Quench time is a measure of how long a steel casting spends at high temperature during quenching. While castings cool, the quench water warms; therefore, there is a one-to-one relationship between the two. This fact allows average casting temperatures to be estimated from a measurement of quench water temperature alone and a knowledge of steel’s heat capacity.

In the 1940s and 1950s, researchers worked to characterize quenchants and quenching operations for steels. They found that two distinct modes of heat transfer determine cooling rate: removal of heat from the workpiece surface into the quenchant by convection; and the transient diffusion of heat from within the workpiece to its surface by conduction. The first is governed by the wall heat transfer coefficient, the second by the thermal diffusivity of the steel. Grossman coined the term “quench severity,” \( H \), for the relative magnitudes of the two modes of heat transfer:

\[
H = \frac{h}{2k}
\]

where \( h \) is the heat transfer coefficient and \( k \) is the thermal conductivity. A higher heat transfer coefficient and higher thermal conductivity both increase the cooling rate, so it seems a dichotomy to have the thermal conductivity in the numerator of an expression that is meant to define “quench severity.” However, thermal conductivity is a material property of the workpiece, and is not expected to be an independent (controlled) variable; therefore, for a given material (steel, in this case), quench severity is primarily governed by the heat transfer coefficient, which can be varied independently by quenchant type and quenching process conditions.

When quench severity is multiplied by a characteristic length \( 2L \) (viz. diameter \( D \) for cylinders, spheres, or section thickness for a plate), one obtains the dimensionless heat transfer coefficient known as the Biot number:

\[
[Bi] = \frac{HL}{k} = HD
\]

Solutions exist for \([Bi]\) vs. centerline cooling rates of cylindrical rods, or more practically, extent of hardening (unhardened diameter to 50% martensite) in standard steel rods. When standard rods are quenched in a given quenchant and the extent of hardening vs. diameter curve is compared with the analytical solutions to find a matching curve, the corresponding Biot number can be read off the chart, and the quench severity can be estimated. This procedure, thus, justifies the choice of expression for quench severity.

In an alternative procedure, steel rods of known hardenability (hardness vs. Jominy end-quench distance) are quenched and their center and half-radius hardnesses measured. These values are then compared with calculated diameter vs. hardness in terms of “equivalent Jominy end-quench distance” curves for given quench severities. The quench severity of a bath can be estimated by quenching only two standard steel rods of different diameters.

Although \( H \)-values have the units of per inch, they are often quoted as unitless factors to rank the various quenchants by their various degrees of agitation/circulation. Quench severity was primarily developed to estimate hardenability. The heat transfer coefficient for \( H \) typically corresponds to an average value at a temperature range of 550º to 710ºC; which envelopes the pearlite nose of an isothermal transformation diagram.

**Cooling stages**

The heat transfer coefficient varies with the quenchant type, degree of forced convection, and the material surface conditions. When a hot workpiece is immersed into a quenchant, it goes through three well-known stages of cooling:

- **Vapor blanket stage.** Initially, a vapor blanket, which tends to be insulating, forms around the workpiece. In this stage, cooling is primarily by radiation and depends on the emissivity of steel.

- **Nucleate boiling stage.** As the surface temperature of the workpiece drops, the vapor blanket collapses and the liquid quenchant comes into intermittent contact with the workpiece, creating nucleate boiling conditions. The enhanced mass transfer of the quenchant at the onset of this stage characteristically causes a sudden rise in the cooling rate. The quenchant temperature has a strong influence on the nucleate boiling stage. In water, the
farther away (lower) it is from its boiling point, the sooner nucleate boiling starts. Alkali and salt solutions cause a speedy transition to nucleate boiling by raising the boiling point of water. Also, forced convection causes the second stage cooling to start and end at higher workpiece temperatures.

