate. For nominally isothermally cooling, the model proved to be capable of accurately describing the loss of toughness and the loss of strength to a much larger loss in strength than previous models. The model also successfully predicted the loss of strength on continuous cooling but provided a conservative over-estimate of the loss of toughness under the same continuous-cooling conditions. It is suggested that this bias arises from the lack of consideration of differences in the microstructure of the precipitates formed during isothermal treatments and those formed during continuous cooling.

I. INTRODUCTION

All precipitation-hardenable-aluminum alloy products progressively lose their ability to develop the maximum strength attainable with a particular aging treatment as rate of cooling from the solution temperature decreases. This quench sensitivity is attributed to loss of solute by precipitation during the quench as coarse, heterogeneously nucleated particles of the equilibrium phase and to loss of vacancies to sinks.

Cahn has shown that kinetics of continuous transformation can be predicted using isothermal transformation kinetics. His approach was modified to predict the ability of precipitation-hardenable-aluminum alloy products to develop strength after continuous cooling. The model has been improved and implemented over the years. The inputs are a time-temperature-property (TTP) C-curve analogous to a time-temperature-transformation (TTT) C-curve and a measured or postulated time-temperature cooling curve (quench curve). In the usual implementation of the model, the C-curve is described mathematically using constants determined by regression analysis of data obtained from isothermal quenching experiments. The C-curve equation, Eq. [1], is given in terms of empirically determined constants, \( K_2 \) to \( K_6 \), but uses a form based on the accepted theory of nucleation:

\[
C(T) = k_2 \exp \left( \frac{k_3 k_4^2}{RT(k_4 - T)^2} \right) \exp \left( \frac{k_5}{RT} \right) \tag{1}
\]

where \( C(T) \) = critical time at temperature \( T \) for attainable strength \( \sigma \);

\( k_2 \) = constant which includes the reciprocal of number of potential nucleating sites;

\( k_3 \) = constant which includes the change in free energy associated with formation of a nucleus;

\( k_4 \) = constant related to solvus temperature;

\( k_5 \) = mobility term; and

\( R \) = gas constant.

To describe a particular level of \( \sigma \), another term, \( k_1 \), is added:

\[
C(T)_i = k_1 k_2 \exp \left( \frac{k_3 k_4^2}{RT(k_4 - T)} \right) \exp \left( \frac{k_5}{RT} \right) \tag{2}
\]

where \( C(T)_i \) = critical time to decrease attainable strength \( \sigma \) to a level where \( \sigma \) equals \( \sigma_i \);

\( k_1 = -\log \left( \frac{\sigma - \sigma_{\text{min}}}{\sigma_{\text{max}} - \sigma_{\text{min}}} \right) \);

\( \sigma_{\text{max}} \) = maximum level of \( \sigma \); and

\( \sigma_{\text{min}} \) = minimum level of \( \sigma \).

To simplify the mathematics in the original version of the model, an approximation was made that strength after infinitely long hold times at temperatures below the solvus, \( \sigma_{\text{min}} \), would equal zero. This model was able to predict loss in strength accurately for those quench paths which result in a loss of up to about 0.10 \( \sigma_{\text{max}} \). In a subsequent version of the model, a better approximation was made which assumed that \( \sigma_{\text{min}} \) is a constant that is independent of temperature. Predictions with this model were useful to losses of about 0.15 of \( \sigma_{\text{max}} \).

II. NEW MODEL

This article describes a new model which recognizes that \( \sigma_{\text{min}} \) is a function of temperature. The model is developed on a sounder mathematical basis and increases the capability to predict strength to much lower percentages of \( \sigma_{\text{max}} \). The new model is, however, still based...
on some assumptions which are described later. Moreover, the format permits easy implementation into more general models depicting the role of metallurgical factors on the structure and properties of aluminum alloys due to thermomechanical processing.

The model assumes that the rate of loss of solute during quenching is a first-order reaction. The assumption has been largely verified by various empirical studies.\(^2,3,5\) The phenomenon is described by a differential equation:

\[
\frac{ds}{dt} = -A(T)(s - s_{\text{min}}(T)) \tag{3}
\]

where \(s\) = concentration of solute in solution; 
\(t\) = time at temperature, \(T\); 
\(A(T)\) = kinetic constant; and 
\(s_{\text{min}}(T)\) = equilibrium solute concentration at \(T\).

