

THE HARDENABILITY OF STEEL

Introduction

Maximum Hardness: Maximum hardness in steels is obtained by producing a fully martensitic structure. This can be done by austenitizing the steel and then quenching it. During the austenitizing treatment all of the carbides dissolve and the ferrite transforms into austenite. Quenching this structure causes the austenite to transform via a shear mechanism into martensite. This transformation is so fast (Martensite needles grow at close to the speed of sound.) that there is no time to the carbon to diffuse out of the martensite grains or to form carbide phases. The martensite, supersaturated with carbon, is very hard and also very brittle.

Carbon, being a very effective solid solution strengthening agent, essentially determines the hardness of the martensite. Cases where a lesser degree of hardening can be attributed to the presence of other alloying elements, but these elements tend to also make it more difficult to obtain a fully martensitic microstructure. So while maximum hardness in a given steel is dependent on our ability to produce a fully martensitic microstructure, the hardness of the martensite is largely determined by its carbon content.

Hardenability: In order to form a fully martensitic structure the steel must be quenched at a rate that is equal to or greater than a critical cooling rate. If the quench is indeed fast enough and the part is thin then one can usually assume that this cooling rate can be achieved through the whole cross-section, producing a fully hardened part. However, this may not be the case for thick sections because the interior cools more slowly than the surface. But if one could modify this steel such that critical cooling rate is lower then thick pieces can be hardened throughout and even thicker pieces can be hardened to a considerable depth. This is of great practical importance not only in terms of our ability to produce a fully hardened part (which will also be fully brittle) but because subsequent tempering will be successful in producing the desired strength and ductility throughout the part. In addition, one could use less severe quenches to avoid problems with warping and cracking.

This ability of a steel to be hardened to a specified depth is called hardenability. In general, the hardenability of a steel is improved through alloying and all alloy additions except cobalt will improve the hardenability of a steel. Coarse grain size and homogeneity of the austenite also improve the hardenability. The reason this is so is not clear but is probably related to the retardation of nucleation and growth of the ferrite, carbide and bainite phases.

Jominy End-Quench: The most direct measure of the hardenability of a steel is the “critical cooling rate”. Hardenability is also demonstrated in cases where large part fails to fully harden. One can measure this in terms of the depth of full hardening, the diameter of bar which will just harden to the center and the depth where the microstructure consists of 50% martensite. A more convenient and very widely used method of measuring hardenability is the Jominy end-quench test. (Developed by Jominy and Boegehold in 1939, standardized in ASTM A255.) In this test a 1-inch diameter by 4-inches long bar is austenitized then quickly removed from the furnace and placed in a fixture where a jet of water of specified temperature and pressure impinges on one end of the specimen. Once cool, the specimen is removed, cleaned, a flat is ground along the length of the specimen and then is hardness tested every 0.0625 to 0.25 inches from the quenched end. The result is a plot of

hardness versus distance from the quenched end. This curve is used to compare the hardenabilities of different steels.

Ideal Diameter: The ideal diameter D_I is another measure of the hardenability of steel. It is defined as the diameter of a bar which would contain 50% martensite at its center following a quench in an ideal medium. Clearly, the larger the ideal diameter, the higher the hardenability of the steel. The ideal diameter of a plain carbon steel having a carbon content of 0.4% (1040 steel) and whose ASTM grain size number is 7 is 0.215 inches. Naturally, varying the grain size or changing the concentration of alloying elements will change the ideal diameter. An empirical method of accounting for these effects is utilizes a series of multiplying factors:

$$D_I = D_{I,base} f_{Mn} f_{Si} f_S f_P f_{Cr} \dots$$

where the base ideal diameter is a function of grain size and carbon content and the multiplying factors f_i are function of composition of element I . The ideal diameter for a 4340 steel (0.8 Cr, 1.75 Ni, 0.25 Mo) is over 6 inches.

The objective of this experiment is the measure the hardenability of several plain carbon and low-alloy steels. The results will be used to explain the influence of alloy composition on the kinetics of martensite formation. They will also be compared to the calculated values of the ideal diameter.

Safety Considerations

This experiment involves heating several steel rods to as high as 875°C, quickly taking them out of the furnace and loading the hot specimens into a quenching fixture and then quenching the specimen. After this the specimens are ground flat along several sides and hardness tested along the length of the specimen. Extreme care should be exercised during the heat treating phase of the experiment as the temperatures are quite high and therefore pose severe burn hazards to personnel and fire hazards to the building. Grinding will be done by technicians in the machine shop so this will not be an issue during this experiment. Hardness testing, however, involves the use of a special fixture and a diamond brale indenter. One should be very careful when using this fixture and the brale indenter so that neither are damaged.

Chemical Hazards

None. No chemicals are used and the specimens are 1-inch diameter rods made from conventional steels.