- **Convective cooling stage.** As nucleate boiling subsides, the workpiece becomes fully covered by the liquid quenchant, and cooling occurs by natural or forced convection. In this stage, the heat transfer coefficient is not necessarily low, but the cooling rate decreases as the temperature difference between the workpiece and the quenchant diminishes.

The Jominy end quench test (ASTM A 255) determines the hardenability of a steel for an ideal quench (H-value approaching infinity at the quenched end) in a standard specimen. Results are displayed as hardness values vs. distance from the quenched end, which also corresponds to a certain cooling rate. The cooling effectiveness of a quench bath then can be determined separately, and from a knowledge of both the cooling effectiveness of a quenchant and the hardenability of a steel, process versus property relationships can be established.

Once separated from metallurgical variables, methods of measuring the cooling effectiveness of a quenchant generally are less expensive and easier to conduct. The most comprehensive among these are the cooling curve analyses on standard specimens fitted with thermocouples. From the cooling curve data, cooling rates and H-values can be derived. In one standard probe, the wall thermal gradient is measured by two closely separated thermocouples for a more direct measurement of wall heat flux and heat transfer coefficient. In the magnetic quencher test (ASTM D 3520), the time for a standard nickel ball to cool from 885°C to its Curie temperature at 355°C is measured. At the latter temperature, the ball becomes magnetic and attracted to a magnet, which is used as an electrical contact to signal the end point. In the hot wire test, a Nichrome wire of standard gage and electrical resistance is immersed into the quenchant and a current is passed until the wire melts. The cooling power is indicated by the maximum current level sustained by the wire. The interval test makes use of the heat absorbed by the quenchant in the first stage of the quench (typically, the first 5 seconds in a standard setup) by measuring the temperature rise in the quenchant and compares this to the overall temperature rise.

Although the above methods are designed to determine cooling effectiveness at higher temperatures (since heat treaters want to bypass the pearlite nose for hardenability purposes), the cooling rate at the end of a quench also can be important. For example, water is a very effective quenching medium, but tends to fast cool at lower temperatures, causing quench cracks. For critical applications, polymer additives or fast oil quenchants are preferred to reverse this trend. In this respect, because it provides information at all stages, the cooling curve analysis is a more complete test.

The uncertainty surrounding the effective section size of a workload is another limitation on using quench severity values to determine the final properties of a workload from its known hardenability. In the methods previously described, quench severity is estimated from a single, standard work piece, and the cooling rate (or hardness) in a given section is found using the standard charts. In a typical workload, however, convective conditions may not be as free as in a single workpiece. The effective section thickness of a workload could be much greater than those of individual parts.

To overcome this uncertainty, cooling curve analyses will need to be performed by embedding thermocouples at suitable locations in the workload. This can be a time consuming and expensive proposition. However, the same could be achieved by measuring the quenchant temperatures. The heat given off by the workload is taken up by the quenchant. Therefore, there is a one-to-one correspondence between the two. The average temperature of a workload and its cooling rate at a given time during quenching can be derived from knowledge of the initial temperatures of a quenchant and the workload, the final equilibrium temperature, and the heat capacities. In the sections below, this method is described for laboratory and industrial experiments.

**Laboratory Experiments**

The quench time analysis was applied to austenitic manganese steel castings with a nominal composition of 1.2% C, 13% Mn. These hypereutectoid steels suffer from intergranular embrittlement as a result of carbide precipitation in the as-cast state. High-temperature solution annealing and quenching heat treatment removes the intergranular carbides and provides the desirable, retained austenite structure. A fast quench is required to minimize any carbide reprecipitation and maximize the impact toughness of these steels. Figure 1 shows an isothermal transformation diagram. Relatively harmless thin grain boundary carbide films form almost immediately, then harmful, thick carbide films nucleate and grow along the grain boundaries. Although this is different from hardenability, it is analogous to bypassing the carbide nose that occurs at a temperature range of 550 to 650°C.

