Hardenability of Steel: the Jominy Test

Andrew Ruble
Department of Materials Science & Engineering
University of Washington
Seattle, WA 98195

Abstract

Controlling a material's properties during processing is pivotal for any engineering field. A specific hardness for a metal is often a desirable characteristic for many applications, so controlling hardness is important during processing. To increase the hardness of steel, it is often quenched from a high temperature to form martensite, a hard yet brittle phase of iron. The extent of martensite formation, including hardness and depth of formation, is known as hardenability. This module provides a classroom lesson and a lab experiment for measurement of hardenability in a high-carbon steel according to, the Jominy End-Quench Test , (ASTM A255 – 10). The demonstration exercise involves quenching one end of a heated steel sample and comparing evaluating the hardness distribution using measurements obtained at different locations on the sample surface.

Module Objectives

- Introduce students to the concepts of hardenability
- Demonstrate hardenability in a steel
- Display the effects on microstructure of the hardening process
- Provide instruction for a full lab experiment on hardenability (if equipment is available)

Student Learning Objectives The student will be able to

- Define hardenability and its importance in processing
- Determine a metal's hardenability with the Jominy End-Quench Test
- Create and interpret a hardenability curve

MatEd Core Competencies Covered

- 0.B Prepare Tests and Analyze Data
- 1.C Demonstrate Laboratory Skills
- 7.A Identify the General Nature of Metals
- 7.J Demonstrate How Materials Properties are Used in Engineering Design
- 8.A Demonstrate the Planning and Execution of Materials Experiments
- 8.E Perform Appropriate Tests of Metallic Materials
- 9.A Define and Describe Constituents, Properties and Processing of Steel
- 17.B Describe Techniques used for Metals Processing

Key Words: Hardness, Hardenability, Jominy test, Quench, Steel

Type of Module: PowerPoint presentation with discussion and lab or in-class demonstration depending on availability of equipment

Time required: two 50 min sessions if the lab is undertaken; one session for the in-class presentation

Suggested prerequisite MatEdu modules:

1. Introduction to Hardness
2. Iron and Steel: Properties and Applications
3. Phase Change Experiment

Target grade level: Advanced High School, Introductory College/Technical School

Equipment and Supplies for the demo and lab:

- PowerPoint projection system
- Electric Furnace at least 5" tall, capable of 1100° C
- Metal tongs, protective gloves, face shield (depending on furnace)
- Water-quenching device and apparatus for holding specimen (see appendix for diagrams of a simple apparatus that can be built by students)
- Jominy samples – 1" diameter by 4" length cylinders from www.laboratorydevicesco.com or similar
- Chop saw
- Belt grinder
- Rockwell Hardness Tester

Table of Contents:

Curriculum Overview

As iron is processed, certain elements are added to achieve specific mechanical properties. The iron may also undergo quenching, a heating and rapid cooling process, that is performed to increase hardness. When heated and rapidly cooled in a quench, steel will form a phase known as martensite, which has high hardness. Hardness is also inversely proportional to the grain size of a metal, which is a large factor in determining other characteristics as well. Because of this, hardness can be used to anticipate these other characteristics. For example, as hardness increases, so does tensile strength. Through the application of selected processing steps, Manipulating the hardness of a metal during processing can help improve can be controlled or improved to adjust these characteristics of the metal as appropriate for the application.

Iron alloys vary on the amount of martensite that can be formed due to differences in alloying elements, so the idea of hardenability was developed. Hardenability is the ability of a metal to improve hardness and martensite formation through quenching. The extent of martensite formation in the steel at given distance from the quench, which can be determined by hardness testing in several areas of a sample, is what hardenability measures. Hardenability also determines the necessary cooling rate, fast or slow, for martensite formation.

The Jominy End-Quench test determines hardenability of any variety of steel, and is straightforward due to its simplicity and minimization of variables. The size and shape of the sample are standardized as well as the quench process, so the extent of martensite formation can be compared quantitatively between different steels. And since steels have similar thermal conductivity, the distance from the quenched end correlates to a certain cooling rate. Knowing this, the hardness of a metal cooled at a given cooling rate can be accurately predicted from the Jominy test results.

The PowerPoint presentation reviews the experimental procedures, which are summarized below.

<u>Test Procedure</u>

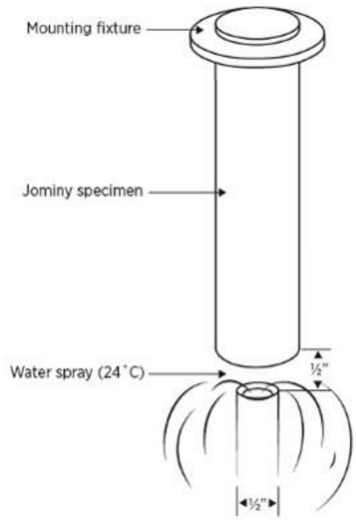

Figure 1: The setup of the Jominy End-Quench test

The procedure for the Jominy End-Quench test is as follows: place the Jominy sample upright in a 1000° C furnace for 30 minutes to create a phase known as austenite completely through the sample. Before removing the sample from the furnace, prepare the water for the quenching the end of the sample in the Jominy setup. The water spray should extend vertically 2.5" without the sample in place, and the bottom of the sample should be 0.5" above the water opening. Remove the sample using extreme caution and place it into the mounting fixture, as seen in figure 1, taking no longer than 5 seconds for the transfer. Apply water for at least 10 minutes, and if the sample is still warm, place sample in room temperature water until cool.

