Machine Steel Hardenability and the Jominy Test 1

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1 Adapted from: Callister, W.; Engineering and Science of Materials, Wiley and Sons, 2007; and other sources.
1 Hardenability of Machine Steel

“Hardenability” is a term used to describe the ability of a steel alloy to be hardened by the formation of martensite as a result of a given heat treatment. Hardenability is not “hardness,” which is the resistance to indentation; rather, hardenability is a qualitative measure of the rate at which hardness drops off with distance into the interior of a specimen as a result of diminished martensite content. A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface but to a large degree throughout the entire section. The influence of alloy composition on the ability of steels to transform into martensite for a particular quenching treatment is related to hardenability. For every different steel alloy there is a specific relationship between the mechanical properties and the martensite content, which in turn is a function of the cooling rate during the austenite \(\rightarrow\) martensite transformation.

Hardenability is particularly relevant for machine steels, which are materials specifically developed to fabricate machine elements such as shafts, gears, cams, and sprockets. Typically, these steels enter service with a tempered martensite microstructure because it renders the best combination of toughness, fatigue strength and hardness. Such tempered martensite condition, obtained by hardening by quenching and then tempering, is known in general as the Q&T condition.

2 Measuring Hardenability

2.1 The Jominy End-Quench Test

One standard procedure that is widely used to determine hardenability is the Jominy end-quench test\(^2\). With this procedure, except for alloy composition, all factors that may influence the depth to which a part hardens (i.e., specimen size and shape, and quenching treatment) are maintained constant. A cylindrical specimen 25.4 mm (1.0”) in diameter and 100 mm (4”) long is austenitized at a prescribed temperature for a prescribed time. After removal from the furnace, it is quickly mounted in a fixture as diagrammed in Figure 1. The lower end is quenched by a jet of water of specified flow rate and temperature. Thus, the cooling rate is a maximum at the quenched end and diminishes with position from this point along the length of the specimen. After the part has cooled to room temperature, shallow flats 0.4 mm (0.016 in) deep are ground along the specimen length and Rockwell hardness measurements are made for the first 50 mm (2”) along each flat; for the first 12.7 mm (1/2”), hardness readings are taken at 1.6 mm (1/16”) intervals, and for the remaining 38.3 mm (1 1/2”), every 3.2 mm (1/8”). A hardenability curve is produced when hardness is plotted as a function of position from the quenched end (Figure 2).

2.2 Hardenability Curves

A typical hardenability curve is represented in Figure 2. The quenched end is cooled most rapidly and exhibits the maximum hardness; 100% martensite is the product at this position for most machine steels. Cooling rate decreases with distance from the quenched end, and the hardness also decreases, as indicated in the figure. With diminishing cooling rate more time is allowed for carbon diffusion and the formation of a greater proportion of the softer pearlite, which may be mixed with martensite and bainite. Thus, a steel that is highly hardenable will retain large hardness values for relatively long distances; a low hardenable one will not. Also, each steel alloy has its own unique hardenability curve. Sometimes, it is convenient to relate hardness to a cooling rate rather than to the location from the quenched end of a standard Jominy specimen. Cooling rate [taken at 700° C (1,300° F)] is ordinarily shown on the upper horizontal axis of a hardenability diagram.

This correlation between position and cooling rate is the same for plain carbon and many low alloy steels because the rate of heat transfer is nearly independent of composition. On occasion, cooling rate or position from the quenched end is specified in terms of Jominy distance, one Jominy distance unit being 1.6 mm (1/16”).

A correlation may be drawn between position along the Jominy specimen and continuous cooling transformations. For example, Figure 3 is a continuous cooling transformation diagram for an eutectoid iron–carbon alloy onto which are superimposed the cooling curves at four different Jominy positions, and corresponding microstructures that result for each (the hardenability curve for this alloy is also included).

This variation of microstructural constitution will manifest itself in actual components as a drop of hardness towards the center of the part. Note, in Figure 4, the different hardness behavior of properly quenched 1045 and a 6140 steel bars of increasingly larger diameters.

