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APPLICATION OF QUENCH FACTOR ANALYSIS TO A356.0 AND A357.0 FOUNDRY ALLOYS

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ABSTRACT

Quench factor analysis has been applied to Al-Si-Mg casting alloys to model time-temperature-yield strength (TTY) curves. These curves, more commonly known as time-temperature-property (TTP) curves, have been modelled semi-empirically from quenching curves and corresponding tensile yield strengths. The TTY curves have been determined for various fractions of the maximum T6 yield strength and give information about the relative quench sensitivities of alloys A356.0 and A357.0. For given TTY curves, quench factors have been determined for various quenching curves to quantify quench severities. It is shown that the T6 yield strength of an industrial A356.0 or A357.0 casting can be predicted from its quench factor if the quenching curve is known.

Keywords: *quench factor, quench sensitivity, modelling, yield strength, TTP, A356.0, A357.0*

1. INTRODUCTION

For precipitation hardening alloys, rapid quenching after solution treatment allows a maximum amount of solute to be made available for the precipitation of fine-scale hardening precipitates during subsequent ageing. Slower cooling results in the loss of solute to non-hardening precipitates which form during cooling. The vacancy concentration is also reduced with slower cooling. The most rapid quench rate therefore gives the highest T6 yield strength in aluminium, but it can also cause unacceptable amounts of distortion or cracking in components. Given these competing effects and that different alloys have different quench sensitivities, significant industrial benefit could be gained from quantifying the severity of a quench in terms of yield strength for different alloys. Modelling of quench effects in aluminium casting alloys can be useful both for adjusting quenching parameters to optimise mechanical properties, and for gaining a better understanding of the quench sensitivity of an alloy.

Quench sensitivity is a measure of the vulnerability of an alloy to nucleation and growth of non-hardening precipitates during quenching and can be represented by an alloy-specific time-temperature-property (TTP) curve. Such TTP curves are analogous to the time-temperature-transformation (TTT) curves widely used by the steel industry. All such curves have been generically called C-curves because of their characteristic C-shape. A combination of both a cooling curve and a TTP curve can be used to describe the quench severity, which is a measure of the cooling path with respect to the position of the TTP curve. Integration of cooling curves and TTP curves allows the severity of a quench to be quantified in terms of a single number, called the quench factor.

Quench factor analysis has been successfully applied to wrought aluminium alloys since the early 1970s to predict the effect of quench severity on yield strength development and corrosion resistance [1]. This paper describes the application of quench factor analysis to A356.0 and A357.0

aluminium casting alloys. The modelling of time-temperature-yield strength (TTY) curves and their application to predicting yield strengths for given quenching curves are discussed.

2. QUENCH FACTOR ANALYSIS

Quantification of cooling rates during quenching from solution treatment temperatures has long been a challenge encountered by metallurgists trying to model quenching processes. The problem is that the cooling rate varies continuously during the quench such that an average cooling rate between, say 450 and 200°C, is at best only an approximation of the real cooling rate. The matter is complicated by the fact that the loss of solute to non-hardening precipitates will occur most rapidly at some intermediate critical transformation temperature represented by the nose of the C-curve. At higher temperatures, the rate of nucleation and growth of non-hardening precipitates will be low because the driving force for precipitation is reduced, whereas at lower temperatures the precipitation rate will also be slow due to slower diffusion rates. Thus the average cooling rate approach can be rather inaccurate, especially for extended hold times above or below the critical transformation temperature.

Quench factor analysis was first developed by Evancho & Staley [1] to overcome these problems and enable the prediction of corrosion and yield strength behaviour of 2xxx and 7xxx wrought aluminium alloys as a function of quench rate. They defined the C-curve of an alloy by:

$$C_t = -k_1 k_2 \exp\frac{k_3 k_4^2}{RT(k_4 - T)^2} \exp\frac{k_5}{RT} \qquad (1)$$

where C_t = critical time required to precipitate a constant amount (the locus of the critical amount is the C-curve),
k_1 = constant which equals the natural logarithm of the fraction untransformed,
k_2 = constant related to the reciprocal of the number of nucleation sites,
k_3 = constant related to the energy required to form a nucleus,
k_4 = constant related to the solvus temperature,
k_5 = constant related to the activation energy for diffusion,
R = gas constant = 8.3143 $JK^{-1}mol^{-1}$,
T = temperature in Kelvin.

Evancho & Staley determined the constants in equation (1) by iteration to provide the best fit of Fink & Willey's interrupted quenching data [2] to the following Avrami-type equation:

$$\sigma = \sigma_{max} \exp(k_1 Q) \qquad (2)$$

where σ = yield strength attained,
σ_{max} = yield strength attainable with infinite quench rate,
k_1 = $\ln \sigma_x / \sigma_{max}$,
σ_x = yield strength represented by the C-curve,
Q = quench factor.

