D. SCOTT MACKENZIE, PH.D., FASM
SENIOR RESEARCH SCIENTIST–METALLURGY /// QUAKER HOUGHTON INC.

Understanding the relationship between properties and quench rate.

Quench factor analysis: quench factor determination

In this column, we will discuss the determination of the quench factor as it is used in quench factor analysis. This will lead into a discussion of determining the time-temperature-property (TTP) curve to be used in quench factor analysis.

INTRODUCTION

The quench factor, τ, is defined as:

$$\tau = \int \frac{dt}{C_t}$$

where τ is the quench factor, t is the time (sec), and C_t is the critical time. The collection of the C_t points, also known as the C-curve, is like the time-temperature-transformation curve for continuous cooling.

In general, the C_t function is described as [1]:

$$C_t = K_1 K_2 \left[exp\left\{\frac{K_3 K_4^2}{RT(K_4 - T)^2}\right\} \exp\left\{\frac{K_5}{RT}\right\}\right]$$

where C_t is the critical time required to precipitate a constant amount of solute. The meaning of each of the constants are described in the previous article.

To determine the parameters K_1, K_2, K_3, K_4, and K_5, it is first necessary to have the C-curve. C-curve data is scarce, and of limited availability. Some coefficients for the C_t function are shown in the previous column and in [2]. Once the C-curve, or time-temperature-property curve, is obtained, the values of the coefficient are obtained by repeated iterations (and minimum error) until the best fit to the C-curve is achieved [3].

One of the problems with the equation for the C-curve is its complex nature and dependence on K_2–K_5. Different sets of K_2–K_5 can provide similar fits to the data, with similar errors, but can provide wildly different time-temperature-property curves [4]. Fitting the time-temperature-property coefficients is severely non-linear, and results in errors regardless of the method used. Independent physical data offer much better fits to the data and result in reduced errors in the C-curve. Data such as the solvus temperature (K_4), solute diffusivities (K_5) and enthalpy for precipitation (K_7) substantially reduce the fitting errors and non-linearity and offer physical meaning to the data and fit. Use of many data points (> 10) reduces the errors. Combining interrupted quench data and continuous cooling data is very effective in reducing C-curve errors.

One additional source of error is some aluminum alloys have competing precipitates forming during quenching and aging. For instance, many types of precipitates may be observed in a single sample. The precipitates may be at the grain interior or at the grain boundary. There may be different precipitates present (θ and S). They could also be different coherency (incoherent and semi-coherent). This results in multiple C-curves, like the pearlite and bainite curves in time-temperature-transformation diagrams for steels. Quench factor analysis, as created by Evancho and Staley [3], assumes only one primary precipitate.

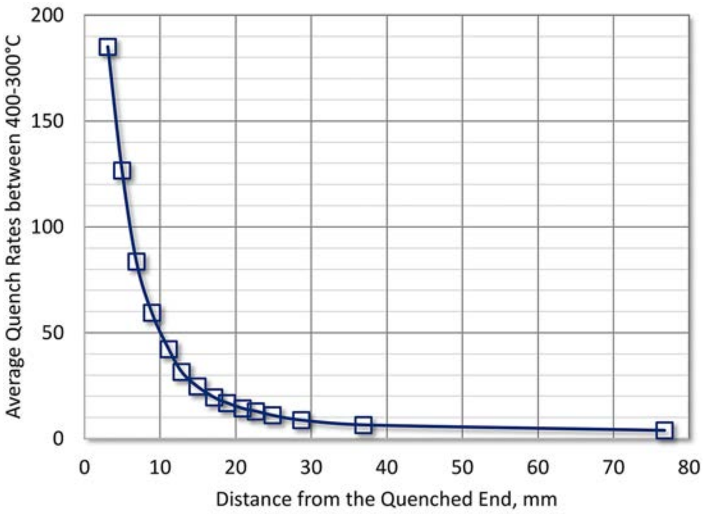

Figure 1: Cooling rate as a function of distance from the quenched end for an aluminum Jominy end-quench sample. Cooling rates were taken as the average from 400-300°C [7].