Based on the assumption that attainable yield strength depends linearly on solute concentration, one can rewrite Eq. [2] as follows:

\[
\frac{d\sigma}{dt} = -k(T)(\sigma - \sigma_{\text{min}}(T)) \tag{4}
\]

For constant temperature, integration of this equation gives

\[
\sigma = \sigma_{\text{min}}(T) + (\sigma_{\text{max}} - \sigma_{\text{min}}(T)) \exp(-k(T)t) \tag{5}
\]

where \(\sigma\) = strength capability after time \(t\) at temperature \(T\); 
\(\sigma_{\text{max}}\) = maximum value of \(\sigma\); 
\(\sigma_{\text{min}}(T)\) = minimum value of \(\sigma\) at temperature \(T\); and 
\(k(T)\) = kinetic constant at temperature \(T\).

It is shown rigorously in Appendix A that for continuous cooling, the term \(k(T)\) can be replaced by

\[
k(T) = \left(\frac{1}{C(T)}\right) \tag{6}
\]

where \(C(T)\) is as defined in Eq. [1].

This leads to the following equation which describes the attainable property after cooling over any path:

\[
\frac{d\tau}{dt} = -\frac{1}{C(T)}(\sigma - \sigma_{\text{min}}(T)) \tag{7}
\]

A model was also developed to predict the ability to develop toughness on aging after continuous cooling. This model is based on the observation that postaged toughness falls as the percentage of intergranular fracture increases due to an increase in grain-boundary precipitates formed by precipitation of solute during cooling. The fall of toughness over a small temperature interval can be predicted from the simultaneous loss in strength scaled by the maximum possible loss in toughness \((K_{\text{max}} - K_{\text{min}}(T))\) that can occur during isothermal holding. The model assumes that the effects of the morphology of the precipitates, which serve to decrease toughness by increasing the proportion of intergranular fracture, are accounted for by the loss of toughness determined empirically by isothermal quenching experiments and, therefore, contains no terms which represent microstructure. In the previous model, the equation for \(K\) was expressed as a function of time.\(^6,7\) For the current model, a differential equation was developed:

\[
\frac{dK}{dt} = -\frac{1}{D(T)(K_{\text{max}} - K_{\text{min}}(T))} \left[\frac{\sigma - \sigma_{\text{min}}(T)}{\sigma_{\text{max}} - \sigma_{\text{min}}(T)}\right]^{C(T)/D(T)} \tag{8}
\]

where \(K\) = measure of fracture toughness; 
\(K_{\text{max}}\) = toughness with maximum quench rate; and 
\(K_{\text{min}}(T)\) = minimum value of toughness at temperature \(T\).

and

\[
D(T) = m_2 \exp\left(\frac{k_2 k_4^2}{RT(k_4 - T)^2}\right) \exp\left(\frac{k_5}{RT}\right) \tag{9}
\]

where \(D(T)\) = critical time at temperature \(T\) for attainable toughness; and 
\(m_2\) = constant which includes reciprocal of number of potential nucleating sites of precipitates which influence \(K\).

The derivation of Eq. [8] is presented in Appendix B.

III. VERIFICATION OF THE MODEL

The model was tested using data from a previous investigation. Full experimental details have been previously published.\(^6,7\) Briefly, panels taken from the midplane of an experimental alloy plate containing 2.7 pct Cu, 1.6 pct Li, 0.09 pct Zr, 0.05 pct Fe, 0.05 pct Si, and 0.10 pct Ti were quenched from the solution heat-treatment temperature into molten metal baths at five temperatures ranging from 250 °C to 450 °C (523 to 723 K), held for a series of times, then quenched to room temperature. The experimental cooling curves of these samples were measured by embedded thermocouples at the sample's midthickness. Because of the lower conductivity of Al-Li alloy products compared to that of standard aluminum alloy products, there was a significant delay, from 15 to 20 seconds, before the sample cooled to within 10 °C of the isothermal hold temperature and hundreds of seconds before the temperature was within 1 °C. The nonisothermal parts of the nominally isothermal treatments were used in the modeling procedure discussed later. For simplicity, the nominally isothermal treatment will be referred to as isothermal treatment for the remainder of this article, even though samples held for the shorter times were more than 10 degrees hotter than the bath temperature at the time of their removal, and few of the samples attained a temperature within one degree of bath temperature.

The phases present in the isothermally treated specimens were determined using X-ray diffraction analyses and their preferred nucleation sites were determined using...