The hardenability curves for five different steel alloys all having 0.40 wt% C, yet differing amounts of other alloying elements, are shown in Figure 5. One specimen is a plain carbon steel (1040); the other four (4140, 4340, 5140, and 8640) are low alloy machine steels. Approximate alloy compositions (wt%) for the
- As alloying elements are added, the hardness "penetrates" over the whole diameter of the section.

Figure 4: Alloying elements effect on hardenability of common machine steels.

Figure 5: Hardenability curves for five different steel alloys, each containing 0.4 wt% C.

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5 steel presented are as follows: 4340–1.85 Ni, 0.80 Cr, and 0.25 Mo; 4140–1.0 Cr and 0.20 Mo; 8640–0.55 Ni, 0.50 Cr, and 0.20 Mo; 5140–0.85 Cr; and 1040 is an unalloyed steel.

Several details are worth noting from Figure 5. First, all five alloys have similar hardness at the quenched end (57 HRC); this hardness is a function of carbon content only, which is the same for all these alloys. Probably the most significant feature of these curves is shape, which relates to hardenability. The hardenability of the plain carbon 1040 steel is low because the hardness drops off precipitously (to about 30 HRC) after a relatively short Jominy distance (6.4 mm, \( \frac{1}{4} \) in.). By way of contrast, the decreases in hardness for the other four alloy steels are distinctly more gradual. For example, at a Jominy distance of 50 mm (2”), the hardnesses of the 4340 and 8640 alloys are approximately 50 and 32 HRC, respectively; thus, of these two alloys, the 4340 is more hardenable. A waterquenched specimen of the 1040 plain carbon steel would harden only to a shallow depth below the surface, whereas for the other four alloy steels the high as quenched hardness would persist to a much greater depth (see Figure 4).

The hardness profiles in Figure 5 are indicative of the influence of cooling rate on the microstructure. At the quenched end, where the quenching rate is approximately 600º C/s (1,100º F/s), 100% martensite is present for all five alloys. For cooling rates less than about 70º C/s (125º F/s) or Jominy distances greater than about 6.4 mm (\( \frac{1}{4} \) in.), the microstructure of the 1040 steel is predominantly pearlitic, with some proeutectoid ferrite. However, the microstructures of the four alloy steels consist primarily of a mixture of martensite and bainite; bainite content increases with decreasing cooling rate.

This disparity in hardenability behavior for the five alloys in Figure 5 is explained by the presence of nickel, chromium, and molybdenum in the steels. These alloying elements delay the austenite-to-pearlite and/or bainite reactions\(^4\); and as explained elsewhere, this permits more martensite to form for a particular cooling rate, thus yielding a greater hardness. The right-hand axis of Figure 5 shows the approximate

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\( ^4 \) Both perlite and bainite formation processes are diffusion controlled.
percentage of martensite that is present at various hardeneses for these alloys. The top axis of this figure (and most all Jominy plots) shows the expected cooling rate a the temperature passes the 700°C (1,300°F). The selection of that temperature is arbitrary. However a good reason for choosing this particular temperature in related to the fact that for most machine steels containing about 0.4 wt% C the “nose” of the isothermal transformation curve is located at about that temperature; i.e. it coinsides with the critical cooling rate for a given alloy.

The hardenability curves also depend on carbon content. This effect is demonstrated in Figure 6 for a series of 8600 machine steels in which only the concentration of carbon is varied. The hardness at any Jominy position increases with the concentration of carbon.

Also, during the industrial production of steel, there is always a slight, unavoidable variation in composition and average grain size from one batch to another. This variation results in some scatter in measured hardenability data, which frequently are plotted as a band representing the maximum and minimum values that would be expected for the particular alloy. Such a hardenability band is plotted in Figure 7 for an 8640 steel. An H following the designation specification for an alloy (e.g., 8640H) indicates that the composition and characteristics of the alloy are such that its hardenability curve will lie within a specified band.

