Back to basics with tempering (Part II)

Fundamental methodology for calculating tempering times and temperatures for steels can simplify the empirical determination of appropriate temperatures to use to process a new part.

After a part has been austenitized and quenched, it must be tempered. As was discussed previously [1], the purpose of tempering is to relieve the transformational residual stresses from quenching, and to transform the brittle martensite to tougher tempered martensite. It can also convert any remaining austenite to tempered martensite or bainite.

One of the issues facing the heat treater is determining the time and temperature to achieve the desired hardness or mechanical properties. Most data is similar to Figure 1, which shows typical hardness after quenching a 25mm round to full as-quenched hardness [2].

There are several methods of determining the appropriate time and temperature for tempering. One method of determining time and temperature is described by Canale et al [3]. As a first step, the desired temperature is calculated using the equation developed by Just [4].

\[
T_t = 917 \sqrt{\frac{\ln \left( \frac{H_q - 8}{H_t - 8} \right)}{S}} - 273°C
\]

Where \( T_t \) is the absolute temperature of tempering (°K) – valid in the range of 390° - 660°C; \( H_q \) is the as-quenched hardness (HRC); \( H_t \) is the required hardness after tempering (HRC); and \( S \) is the ratio of the as-quenched hardness versus the maximum hardness (\( S = \frac{H_q}{H_{max}} \)).

The total tempering time including heat-up and soaking time is calculated from [5] [6]:

\[
t = \frac{m}{A} + b
\]

where \( t \) is the time in minutes, \( m \) is the mass of the load (kg), \( A \) is the total surface area (\( m^2 \)), and \( a \) and \( b \) are constants that are developed empirically for each furnace used. This method requires significant empirical work to be done to evaluate each possible furnace and alloy and load combination.

Tempering is dependent on time, temperature carbon content, and alloying elements. Alloying elements retard softening during tempering, and change the kinetics of tempering [7]. Figure 2 shows the hardness of iron-carbon alloys tempered at various temperatures.

One relationship that has been used successfully in determining the time for tempering is the Holloman-Jaffe equation [8], also known as the Larson-Miller equation [9]:

\[
T_1 (C + \log t_1) = T_2 (C + \log t_2)
\]

\( T_1 \) and \( t_1 \) are the known temperatures and times for \( T_2 \) and \( t_2 \) are the desired temperatures and times. \( C \) is a constant, which varies by steel grade, and ranges from 15-22. It is generally accepted to have a value of 20, but some authors recommend a value 18 [1]. Table 1 shows Larson-Miller values of \( C \) for various alloys.

One of the problems with the use of the Larson-Miller equation is that it assumes an isothermal process. However, the process of tempering involves heating the parts to temperature, holding at the desired temperature for the desired amount of time, and cooling the parts to room temperature. During the heating of parts, there will be...
some transformation of the martensite to temperature martensite. This is also true of the cooling process. To overcome these issues, the effect of heating and cooling was examined by Gulvin et al., using the Larson-Miller equation to determine appropriate times for stress-relieving. An additional equivalent time $T_{eq}$ at the tempering temperature, based on linear heating and cooling, was calculated [11][12].

$$T_{eq} = \frac{T}{2.3k(20 - \log k)}$$

where $T$ is the tempering temperature in °K, and $k$ is the heating or cooling rate in °K/hr. The total time during tempering is then:

$$t_2 = t_{eq-heating} + t_{soak} + t_{eq-cooling}$$

From the above equations, the tempering time can be estimated if one time-temperature relationship is known.

**CONCLUSIONS**

In this short article, the basic methodology for calculating different tempering times and temperatures for steels was provided. While somewhat math intensive, it can simplify the empirical determination of appropriate temperatures to use when processing a new part.

Should you have any questions regarding these calculations, or to suggest a future heat-treating article, please contact the author at the email address at the end of the article.

**REFERENCES**


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