Massachusetts Institute of Technology
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2.002 Mechanics and Materials II

Laboratory Module No. 5 – Heat Treatment of Steels

Heat Treatment of Low-alloy Steels: Effects on Macroscopic Mechanical Properties.

1 Overview and Objectives

Iron is one of the oldest known metals, and carbon is the cheapest and most effective alloying element for hardening iron. Iron-Carbon alloys are known as **carbon steels** and account for more than 70% of the tonnage of metallic materials used in the United States for engineering applications.

The carbon content in steels ranges from 0.04 to 2 wt%. The microstructure and resulting mechanical properties of these steels are amenable to modification via **heat treatment**, and a wide range of mechanical properties can be obtained by proper variations of heating and cooling cycles.

Modest amounts (up to a few wt.% each) of costlier alloying elements such as manganese (Mn), molybdenum (Mo), chromium (Cr), and nickel (Ni) can be added to the composition, resulting in **low-alloy** steels that possess additional desirable properties, including attainability of high strength and good ductility in larger sections.

In this laboratory module we will demonstrate the essential steps involved in the heat treatment of a medium carbon AISI[1] 4140 steel (0.4C, 0.75Mn, 0.8Cr, 0.15Mo wt.%), and measure macroscopic mechanical properties of the materials after different heat treatments, noting trends and correlations in the resulting mechanical behaviors.

[1]AISI: American Iron and Steel Institute.

2 Laboratory Tasks

In this laboratory module we will perform the following tasks:

- Briefly review the essential steps of **austenitizing**, **quenching**, and **tempering** involved in the heat treatment of steels, along with a brief discussion of the differing microstructural features which these processes create in the steel.
- Conduct **austenitizing**, **quenching**, and **tempering** heat-treating procedures on the AISI 4140 steel.
- Conduct mechanical tests on specimens of 4140 steels which have been subjected to three different heat treatment procedures:
  1. Austenitized and furnace-cooled ("**annealed**");
  2. Austenitized and oil-quenched ("**as-quenched**"); and
  3. Austenitized, oil-quenched, and tempered ("**quenched and tempered**").

  For each material condition and associated microstructure we will perform the following mechanical tests:
  1. A manual bending test to infer tensile yield strength from fully-plastic bending.
  2. A tensile test.
  3. A Rockwell A scale hardness test.
  4. A Charpy V-notch impact test.
- We will discuss the correlations between the measured mechanical properties (strength, hardness, ductility, impact energy) in the various heat-treated conditions.

3 Lab Assignment: Specific Questions to Answer

1. Describe the heat treatment processes conducted on the 4140 steel during the laboratory session.

2. Tensile stress-strain data for 4140 steel, in the three conditions considered, was generated and recorded.

   Plot engineering stress- vs. engineering strain curves for each of the three heated-treated material states, and from them obtain the following tensile properties:

   (a) Tensile yield strength (0.2 percent offset), σ_y;

   (b) Ultimate tensile strength, σ_{TS};

   (c) The reduction in area at fracture, $q \equiv (A_0 - A_f)/A_0$ where $A_0 \equiv$ original cross-sectional area, and $A_f \equiv$ final cross-sectional area of the tensile test specimens. Note that q is a measure of ductility, or plastic strain to failure.

3. Based on the results of manual, fully-plastic bending tests, provide <u>estimates</u> of the tensile yield strength, $\sigma_y^{(\mathrm{f-p\,bend})}$, of the steel in the three heat-treated conditions. Is your estimate for the as-quenched steel credible? Explain why or why not.

4. Based on the Rockwell A-scale hardness (HRA) data collected during the lab session, provide <u>estimates</u> of the ultimate tensile strength $\sigma_{\mathrm{TS}}^{(\mathrm{HRA})}$ of the steel in the three heat-treated conditions. To complete this task, use the conversion charts contained in the Lab 5 Background handout. How well do the hardness-based estimates ($\sigma_{\mathrm{TS}}^{(\mathrm{HRA})}$), compare with the measured tensile strengths, σ_{TS}? In particular, what is the source of discrepancy for the data from the **as-quenched** condition?

5. Tabulate, for each heated-treated condition, the tensile properties, $(\sigma_y, \sigma_{\mathrm{TS}}, q)$, the Rockwell hardness and corresponding estimated tensile strength $\sigma_{\mathrm{TS}}^{(\mathrm{HRA})}$, the fully-plastic bending estimate of yield strength, $\sigma_y^{(\mathrm{f-p\,bend})}$, and the Charpy V-notch impact energy ($\mathcal{E}_V^{(\mathrm{Charpy})}$) data.

6. Over the set of lab sections, tensile and hardness data was obtained for the quenched-and-tempered condition using a range of tempering temperatures (see the web page for a summary of the results). Plot the data as a function of tempering temperature, and identify and discuss trends in the resulting properties.

7. Identify and discuss major trends in the data. In particular, how do the strength, ductility, hardness and impact energy change with heat treatment? What measured material properties are are strongly correlated? Inversely correlated?

Name:
Lab Section:
Pre-Lab Assignment:

(Please review the Lab 5 Background handout)

Describe what phase (or phases) are present in the 4140 steel at the temperature of 850°C, and describe how and where the $0.4\,wt\%$ carbon is distributed within the material.

Describe what phase (or phases) are present in the 4140 steel immediately following a rapid quenching step from 850°C, and describe how and where the $0.4\,wt\%$ carbon is distributed within the material.