The next task is to measure the hardness of the sample. Using the chop saw, cut the cap from the sample to create cylinder and mark the top. Create a flat edge, using a grinder, at least 0.015" deep running along two opposite sides of the cylinder, as seen in figure 2. Grind at a low speed setting to avoid creating too much heat, as heating may change the material properties achieved during the quench; this should be accompanied by water spray to keep the sample cool.

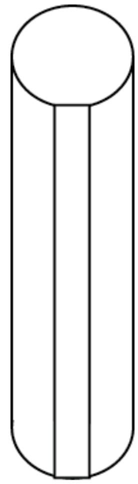

Figure 2: Grind a flat edge running along the side of the cylinder on each side.

Using the Rockwell Hardness measurement equipment with diamond braille indenter (Scale C), take measurements from the end at 1/8th inch increments up to 1/2 inch, then 1/4 inch increments up to 2 inches. Round each hardness value to the nearest integer, and discard any values near the end that seem especially low since oxidation has occurred and will affect hardness. Each hardness data point should be plotted vs. the distance from the quench, which correlates to a certain cooling rate for steel, as shown in Table 1.

Table 1: Cooling rates associated with distance.

Inches	°F/s	°C/s
1/8"	305	170
1/4"	125	70
3/8"	56	31
1/2"	33	18
3/4"	16.3	9
1"	10	5.6
1 1/4"	7	3.9
1 1/2"	5.1	2.8
2"	3.5	2

The final graph will look like figure 3, which has some sample data for different steels. As shown, 4340 steel has high hardenability, maintaining a higher hardness even an inch away from the quench. This indicates that martensite formation is prevalent and will happen even at slow cooling rates. Conversely, 1040 steel requires a quick quench for martensite formation; even the fastest quench cannot match the martensite formation of 4340 steel.

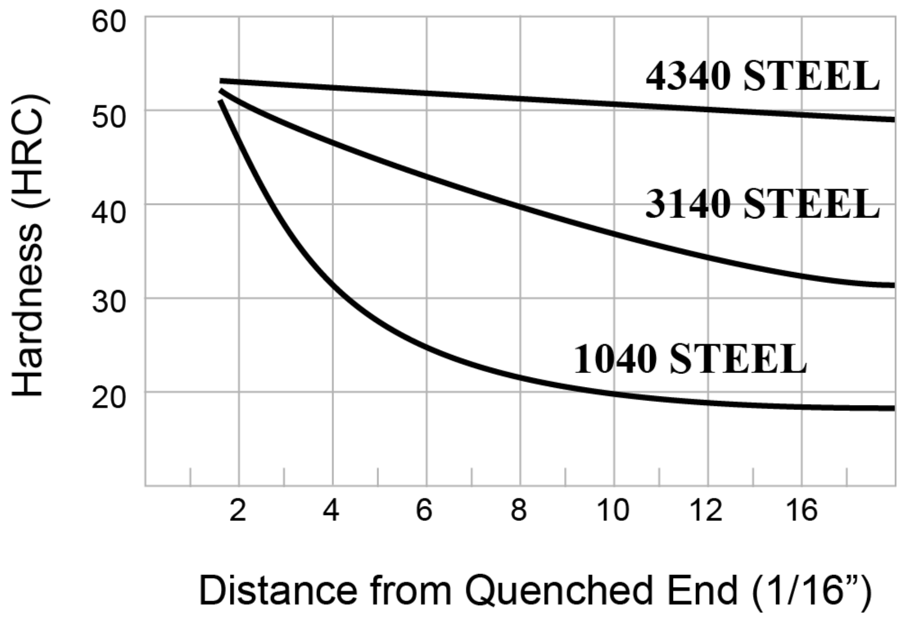

Figure 3: A sample graph of hardenability for three different steels. The graph plots the hardness measurements as a function of distance from the quenched end as obtained from the Jominy test.

Module Procedure:

1. Discussion
    1. **When is hardness important?** Hardness indicates resistance to deformation, so anytime a load is applied, hardness is important. When we think of hardness we usually think about a hammer or a knife, but resistance to deformation is important for beams and structures as well. Hardness values can correlate to other properties like tensile strength.
    2. **Planning hardness** – When producing an engineering component for an application, the final product's hardness requirements need to be met during processing. We might need to perform tests on the metal or use known values of similar metals that were achieved through specific processing steps.