DETERMINATION OF PROPERTY DATA AS A FUNCTION OF QUENCH RATE

From the previous discussion, the modeling of aluminum alloys is dependent on the data generated through interrupted quench data or from continuous cooling data. Typically, it is necessary to measure the quench path of several sheets of material, and then measure the properties after processing. The quench factor is determined for each quench path and associated with the measured properties. Typically, hardness and tensile properties have been used.

The Jominy end quench [5] provides a method of determining both the quench factor and the C-curve. The Jominy end-quench test has many advantages for determining quench sensitivity of aluminum and other alloys such as titanium [6]. The method offers many advantages over traditional quenching of sheet and plate. The observed quench rates vary from 200°C/s at 3 mm from the quenched end to less than 3°C/s at 78 mm from the quenched end [7] (Figure 1). Further, it is a data-rich specimen. Once quenched, and hardness and conductivity has been measured, the specimen can be sliced at specific locations for TEM and DSC analysis [8] [9].

Properties are then related to the quench factor by the equation:

$$p = p_{max} exp(K_1 Q)$$

where p is the property of interest, pmax is the maximum property

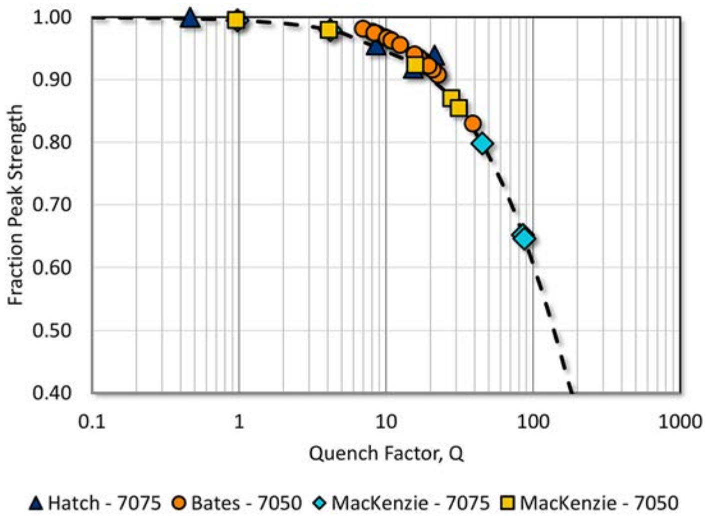

Figure 2: Comparison of quench factors generated by the Jominy end quench by MacKenzie [9], compared to interrupted quench data generated by Fink and Wiley [11] and Bates [12].

attainable with infinite quench rate, and K_1 is -0.005013 (natural log of 0.995).

By rearranging the above equation, the quench factor, Q, can be determined for hardness on the Jominy end quench:

$$Q = \frac{1}{K_1} ln\left(\frac{H_{VN}}{H_{max}}\right)$$

where H_{VN} is the hardness at a specific location on the Jominy end quench bar, and H_{max} is the maximum hardness. The maximum hardness, H_{max}, is generally an average of the first several hardness indentations.

Therefore, for a specific set of processing conditions, the quench factor can be determined for multiple quench rates, using the Jominy end quench. The data generated can be used to predict properties occurring in similar material and similar operating conditions. This is illustrated in Figure 2. In this figure, the percentage of the attainable property from hardness (7075-T6 and 7050-T6 from the Jominy end quench), is compared with that obtained by Hatch [10] by quenching individual panels and measuring the yield strength. This method allows for the determination of the quench factor without knowledge of the C-curve.

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CONCLUSION

In this short column, we have illustrated methods of determining the quench factor as a function of quench rate. In the next column, we will discuss a method of determining the C-curve, and the different coefficients in the C-curve equation.

Should you have any questions regarding this article, or have suggestions for any additional columns, please contact the writer or the editor.

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ABOUT THE AUTHOR

D. Scott MacKenzie, Ph.D., FASM, is senior research scientist-metallurgy at Quaker Houghton. He is the past president of IFHTSE, and a member of the executive council of IFHTSE. For more information, go to www.quakerhoughton.com.