Physical Hazards

1. The potential for very serious burns exists. Temperatures approaching 900°C are used during these experiments. At these temperatures one can easily be burned while loading and unloading specimens from the furnaces, even if the hot specimens and furnace are not touched. It will be important to wear heat resistant gloves and to use long tongs. One should also take care to prepare a clear area to work, have an emergency procedure in place in case hot specimens are dropped on the floor, etc. It would be a good idea to rehearse the procedures for handling hot specimens.

2. Hardness testing poses very little hazard if proper testing procedures are followed. Using the proper anvil and indenter and a clean specimen will minimize the chance

of damaging the equipment or injuring personnel.

Biohazards

None.

Radiation Hazards

None.

Protective Equipment

Recommended: The use of safety glasses is recommended during the hardness testing phase of the experiment. The use of protective coverings for the floor and counter tops is also recommended.

Required: safety glasses, heat resistant gloves and long tongs for the heat treatment phases of the experiment.

Waste

Used specimens can be recycled as scrap steel.

Materials

The alloys used in this experiment are standard grades of the following steels: 1045, 4140, 4340 and 8620. Several have the same carbon content but have different concentrations of the other alloying elements. The specimens are standard Jominy specimens, 1 inch in diameter and 4 inches long with a flat washer pressed onto one end. (This washer can be removed after quenching.) One the end which has the washer a single letter which identifies the steel by composition has been stamped. During the austenitizing treatment this stamp will probably be lost due to oxidation or carburization. A more substantial marking should be used.

Procedure

1. Preliminary

Obtain a copy of ASTM A255 and read it.

Consult the reference books and databases to find out what the ideal diameters for the steels being tested are.

Calculate the ideal diameters and the Jominy curves for your steels.

List the nominal compositions of each of the alloys. Mark, engrave or notch each specimen so that they can still be identified after having spent an hour or so in the furnace.

2. Prepare the Jominy quench tank

Set up the quench tank over a sink and connect a hose to the faucet. Place a specimen in the quench tank. Open the valve on the quench tank and, using the valve on the faucet, adjust the flow of water so that the height of the column of water is $\frac{1}{2}$ -inch above the bottom of the specimen. Close the valve on the quench tank but do not adjust the valve on the faucet.

3. Austenitizing Treatments

Preheat a furnace to 850°C and place the specimens in a container filled with graphite and place this

in the furnace. Allow the specimens to soak at this temperature for one hour.

4. Prepare to quench the specimens

The purpose here is to prepare the work area for handling red-hot steel safely. Start by clearing a path between the furnace and the Jominy quench tank. Next, devise a plan for dealing with accidents such as dropping a hot specimen on the floor. Collect up gloves, tongs and safety equipment that will be used to move the specimens to the quench tank. Decide who will remove the specimen from the furnace and place it in the quenching fixture, who will assist in pushing the specimen through the hole in the quenching fixture (if necessary), who will turn on the water, who will monitor the time it took to start the quench, and who will execute the emergency procedures. Rehearse the procedure several times using a cold specimen.

5. Quench the Specimens

Clear a path between the furnace and Jominy quench tank. Quickly but carefully remove a specimen from the furnace and place it in the quenching fixture and immediately turn on the water using the valve on the quench tank. Continue the quench until the specimen is cool enough to handle using bare hands. Remove the specimen from the fixture and engrave or paint an ID code on it.

6. Hardness test the specimens

Clean the specimens and grind a flat surface 0.015 inches deep along four sides (90° apart) of the specimen. This will have to be done in the machine shop.

Set up a Rockwell-type hardness tester for measuring hardness values on the C scale. Hardness test a couple of test blocks to make sure everything is working properly. Install the Jominy hardness testing fixture.

Take a hardness reading every 1/16 inch from the quenched end of the specimen. After the first 1/2 inch increase this interval to 1/8 inches and after the first full inch increase the interval to 1/4 inches. Repeat this procedure for each of the flats on the specimen and then plot each of the four sets of results on a single graph.

Analysis

1. Compare the results (maximum hardness and the hardenability curves) with published data.
2. Compare the results with the calculated Jominy curves and ideal diameters.
3. Compare the maximum hardnesses obtained for the four alloys.
4. Compare the Jominy curves to the ideal diameters.
5. Discuss the differences in the hardenabilities of the four alloys. You can use depth to obtain a specified hardness value or the inflection point on the curves as your basis for comparison.
6. Discuss the results in terms of composition and the TTT curves.

References and Further Reading

1. E.C. Bain and H.W. Paxton, Alloying Elements in Steel, ASM, Metals Park, OH, 1966.
2. Properties and Selection: Irons and Steels, Metals Handbook, volume 1, 9th edition, ASM,

- Metals Park, OH, 1986.
3. Atlas of Isothermal Transformation and Cooling Transformation Diagrams, ed. H.E.Boyer, ASM, Metals Park, OH, 1977.