Four 3-in. (75mm) austenitic manganese steel Y-blocks (ASTM) were cast in laboratory heats. The steels were solution annealed at 1060°C for 4 hours. The temperature was gradually ramped up to avoid any thermal stresses that would have caused intergranular cracking in the brittle, as-cast structure. The first Y-block was fitted with an S-type thermocouple in its center, inside a cast-in-place quartz tube shield, and was water quenched from 1060°C. Other Y-blocks were quenched after the furnace temperature was dropped to 1000°, 950°, and 900°C at 90 min. intervals. The original objective of this work was to increase the quenching efficiency by stepping down the furnace temperature after
complete solutionizing to lessen the heat to be removed in the quench tank.

The Y-blocks were quenched in a tank containing 170 l of water, initially at 6°C. The tank was stirred by two 4 in. dia. impellers rotating at 1000 rpm. The two mixers were placed in opposite corners to cause a clockwise movement of water. The Y-blocks were guided into the centre of the tank, and a steel grid kept the castings 6 in. off the tank floor to facilitate water movement below.

Figure 2 shows the measured temperatures of the Y-block with embedded thermocouple and the quench water. The exothermic deflection in the cooling curve of the Y-block at 600° to 625°C, about 2.5 minutes into the quench, is indicative of some grain boundary carbide precipitation. The quench water temperatures could be used to estimate the average Y-block temperature using the following heat balance:

\[
Q = m_C \cdot C_C \cdot (T_{C1} - T_{C2}) + m_W \cdot C_W \cdot (T_{W2} - T_{W1})
\]

where:
- \(m_C\) = mass of casting. The Y-block with embedded thermocouple was 21.1 kg.
- \(m_W\) = mass of water in the quench tank, 170 kg.
- \(C_C\) = heat capacity of austenitic manganese steel.
- \(C_W\) = heat capacity of water, 4180 J/kg°C.
- \(T_{C1}, T_{W1}\) = casting and water temperatures at time \(t_1\).
- \(T_{C2}, T_{W2}\) = casting and water temperatures at time \(t_2\).

Thus, the average casting temperature can be calculated from water temperatures and a conceptualized surface temperature plot. Water temperatures belong to different Y-blocks.

The heat capacity of austenitic manganese steel varies with temperature as shown in Fig. 3. If the steel is free from carbides, slow heating or cooling causes an exothermic displacement on heat capacity while the carbides precipitate. However, if the steel is cooled sufficiently fast to prevent any significant carbide precipitation, heat capacity is given by the dashed line. Thus, the average casting temperature calculated from water temperatures could be determined from water temperatures and a conceptualized surface temperature plot. Water temperatures belong to different Y-blocks.

The Y-blocks were quenched in a tank containing 170 l of water, initially at 6°C. The tank was stirred by two 4 in. dia. impellers rotating at 1000 rpm. The two mixers were placed in opposite corners to cause a clockwise movement of water. The Y-blocks were guided into the centre of the tank, and a steel grid kept the castings 6 in. off the tank floor to facilitate water movement below.

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Thus, the average casting temperature can be calculated from water temperatures and a conceptualized surface temperature plot. Water temperatures belong to different Y-blocks.

A more detailed analysis of the quenching process can be obtained by taking the time differential (heating rate) of the water temperature, which directly corresponds to the cooling rate of the casting. This is shown in Fig. 5, for the last three Y-blocks. The graphic clearly identifies the three stages of quenching and when the blocks enter the nucleate boiling stage. Delays entering the nucleate boiling stage could be caused by poor circulation of the quench water, which could be remedied. Therefore, this analysis could be used as another process control tool.

If the isothermal transformation data are known, then they can be used to ascertain if any transformation has occurred during quenching. This is achieved by the additivity rule, which states that the fractions of time spent to transformation at all temperatures can be added, and when the sum equals one, transformation occurs:

\[
Q = \sum \frac{\Delta t}{t_i(T)}
\]

where \(Q\) is the quench factor, \(t_i(T)\) is the time to start thick carbide precipitation and \(\Delta t\) is the time the casting spends at temperature \(T\). This has been done for the thermocouple block, for the central and average cooling curves.