The quenching curve and the C-curve are combined in the quench factor, Q, which is determined by the integral:

$$Q = \int_{t_0}^{t_f} \frac{dt}{C_t(T)} \qquad (3)$$

where t = time,
t_0 = time at the start of the quench,
t_f = time at the end of the quench,
$C_t(T)$ = critical time from the C-curve.

Equation 3 assumes that the transformation reaction is additive, which means that the reaction rate is a function only of the amount of transformation and the temperature [3]. The quench factor calculated in this manner is a single number describing the severity of a quench based on the C-curve and the actual quench path. Slow quench rates produce high quench factors, whereas rapid quench rates give low quench factors. When Q = 1, the real fraction transformed equals the fraction transformed on the C-curve. In terms of yield strength, a quench producing a quench factor of 1 (based on a 90% of σ_{max} TTY curve) will give a yield strength of 270 MPa if σ_{max} = 300 MPa.

3. EXPERIMENTAL AND MODELLING

In order to calculate a quench factor, it is necessary to have both a quenching curve and a C-curve for the alloy. Since no reliable C-curves are available for Al-Si-Mg casting alloys, TTY curves need to be determined for alloys A356.0 and A357.0. However, the traditional method of performing step quenching and isothermal holding experiments is impractical for at least two reasons. Firstly, in order to achieve very fast equilibration times to the intermediate isothermal holding temperatures, specimens too small and thin for tensile testing are required. Secondly, very short isothermal holding times are impractical because the equilibration times to the isothermal holding temperature can be as long as or even longer than the isothermal hold itself.

To avoid these problems, a method of modelling TTY curves was developed based on established quench factor analysis theory. Cylindrical sand castings of strontium-modified alloys A356.0 and A357.0 (Al-7wt%Si-0.40wt%Mg and Al-7wt%Si-0.61wt%Mg respectively) were sectioned into 5 mm x 10 mm x 60 mm bars. Dendrite arm spacings in these bars ranged from about 30 to 50 µm. The bars were placed into wire baskets (up to 10 bars per basket) and solution heat treated in a fluidised bed furnace at 540°C. The A356.0 bars were held at 540°C for 75 minutes, whereas the A357.0 bars were held at 540°C for 120 minutes to ensure the dissolution of all Mg_2Si. Following the solution treatment, the wire baskets were removed from the furnace and immediately subjected to the following quenching environments: 25°C water (RTWQ), 60°C water (60WQ), 100°C water (BWQ), forced air cool (FAC), still air cool (SAC) and a very slow cool in the fluidised bed furnace over a period of about 23 hours (FBFC). Quenching temperature-time data were collected digitally from thermocouple wires inserted into the centres of identical dummy test bars. As soon as the bars had cooled to ~30°C, they were immersed in salt baths and aged for 8 hours at 170°C. Following this ageing treatment, the bars were machined into flat tensile specimens with a gauge length of 15 mm and a cross-sectional area of 20 mm^2. Yield strengths (0.2% proof stresses) were determined using an Instron automated materials testing system. The cross-head speed was 1 mm/min and an extensometer was used to measure displacement.

Since both a quench curve and a C-curve are required to determine quench factors, a C-curve was generated using equation (1) with hypothetical constants. Hypothetical quench factors were then determined using equation (3). Equation (2) was modified to include both a minimum yield strength term [1] and the exponent, n, as follows:

$$\frac{\sigma - \sigma_{min}}{\sigma_{max} - \sigma_{min}} = \exp\left(k_1 Q^n\right) \tag{4}$$

where
σ = T6 yield strength attained,
σ_{min} = minimum T6 yield strength attained with the FBFC,
σ_{max} = maximum T6 yield strength attained with the RTWQ,
$k_1 = \ln\left(\frac{\sigma_x - \sigma_{min}}{\sigma_{max} - \sigma_{min}}\right)$,
σ_x = nominal yield strength for the particular C-curve,
Q = quench factor.

The σ_{min} term was introduced to make equation (4) hold for both high and low σ values. The Avrami exponent, n, was ignored by Evancho & Staley [1] since their $-\log(\sigma/\sigma_{max})$ vs time plots of both Fink & Willey's and McAlevy's interrupted quench data gave slopes of 1. It has subsequently been assumed by numerous authors that n = 1 is a reasonable approximation for wrought aluminium alloys [4, 5, 6]. In the current work on casting alloys, the n-exponent was re-introduced into the equation because n-values other than 1 gave the best fit to the experimental data [7].