3 Influence of Quenching Medium, Specimen Size and Geometry

The preceding treatment of hardenability discussed the influence of both alloy composition and cooling or quenching rate on the hardness profile in a given component. The cooling rate of a specimen depends on the rate of heat energy extraction, which is a function of the characteristics of the quenching medium in contact with the specimen surface, as well as the specimen size and geometry.

The main analytical complication underlying the quenching process is the fact that heat transfer mode changes drastically during the cooling process. As shown in Figure 8, heat transfer mechanisms during the quenching of a properly austenized steel in a vaporizing medium change from vapor blanket insulation (100-250 W/m²K) to nucleate boiling 10-20 kW/m²K to convection (700 W/m²K)\(^5\).

Several strategies have been develop to quantify the effect of quenching on the properties of hardened steel, ranging from simple methods such as the quench severity index H originally

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defined by Grossman, Asimow and Urban\(^6\), to very complex numerical methods like the Quench Factor Analysis introduced by Kavalco and Canale\(^7\).

In this context, the “severity of quench” concept is used to indicate the rate of cooling; the more rapid the quench, the more severe the quench. Of the three most common quenching media—water, oil, and air—water produces the most severe quench, followed by oil, which in turn is more effective than air\(^8\). The degree of agitation of each medium also influences the rate of heat removal. Increasing the velocity of the quenching medium across the specimen surface also enhances the quenching effectiveness.

### 3.1 Quenching Mediums

Quenching mediums extract heat from the surface of a specimen by convection and then “carry it away” by conduction; both characteristics are difficult to measure. In common practice, a quench severity index \(H\), which was originally defined by Grossman, Asimow and Urban\(^6\), represents the relationship between both thermal properties of the fluid at around 1,300\(^\circ\)F (700\(^\circ\)C) according to the following equation:

\[
H = \frac{f}{K} = \left[\frac{\text{BTU/}in^2\cdot\text{s}\cdot\text{\^\circ}\text{F}}{\text{BTU/}in\cdot\text{s}\cdot\text{\^\circ}\text{F}}\right] = \left[\frac{1}{\text{in}}\right]
\]

where \(H\) is the severity of the quenching medium, \(f\) is the coefficient of heat transfer by convection and \(K\) is the coefficient of heat transfer by conduction. Most commonly used quenching mediums have been characterized experimentally; usual values are found in Table 1.

<table>
<thead>
<tr>
<th>Agitation of Quenching Medium</th>
<th>Movement of Specimen</th>
<th>Severity of Quench Medium</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>None</td>
<td>0.02</td>
</tr>
<tr>
<td>None</td>
<td>Moderate</td>
<td>0.40.6</td>
</tr>
<tr>
<td>None</td>
<td>Violent</td>
<td>0.6-0.8</td>
</tr>
<tr>
<td>Spray</td>
<td>None</td>
<td>1.0-1.7</td>
</tr>
</tbody>
</table>

Figures 9a and 9b show the quenching rate at 700\(^\circ\)C (1,300\(^\circ\)F) as a function of diameter for cylindrical bars at four radial positions (surface, 3/4 radius, 1/2 radius, and center) for quenching in mildly agitated water and oil respectively; cooling rate is also expressed as equivalent Jominy distance, since these data

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\(^8\) Aqueous polymer quenchants [solutions composed of water and a polymer [normally poly(alkylene glycol) or PAG]] have recently been introduced that provide quenching rates between those of water and oil. The quenching rate can be tailored to specific requirements by changing polymer concentration and quench bath temperature.

Figure 9: Cooling rate equivalent as a function of diameter at surface, $\frac{3}{4}$ radius, $\frac{1}{2}$ radius, and center positions for cylindrical bars quenched in (a) mildly agitated water and (b) oil. Equivalent Jominy positions are included.

are often used in conjunction with hardenability curves. Note that in these figures the roll of the severity of the quenching medium; the higher the severity, the higher the hardness at a given radial position. Diagrams similar to those in Figure 8 have also been generated for geometries other than cylindrical (e.g., flat plates) and are available, in detailed form, elsewhere.

