EMSE-290
Materials Laboratory III

Phase Transformations and Hardenability of Steel

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1 Overview

Steel can be engineered to display an amazingly wide range of mechanical properties. One the one hand, it can made as a soft, ductile material, capable of being stamped into complex shapes (auto body parts, for example) at room temperature. On the other hand, steel can be made as a practically unyielding (and yet flexible) material, useful, for example, as cutlery or springs. The properties of steel not only depend on its composition, but are determined to a large extent by the relative volume fractions of particular phases and their dispersion within the material – a result of the material's *thermal history*[1]. It is this *combined* influence of composition and thermal history on the microstructure and the mechanical properties of steel that we will investigate.

For this purpose, we will expose a suite of four different steels with different compositions to the same heat treatments and then analyze their microstructure measure their hardness, which is directly related to the mechanical strength. The experiment has two parts. In part I, we will perform Jominy end-quench tests in order to generate locally different thermal histories in one piece of material. In part II, we will simulate industrial practice by adjusting the quenching rate after annealing via the composition of the cooling agent (air, oil, water, brine).

The order in which the two parts are carried out is not important. However it shall be recognized that the results of the two parts correspond to each other.

2 Part I: Phase Transformations in Steels

2.1 Objective

The objective of this part of the experiment is to examine the decomposition of austenite as a function of cooling rate, and to examine the decomposition of martensite as a function of temperature in plain-carbon steels (1018 or 1045) and alloy steels (4140 or 4340).

2.2 Equipment and Materials

- 11 specimens of each alloy composition.

[1] The mechanical history is also important, but not considered here.

- Furnaces set to each of the following temperatures: on 900, 200, 400, and 700 °C.
- A salt, lead bath, or fluidized bed at 350 °C.
- A bucket of water for quenching.
- Polishing and etching equipment.
- A Optical microscope.
- A Rockwell hardness tester.

2.3 Procedure

1. Heat 10 specimens of each composition to 900 °C for 1 h.
2. Quench 7 specimens in water.
3. Quench one specimen from the austenizing furnace into the bath at 350 °C and keep it there for 3 h.
4. Take one specimen out of the furnace and allow to cool in room air.
5. Leave two specimens in the furnace by simply switching off the power. **Do not remove the sample from the furnace until the temperature has dropped below 500 °C.**
6. Reheat three of the water-quenched specimens for 1 h at 200, 400, and 700 °C, respectively.
7. Reheat one of the water-quenched specimens for 24 h at 700 °C.
8. Examine the microstructure of each specimen and measure its Rockwell hardness. Use scale "C" when possible, "B" when necessary. For all specimens, note the nature and extent of microstructural changes near the surface. These changes originate from decarburization. Therefore, you should make sure that the microstructural changes you report are actually those characteristic of the bulk and not an artifact of surface decarburization.

2.4 Observations

1. Tabulate measured hardness values against different cooling rates from the austenizing temperature.
2. Tabulate measured hardness values for different tempers.
3. Describe the microstructure in each case.
4. Prepare a representative photomicrograph for each specimens examined. Be sure to employ an appropriate magnification, such that the field of view includes all characteristic features.

2.5 Questions to be Discussed in the Report

1. How does the hardness vary with the cooling rate for the alloys studied?
2. How do the microstructures observed compare with the "standard" microstructures of coarse pearlite, fine pearlite, bainite, martensite, and tempered martensite?
3. How does the hardness of very with the annealing temperature and the time?
4. How does the measured hardness of the specimen annealed at 700 °C compare to that of the furnace-cooled specimen?
5. For applications that require machining, a tempered steel is preferred to a furnace-cooled material. Can you explain this from the observed microstructures?
6. Why is it necessary to effect the transfer from the annealing furnace to the quenching medium *quickly*? How quick is quick enough?
7. How do your measured hardness values compare to published data?

3 Part II: Hardenability of Steels

3.1 Objective

The objective of this part is to examine the hardenability of both plain-carbon and alloy steels, and to gain familiarity with the execution of the Jominy end-quench test.

3.2 Equipment and Materials

- One Jominy test bar for each one of the four different steels.
- A Jominy quenching tank.
- Tongs.
- A furnace operating at 900 °C.
- A Rockwell hardness tester.
- Metallographic polishing equipment.
- A light optical microscope.

3.3 Procedure

1. Place the sample in a furnace at 900 °C.
2. Adjust the water flow rate such that the water column is approximately 16.5 cm above the end of the pipe when the water flow is unobstructed.
3. After the sample has come to temperature (after 15 min or longer), remove the sample from the furnace and promptly place it directly into the quenching fixture. Immediately start the water flow, such that it impinges on the bottom of the hot bar at the preset flow rate.
4. After the entire sample has cooled to room temperature, turn of the water. Grind off the oxidation scale to obtain a flat surface, which can be polished, metallographically etched and examined, and used for hardness testing.
5. Etched the polished surface and metallographically examine it in a light-optical microscope. Note the microstructural changes along the entire length of the bar. For each one of the four steels, describe the microstructure and its variation along the polished surface, and prepare a representative photomicrograph.Be sure to employ a magnification that insures that the field of view includes the typical elements of the microstructure.
6. Measure the hardness as a function of the distance from the quenched end. Use increments no coarser than 0.2 mm ($^1/_8$ in) for the first inch and 0.5 mm ($^1/_4$ in) from that point on.

3.4 Questions to be Discussed in the Report

1. How does the measured hardness correlate with the microstructure observed?

2. Can you correlate the results of the Jominy end-quench test to published TTT and CCT curves?

3. Can you relate the results of the Jominy end-quench test to the results from Part I this experiment?

4. Explain how the results of the Jominy test could be extended to other specimen geometries and other quenching media (oil, for example).

5. From the literature or information available on the internet, provide five applications quench hardened steels cite the reference for each one.

4 References

The backgound of the experiment is found in any of the materials science texts recommended for EMSE 201 ([3, 2, 10]. Any other general textbook on materials science and engineering or physical metallurgy ([**?**, 6], recommended) would do equally well. Investigate sections on the iron–carbon phase diagram, TTT and/or CCT curves, hardenability, and Jominy tests. The well-known textbook [7] as well as reference [9] focus on phase transformations, while [4] stresses their metallographic appearance. References [1] and [5] present data for a variety of steels.

References

[1] M. Atkins. *Atlas of Continuous Cooling Transformation Diagrams for Engineering Steels*, volume revised US edition. American Society for Metals, Metals Park, Ohio, 1980.

[2] W. D. Callister. *Materials Science and Engineering*. John Wiley and Sons, New York, 5 edition, 1999.

[3] W. D. Callister. *Materials Science and Engineering*. John Wiley and Sons, New York, 6 edition, 2002.

[4] G. A. Chadwick. *Metallography of Phase Transformations*. Crane, New York, 1972.

[5] G. F. Van der Voort, editor. *Atlas of Time-Temperature Diagrams for Irons and Steels*. ASM International, Materials Park, Ohio, 1991.

[6] P. Haasen. *Physical Metallurgy*. Cambridge University Press, New York, 2 edition, 1987.

[7] David A. Porter and K. Easterling. *Phase Transformatins in Metals and Alloys*. Chapman and Hall, New York, 2 edition, 1992.

[8] R. E. Reed-Hill. *Physical Metallurgy Principles*. Van Nostrand, Princeton, 2 edition, 1972.

[9] P. G. Shewmon. *Transformation in Metals*. McGraw Hill, New York, 1969.

[10] W. F. Smith. *Principles of Materials Science and Engineering*. Cambridge University Press, New York, 3 edition, 1987.