The experimental yield strength data were plotted as $\ln\left[\left(\frac{1}{k_1}\right) * \ln\left(\frac{\sigma-\sigma_{\min}}{\sigma_{\max}-\sigma_{\min}}\right)\right]$ *vs* ln(Q) based on equation (4). The constants in equation (1) were manually adjusted until the hypothetical quench factors gave the line of best fit. With the intercept passing through the origin, the n-exponent was found from the slope of the line of best fit. The corresponding C-curve was taken to be the real TTY curve for the alloy. A plot of yield strength vs quench factor was used to model the decrease of yield strength with increasing quench factor and to enable the prediction of yield strength for any given quench factor. All calculations were performed using a Microsoft Excel spreadsheet.

4. RESULTS AND DISCUSSION

The results are presented in Figures 1-3 for both 99.5% (dotted lines) and 90% (solid lines) of the maximum T6 yield strengths. From the slopes in Figure 1 the n-exponents were determined to be 0.45 and 0.62 for A356.0 and A357.0, respectively. The corresponding TTY curves are presented in Figure 2. For both the 99.5% and the 90% of maximum yield strength cases, the A356.0 TTY curves occur at shorter times than the A357.0 curves. The TTY nose times, temperatures and corresponding yield strengths are presented in Table 1.

There are only a few published C-curves for aluminium casting alloys, and the effect of quench rate on properties has not been rigorously quantified. The noses for A356.0 are variously positioned at about 45-60 seconds [8] and 10-90 seconds [9]. The variation in nose times is a consequence of the different experimental methods employed and represents different fractional transformations or strengths. Nevertheless, the TTY nose positions in the current paper are comparable to those in the literature.

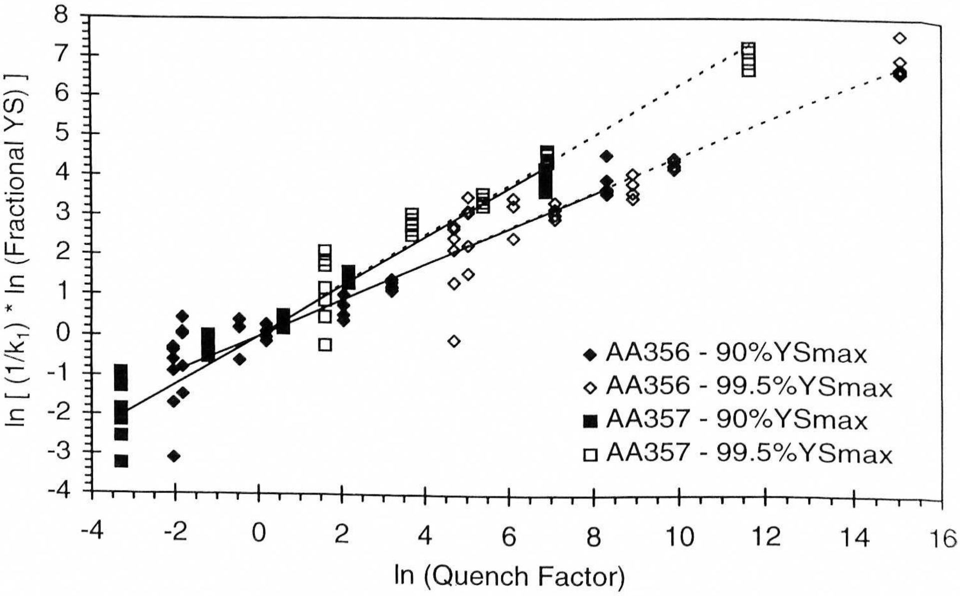

Figure 1: Lines of best fit to experimental data used to determine correct quench factors and n-values. Solid lines correspond to 90% of $\sigma_{\max}$ and dotted lines correspond to 99.5% of $\sigma_{\max}$.