3.2 Specimen Size and Geometry

Typical laboratory samples are cylindrical; however, not all parts to be heat treated have that geometry. Therefore, relationships between a given position in the component and the equivalent Jominy bar position have been developed. Figure 10 shows the relation between the diameter of cylindrical bars at four radial positions (surface, $\frac{3}{4}$ radius, $\frac{1}{2}$ radius, and center) for quenching with diverse “H” quenching severities ranging for 0.20 (none agitated air) to 5.00 (violently agitated water). Figure 11 shows the relation between the center position of squares, 1 to 2 flats, and plates for ideal-, in water- and in oil quenching. Together, Figures 9, 10 and 11 server to select a specific steel alloy and design the corresponding quenching processes for diverse geometry components.

4 Properties of Tempered Martensite

Tempering martensite has a two-fold effect: a residual stress relieve effect and then a diffusional phase transformation effect. Although specifically described elsewhere, one can safely assume that tempering martensite will reduce hardness and strength as it recovers ductility and toughness.
Figure 10: Cooling rate equivalent as a function of diameter at (a) center positions, (b) \( \frac{3}{4} \) radius, (c) \( \frac{1}{2} \) radius, and (d) surface and diverse “H” quenching severities for cylindrical bars. Equivalent Jominy positions are included\(^8\).

Figure 11: Size for (a) squares, (b) 1 to 2 flats, and (c) plates at different “H” quenching severities as a function of equivalent Jominy positions\(^8\).
And, because machine steels always enter service in a Q&T condition (and other high alloy steels as well), it is customary to temper Jominy test specimens and report the corresponding hardness profile on the same plots. Note in Figure 12 the superposition of the “tempered” hardness profile in addition to the “as quenched” hardness profile for an AISI-SAE 4140 alloy. A series of Q&T Jominy curves are to be found in Appendix A.

Furthermore, a remarkable correlation exists in the constant relationship between hardness, tensile strength, yield strength, elongation, and reduction in area of quenched and tempered low alloy steel regardless of composition. This similarity prevails, provided that the steel is quenched to a fully martensitic structure prior to tempering, and the tensile strength does not exceed 1,400 MPa (200,000 lb/in$^2$). A plot of this relationship is shown in Figure 13. It should be recognized that other properties and distinctive characteristics may differ greatly between the respective alloy groups.

5 Using the Available Jominy Test Data hardness of at least 38 HRC

Assume that it is necessary to select a steel alloy for a gearbox output shaft. The design calls for a 1” diameter cylindrical shaft having a $3/4$ radius strength of 160 ksi and a minimum elongation, at $3/4$ radius, of 12%. How can an engineer go about the problem of specifying an alloy and treatment that meet these criteria?

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First of all, cost is also most likely an important design consideration. This would probably eliminate relatively expensive steels, such as stainless and those that are precipitation hardenable. Therefore, one can begin by examining plain-carbon and low-alloy steels, and what treatments are available to alter their mechanical characteristics. Furthermore, it is unlikely that merely cold-working one of these steels would produce the desired combination of hardness and ductility. For example, a hardness of 38 HRC for tempered martensite corresponds to a tensile strength of 160 ksi (110 MPa) (175 ksi). The tensile strength in medium carbon steels as a function of percent cold work for carbon steels, even at 50% CW, reach only about 900 MPa (130 ksi), and the corresponding ductility is approximately 10%. Hence, both of these properties fall short of those specified in the design.

Another possibility is to perform a series of heat treatments in which the steel is austenitized, quenched (to form martensite), and finally tempered. Let us now examine the mechanical properties of various plain-carbon and low-alloy steels that have been heat treated in this manner. To begin, the \( \frac{3}{4} \) radius hardness of the quenched material (which ultimately affects the tempered hardness) will depend on both alloy content and shaft diameter, as discussed in the previous sections.

Note the property combination of tempered martensite in Figure 13. A tensile strength of 160 ksi will produce an elongation better than 12%, and with a hardness of about 34-36 HRC, just what the specification establishes. Now, all that remains to be discovered is which of the available carbon- or low alloy steels will produce those properties at the lowest cost.