2. Show the PowerPoint presentation and discuss each slide.
    1. "Hardness" – As mentioned in discussion, hardness can be desirable for a metal. A steel's hardness depends on many factors, mostly its phase (which depends on the alloy content and processing), as well as grain size. When steel is rapidly cooled or quenched and has sufficient carbon content, the

iron forms a phase known as martensite, which has a high hardness. The hardness is also indicative of tensile strength values.

2. “Jominy” – In order to better plan material processing, a test has been created to see how well a metal’s hardness increases when quenched. This test has been “standardized” and uses a uniform size sample of different metals, heated and then quenched on one end. Afterwards, hardness tests are performed on the sample as a function of distance from the quenched end.
3. “Quench and Cooling Rate” – Martensite only forms if the steel is cooled quickly enough, and the necessary cooling rate varies between different steels. The Jominy sample is quenched at one end, and the distance from the quench correlates with a specific cooling rate.
4. “Hardenability” – The ability for steel to form martensite at different cooling rates. Hardenability represents the ease of martensite formation or the necessary cooling rate, as it is easier to cool slowly. This helps metallurgists create the proper procedures needed for the engineer to achieve the desired properties for a component. Hardenability is shown as a curve of hardness plotted against cooling rate.
5. “Procedure Pt 1” – The procedure for the Jominy experiment is as follows: The sample is heated in a furnace at 1000 degrees C for the 30 minutes, then placed into the special Jominy fixture with water running. After 10 minutes, if the sample is not cool, place in water to finish cooling.
6. “Procedure Pt 2” – Once cooled, chop off the cap of the sample from the top, marking the top end for reference. Using a grinder, grind a flat edge on opposite sides of the sample, being careful to grind at slow speeds and cooling with water to avoid heating the sample enough to cause changes in the sample. Once flat, perform hardness testing on the flat edges.
7. “Results” – Plotting hardness against quenched end distance shows hardenability curves for the sample. Note that the 4340 Steel data shows that it can be cooled slowly and still form martensite while 1040 steel needs to be cooled rapidly to form martensite. This shows that 4340 has a higher hardenability.
8. “Microscopy” – Grain size is a contributing factor to hardness and hardenability. Micrographs can be taken and grain size measured for another quantitative test. Here are some sample micrographs. Examine the grain size in each picture. What does the hardenability curve look like for this metal? Is it a horizontal line or does it have a negative slope? The slides show an increasing grain size, which means hardness would be decreasing with distance, so it would have a negative slope.
9. “Jominy Review” – In review, the Jominy test shows how different metals behave when quenched, and their ability to increase hardness. Useful because even though steel is very similar with iron and carbon, small alloying elements can have a big change.

References and Materials for Further Study

1. Jominy Test ASTM A255 - http://www.astm.org/Standards/A255.htm
2. "Jominy End Quench Test" University of Cambridge DoITPoMS - http://www.doitpoms.ac.uk/tlplib/jominy/index.php
3. Hardenability – "https://en.wikipedia.org/wiki/Hardenability"
4. "New Science of Strong Materials" by J.E. Gordon. Princeton University Press, 2006.

Further Questions and Thoughts

1. Does it take more effort to cool something quickly or slowly? Why?

Optional:

Lab report - Have students create a report, discussing hardenability including details from the lab (or sample data) and conclusions from the results.

Jominy Sample Data		
	Hardness, Rockwell C	
Distance (in)	**4140**	**1045**
1/8	56	54
1/4"	55	30
3/8	52	28
1/2	51	27
3/4	48	24
1	46	23
1 1/4	43	19
1 1/2	40	15
1 3/4	38	15
2	34	13

Evaluation

Student evaluation (discussion/quiz)

1. Why is hardness important?
2. What is hardenability? Where is it used in industry?
3. Do all steels have the same hardenability? Why or Why not?
4. How does the hardness change as a function of distance from the quenched end?
5. How does grain size relate to hardness? What would a graph of grain size as a function of distance look like?

Instructor evaluation

1. What grade level and class was this module utilized for?
2. Were the students able to grasp the key concepts introduced in the module?
3. Was the level and rigor of the module acceptable for the grade level of the students? If no, how can it be improved?
4. Was the demonstration/lab work as outlined? Did it help the students in learning the material? Were there any problems encountered?
5. Was the background on hardenability sufficient for your understanding and for the discussion with the students?

Any comments and/or suggestions on improving this module are encouraged.

Course evaluation questions

1. Was the demonstration/lab clear and understandable?
2. Was the instructor's explanation comprehensive and thorough?
3. Was the instructor interested in your questions or concerns?
4. Was the instructor able to answer your questions thoroughly and to your satisfaction?

Acknowledgments

The author wishes to thank Professor Tom Stoebe for developing and editing this module, as well as the Materials Science and Engineering department at the University of Washington.