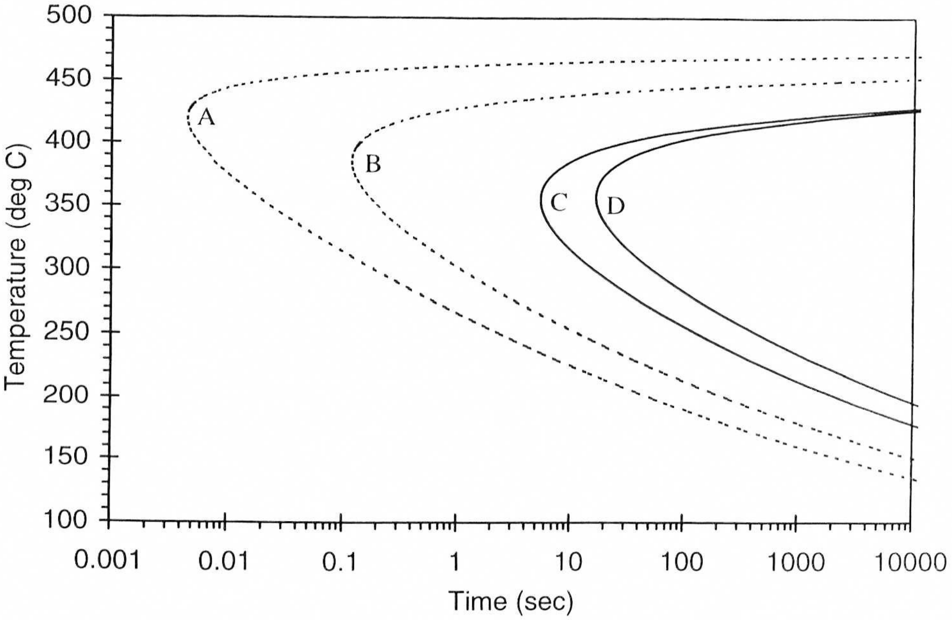

Figure 2: Modelled TTY curves for alloys A356.0 (A and C) and A357.0 (B and D) for 99.5% (dotted curves) and 90% (solid curves) of maximum T6 yield strengths.

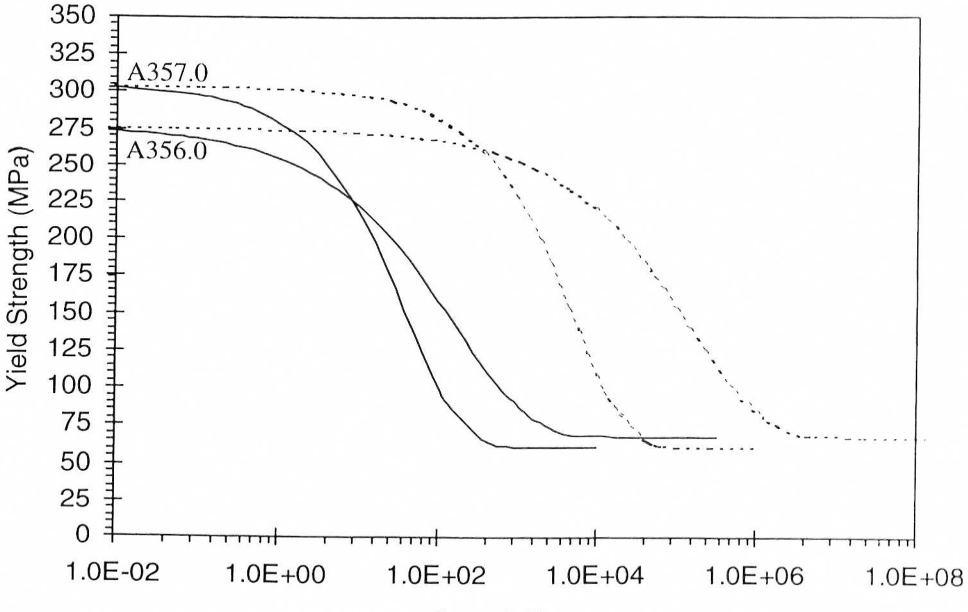

Figure 3: Variation of yield strength with quench factor based on 99.5% (dotted curves) and 90% (solid curves) TTY curves.

Table 1: Curve nose positions and corresponding yield strengths for TTY curves in Figure 2.

Alloy	% of σ_{max} (%)	σ Extremes (MPa)	Actual σ (MPa)	Nose Time (sec)	Nose Temp. (°C)	Corresponding Curve in Fig. 2
A356.0	99.5	Max: 276	275	0.004	419	A
	90	Min: 66	248	5	356	C
A357.0	99.5	Max: 304	303	0.1	385	B
	90	Min: 60	274	16	358	D

Maximum T6 yield strengths were obtained by quenching into water at 25°C (RTWQ) and ageing at 170°C for 8 hours immediately after the quench. Minimum yield strengths were obtained by slowly cooling the bars in the fluidised bed furnace (FBFC) before ageing them at 170°C for 8 hours. The T4 and T6 yield strengths after slow cooling were identical, indicating that equilibrium conditions were approached.

Figure 3 shows the variation of yield strength with quench factor for both alloys based on the 99.5% and the 90% TTY curves. At low quench factors (high cooling rates) the yield strength approaches the maximum yield strength of the alloy and there is little advantage in faster quenching. At high quench factors (slow cooling rates), the yield strength eventually approaches the minimum yield strength of the alloy.

5. CONCLUSION

Quench factors can be calculated and used to determine a cooling rate which minimises quenching stresses for a given minimum yield strength requirement. The current work has produced both TTY curves and a methodology for the prediction of yield strengths as a function of quenching rate for Al-Si-Mg casting alloys. The application of quench factor analysis to these alloys facilitates a deeper understanding of their quenching behaviour and also enables the prediction and/or design of optimal industrial quenching procedures for given yield strength requirements.

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