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From Figure 10 (b), and considering a moderately agitated oil quench (H=0.5), the corresponding Jominy position to the \( \frac{3}{4} \) radius position of a 1” round bar is 0.250”. Therefore, the task is to find an alloy which shows a Q&T hardness of at least 34~36 HRC at 0.250” along the Jominy bar.

From Appendix A it can be seen that the alloys which fulfill the 36 HRC at the 2\(^{nd}\) \( \frac{1}{16} \)” are 4140 & 4340. From these two steels, 4140 is by far less expensive as it does not contain Ni.

If a moderately agitated water quench (H=2.0) is acceptable, then the corresponding Jominy distance for the \( \frac{3}{4} \) radius position of a 1” cylindrical bar is 1/16” or less. In this case, the alloys which make the 36 HRC at the 1\(^{st}\) \( \frac{1}{16} \)” cut are also 4140 & 4340. Therefore, a 4140 steel quenched in a less severe medium, reducing distortion and propensity to cracking, should be the better answer.

Other alloys could do the job, however, the Q&T Jominy curves should be available.

6 Procedure\(^{12}\)

The Jominy end quench test should be performed with wrought or cast specimens.

6.1 The Specimen

Wrought end-quench specimens shall be prepared from rolled or forged stock and shall represent the full cross section of the product. If agreed, the end-quench specimen may be prepared from a given location in a forged or rolled product (or from a continuous cast billet). The test specimen shall be 1.0” (25.4 mm) in diameter by 4.0” (101.6 mm) in length, with means for hanging it in a vertical position for end quenching.

The specimen shall be machined from a bar previously normalized and of such size as to permit the removal of all decarburization in machining to 1.0” round. The end of the specimen to be water cooled shall have a reasonably smooth finish, preferably produced by grinding. Normalizing may be waived if material, in the as received condition, is annealed or normalized. In any case, the previous thermal history of the specimen tested shall always be recorded.

As cast end-quench specimens may be used for non-boron steels. Cast specimens are not suitable for boron steel grades due to erratic results. A graphite or metal mold may be used to form an overlength specimen 1.0” (25.4 mm) in diameter which shall be cut to the standard specimen size. The mold may also be used to form a 1.25” (31.8-mm) diameter specimen which shall be machined to the final specimen size. Cast samples need not be normalized.

6.2 Normalizing Procedure

The wrought product from which the specimen is to be prepared shall be normalized to ensure proper hardening characteristics. The sample shall be held at the temperature listed in Table 2 for 1 hr and cooled in air. Tempering of the normalized sample to improve machinability is permitted.

6.3 Austenitizing

Heating to austenitizing the specimen is done at the specified austenitizing temperature (Table 2). Holding time at this temperature should be 30 min. In production testing slightly longer times, up to 35 min, may be used without appreciably affecting results. It is important to heat the specimen in such an atmosphere that practically no scaling and a minimum of decarburization takes place. This may be accomplished by heating the specimen in a vertical position in a container with an easily removable cover containing a layer of cast-iron chips with the bottom face of the specimen resting on the chips.

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\(^{12}\) Adapted from: “Standard Test Methods for Determining Hardenability of Steel”, ASTM A255
<table>
<thead>
<tr>
<th>Steel Series</th>
<th>Ordered Carbon Content max %</th>
<th>Normalizing Temperature °C (° F)</th>
<th>Austenitizing Temperature °C (° F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000, 1300, 1500, 3100, 4000, 4100, 4300, 4400, 4500, 4600, 4700, 5000, 5100, 6100*8, 8100, 8600, 8700, 8800, 9400, 9700, 9800.</td>
<td>0.25 and under</td>
<td>925 (1,700)</td>
<td>925 (1,700)</td>
</tr>
<tr>
<td></td>
<td>0.26 to 0.36, inclusive</td>
<td>900 (1,650)</td>
<td>870 (1,600)</td>
</tr>
<tr>
<td></td>
<td>0.37 and over</td>
<td>870 (1,600)</td>
<td>845 (1,550)</td>
</tr>
<tr>
<td>2300, 2500, 3300, 4800, 9300</td>
<td>0.25 and under</td>
<td>925 (1,700)</td>
<td>845 (1,550)</td>
</tr>
<tr>
<td></td>
<td>0.26 to 0.36, inclusive</td>
<td>900 (1,650)</td>
<td>815 (1,500)</td>
</tr>
<tr>
<td></td>
<td>0.37 and over</td>
<td>870 (1,600)</td>
<td>800 (1,475)</td>
</tr>
<tr>
<td>9200</td>
<td>0.50 and over</td>
<td>900 (1,650)</td>
<td>870 (1,600)</td>
</tr>
</tbody>
</table>