<table>
<thead>
<tr>
<th>Location</th>
<th>Temperature determination</th>
<th>(Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-block center</td>
<td>By thermocouple</td>
<td>1.22</td>
</tr>
<tr>
<td>Y-block Deduced from Y-block</td>
<td>From average water temperatures</td>
<td>1.01</td>
</tr>
</tbody>
</table>

The quarter thickness location in a section should well represent the block average. Therefore, from this location to the casting surface, we expect no thick carbide precipitation, and toward the center, formation of some thick carbides. Figure 6 shows the microstructures near the casting surface and
center of one of the Y-blocks. Table 1 gives its chemical composition and Charpy impact toughness. It will be seen that, unlike the above prediction, a much greater proportion of thick carbide precipitation has occurred, and the impact toughness has decreased from a nominal value of 180 J for a well heat-treated casting to 77 and 40 J near the casting surface and center, respectively. One likely cause for this deviation is the higher carbon content of the castings. Above 1.2% C, the kinetics of carbide precipitation increase rapidly, moving the transformation curve for thick carbide precipitation to the left. This exercise demonstrates the importance of combining the cooling curve data with accurate kinetic data to make reliable predictions. Castings having 1.1 to 1.2% C display adequate toughness when their 90% quench-time is less than 10 minutes, in agreement with Fig. 1.

To be continued . . .

This concludes Part I of “Quench Time Measurement as a Process Control Tool.” Part II will be published in the March/April 2005 Heat Treating Progress. It describes experiments using industrial quench tanks, and includes an expanded list of references.

References

For more information: Selcuk Kuyucak is casting group leader, CANMET Materials Technology Laboratory, Minerals & Metals Sector, Natural Resources Canada, 568 Booth St., Ottawa, ON, Canada K1A 0G1; tel: 613/992-2253; fax: 613/992-8735; e-mail: skuyucak@nrcan.gc.ca. Sivyer Steel and M E Global are foundries that cast carbon and low-alloy steels, among other alloys.

Fig. 4 – Construction to determine quench time from quench water measurements for the Y-block with thermocouple in Fig. 2. Quench time is defined as the time to extract 90% of the heat from the casting during its quench.

Fig. 5 – Quench water temperatures and warming rates for the last three Y-blocks in Fig. 2.

Fig. 6 – Photomicrographs of the ends of Charpy specimens of the Y-block quenched from 950°C. (a) 0.25 in. (6.35 mm) from casting surface. Block arrow indicates transition from a thin to a thick grain boundary carbide film. (b) 0.25 in. (6.35 mm) from casting center. Composition of steel and impact toughness values are given in Table 1. Etched in equal-part solution of conc. HNO₃, conc. HCl, and water.

Table 1 – Composition, wt%, and impact properties of Y-block shown in Fig. 6

<table>
<thead>
<tr>
<th>Heat</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>P</th>
<th>S</th>
<th>N</th>
<th>O</th>
<th>Near surface</th>
<th>Near center</th>
</tr>
</thead>
<tbody>
<tr>
<td>P9037</td>
<td>1.27</td>
<td>12.7</td>
<td>0.43</td>
<td>0.63</td>
<td>&lt;0.08</td>
<td>0.029</td>
<td>0.031</td>
<td>0.013</td>
<td>0.016</td>
<td>0.0030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block</td>
<td>Weight, kg</td>
<td>Quenched from . . . , °C</td>
<td>Quench time, t₉₀°C, min</td>
<td>Charpy V-notch impact energy, J</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P9037A</td>
<td>20.7</td>
<td>950</td>
<td>4.80</td>
<td>77</td>
<td>40</td>
<td></td>
<td></td>
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