A A variation of +/-6°C (+/-10°F) from the temperatures in this table is permissible.

B Normalizing and austenitizing temperatures are 30°C (50°F) higher for the 6100 series.

Other methods consist of placing the specimen in an appropriately sized hole in a graphite block or placing the specimen in an upright tube attached to a flat base, both of a heat-resistant metal, with the collar projecting for a tong hold. Place a disk of graphite or carbon, or a layer of carbonaceous material such as charcoal, in the bottom of the tube to prevent scaling.

For a particular fixture and furnace, determine the time required to heat the specimen to the austenitizing temperature by inserting a thermocouple into a hole drilled axially in the top of the specimen. Repeat this procedure periodically, for example once a month, for each combination of fixture and furnace.

### 6.4 End-Quenching

Adjust the water-quenching device so that the stream of water rises to a free height of 2.5” (63.5 mm) above the 0.5” (12.7-mm) orifice, without the specimen in position. The support for the specimen shall be dry at the beginning of each test. Then place the heated specimen in the support so that its bottom face is 0.5 in. above the orifice, and turn on the water by means of the quick-opening valve. The time between removal of the specimen from the furnace and the beginning of the quench should not be more than 5 s. Direct the stream of water, at a temperature of 40°F to 85°F (5°C to 30°C), against the bottom face of the specimen for not less than 10 min. Maintain a condition of still air around the specimen during cooling. If the specimen is not cold when removed from the fixture, immediately quench it in water.

### 6.5 Hardness Measurement

Two flats 180° apart shall be ground to a minimum depth of 0.015” (0.38 mm) along the entire length of the bar and Rockwell C hardness measurements made along the length of the bar. Shallower ground depths can affect reproducibility of results, and correlation with cooling rates in quenched bars.

The preparation of the two flats must be carried out with considerable care. They should be mutually parallel and the grinding done in such a manner that no change of the quenched structure takes place.
Figure 14: Typical hardenability chart.

Very light cuts with water cooling and a coarse, soft-grinding wheel are recommended to avoid heating the specimen. In order to detect tempering due to grinding, the flat may be etched with the following procedure:

a) Wash the sample in hot water.
b) Etch in a 3-5 % nitric acid (concentrated) and water solution until black.
c) Wash in hot water.
d) Immerse in a 4-50 % by volume hydrochloric acid (concentrated) and water solution for 3 s.
e) Wash in hot water.
f) Dry in air blast.
The presence of lighter or darker areas indicates that hardness and structure have been altered in grinding. If such changes caused by grinding are indicated, new flats may be prepared.

When hardness tests are made, the test specimen rests on one of its flats on an anvil firmly attached to the hardness machine. It is important that no vertical movement be allowed when the major load is applied. The anvil must be constructed to move the test specimen past the penetrator in accurate steps of \( \frac{1}{16}'' \) (1.5 mm). Resting the specimen in a V-block is not permitted.

Hardness readings shall be taken in steps of \( \frac{1}{16}'' \) (1.6 mm) for the first 16 sixteenths (25.4 mm), then 18, 20, 22, 24, 28, and 32 sixteenths of an inch. Values below 20 HRC are not recorded because such values are not accurate. When a flat on which readings have been made is used as a base, the burrs around the indentation shall be removed by grinding unless a fixture is used which has been relieved to accommodate the irregularities due to the indentations.

Hardness readings should preferably be made on two flats 180° apart. Testing on two flats will assist in the detection of errors in specimen preparation and hardness measurement. If the two probes on opposite sides differ by more than 4 HRC points at any one position, the test should be repeated on new flats, 90° from the first two flats. If the retest also has greater than 4 HRC points spread, a new specimen should be tested.

6.6 Reporting End-Quench Test Results

For reporting purposes, hardness readings should be recorded to the rounded integer. Test results should be plotted on a standard hardenability chart prepared for this purpose, in which the ordinates represent HRC values and the abscissae represent the distance from the quenched end of the specimen at which the hardness determinations were made. When hardness readings are taken on two or more flats, the values at the same distance should be averaged and that value used for plotting. A facsimile of the standard ASTM hardenability chart on which typical hardenability curves have been plotted is shown in Figure 14.
Appendix A: Q&T Jominy Curves for Selected Low Alloy Steels\textsuperscript{13}

1045

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{Type} & \textbf{Chemical Analysis} & \textbf{Mn} & \textbf{Si} & \textbf{S} & \textbf{Cr} & \textbf{Ni} & \textbf{Mo} & \textbf{Cu} & \textbf{Al} & \textbf{V} & \textbf{W} & \textbf{B} \\
\hline
\textbf{1045} & \textbf{AUSTENITIZED 1600° F.} & & & & & & & & & & & \\
\hline
\textbf{OIL QUENCH} & 4-5 Hr & 1 & 2 & 3 & 4 & 5 & 6 & 6' & 6" & & & \\
\hline
\textbf{MILD WATER QUENCH} & & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 6' & 6" & 6' & 6" & 6' & 6" & 6' & 6" \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{1045_curve}
\end{figure}

1340

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|c|}
\hline
\textbf{Type} & \textbf{Chemical Analysis} & \textbf{Mn} & \textbf{Si} & \textbf{S} & \textbf{Cr} & \textbf{Ni} & \textbf{Mo} & \textbf{Cu} & \textbf{Al} & \textbf{V} & \textbf{W} & \textbf{B} \\
\hline
\textbf{1340} & \textbf{AUSTENITIZED 1500° F.} & & & & & & & & & & & \\
\hline
\textbf{OIL QUENCH} & 4-5 Hr & 1 & 2 & 3 & 4 & 5 & 6 & 6' & 6" & & & \\
\hline
\textbf{MILD WATER QUENCH} & & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 6' & 6" & 6' & 6" & 6' & 6" & 6' & 6" \\
\hline
\end{tabular}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{1340_curve}
\end{figure}

8640

<table>
<thead>
<tr>
<th>TYPE</th>
<th>HEAT TREATMENT</th>
<th>CHEMICAL ANALYSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>8620</td>
<td>NORMALIZED 1700° F. — AUSTENITIZED 1700° F.</td>
<td>C 0.20  Mn 0.85  P 0.010  Si 0.14  S 0.10  Cr 0.50  Ni 0.01  Mo 0.09  Cu 0.09  Al 0.31  V —  W —  B —</td>
</tr>
</tbody>
</table>

ROUND SECTION WITH SAME HARDNESS AT MID-RADIUS

As-Quenched 8640

4340

<table>
<thead>
<tr>
<th>TYPE</th>
<th>HEAT TREATMENT</th>
<th>CHEMICAL ANALYSIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>4340</td>
<td>HOT ROLLED — AUSTENITIZED 1600° F.</td>
<td>C 0.41  Mn 0.74  P 0.014  Si 0.15  S 0.30  Cr 0.72  Ni 1.75  Mo 0.26  Cu 0.13  Al —  V —  W —  B —</td>
</tr>
</tbody>
</table>

ROUND SECTION WITH SAME HARDNESS AT MID-RADIUS

As-Cooled 1000° F. TEMPER-2 HOURS
SAE HARDENABILITY BAND
AUSTENITIZING TEMPERATURE 1600° F.
Annex B: Numerically estimating the as quenched and tempered Jominy test results

Reference Material